Sensor Networks and Their Applications: Investigating the Role of Sensor Web Enablement

A Thesis submitted for the degree of
Communications Engineering Doctorate (EngD)

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Statement of Originality

I, Jeffery George Foley, confirm that the work presented in this thesis is my own.

Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signed: ________________________________

Date: ________________________________

Abstract

The Engineering Doctorate (EngD) was conducted in conjunction with BT Research on state-of-the-art Wireless Sensor Network (WSN) projects. The first area of work is a literature review of WSN project applications, some of which the author worked on as a BT Researcher based at the world renowned Adastral Park Research Labs in Suffolk (2004-09). WSN applications are examined within the context of Machine-to-Machine (M2M); Information Networking (IN); Internet/Web of Things (IoT/WoT); smart home and smart devices; BT's 21st Century Network (21CN); Cloud Computing; and future trends. In addition, this thesis provides an insight into the capabilities of similar external WSN project applications.

Under BT's Sensor Virtualization project, the second area of work focuses on building a Generic Architecture for WSNs with reusable infrastructure and 'infostructure' by identifying and trialling suitable components, in order to realise actual business benefits for BT.

The third area of work focuses on the Open Geospatial Consortium (OGC) standards and their Sensor Web Enablement (SWE) initiative. The SWE framework was investigated to ascertain its potential as a component of the Generic Architecture. BT's SAPHE project served as a use case. BT Research's experiences of taking this traditional (vertical) stove-piped application and creating SWE compliant services are described. The author's findings were originally presented in a series of publications and have been incorporated into this thesis along with supplementary WSN material from BT Research projects. SWE 2.0 specifications are outlined to highlight key improvements, since work began at BT with SWE 1.0.

The fourth area of work focuses on Complex Event Processing (CEP) which was evaluated to ascertain its potential for aggregating and correlating the shared project sensor data ('infostructure') harvested and for enabling data fusion for WSNs in diverse domains. Finally, the conclusions and suggestions for further work are provided.

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International Conferences and Summer Schools
In addition, our research ideas have been presented and well received at a number of international conferences and summer schools on WSNs. They were organised by leading experts, so thanks to all the organisers which further inspired me on sensor networks and their applications:

- **RUNES** – Dr. Costis Kompis (Vodera, Sensors & Instrumentation - WiSIG);
- **Senzations** – Srdjan Krco (Ericsson) and Konrad Wrona (NATO C3 Agency);
- **MCANAE** – GKmM and Darmstadt University;
- **SENIOT** – CONET, Dr. Kay Römer and Prof. Friedemann Mattern (ETH Zurich);
- **EuroSSC** – Dr. Gerd Kortuem (Lancaster University, UK);
- **ISWPC** – University of Patras, Greece;
- **COMSWARE** – Trinity College Dublin;
- **S-CUBE** – Dr. Kay Römer (ETH Zurich);
- **LCS** – University College London.

Please refer to Appendix J for further details of summer schools or p.35 for conference publications.

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List of Abbreviations

6LoWPAN	IPv6 over Low power Wireless Personal Area Networks (IETF Internet WG and alternative to ZigBee)
21CN	BT's 21st Century Network
µAMPS	Power Aware Wireless Microsensor Networks (MIT / DARPA project)
AFIS	Advanced Fire Information System
AI	Artificial Intelligence
AODV	Ad-hoc On-Demand Distance Vector routing protocol for mobile ad-hoc networks (MANETs)
API	Application Programming Interface (e.g. Java wrapper)
ARC	Austrian Research Centers (e.g. SANY)
ArcIMS	Internet protocol Multimedia Subsystem Web server (AFIS)
AUV	Autonomous Underwater Vehicle (military drones)
B2B	Business-to-Business (commerce transactions between businesses, e.g. manufacturer and wholesaler or wholesaler and retailer)
B2C	Business-to-Consumer
B2G	Business-to-Government
BAEWP / BOP	Building Awareness for Enhanced Workplace Performance / Making Sense of Space
BAN	Body Area Network (RUNES project)
BGS	British Geological Survey (Nottingham HQ, UK)
Bi-morphs	Developed by Imperial College (PIPES project)
BMS	Building Management System (BOP project e.g. HVAC)
BRIDGE	Building Radio frequency Identification for the Global Environment (BT project)
BSN	Body Sensor Network (e.g. SAPHE)
BWRC	Berkeley Wireless Research Center (UC Berkeley, California)
C2CCC	Car-to-Car Communications Consortium
CAN	Controller Area Network bus (Traffimatics project)
CBM	Condition Based Maintenance (industrial apps, e.g. monitoring of automated assembly lines)
CCL	Continuous Computation Language (Sybase CEP)
CCTV	Closed Circuit Television cameras
CENS	Center for Embedded Networked Sensing (UCLA)
CEP	Complex Event Processing (e.g. EsperTech; Sybase/Coral8; StreamBase)
CF	Component Frameworks (RUNES project)
CISG	Communications & Information Systems Group (Dept of Electronic & Electrical Engineering)
CITRIS	Center for Information Technology Research in the Interest of Society (UC system research)

CMOS	Complementary Metal Oxide Semiconductor (technology for constructing integrated circuits)
COMSWARE	Conference on Communication System Software & Middleware (Dublin, Ireland 2009)
CONET	Cooperating Objects Network of Excellence (EU-funded project under ICT, Framework 7)
Contiki	An open source operating system for the Internet of Things (SICS / RUNES project)
COTS	Commercial-off-the-shelf (e.g. hardware components or software)
CRM	Customer Relationship Management
CSIR / SAC	Council of Scientific & Industrial Research (India) / Satellite Application Centre (AFIS)
CSMA / CA	Carrier Sense Multiple Access / Collision Avoidance
CS-W	Catalogue Service for Web (SWE Registry)
CVIS	Cooperative Vehicle-Infrastructure Systems (TfL)
CWAB	Collision Warning with Auto Brake (Developed by Volvo)
DDD	Delay-tolerant Data Dolphin
DIP	Data, Information & Process Integration with Semantic Web Services (NGWR)
DSR	Dynamic Source Routing protocol for wireless mesh networks
DTI	formerly Department of Trade & Industry, renamed TSB
EO-1	Earth Observation (NASA)
EML	Event Pattern Markup Language (SWE specifications)
E2E	End-to-End (e.g. Network Security)
ENGD	Engineering Doctorate in Communications
EPL	Event Processing Language (CEP e.g. EsperTech)
EPSRC	Engineering and Physical Sciences Research Council (funded EngD)
ERP	Enterprise Resource Planning
ESA	European Space Agency
ESKOM	South African Electricity Company (AFIS)
ESP	Event Stream Processing (Event pattern for SES)
ETSI / STF	European Telecommunications Standards Institute / Special Task Force
ETH Zurich	Engineering, science, technology, mathematics and management university
EuroSSC	European conference on Smart Sensing and Context (Kendal, UK 2007)
FFT	Fast Fourier Transformation
FMCG	Fast-Moving Consumer Goods (e.g. grocery items and consumer electronics)
FoI	Feature of Interest (SWE)
FON	Fon Wireless Ltd. operates a system of dual access wireless networks
FreeRTOS	Free Real Time Operating System (RUNES project)
GEOSS	Global Earth Observing System of Systems (OGC / OOSTethys / Wildfire)
GIS	Geographical Information System
GMES	Global Monitoring for Environment and Security (ESA)

GML	Geographic Markup Language (Google Maps)
GNSS	Global Navigation Satellite System (Galileo)
GPL	General Public Licence / Open Source licence
GPON	Gigabit Passive Optical Network fibres
GPS	Global Positioning System (US satellites)
GS1	Supply-chain standards system used around the world e.g. RFID (BRIDGE project)
GSM	Global System for Mobile Communications (Telecoms Standard)
HMA	Heterogeneous Mission Accessibility (ESA)
HMD	Head-Mounted Display (3D Virtual / Augmented Reality e.g. RUNES project)
HPAC	Hazard Prediction & Assessment Capability
HTTP	Hypertext Transfer Protocol (Internet)
HVAC	Heating, Ventilation & Air Conditioning system
ICT	Information & Communications Technology
ICT4EO	Information & Communications Technology for Earth Observation (CSIR)
IDA	Intelligent Data Analysis (Telecare)
IDE	Integrated Development Environment (Java)
IETF	Internet Engineering Task Force (e.g. 6LoWPAN)
IMS	IP Multimedia Subsystem
IN	Information Networking (BT Research theme)
IOOS	Integrated Ocean Observing System (US Marine)
IoT	Internet of Things
IP	Internet Protocol stack
IPv6	Internet Protocol version 6 (superseded version 4)
IPsec	Internet Protocol Security
ISM	Industrial, Scientific & Medical (RF spectrum bands)
ISP	Internet Service Provider
IST	Information Society Technologies
ISWPC	International Symposium on Wireless Pervasive Computing (Santorini, Greece 2008)
ITS	Intelligent Transport Systems (C2CCC)
ITU	International Telecommunication Union
JHU	John Hopkins University (Baltimore, Maryland, USA)
JIT	Just-In-Time management (business inventory strategy)
JTS	Java Topology Suite (Open Source Library)
LAN	Local Area Network
LBS	Location Based Services (C2CCC / Traffimatics project)
LCS	London Communications Symposium
LWIMs	Low Power Wireless Integrated Microsensors (UCLA / Rockwell Science Center)
M2M	Machine-to-Machine (BT Research theme)
MAC	Medium Access Control
MANET	Mobile ad hoc networks (e.g. Mesh networking topology)

MCANAE	Monitoring & Coordination Across Networked Autonomous Entities (GKmM event)
MCU	Micro Controller Unit
MEMS	Micro Electro-Mechanical Systems (e.g. Games console component)
MIT	Massachusetts Institute of Technology (e.g. µAMPS project)
MMI	Marine Metadata Interoperability
MPU	Micro Processor Unit (e.g. Mote microchip)
NEMS	Nano Electro-Mechanical Systems
nesC	Network Embedded Systems C programming language used for TinyOS
netCDF	network Common Data Form (OGC)
NFC	Near Field Communication (alternative to RFID trialled by Telenor)
NGN	Next Generation Network (e.g. BT's 21st Century Network)
NGWR	Next Generation Web Research (BT Research Group)
NTS	NetTopologySuite (.NET port)
NWGISS	NASA HDF-EOS Web GIS Software Suite
OCEANS IE	Ocean Science Interoperability Experiment (OOSTethys / OGC)
OGC	Open Geospatial Consortium (Developed SWE)
OOI	Ocean Observatories Initiative (US Marine)
OOSTethys	Ocean Observing System Architecture (US Marine)
ORM	OGC Reference Model
O&M	Observations & Measurements (SWE specifications)
ORION	Ocean Research Interactive Observatory Networks
ORNL	Oak Ridge National Laboratory
OSGeo	Open Source Geospatial Foundation
OSI	Open Systems Interconnection model stack
OSWA	Open Sensor Web Architecture (OGC)
OWL	Web Ontology Language (Semantic Web)
OWS	OGC Web Service Framework / Phases
PAN	Personal Area Network
PCT	Primary Care Trust (Division of National Health Service, UK)
PDA	Personal Digital Assistant
PICT	Pervasive Information & Communications Technology Centre (BT Research)
PIPES	Personalised Information from Prioritised Environmental Sensing (BT project)
PIR	Passive Infra-red sensors
POE	Post Occupancy Evaluation, paper-based (BOP project)
PVR	Personal Video Recorder
RAG	Live Web portal - wards classified as Red, Amber or Green (SAPHE)
RF	Radio Frequency
RFID	Radio Frequency Identification tagging. Also, RFID Reader to detect sensors
RHCS	Remote Health Care System based on WSNs (Peng Zhang)
RPC	Remote Procedure Calls

RT	Real-Time
RTE	Real-Time Enterprise
RUNES	Reconfigurable Ubiquitous Networked Embedded Systems (UCL project)
SAEOS	South African Earth Observation Strategy (CSIR Meraka Institute)
SAFNET	Southern African Fire Network (CSIR Meraka / AFIS)
SANY	Sensors Anywhere (IST FP6 project led by Dr. Denis Havlik of ARC)
SAPHE	Smart & Aware Pervasive Healthcare Environment (BT project)
SAS	Sensor Alert Service (superseded by SES in NG SWE 2.0)
SDI	Spatial Data Infrastructures (NG SWE 2.0)
SDK	Software Development Kit
SDS	Sensor Dispatch System (Developed by Nortel Networks)
SensorML	Sensor Model Language (Developed by Dr. Mike Botts of VAST for OGC SWE)
SES	Sensor Event Service Interface Spec (NG SWE 2.0)
Senzations	Summer School on WSNs Warsaw, Poland 2007
SHM	Structural Health Monitoring (University of Southern California project developed Wisden and NET-SHM systems)
SICS	Swedish Institute of Computer Science (Luca Mottola)
SID	Sensor Interface Descriptor (NG SWE 2.0)
SIR	Sensor Instance Registry (NG SWE 2.0)
SMS	Short Message Service (text messages)
SPS	Sensor Planning Service (SWE specification)
Sun SPOT	Small Programmable Object Technology (Motes developed by Sun Microsystems)
SWE	Sensor Web Enablement (Developed by OGC)
SECOAS	Self-Organising Collegiate Sensor (BT project)
SENIOT	From Sensor Networks to Networked Intelligent Objects (CONET event 2009)
Sentilla	Formerly Moteiv (e.g. Tmote Sky mote)
SFS	Simple Features – SQL (OGC)
SAPHE	Smart & Aware Pervasive Healthcare Environment (BT project)
SNG	Sensor Networks Group (BT Research, PICT Centre)
SNR	Signal-to-Noise Ratio
SOA	Service Oriented Architecture (NGWR projects)
SoC	System-on-Chip (e.g. integrated systems on a single chip, embedded processors from Atmel, Intel and Texas Instruments)
SOC	Secure Operation Centre (BT Redcare's Trackit)
SOR	Sensor Observable Registry (NG SWE 2.0)
SOS	Sensor Observation Service (SWE)
SpO2	Spot Oxygen Saturation (SAPHE)
SRD	Short-Range Device
SSL	Secure Socket Layer

SURA / SCOOP	Southeastern Universities Research Association / Coastal Ocean Observing and Prediction
SWAP	Sensor Web Agent Platform
SWS	Semantic Web Services
Telco	Telecommunication Company
TinyOS	Tiny open source / operating system. Developed by UC Berkeley, Intel Research and Crossbow Technology (e.g. Xbow motes)
TfL	Transport for London (CVIS, Tube, Trains, Taxis, Buses)
TLS	Transport Layer Security
TML	Transducer Mark-up Language (defunct in NG SWE 2.0)
TSB	Technology Strategy Board (formerly DTI)
TSMP	Time Synchronized Mesh Protocol developed by Dust Networks for self-organising networks of wireless devices called motes.
UAH	University of Alabama in Huntsville (VAST led by Mike Botts)
UART	Universal Asynchronous Receiver/Transmitter
UAS	Unmanned Aerial System-based and ground based sensors
UAV	Unmanned Aerial Vehicle (military drones)
UCB	University of California, Berkeley (e.g. PicoRadio team)
UCLA	University of California, Los Angeles (e.g. Medusa and WINS)
UDF	User Defined Functions
USN	Ubiquitous Sensor Network
UWSN	Underwater Wireless Sensor Networks
VAST	VisAnalysis Systems Technologies (UAH developed SensorML)
VM	Virtual Machine (Java)
VPN	Virtual Private Network (e.g. SAPHE project secure login)
WAN	Wide Area Network
WCS	Web Coverage Service (OGC)
WCTS	Web Coordinate Transformation Service (OGC)
WFS	Web Feature Service (OGC)
WiFi	Wireless Fidelity standard for Internet connection
WINS	Wireless Integrated Network Sensors (e.g. Rockwell Science Center processor & radio boards)
WLAN	Wireless Local Area Networks
WMS	Web Map Service (OGC)
WoT	Web of Things
WPAN	Wireless Personal Area Network
WPS	Web Processing Service (OGC)
WS	Web Services
WTS	Web Terrain Service (OGC)
WG	Working Group

WSN	Wireless Sensor Network
XBOW	Crossbow Motes
ZigBee	Specification for a suite of high level communication protocols using small, low-power digital radios based on an IEEE 802 standard for PANs.

CHAPTER 1 Sensors Are Everywhere

1 Introduction

Chapter 1 explains why "sensors are everywhere" by introducing wireless sensor network (WSN) domains and applications and an explanation as to why sensor motes are expected to become ubiquitous in the future. The author considers it important to provide a research context to WSNs and therefore outlines key related areas, namely Machine-to-Machine (M2M); Information Networking (IN); Internet/Web of Things (IoT/WoT); smart home and smart devices; BT's 21st Century Network (21CN); Cloud Computing; and future trends. Over the last ten years, BT Research has collaborated in a number of projects that utilise sensor network infrastructure, covering a wide range of application domains. Therefore, deployments from around the world including the USA, South Africa, UK and European initiatives are exemplified.

1.1 Domains and Applications

WSNs are at the forefront of innovative projects and emerging industry standards and as a result are becoming increasingly pervasive in society. For instance, WSNs are a leading part of the IoT and key to healthcare applications such as BT's Telecare, and SAPHE (Smart & Aware Pervasive Healthcare Environment) projects. A vast amount of valuable, high-quality data can be captured such as proximity, vibration, light, humidity and temperature by an array of sensor network nodes, prior to being stored and analysed. The potential of WSNs became apparent to the author while surveying WSNs, identifying the domains and developing the "bubble" diagram (Figure 1) from 2007. The diagram continued to be revised to represent key domains as new WSN projects commenced. As illustrated in Figure 1, WSNs are already pervasive in the majority of domains due to their versatility across applications and relatively cheap deployment costs. A varied array of exciting WSN projects were identified during the survey which already had proven benefits for society and encompass the following domains and critical applications:

Health Monitoring and Assisted Living

- In-home tele-monitoring of patient physiological data (e.g. Telecare and SAPHE);
- Body Sensor Networks (BSN) monitoring mobile patients;
- Intel Alzheimer's Pilot use of WSNs for Telecare;
- Intel IrisNet (Internet-scale Resource Intensive Sensor Services);
- Hitachi Collectlo;
- A Remote Health Care System Based on WSNs;
- Drug administration and inventory control in hospitals.

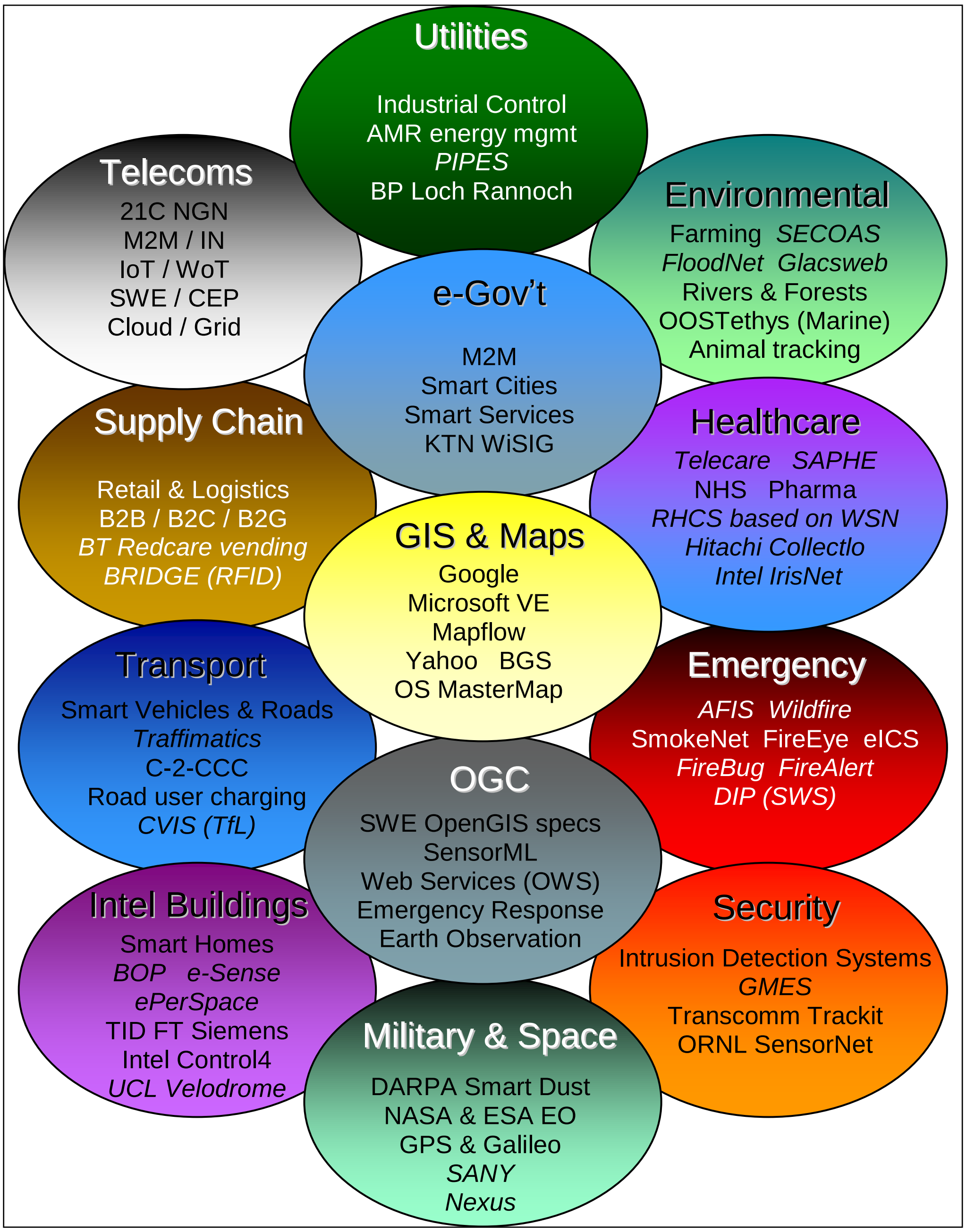

Figure 1 - WSN Domains Bubble Diagram [1]

Intelligent Agriculture and Environmental Sensing

- Weather stations, environmental monitoring and habitat study (e.g. Marine);
- Precision agriculture monitoring and land management to ascertain the quality of the soil moisture for crop growing and optimal farming conditions in developing countries;
- Monitoring habitat for conservation of natural heritage (e.g. Redwood trees) and Bio-complexity mapping of the environment;
- Factories and oil wells to monitor industrial motors and fuel emissions;
- Structural monitoring (e.g. highways and bridges);

- At sea to measure wave heights and monitoring coastal erosion around small islands intended for wind farms (e.g. SECOAS);
- Providing flood detection and warning in the UK (e.g. FLOODNET);
- Cleaning up river pollution to ensure the protection of wildlife which depends on the local habitat for survival;
- Monitoring the temperature of glaciers to determine the effects of global warming (e.g. GLACSWEB);
- Forest fire prediction (e.g. AFIS, FireBug, FireAlert, Bushfire CRC);
- Livestock monitoring and animal tracking (e.g. sheep, fish farms, dolphins, sealions, zebras);
- Monitoring the micro-climates around Storm Petrel nesting burrows (e.g. Great Duck Island project by Intel Research and UC Berkeley in 2002);
- Monitoring natural disasters (e.g. land-slide prediction, volcanoes to ascertain seismic activity).

Smart Vehicles

- Vehicle Telematics for smart vehicles and for interfacing with traffic infrastructure (e.g. Traffimatics and C2CCC);
- Transportation, logistics and tracking car thefts (e.g. BT Trackit);
- Autonomous Underwater Vehicle (AUV) and Unmanned Aerial Vehicle (UAV) remote-controlled military drones;
- BP using RFID and motes on railcars and onboard Loch Rannoch for predictive maintenance.

Intelligent Buildings and Infrastructure

- Workplace monitoring (e.g. BOP, Meraka robotic cameras);
- Utility infrastructure monitoring (e.g. PIPES) and Automated Meter Reading (AMR);
- RFID and supply chain management (e.g. BRIDGE);
- Home automation and smart environment (e.g. Control4, ePerSpace, smart devices with GPS/MEMs);
- WSN monitoring of the Olympic Velodrome conducted by UCL;
- Monitoring fitness machine usage patterns for maintenance and enabling gym users to keep track of their personal workouts via an accelerometer;
- Interactive museums and historic sites (e.g. National Trust, English Heritage, CADW);
- Mood Detection (e.g. e-Sense).

Asset Tracking and Supply Chain Management

- Warehousing, tracking, location, logistics (e.g. RFID tags and readers, GPS);
- Industrial monitoring (e.g. Intelligent buildings and infrastructure / utility monitoring);
- Managing inventory control (e.g. BRIDGE; BT Redcare’s Vend Online);
- Anti-theft of copper and cabling (e.g. PIPES);

- Energy harvesting (e.g. UCL's Efficient Energy Management in Energy Harvesting WSNs).

Military and Security Sensing

- Front-line reconnaissance of enemy forces and hostile terrain (e.g. DARPA Smart Dust);
- Battle damage assessment - Nuclear, biological and chemical attack detection (e.g. DARPA, Cogent's bomb-proof suit);
- Search and rescue services and disaster response management (e.g. OWS-4 "Dirty Bomb");
- National security and Police shot-stopper (e.g. CCTV, Biometric sensors);

Figure 2 conveys the potential scale of sensors, sensor systems and WSNs. Whether sensor deployments are small or medium-sized (e.g. environmental monitoring) to full-scale sensor systems (e.g. satellites in orbit or seismic sensors deployed on the seabed).

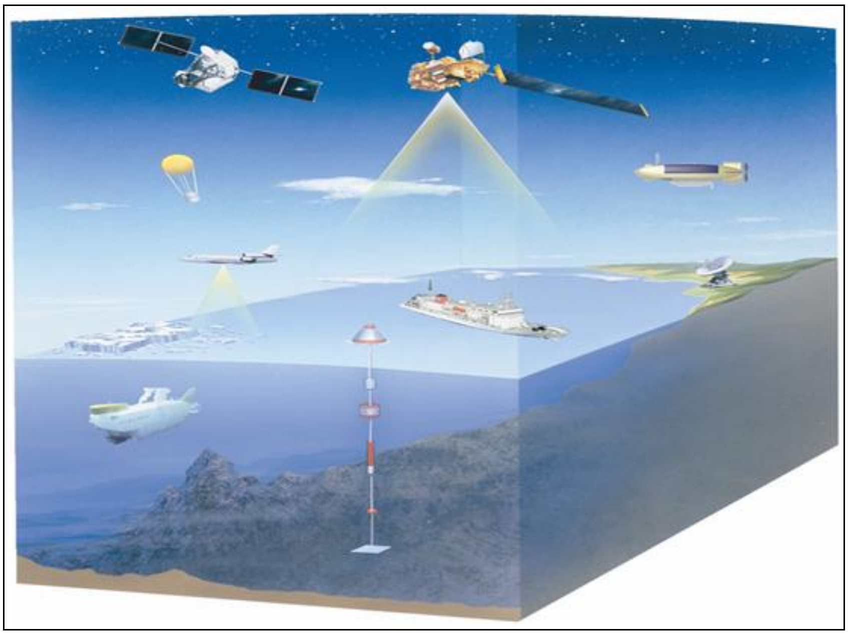

Figure 2 - Sensors & Sensor Systems [2]

Libelium's recent and comprehensive "Fifty Sensor Applications for a Smarter World" **[3]** includes all the domains in which BT Research has participated in WSN projects as well as some new areas. WSNs will go beyond niche applications for smart vehicles or smart buildings to form more expansive and integrated domains such as Smart Cities and the Internet of Things. Refer to Appendix A for the full list. The OGC's and Libelium's literature provide evidence to support the author's assertion that "sensors are everywhere". Professors, sensor network experts, BT researchers and futurologists agree that sensors are becoming pervasive and ubiquitous throughout society (see Figure 1 "bubble" diagram). For example, sensors used in everyday life already include, passive infrared (PIR) motion detector sensors for corridor or office lighting, intruder alarm, CCTV security systems, smoke alarm, fire sprinkler systems, contact switches, bed occupancy sensors, accelerometer, ECG recorder (chest), SpO2 (Spot Oxygen Saturation), location (GPS), weighing scales, bathroom sensors, etc. A single sensor may act in isolation to detect a type of phenomenon (usually between a range of values or within a certain threshold) and perform a simple pre-defined task. Similarly, a number of sensors may act as part of a system to achieve a given task. Government, industrial and academic research initiatives (e.g. WiSIG) and collaborations in the UK, Europe and around the world are collaborating to standardise, expand and harness the increasing capabilities of WSN motes.

In fact, sensor motes continue to evolve together with the advent of smart and innovative electronic devices (such as those by Apple) becoming more powerful, affordable, reliable and miniaturised with integrated functionality (i.e. sensing, actuation, computation and communication components) as well as their ability to share sensor data.

The Internet and World Wide Web have become indispensable over the last twenty years. Similar to and facilitated by its predecessor, WSNs are expected to become ubiquitous as there is a rapid increase in applications envisaged and developed. Indeed, there are exciting future opportunities as individuals, companies and universities harness the potential of WSN applications and realise the Sensor Web. WSN is next generation technology, but is happening now and it is envisaged that a future proliferation of WSNs will lead to there being more sensors than people. In 2008, Ernest and Young predicted, “By 2010, there will be 10,000 telemetric devices for every human in the planet!” **[4]**. In 2010, Stephen Brobst, CTO of Teradata speaking on ‘Big Sensor Data’, claimed, “Within the next 3 to 5 years, I expect to see sensor data hit the crossover point... From there, the former [sensor data] will dominate by factors; not just by 10-20 percent, but by 10-20 times that of social media” **[5]**. In 2011, Verizon and Ericsson predicted, “The number of internet-connected devices will reach between 50 and 60 billion by the end of the decade” **[6]**.

1.2 BT Research Context and Sensor Networks Group (SNG)

As explained by Dr. George Bilchev **[7]** in 2005, the Sensor Networks Group (SNG) was formed in BT at Adastral Park investigating the issues and challenges surrounding sensor networks, Machine-to-Machine (M2M), pervasive information and pervasive computing. BT Research already had great expertise in the field of sensor networks based on a number of previous research projects and the new group became a focus of this kind of research activities within the company. Of research interest to the group are topics like optimal wireless connectivity and routing, data fusion, distributed processing, semantic data interpretation and querying the physical world to name a few. On a higher level the SNG were interested in researching the challenges of ‘sensing the real-world’ in the context of the Real-Time Enterprise (RTE) as well as the management of the large scale of sensor nodes and information flow.

The author was a researcher in the SNG, therefore he was privileged to contribute and observe / learn first-hand of regular developments during team meetings, presentations, blog reports and emails. For instance, the author’s manager, Dr. Bilchev led the Traffimatics (vehicle Telematics or “smart vehicles”) project. Dr. Jane Tateson and Dr. Chris Roadknight had leading roles within SECOAS (environmental monitoring); PIPES (pipeline infrastructure monitoring) and BOP (workplace monitoring) projects; Paul Bowman led Telecare and BRIDGE (RFID supply chain and asset management). Nigel Barnes and Tom Mizutani led the SAPHE healthcare project.

Therefore, the author had the authorisation and co-operation of the senior BT Researchers to include these WSN projects in this thesis, especially since he made contributions to some of them. In fact, without the knowledge of these WSN projects and the foresight of his BT colleagues, the author would not have learned as much about the compelling capabilities of WSNs and the fascinating applications, in order to complete the EngD requirements.

BT Redcare and ongoing R&D in healthcare innovations hence continued projects with the NHS. Over ten years of Telecare research and trials by BT and its project partners, Telecare is increasingly regarded as the solution to the ageing population and the limited number of healthcare professionals. However, as brilliant and beneficial as the Telecare concept is, to enable the discreet and accurate WSN monitoring of the vital health statistics for a number of patient conditions while located in their home or on the move (BSN for outdoors), it has yet to be rolled out throughout the UK – only limited trials in Liverpool during the SAPHE project.

BT Research successfully trialled the SWE Framework and CEP for some of their WSN projects, notably SAPHE and BRIDGE. The future of BT Research continues to be at the forefront of innovative technological developments and indeed, the SNG had already begun investigating how to integrate WSNs with Intelligent Networking (IN) platforms such as Solace Systems' content networking routers and Cloud Computing (2008-09). The Cloud returns to the centralised processing model, whereby intelligence, resources and power are back at centre of the network. Cloud Computing entrusts remote services with a user's data, software and computation.

For instance, under the IN theme, the author trialled CEP (i.e. Esper, Coral8) to aggregate and correlate sensor data streams and explored how WSN node data may be used within IN / Cloud Computing / Intelligent Routing. Mozilla Firefox and the Piggy Bank and Solvent add-ons were used to perform Semantic Web technology screen-scraping of live UK airport flight schedules, train timetables, car parking tariffs, weather stations, RSS feed subscriptions in order to create a mash-up (data fusion) of online sensor data combined with real-time information sources.

BT Research continued to develop the IN theme under a team including my former BT colleague, Paul Deans. BT Research also pursues excellence in Intelligent Network (network integration) and Services (convergence) with 21CN; Semantic Sensor Web and Service Oriented Architectures (SOA) as explored in a number of projects by Dr. John Davies' Next Generation Web Research (NGWR) Group and Phil Bull's Customer Networks Group. The NGWR recently developed transport technologies for the Internet of Things, such as a journey planner and BT Global Trace for E2E supply chain visibility **[8]**.

Before discussing WSNs in more detail, the author considers it essential to provide a context to WSNs and therefore to explain key related areas, namely NGN; M2M; IoT; WoT; Smart home and devices; 21CN; Cloud Computing; and Future Trends.

1.3 Next Generation Networks (NGN), Machine-to-Machine (M2M) and the Internet of Things (IoT)

Next Generation Networks (NGN) such as BT's 21st Century Network are an enabling factor, since the Telecoms Infrastructure using Broadband and Ultra Wide Band (UWB) is the backbone enabling the delivery of M2M, IoT, smart services and WSN applications. BT Infinity was rolled out in the UK in 2011 and BT also offer OpenZone and a FON hotspots app. BT and other UK mobile network operators and internet service providers such as EE (Everything Everywhere, a merger between Deutsche Telecom and Orange in 2010) offer free wireless Internet access while on the move and accessible in cafes, hotels, airports, trains, coaches, ferries and the London Eye WiFi-enabled capsules. In Japan, South Korea and Dubai, Gigabit Passive Optical Network (GPON) fibres are commonplace NGNs.

M2M refers to Information and Communication Technology (ICT) business solutions that are characterised by the communication between remote devices and central management applications enabling real-time control and monitoring. M2M is a global technological and business phenomenon, also known as the Pervasive Internet. BT Research defined M2M as "the automated communication between remote machines and central management applications, enabling real-time control and monitoring, without human intervention in the transfer of data". The term M2M has been loosely used outside BT to cover a broad range of communication modes including Machine-to-Machine, Machine-to-Application, Machine-to-Man and vice-versa **[9]**.

M2M portrays an era where:

- All manufactured objects (e.g. buildings, vehicles, appliances, medical devices) and people are connected (e.g. healthcare specialists - patients already implanted with microchips);
- All manufactured objects could sense their environment, status, condition and performance;
- Major business opportunities lie in the ability to harvest the pervasive wealth of information to offer extraordinary business advantage;
- Customer service, resource allocation and productivity could be radically transformed;
- 21CN smart services, system applications, network services, connectivity are commonplace;
- The Cloud infrastructure is employed and interoperable with other platforms (as illustrated in Figure 3).

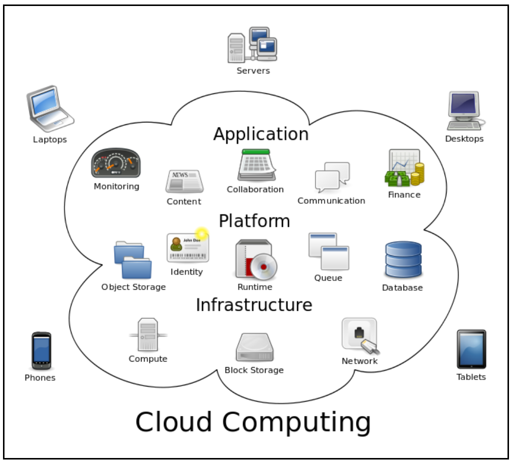

Figure 3 - Cloud Computing [10]

It is perhaps more useful to talk about what M2M attempts to achieve – the automation of the physical world. To achieve this we need both monitoring and control capabilities. Early examples of M2M have been dominated by monitoring, with control feedback often through human processes. Future applications will see more actuators and devices in the environment that can be directly controlled. We will also see information sharing between devices and localised intelligence with many processes no longer requiring the support of centralised applications. As more of the physical world becomes connected and automated, what we consider currently to be separate applications will begin to merge. We will see new applications that use a fusion of data from different domains, companies and device types. What has started as the automation of selected processes will lead us towards a connected physical world, and some of the hardest research challenges that lie ahead will be to enable this vast and complex infrastructure to be managed.

As Kevin McNulty, the CEO of BT Transcomm stated, "BT through its Redcare unit is a significant player in the UK M2M market through its security and vending businesses". The M2M service platforms of Transcomm are shown in Figure 4.

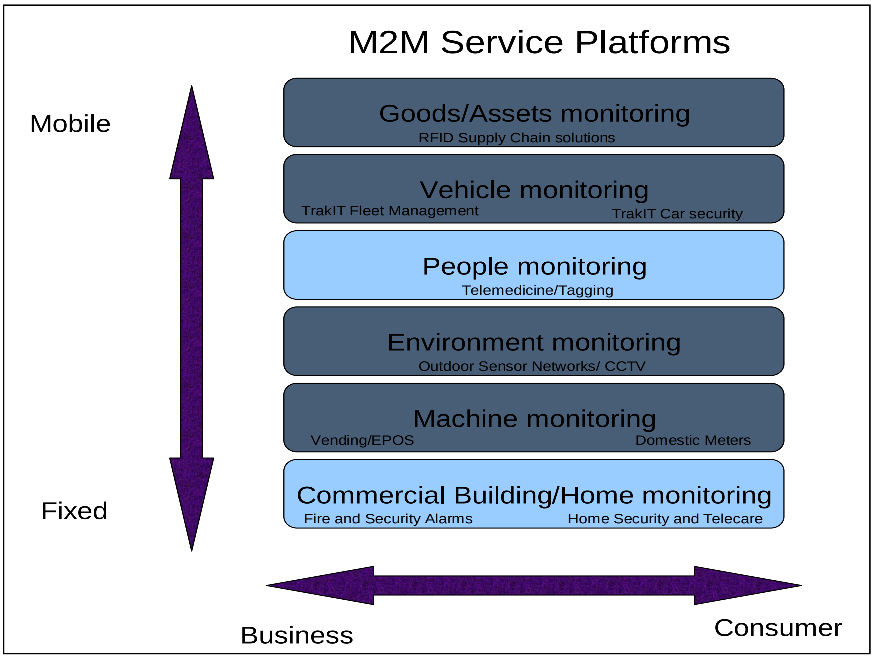

Figure 4 - M2M Service Platforms [11]

M2M research has existed for many years across different research fields. Some research areas such as ubiquitous or pervasive computing, automated manufacture or sensor networks have direct applicability. Many other research topics draw their roots from complex systems, enterprise integration and systems engineering. Although some research questions are restricted to certain layers of the framework, many span all the layers. For example, although battery life may initially appear to be a device problem, it has implications on both the design of the network, and the capabilities of the middleware.

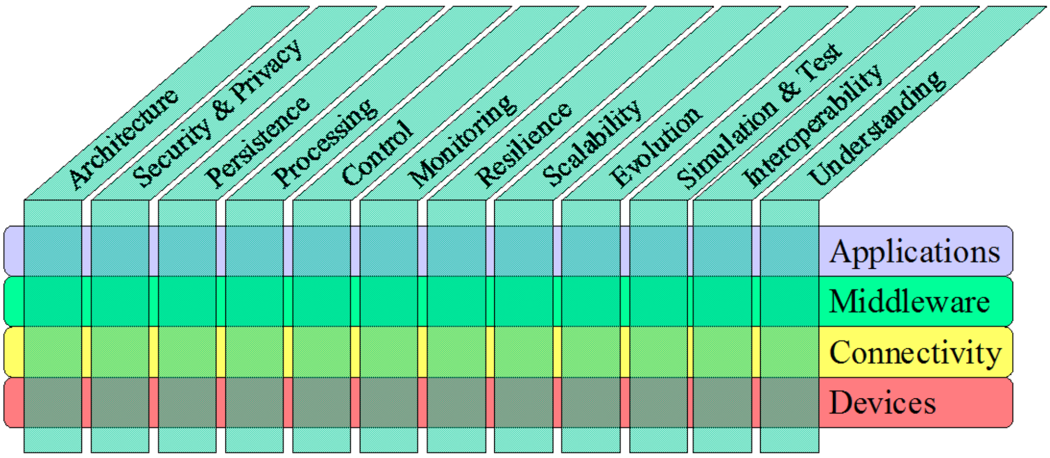

Figure 5 - M2M Research Space [12]

The topics shown in Figure 5 are only one way of dividing the research space, but show the breadth of the problem even though necessarily some questions will not immediately fall into the topics shown. On browsing the additional material below, the reader will notice that each topic provides a unique angle to view the research space, but is not detached from the other topics. Indeed much of the complexity of M2M research comes from balancing the many overlapping requirements.

For BT Research's M2M and Information Networking (IN) themes the following components were identified:

- Sensor Virtualization – a common interface and description for all sensors (e.g. SWE);
- CEP engines – creating business information from sensed data (e.g. Esper, Coral8, StreamBase);
- Geospatial Reasoning and Visualization – access to geospatial functionality (e.g. MapServer, Google Earth, Microsoft Virtual Earth, NASA World Wind).

These three elements – sensors, tags and communication / processing capacity - together make up a future network vision identified by a number of different names. Some use the terms 'invisible', 'pervasive' or 'ubiquitous' computing, while others refer to 'ambient intelligence' or to describe a future 'Internet of Things'.

The Internet of Things is defined as:

- Ubiquitous computing - cheap, always-on technology to enhance people's lives and work;
- Objects could sense, communicate and interact (i.e. context aware);
- Security Challenges - personalisation and privacy are important elements for WSNs;
- Service-Oriented Architecture (SOA) - All objects have a digital equivalent.

Future Trends

The Pervasive Internet and the new world of Smart Systems are ushering in an era where people, machines, devices, sensors, and businesses are all connected and able to interact with one another. As these previously disaggregated parties come together, new modes of collaboration and intelligence will abound fostering a trend that Harbor Research call 'Smart Business.' M2M communication systems are merely the starting point. The development of the Pervasive Internet and the evolution toward Smart Business practices will enable a truly connected world. Inputs from machines, people, video streams, maps, news feeds, and sensors will be digitized and placed onto networks. This will lead to the convergence of the physical and virtual worlds, thus enabling collective awareness, creativity, and better decision making capabilities for societies that increasingly rely on real-time information and interactions. Many observers believe that this phenomenon will drive the largest growth opportunity in the history of business **[13]**.

Therefore, WSNs are likely to become as pervasive as the World Wide Web, especially since ubiquitous and fashionable smart devices such as 4G mobile phones, tablet computers and video games consoles (e.g. market saturation, cheap, apps, web and sensor capabilities) feature accelerometers, GPS, camera and video functionality, MEM technology) and may be classified as 'sensors' in the terminology of the Internet of Things.

Probably the greatest opportunity for future development lies in the actual application of wireless sensor networks. The opportunity for the development of creative uses for these small, inexpensive, low-power, self-organising communication systems appears limitless **[14]**.

Frameworks for Internet of Things / Web of Things

While the Sensor Web describes an infrastructure for heterogeneous sensors, which may be networked or individual, stationary or mobile, and can incorporate in-situ or remote sensing devices, the vision of the two related research fields of Internet of Things and Web of Things is on integrating general, real-world 'things' with the Internet or Web, respectively.

Remote Home Automation / Monitoring

Electronic Personalised Spaces (ePerSpace **[15]** 2004-06) was the author's first IST European collaborative project and set the scene for futuristic services with the smart home "bubble" scenarios. Interestingly, the ePerSpace project provided a glimpse of likely future trends where a number of scenarios will become possible by a fusion of smart home technology and hi-tech sensors used to augment and improve lifestyle, personalisation and security within the home and while on the move.

Companies such as Telefonica (Figure 6), Control4 and Siemens offer various home automation and control solutions dependent on price and user configuration preferences. The smart home features elaborate communication gadgets and sophisticated home entertainment systems, which can be built into new homes or fitted retrospectively. White goods incorporate visual displays, are connected to the smart home residential gateway or home hub, enabling the user to manage their chores more speedily and therefore freeing up time to relax. An alarm system provides home security which may be configured to send SMS alerts to the owner if intruders are detected by external motion sensors or cameras. Perhaps a personal mobile GPS/Galileo sensor unit (that works indoors) linked to a smart home console and display may be used to track the real-time whereabouts of residents, while in different rooms of the house, in the garden, or shopping locally.

Figure 6 - Telefonica's Smart Home in Madrid [16]

Ever-increasing Broadband bandwidth will enable a multitude of NGN services to be delivered to the home. Telefonica R&D in Madrid and the BT showcase at Adastral Park demonstrate the smart home concept. The following are examples of smart home services:

- Home Entertainment (e.g. MP3 music/movie downloads or streaming via iTunes, iPlayer, BT TV/Sport, Netflix, Lovefilm, Blinkbox; online gaming and shopping; social networking (e.g. Facebook, Twitter, YouTube, Flickr);
- Video Communication (e.g. home-workers contacting local offices for remote meetings or virtual chats between family members living in different parts of the world);
- Home Control (e.g. white goods, mood lighting, heating, ventilation and air conditioning, roller blinds);
- Home Security (e.g. access control, alarm systems, surveillance cameras, security lighting, electronic gates and shutters, personal alerts);
- Healthcare Services (e.g. remote diagnosis from medical specialists, ePrescriptions, health insurance).

Automating mundane but essential tasks, thus freeing up time for a more exciting lifestyle:

- Improved security (e.g. IPsec, IPv6, TLS/SSL (https), VPN, E2E and app specific);
- Wireless computing (e.g. WiFi, Bluetooth, ZigBee, RFID, NFC);
- Faster Broadband speeds (e.g. BT Infinity, Virgin Media, Sky, O2, Plusnet acquired by BT);
- Personal video recorder (e.g. BT YouView, Virgin Media TiVo, Sky+);
- BT’s Fusion phone or Skype;
- Sensors integrated to detect light, motion/vibration, temperature or mood.

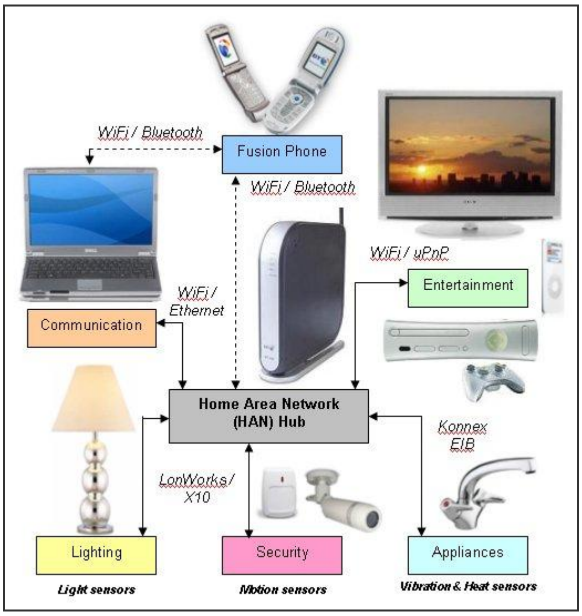

Figure 7 - Smart Home Devices with Sensors [17]

As Dr. Friedemann Mattern (ETH Zurich) **[18]** and Ian Neild (BT Technology Timeline) **[19]** confirmed it is virtually impossible to accurately predict future innovations and difficult to identify the next "killer application". However, trends may be identified and this knowledge combined with the increasing capabilities and speed of NGNs; exponential miniaturisation of mote microprocessor chips (according to Moore's Law) which continue to enable innovative WSN applications to be realised.

During his OGC Standards Tutorial, Dr. Steve Liang (GeoCENS) highlights the SWE for IoT Standard WG and provides the following smart device examples:

- Koubachi - slow motion sensor allows an indoor plant to 'talk' (e.g. plant needs more light, water or is dying);
- NEST (home heating control and monitoring, detects user is back and switches on heating);
- Withing (weighing scales monitor);
- Belkin WEMO plug for smart devices (e.g. iPhone compatible).

Dr. Liang astutely concludes that, "These sensors are trying to invent their way into our lives very, very quickly" **[20]**. However, even though most companies require data to feed into their own business models, at present, all the devices above use proprietary system standards, so one is unable to combine data easily.

1.4 Motivation and Aims

Motivation and aims were driven by working at BT Research in the SNG on WSN projects. BT Research forged close links with UCL, especially since they had a campus at Adastral Park which presented the opportunity for the author to begin the EngD. Sensor Networks have featured in BT Telecare projects for over ten years, but they first came to the author's attention with the SECOAS (2003-06) and Traffimatics (2004-06) projects. Within this exciting, innovative and rich research environment, the EngD was conducted from a Telco perspective and focused on the application layer of WSNs rather than the more scientific or engineering protocol stack.

Prior to commencing the EngD, in 2005-06, the author and Dr. Chris Roadknight formerly of BT Research, contributed to Eurescom's "Sensor Telcos - New Business Opportunities" (P1555) project **[21]** with partners Portugal Telecom (lead) and Telenor of Norway. The study was conducted from a telecommunications perspective, so each Telco provided their expertise to explore the potential of WSNs. The study identified main technology trends, capabilities of devices and service examples. It also examined how new applications could utilise or pass through their respective Broadband infrastructure (e.g. BT's 21CN) or even provide services at the edge of their networks. WSN domain areas were identified and publications were also reviewed. The collaboration resulted in producing a comprehensive survey and there was a follow-on Eurescom project also led by PT and entitled, "M2M - Opportunities in New Service Paradigms" (P1653) **[22]**.

During the study the author's interest and knowledge of WSNs developed rapidly, this together with BT Research projects covering a range of innovative sensor network deployments, served as a catalyst for the EngD. Following the P1555 survey, the author contributed to a number of DTI WSN projects, including Smart & Aware Pervasive Healthcare Environment (SAPHE) and to a lesser extent Personalised Information from Prioritised Environmental Sensing (PIPES) and Building Awareness for Enhanced Workplace Performance (BOP).

1.5 Organisation of the Thesis

Following the introductory chapter, the structure of the thesis is as follows:

Chapter 2 - describes the fundamentals of WSNs and defines the typical characteristics and capabilities of sensor motes.

Chapter 3 - provides a literature review of collaborative WSN projects conducted by BT Research and its consortium partners under UK or European initiatives. It also provides an insight into the emerging applications of WSNs.

Chapter 4 - introduces the Open Geospatial Consortium (OGC) specifications and defines the Sensor Web Enablement (SWE) framework and related Sensor Model Language (SensorML) from VAST. It elaborates on BT Research's Generic Architecture work carried out under the Sensor Virtualization project. Notable SWE-enabled projects are exemplified. Finally, New Generation SWE 2.0 is outlined to highlight the key improvements to the framework, since BT Research work commenced with SWE 1.0 specifications.

Chapter 5 - discusses SWE applied to SAPHE - the SNG realised that each WSN project was employing a highly customised stove piped (vertical) solution and although these solutions were adequate, we identified a requirement for a Generic Architecture. Refer to Figures 41 and 42 (p.106) to enable component reuse and cost savings for a Telco business, specifically for BT to employ on a number of disparate WSN projects. Building on the expertise acquired during the different phases of Telecare projects, SAPHE aims to provide a real solution for the care and assisted-living of the elderly within their homes and while on the move, especially since there is an increasing shortage of healthcare professionals.

Chapter 6 - discusses the author's experiences with extending the SWE specifications by applying Complex Event Processing (CEP). CEP was investigated to ascertain its potential to aggregating and correlating the shared project sensor data harvested and enabling data fusion for WSNs deployed in a number of diverse environments.

Chapter 7 - provides a summary of the research work carried out by the author and other WSN project consortiums. Ultimately, evaluates whether the SWE 1.0 and SWE 2.0 framework combined with CEP are suitable candidates to realise BT's WSN Generic Architecture, which is capable of sharing components (infrastructure) and sharing sensor data ('infostructure'). Finally, conclusions and suggestions for further work are provided.

1.6 Key Contributions

Please refer to the BT Research list (p.4-5) for all publication authors and project team leaders / members. More specifically, this thesis demonstrates the author's personal contributions to the BT Research themes and the Sensor Network Group's (SNG) Wireless Sensor Network (WSN) projects as listed below:

1. Wireless Sensor Networks study and their use in BT WSN project applications:
    - Demonstrates the OGC's Sensor Web Enablement (SWE) SensorML encodings and Sensor Observation Service (SOS) (Chapter 4 - Enabling the Sensor Web and Chapter 5 - Applying SWE to SAPHE);
    - Identifies shortcomings in standalone WSN projects (Chapter 3 - Real World Sensor Networks and Chapter 4 - Enabling the Sensor Web);
    - Demonstrates the need for sensor data aggregation and integration (data fusion) amongst multiple and diverse WSN projects (Chapter 6 - Complex Event Processing);

2. Development of Generic and Context Architectures for WSNs to realise a smart and reusable architecture for a number of BT WSN projects:
    - A shared infrastructure and 'infostructure' (shared information space) (Chapter 4.1 - Sensor Virtualization);
    - Implemented parts of the architecture as a prototype (Chapter 4.8 - The Design of a Generic Sensor Network Architecture);

3. Integration of SWE and Complex Event Processing (CEP) in the architecture to extend SWE capabilities:
    - Extends the SWE framework by applying a CEP engine to aggregate and correlate sensor data (Chapter 6 - Complex Event Processing);
    - Trials and evaluates SWE specifications for BT WSN projects SAPHE and BRIDGE to facilitate interoperability (Chapter 5 - Applying SWE to SAPHE and Chapter 3.7 - BRIDGE);
    - Identifies the requirement for the SWE framework to enable mobile features of interest (FoI) which were later introduced in SWE 2.0 (Chapters 4.7 - New Generation SWE 2.0 and 4.10 - Context Architecture);

- Upgraded the SAPHE Web monitoring portal (C# programming / Dundas Chart) to enable community matrons to perform live patient data analysis (Chapter 5.5 - Key Challenges in SAPHE).

1.7 List of Publications

The research in this thesis has led to the following publications:

1. J. Foley and G. Churcher; "Sensor Networks: Enabling the Sensor Web and Facilitating Data Fusion". London Communications Symposium, UCL, London (10th September 2010).

2. G. Churcher and J. Foley; "Applying CEP and Extending SWE to a Health Care Sensor Network Architecture". ICST S-Cube, Pisa, Italy (7th September 2009).

3. J. Foley and G. Churcher; "Applying Complex Event Processing and Extending SWE to a Health Care Sensor Network Architecture". LCS, UCL, London (3rd September 2009).

4. G. Churcher and J. Foley; "Applying and Extending SWE to a Telecare Sensor Network Architecture". ICST Fourth International Conference on COMmunication System software and middleware (COMSWARE) Dublin, Ireland (17th June 2009).

5. G. Bilchev; G. Churcher; J. Foley; R. Gedge; T. Mizutani "Experiences Applying Sensor Web Enablement to a Practical Telecare Application". IEEE International Symposium on Wireless Pervasive Computing (ISWPC) Santorini, Greece (7th May 2008).

6. J. Foley and G. Churcher; "Recent Developments in the Design of Sensor Network Architectures". LNCS Adjunct Proceedings Second European Conference on Smart Sensing and Context (EuroSSC) Kendal, England (23rd October 2007).

CHAPTER 2 Wireless Sensor Networks Demystified

2. Introduction

This chapter provides an overview of Wireless Sensor Networks (WSNs). It provides a background with DARPA Smart Dust origins and Eurescom's Telco survey, discusses components, wireless standards, identifies typical characteristics and capabilities of sensor motes, sensor data collection, energy harvesting, mote deployment, and management of the network.

2.1 Sensors, Sensor Systems, Wireless Sensor Networks

The following terms define and clarify the differences between sensor terminology:

- Sensors only which serve a specific sensor task within another system to monitor and feedback (e.g. car reverse parking sensors, "Hawkeye" base-line sensors at Wimbledon, the Premier League installed similar goal-line technology for the 2013/14 season);
- Sensor Systems are collections or clusters of sensors to form a complete system (e.g. weather station or military Autonomous Underwater Vehicle (AUV) and Unmanned Aerial Vehicle (UAV));
- WSNs comprise of motes forming an ad-hoc network, data packets are sent using multi-hop via a gateway to a data sink for monitoring phenomena and data analysis.

Sensor networks involve three areas: sensing, communications, and computation (hardware, software and algorithms). A sensor network is a computer network of many, specially distributed devices using sensors to monitor conditions at different locations, such as temperature, sound, vibration, pressure, motion or pollutants. Usually these devices called motes are small and inexpensive, so that they can be produced and deployed in large numbers, and so their resources in terms of energy, memory, computational speed and bandwidth are severely constrained. Each device is equipped with a radio transceiver, a small microcontroller, and an energy source, usually a battery. Sensor motes form an ad-hoc network by communicating using multi-hop routing protocols (e.g. ZigBee) to transport data (via a gateway mote) to a monitoring computer (data sink).

A WSN can be setup in a few hours with data being relayed to the users in near real-time. Network maintenance involves replacing faulty or missing sensors, which may show inaccurate relative to nearby sensors or nil, or replacement batteries as necessary. However, the WSN will still function with a reduced topology due to sensors being out of action.

After the initial deployment (typically ad-hoc), sensor nodes are responsible for self-organising an appropriate network infrastructure, often with multi-hop connections between sensor nodes. The onboard sensors then start collecting data such as acoustic, seismic, infrared or magnetic information about the environment, using either continuous or event driven working modes **[23]**.

Besides hardware technologies, the development of WSNs also relies on wireless networking technologies. The 802.11 protocol, the first standard for Wireless Local Area Networks (WLANs), was introduced in 1997. It was upgraded to 802.11b with an increased data rate and CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) mechanisms for Medium Access Control (MAC). Although designed for wireless LANs that usually consist of laptops and PDAs, the 802.11 protocols are also assumed by many early efforts on WSNs. However, the high power consumption and excessively high data rate of 802.11 protocols are not suitable for WSNs. In 2006, the 802.15.4-based ZigBee protocol was revised, which was specifically designed for short range and low data rate Wireless Personal Area Networks (WPAN). Its applicability to WSNs was soon supported by several commercial sensor node products including MicaZ, Telos, and Ember products.

WSNs offer new challenges for researchers since sensor motes are low-cost and have limited processing and memory power. In-field motes are battery operated (early motes required AA-sized batteries which constrained miniaturisation) since a mains power supply is scarce in most harsh environments. WSNs are a particular type of ad-hoc networks, in which the nodes are sensors equipped with wireless transmission capability. Hence, they have the characteristics, requirements and limitations of an ad-hoc network. To support scalability, sensor nodes must be autonomous and self-organising.

A WSN is usually composed of a large number of sensing nodes in the order of tens, hundreds or even thousands scattered in a field and one or a few base stations, which connect the sensor networks to the users via the Internet or other networks. The nodes are deployed either inside the observed phenomenon or very close to it. Sensor nodes are equipped with sensing, data processing and communicating components to accomplish their tasks. Each sensor node is capable of data collection and routing the data back to the sink by network traversal via multi-hop paths.

Base stations are part of the WSNs, but do not have sensors. Instead, they receive data from the rest of the network and provide point of access for users. Most base stations will be connected to infrastructure such as the power grid and Internet **[24]**. The design of a WSN can be divided into data handling and communication aspects. Data handling tackles areas including the sensing interface, data sampling rate, data compression and fusion, clustering, decision making and result reporting. The communication aspects of a WSN include the radio module, network synchronisation, MAC scheduling, topology control and networking strategy and information dissemination. The protocol stacks of a WSN can be variable with different applications.

2.2 DARPA Origins

Similar to many technological advancements, WSN motes were inspired by the US military Defense Advanced Research Projects Agency (DARPA). DARPA funded developments and early innovations by US universities, such as UC Berkeley. They began developing ‘Smart Dust’ in 1999, these tiny form factor motes were integrated with sensors to track light, temperature, humidity, sound/vibration, etc.

The Smart Dust project at UC Berkeley released the first node, WeC in their product family of motes. Along this line, the Mica family was released in 2001, including Mica, Mica2, Mica2Dot, and MicaZ. This eventually led to more advanced projects such as Berkeley Webs, NEST and Center for embedded and Networked Sensing at UCLA **[25]**.

An interesting research testbed is the Spec platform which integrated the functionality of Mica onto a single 5 mm^2 chip. Spec was built with a micro-radio, an analog-to-digital converter, and a temperature sensor on a single chip. This single-chip integration also opened the path to low cost sensor nodes. The integrated RAM and flash memory architecture has greatly simplified the design of the mote family. However, the tiny footprint also requires a specialised operating system, which was developed by UC Berkeley, called TinyOS.

The Spec Node projects seek to create low-powered, low-cost wireless sensor devices, or motes, roughly the size of a grain of sand. Massive numbers of these millimetre-scaled motes could be used in self-organising WSNs for such innovative applications as monitoring seabird nests in remote habitats, pinpointing structural weaknesses in a building after an earthquake, or warning of the presence of biochemical toxins. The fundamental principle behind smart dust is to enable WSNs to ‘talk’ to other nearby motes via multi-hop, rather than increase the power of a single mote so that it can transmit through hundreds of feet of building space. The biggest challenge to small form factor is power. “Lower power means smaller batteries. For instance, the two AA batteries used to power the Mica mote account for the bulk of its size. As the volume of battery goes down, the energy it contains decreases. The major hurdle in miniaturising the motes was the power. One of the huge advantages of the Spec chip over prior generations of motes is a 30-fold reduction in total power consumption” **[26]**.

Smart dust could be packed into the nose cones of planetary probes and then released into the atmospheres of planets, where they would be carried on the wind. For a planet like Mars, smart dust particles would each have to be the size of a grain of sand. By applying a voltage to alter the shape of the polymer sheath surrounding the chip, dust particle could be steered towards a target, even in high winds. Many other applications have been proposed for smart dust. One idea is to use particles to gather information on battlefields. Another idea involves mixing the particles into concrete to internally monitor the health of buildings and bridges. If smart dust were scattered all over the globe, weather data would become more dense, allowing for more accurate forecasts and better information about coming natural disasters. Climatologists could also use more accurate temperature data to learn about climate change **[27]**.

In 2001, dozens of Rene motes, the precursor to Mica, were dropped from a plane alongside a road in a test at Twenty-nine Palms, California. The matchbox-sized motes successfully tracked the speed and direction of passing vehicles based upon the vibrations in the ground. WSNs were deployed in Iraq and Afghanistan by the US military in order to aid intelligence and counter insurgent attacks. GPS satellite surveillance coupled with sensors deployed in the field may be used with rich 3D virtual environments in order to create an accurate representation of a hostile terrain, number of enemy troops, vehicles and weapons, so they may be accurately identified and targeted more effectively by remote controlled drones.

2.3 Components

WSNs are composed of three basic elements:

1. Sensors and their local interconnections, including the Gateway to the external world;
2. Transport Network that conveys the data to its storage and processing site;
3. Service Platform that uses the data and supports applications and users.

Figure 8 depicts the main components and interfaces of WSNs from a Telco's perspective.

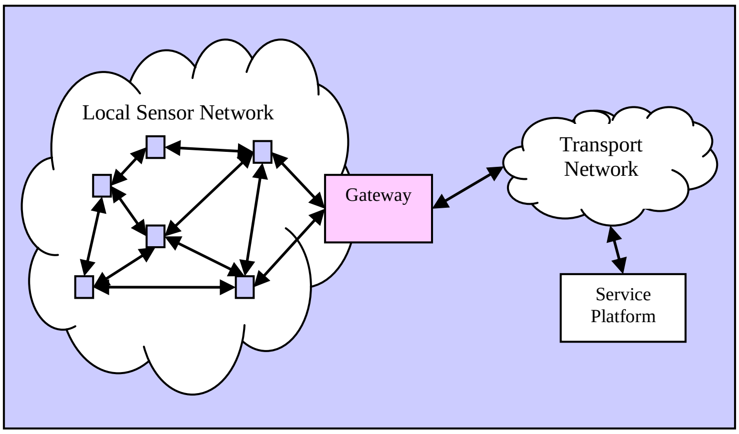

Figure 8 - WSN Components and Interfaces [28]

Telcos are ideally placed to exploit the potential of WSNs, since they possess the backend infrastructure (e.g. BT's 21CN) to support future WSN-based services. The network is fast and secure and a service platform is designed to access these services. Increasingly, open source development uses shared SDK tools such as Ribbit to facilitate the creation of additional services or applications **[29]**. Ribbit is now integrated into BT's new Technology, Service and Operations for their Voice over Fibre programme. Much like Google's Android operating system, bugs are eradicated and functionality is expedited by a talented community of developers.

2.4 Wireless Standards

There is not a "one size standard that fits all" solution of passing data on a sensor network and there is no solution that will always be optimal. To understand which solution best fits which problem space, one needs to carefully consider what each wireless communication standard offers.

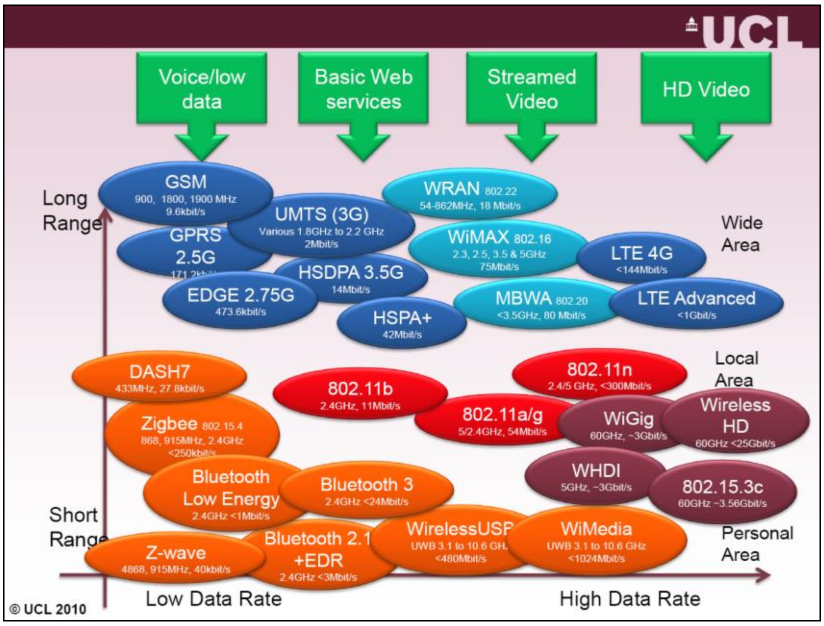

Figure 9 - Wireless Standards [30]

Figure 9 illustrates the myriad of wireless standards which devices may use to access telecom networks. The diagram divides the standards into three groups based on range: Personal Area Networks (PANs - short range), Local Area Networks (LANs - medium range) and Wide Area Networks (WANs - longest ranges). It also shows the low to high data rates, as well as providing application specific examples from voice/low data to high definition (HD) video.

2.5 Mote Characteristics and Capabilities

WSN applications can be assigned to one of the following broad categories; detection or tracking or monitoring. A WSN comprises sensors and an independent power source. The various different types of sensors can be used for collecting and transmitting data about their surrounding environment.

A WSN is defined as a network that is formed when a set of sensor devices are deployed that co-operate to measure physical phenomena. A WSN consists of numerous small independent sensor devices known as nodes or motes, which are packed with sensors. Sensors may include proximity Passive Infrared (PIR); light (photosensors or photodetectors); temperature (thermistor or thermometer); accelerometer; Global Positioning System (GPS) optical sensors. The sensor motes are self-contained units consisting of a battery, radio, sensors, and a minimal amount of on-board computing power.

The following list comprises of the main characteristics and capabilities of WSNs:

- WSNs derived from US military technology - DARPA ‘Smart dust’;
- Tiny form factor so easily concealed, making military apps difficult to detect by enemy troops;
- Ideal for deployment in harsh or volatile environments due to their origins, engineered to be robust in extreme conditions (e.g. war zones, volcanoes, space, fire, flooding, icebergs);

- Low-cost and disposable devices at around $1 per chip;
- WSNs are autonomous, self-organising (scalability) and provide distributed services;
- Multi-hop means resilient to failure, densely deployed around target area so if one node fails, others re-route to create a new network path traversal with neighbouring nodes;
- Form ad-hoc networks (do not require a base station unlike mobile communication networks);
- Require three or more motes, one acts as a gateway to the data sink;
- Functionality can be upgraded with additional plug-in sensor boards for extra measurement capabilities;
- Myriad of novel applications – health; environmental; smart vehicles; intelligent buildings; RFID projects demonstrate that WSNs are feasible and cost effective;
- RFID technology important in WSNs;
- Low energy conversion / low power consumption - battery life extended by active / sleep time cycle - programmed to "sleep" to conserve battery power;
- Mostly battery operated as mains unlikely in the field. Battery life up to ten years – (e.g. based on mobile phone and laptop battery technology, the longest lasting, small form factor power sources developed so far);
- Low network maintenance (only replace faulty sensors or spent batteries);
- Design and robustness of motes varies for industrial and military applications;
- Short range wireless ad-hoc networks quicker to deploy (than a wired network) and self-maintaining;
- Limited processing power and limited memory (e.g. 1kB);
- Architectures such as SWE may be adapted and applied to most sensor system project domains;
- Better supported via frameworks (e.g. SWE 2.0, TinyOS, Contiki) so easier to program;
- Sharing WSN data amongst diverse projects possible (data fusion) via SWE 2.0 and CEP;
- Robust motes with customised hard casings to protect components from weather and damage;
- Motes may be fitted retrospectively inside buildings or vehicles;
- Data harvested (aggregated) from WSNs and correlated using CEP in real-time;
- Alternatives such as ZigBee and Mesh Radio Systems;
- Artificial Intelligence (AI) techniques may be applied to learn thresholds of results;
- Easily deployed (node mobility) e.g. BSN dynamic not static, flexibility, coverage.

Security

WSNs have recently attracted a lot of interest in the research community due their wide range of applications. Due to the distributed nature of these networks and their deployment in remote areas, these type of networks are vulnerable to numerous security threats that can adversely affect their proper functioning. This problem is more critical if the network is deployed for some mission-critical applications such as in a tactical battlefield or for Telecare. For instance, in the BT project, a Virtual Private Network (VPN) is used to secure the Smart & Aware Pervasive Healthcare Environment (SAPHE) web portal. Random failure of nodes is also very likely in real-life deployment scenarios.

Due to resource constraints in the sensor nodes, traditional security mechanisms with large overhead of computation and communication are infeasible in WSNs. Security in sensor networks is, therefore, a particularly challenging task **[31]**.

Sensor Data Traffic and Capture

The choices in protocol design depend on factors such as how often to sense, how often to send the data to the sink, the quantity of data involved, and the data fidelity requirement. These vary widely depending on the WSN application **[32]**.

For effective analysis, actions should be triggered by certain key events, which are detected by various types of sensor nodes. For example, BT's Telecare project uses light and vibration sensors strategically placed in the homes of elderly residents in Liverpool to monitor their well-being. The intervals between sensor readings have to correspond accordingly to the requirements of a specific application. For example, for the majority of healthcare applications such as heart rate sensors, it is vital that data is captured in real-time. Whereas Crossbow motes used onboard BP's Loch Rannoch for predictive maintenance, only collect data every six to eighteen hours, which is an adequate interval **[33]**. However, excessive sensor data collection from data rich environments may be unrelated, irrelevant (chaotic) or difficult to place in time (temporal) and space (spatial) and probably impossible to analyse.

Most sensor network experts agree that the real challenge is in the fusion (aggregation) of the data captured from several isolated sensors. Moreover, it is imperative that sensors work in unison to correlate data and to identify distinct behavioural patterns (i.e. feature detection). Data fusion was investigated by BT colleagues in the BOP ("intelligent buildings") project and the M2M and IN themes, which encompassed the "Sensor Virtualization" project carried out by the SNG under the Pervasive ICT Centre.

Information fusion is an important topic for collaborative signal processing. Since sensor readings are usually imprecise due to strong variations of the monitoring entity or interference from the environment, information fusion can be used to process data from multiple sensors in order to filter noise measurements and provide more accurate interpretations of the information generated by a large number of sensor nodes. A rich set of techniques is applicable in this context, including Kalman Filtering, Bayesian Inference, Neural Networks, and Fuzzy Logic. Other signal processing techniques that have been developed for WSNs include time synchronisation, localisation, target tracking, edge and boundary detection, calibration, adaptive sampling, and distributed source coding **[34]**.

The sensor networks data sampling intervals may be adjusted so that data is only transmitted if the values change substantially or if the temperature falls below or rises above a certain predefined threshold. Variables include sensor intervals, sleep/inactive, faulty or destroyed, etc. Therefore, from all sensor data establishing important key events is vital. As discussed with Prof. Ian Marshall of Lancaster University regarding a reservoir dam which is about to break, only send exception data (which deviates from the expected norm) when excessive pressure readings are detected, because it is pointless transmitting identical values frequently because it tells one nothing new **[35]**. Once captured, sensor readings may be filtered or 'cleaned-up' as many of the readings may be identical if no changes are detected by the sensors, then no significant events have occurred. Intervals will vary according to the specific application, for example, healthcare readings will typically be recorded more frequently than those of a predictive maintenance monitoring of infrastructure.

Energy Harvesting

Motes are limited by their sensing, computation and communication capabilities, which are dictated by their battery energy reserves. The management of network resources therefore becomes vital in extending the operational longevity of motes deployed in the field. Energy harvesting, also known as power harvesting or energy scavenging recharges or extends the life of the battery. Energy harvesting includes photovoltaics (solar); thermovoltaics (heat differences); piezoelectrics (vibration); and electrodynamics (electric charges and currents); which may be used to power a wide variety of WSN motes. Power is usually derived from mains electric or battery sources, but solar panels also enable power scavenging. Energy harvesting is a process by which energy is derived from external sources e.g. solar power (sunlight); thermal energy (heat differences); wind energy; salinity gradients; and kinetic energy; captured, and stored for small, wireless autonomous devices, like those used in wearable electronics and WSNs. "Sleep time" conserves battery power if motes are configured optimally for the project. With the advancement in autonomous, battery operated sensing platforms, multi-modal sensor based systems are becoming powerful sources of information that support a wide collection of intelligent applications **[36]**.

2.6 Mote Manufacturers

Mote manufacturers include the following companies, some of which began as University start-ups, such as from UC Berkeley, MIT, UCLA or Virginia Tech. Some start-ups have since been acquired by larger corporations to bolster their WSN division and increase their product offerings. Typical motes will include an accelerometer, temperature and light sensors. However, additional low-power sensor boards may be stacked on top of the standard processor board. For example, pluggable sensor boards housing vibration or humidity sensors "piggy-back" on top of the processor board to extend mote functionality. Refer to Appendices B and C for further details of mote manufacturers and specifications. A typical sensor mote may have the following characteristics in Table 1:

Table 1 - Typical Sensor Mote Characteristics [37] and [38]

Operating System:	Contiki; TinyOS; ERIKA Enterprise; Nano-RK; LiteOS; OpenTag; NanoQplus
Industry Standards:	802.15.4; ZigBee; 6LoWPAN; WirelessHART; ANT; DASH7; ONE-NET; Z-Wave; Wibree; MiWi
Variety of on-board sensors:	Internet-connected; Biometrical; Physiological; Biological; Inertial; Virtual; Light; Temperature; Humidity; Sound/Vibration; Passive Infrared (PIR); Power; Water flow; 'Cooking' sensor; Entry switch (reed relay); Pressure; Wireless; Acoustic/Seismo-acoustic; Gas; Water/Fluvial; Accelerometer/Gyros (orientation); Proximity (iPhone); Fibre; RFID tags; ambient; body; toilet flush; bed occupancy

Programming languages:	nesC; LabVIEW; C; Python
Hardware:	Crossbow; Sun SPOT; Arduinos, Bengt Polls; Beasties; Bi-morph; Sentilla; Iris Mote (Xbow); Xbee; MSB430 ESB; TmoteSky; BTnodes; EyesIFXv2; MicaZ; Mica2; Mica2Dot; Imote2
Software:	TinyDB; TOSSIM; OPNET; LinuxMCE; Tesserae;
Applications:	Sensor Web; Telemetry; Key distribution; Location estimation; Intelligent data analysis (IDA); Home automation systems; Medical sensors and Telecare applications; Security and alarm systems; Industrial monitoring systems; Aircraft safety monitoring system; Robotics; Tessella (activity monitoring, motion capture, location tracking)
Wireless Protocols:	AODV (Ad-hoc On-Demand Distance Vector) is a routing protocol for mobile ad-hoc networks (MANETs) and other wireless ad-hoc networks. DSR (Dynamic Source Routing) a protocol for wireless mesh networks. It's similar to AODV since it forms a route on-demand when a transmitting computer requests one. However, it uses source routing instead of relying on the routing table at each intermediate device. TSMP (Time Synchronized Mesh Protocol) developed by Dust Networks as a communications protocol for self-organising networks of motes.

Deployment

Ubiquitous Sensor Networks (USN) are networks of intelligent sensor nodes that may be deployed "anywhere, anytime, by anyone and anything". Sensor nodes can be either thrown in mass or placed one by one in the field. Sensors may be deployed by:

- Dropping from a plane;
- Delivering in an artillery shell, rocket or missile;
- Throwing by a catapult (from aboard a ship, etc);
- Placing in factory;
- Placing one by one either by a human or a robot **[39]**.

As technology progresses, WSNs could ideally be deployed from the air, as shown in the futuristic vision of the Theoretical Computer Science (TCS) of the University of Geneva (UG). Figure 10 depicts how Smart Dust fire detection motes may be dynamically deployed in the future, like 'Dandelion seeds' from an aeroplane or helicopter into the surrounding region of a forest fire.

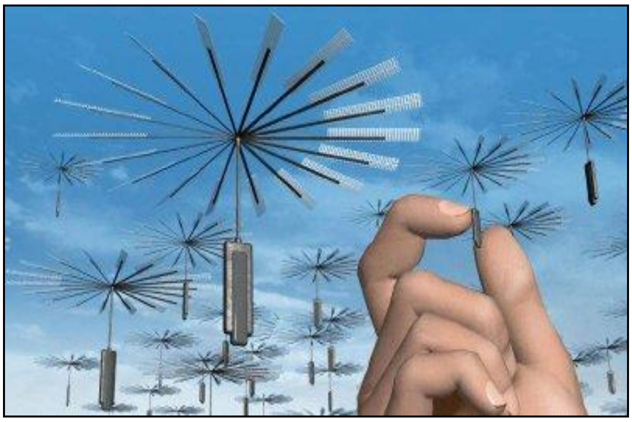

Figure 10 - Concept Deployment of Smart Dust [40]

Sensor nodes are densely deployed either very close or directly inside the phenomenon to be observed. Therefore, they usually work unattended in remote geographic areas. They may be working:

- In busy intersections;
- In the interior of large machinery;
- At the bottom of an ocean;
- Inside a tornado;
- On the surface of an ocean during a tornado;
- In a biologically or chemically contaminated field;
- In a battlefield beyond the enemy lines;
- In a home or a large building;
- In a large warehouse;
- Attached to animals;
- Attached to fast moving vehicles;
- In a drain or river moving with current **[41]**.

2.7 Management of the Network

The increasing use of these pervasive ad-hoc sensor networks presents a number of problems, the main one of interest to BT being how to manage these wireless devices and networks. Management challenges include the following **[42]**:

- 21CN BT Infinity UWB enables speedier services (e.g. real-time, multi-player online gaming; HD video; HQ music streaming, etc);
- Ensuring a reliable ad-hoc network (data tamper proof and reliable/trustworthy);
- Self-form and self-heal (reconfigure topology via multi-hop based on network neighbours);
- Deployment of software updates without nodes having to be recalled or interrupted (offline);
- Provisioning of new services which are value add;
- Edge of network management by smart home / devices (decentralised processing);
- The Cloud uses the centralised processing network model for remote storage and computation.

2.8 Summary and Conclusion

Chapter 2 provided an overview of WSNs and defined the typical characteristics and capabilities of wireless sensor devices known as network nodes or motes. Key terms and examples of sensors, sensor systems and WSNs were introduced. A brief history of the DARPA origins of WSNs was described as well as network components and wireless standards. Finally, an insight into the management of the WSN was given.

CHAPTER 3 Real World Sensor Networks

3. Introduction

Chapter 3 provides a literature review of WSN projects conducted by BT Research and its consortium partners under UK or European initiatives. As shown in Figure 11, over the last decade, BT Research has collaborated in a number of projects that utilise sensor network infrastructure, covering a wide range of application domains featuring healthcare and assisted living (Telecare); Traffimatics ('smart vehicles'); environmental monitoring (SECOAS); workplace monitoring (BOP); infrastructure monitoring (PIPES); RFID and supply chain management (BRIDGE). In addition, it provides an insight into the similar state-of-the-art WSN project applications carried out by other project consortiums.

Figure 11 - WSN Deployments [43]

WSNs in Action

For a long time sensors have played an important role in almost every field of human activity: industry, transportation, environmental data acquisition, medical applications, home - the list is virtually endless. Progress in radio communications, electronics and networking have, in recent years, allowed the emergence of Sensor Networks as a fast expanding research field. WSN technology has reached a tipping point, because the necessary lower power electronics and more efficient energy gathering and storage are now sufficiently affordable, reliable and longer lived for a huge number of applications to be practicable **[44]**.

3.1 Telecare

The use of ICT to remotely support the provision of care to individuals, referred to as Service Users, within their own home is often termed 'Telecare'. Telecare is defined by the UK Department of Health (DH) as, "enabling thousands of older people to live independently, in control and with dignity for longer. Telecare is as much about the philosophy of dignity and independence as it is about equipment and services. Equipment is provided to support the individual in their home and tailored to meet their needs. It can be as simple as the basic community alarm service, able to respond in an emergency and provide regular contact by telephone. It can include detectors or monitors such as motion or falls and fire and gas that trigger a warning to a response centre." It is widely acknowledged that a rising elderly population and a falling carer support ratio renders many of the current care provision models for older people unsustainable. Moreover, in January 2012, ITN reported that care for the elderly is "on the verge of collapse" due to a shortage of carers and NHS funding. Therefore, Telecare appears to be the UK's only viable solution. The Telecare project aims were to "assess a system that responds to crises in the home" via monitoring the elderly in everyday activities. Telecare may be positioned within the WSN domains of healthcare and intelligent buildings.

The Telecare Pilot is part of an ICT partnership deal with consortium partners to develop, trial and evaluate the use of technology to support the independent living of older people. The introduction of such 'Telecare' services is seen as key to enable the continued provision of care services within the community given the radically changing demographic landscape and the increasing costs associated with traditional care provision. The Pilot consists of the deployment of prototype Telecare technology based on non-intrusive sensing technology to monitor activity levels and related events, such as the opening and closing of doors and windows, within an individual's home. This information is used to determine situations within the home which may be of cause for concern in relation to the well-being of the individual. In response to detected situations an automatic alert message is sent to the individual themselves, but a negative or lack of response escalates the situation to an alarm into the Social Service call centre operated by Liverpool Direct Limited.

According to the DH, Improving Chronic Disease Management, 2004 and WHO 2002:

- Chronic disease will be the leading cause of disability by 2020;
- Two-thirds of patients admitted as medical emergencies have exasperation of chronic disease or have chronic disease;
- The use of preventative care and effective chronic disease management to reduce dependence on health and social care services is a national priority.

Remote Wellbeing Monitoring - People are getting older

In 2003, 21 per cent of the UK population was over 60 years of age but by 2031 this will have risen to 32 per cent. UK Government surveys show that old or otherwise 'frail' people want to remain living in their own homes for as long as possible. Given the choice, 80 per cent want to stay in familiar surroundings rather than move into sheltered accommodation, followed by residential care and finally a nursing home. It is widely acknowledged that the rising elderly population and a falling carer support ratio renders many of the current care provision models for older people unsustainable. BT is working with Government, universities and equipment manufacturers to understand the role that information and communications technology (ICT) can have in the provision of high quality, cost-effective care for our aging population.

Table 2 - Three Generations of Telecare Monitoring [45]

3G	Well-being analysis - pre-emptive, long term trend analysis Migrates Telecare from a crisis safety net to an assessment tool Will enable intervention outcome measures and optimisation 3G Telecare is a tool for providing the carer with activity information enabling them to identify significant changes in the general well-being of their client. Its aim is to enable carers to prevent incidents from occurring in the home. Shift from response (r-mode) to prevention (p-mode)
2G	Telecare systems - adaptive, personalised but event driven Exhibits aspects of reasoning An emerging care intervention package Non-invasive home monitoring Data capture and intelligent analysis via activity monitoring
1G	Social alarms - dispersed panic alarm with pendant and pull cords Addition of passive sensors for auto alerts An existing care intervention package

Advanced Telecare and eHealth Solutions

As described in Table 2, BT has undertaken a number of Telecare research projects which demonstrate how ICT can support independence, increase choice and contribute to the overall quality of life and 'wellbeing' of elderly individuals **[46]**. In partnership with Liverpool City Council and Liverpool Direct Limited, BT has run a Telecare pilot to 20 of the Council's Social Services' clients for over three years. The Liverpool pilot used unobtrusive ambient sensors to continually monitor an individual's behavioural patterns within their own home without the need for them to wear or carry any devices. Through the use of novel Intelligent Data Analysis (IDA) techniques it is possible to learn the normal behaviour of a user and to determine when departures from normal behaviour occur. If these departures represent causes for concern then they can be automatically communicated to carers via the broadband network. This means that in a crisis situation help can then be provided to a Service User without the need for them to initiate a call for assistance themselves. The proactive alert raising mechanism is of heightened importance when scenarios exist which prevent the user from being able to request assistance themselves, for example after a fall. Since early 2004 the Telecare pilot system has helped to make a real difference in the lives of 20 frail and elderly Liverpool residents, as well as providing a research platform for other advanced Telecare technologies, such as wellbeing monitoring.

Following on from the research pilot, Liverpool Direct Limited (a joint venture between BT and Liverpool City Council) delivered a commercial Telecare service to the Council. Around 250 Service Users were trialled on this service in March 2008.

Wellbeing Monitoring

In addition to identifying situations requiring immediate intervention, the type of unobtrusive monitoring which can be carried out by ambient sensors is also of use in understanding the wellbeing of a Service User. Through the use of advanced IDA techniques it is possible to remotely track the activities performed in the home and to use long-term trend analysis for uncovering early indicators of deteriorating health. The benefit of early identification is that preventative arrangements can then be put in place to help avoid crisis situations. By working with healthcare professionals such an advanced Telecare system has been demonstrated in the homes of elderly individuals as an extension to the Liverpool pilot. Much of this work was undertaken as part of a DTI sponsored virtual research centre, Care in the Community. The centre was led by BT and involved the universities of Bristol, Dundee, Liverpool and Loughborough.

Body Sensing

Body Sensor Networks (BSNs) **[47]** provide a platform for collecting physiological/context information about a Service User. New research is looking at combining wearable body sensors with the ambient sensor approaches described here. An integrated sensor approach has the potential to extend the level of monitoring that can be carried out in the home and to exploit the potential of ICT for managing chronic diseases. Chronic diseases are responsible for a significant proportion of the UK healthcare costs and can unnecessarily negatively impact on the lives of millions of individuals.

Body sensors need to be small with a functional physical design, so wearing is feasible and comfortable, e.g. lightweight, sewn into clothes and even washable. They also need to be low on power consumption requiring 802.15.4 (ZigBee) or similar short haul wireless solutions. There is already a substantial market for health sensors of different kinds. Thus, several players are active in this market today offering solutions to individuals as well as to private and public health services. However, there is currently no structured storage or reuse of this data for statistical purposes or as part of the patient's medical record.

BT has a long history in harnessing communications technology to contribute to the world of medicine. Remote diagnostics, video training for surgeons and dentists, and a 'Telemedicine' system to help paramedics at the scene of an accident are among developments that have made specialist medical expertise more readily available when and where it is most needed. But, with an ageing population in the UK, the latest efforts are in 'Telecare' with the aim of keeping people at home – where they want to be – rather than in hospital or under local authority supervision. BT's role in helping those in need could not be more important in both human and monetary terms and recent deals with the National Health Service (NHS) are amongst the biggest corporate contracts the company has ever signed. Whilst such schemes fall within BT's remit as a major service provider to large organisations, the Telecare concept is entirely different. However the potential savings it could deliver to the NHS and local authorities are just as significant.

The project consortium began gathering data for two client trials consisting of 20 users in mid-August and early October, 2005. As illustrated in Figure 12, the Pilot trial and well-being sensors were deployed in the homes of participants based in Liverpool. Twelve wireless sensors are deployed in each home, which include Passive Infrared (PIR) sensors, entry switch sensors, occupancy sensors, a toilet flush sensor and a temperature sensor. These sensors are connected to a central gateway, developed by BT, while a secure broadband IP channel links the home with the BT server farm at Adastral Park, Ipswich **[48]**.

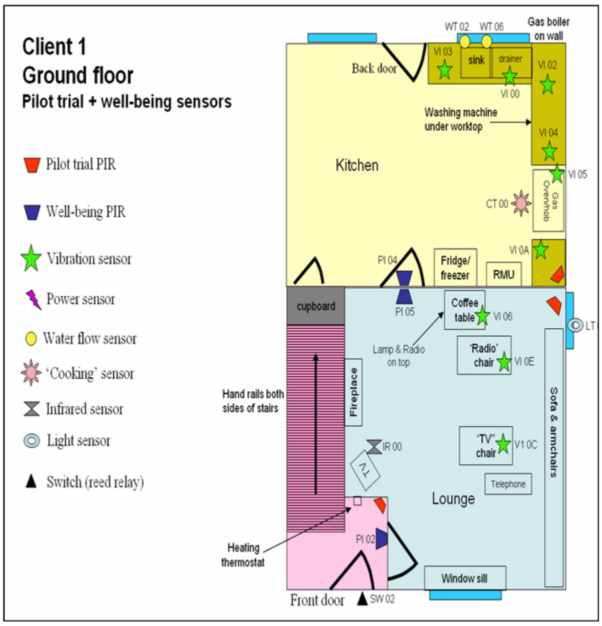

Figure 12 - Telecare Pilot Trial & Well-being Sensors [49]

Features of the system:

- Low cost, autonomous, wireless, low power sensors;
- Sensors readily deployed with minimal disruption (retro-fitted into buildings);
- Easy to set up and maintain;
- Battery life improving and easy to replace;
- Non-intrusive unlike CCTV;
- Trialled by Liverpool PCT and City Council.

Sensors deployed for the client trials:

- Pilot trial Passive Infrared (PIR);
- Well-being PIR;
- Vibration sensor;
- Power sensor;
- Water flow sensor;
- 'Cooking' sensor;
- Infrared sensor (TV remote);
- Light sensor;
- Switch (reed relay).

Telecare Demo at Adastral Park

Community care projects like Telecare provide a novel solution with continuous, non-intrusive monitoring to determine the well-being of elderly residents by managing healthcare. Non-invasive biometrical or physiological sensors are deployed, which enable healthcare professionals to support those who may live alone to remain independent in their homes and only invoking assistance as required. Hundreds of sensor readings were captured each day to track all the key events within the individual rooms of the houses involved in the trial. The sensors were purposely selected because of their non-invasive, low battery power and easy to maintain attributes. For example, vibration, light, passive infrared sensors were preferred to more intrusive video surveillance cameras (only blob camera not CCTV). All sensors were retro-fitted to standard items of furniture such as inside kitchen cupboards or attached to chairs. Pressure sensors were considered for use on the chairs, but vibration sensors were preferred to detect movement.

In the demo situated in the HIC (3rd Floor of Orion building at Adastral Park) sensors are triggered by the following activities:

- Drawers and cupboards opened or closed (light sensors);
- Telephone receiver on or off hook (vibration sensors);
- Infrared remote control used for TV (passive infrared sensor);
- Tap open or closed (water flow sensor);
- Kettle when switched on (vibration sensor).

Thorough analysis was done on the Telecare project data captured by Paul Bowman **[50]**. In fact, temporal data was captured too frequently, but was intelligently filtered and useful in proving that inferences regarding the daily routines and whereabouts of clients and their well-being were made by the relatively simple and non-invasive sensor deployments. For example, sensors accurately detected when a patient had risen from their bed (SAPHE bed occupancy sensor), walked down the hall (passive infrared sensor), went into the kitchen and filled the kettle (water flow sensor innovatively clipped on to the water pipe), switched on the kettle (vibration sensor attached to the kettle's electrical cable) and opened the cupboard for teabags (light sensor triggered by opening the cupboard). All of these activities were impressively displayed in real-time (by invoking an appropriate short video clip) on a small monitor to ascertain every time the sensors were triggered. A purpose-built small Mini-ITX PC captured the data and the unit was easily concealed in the mock kitchen which the demo comprises of. This is certainly what can be termed a smart home without being intrusive or over-engineered.

The use of wireless sensor networks in health monitoring is expected to accelerate due to the development of biological sensors compatible with conventional CMOS integrated circuit processes. These sensors, which can detect enzymes, nucleic acids, and other biologically important materials, can be very small and inexpensive, leading to many applications in pharmaceuticals and medical care **[51]**.

The BBC's "Click" programme featured the latest commercial-off-the-shelf (CotS) healthcare monitoring devices to get fit. Smart devices are capable of monitoring heart rate and other vital statistics. Athletes use an accelerometer for a step counter enabling them to monitor their health and track their route in real-time and publish to an online blog **[52]**.

3.2 Environmental Sensing

Environmental monitoring may include remote, harsh, inaccessible or even volatile locations. A WSN is ideal for deployment in these unpredictable environments and typically takes a day to set up and then data is immediately available. WSNs are gaining interest as both a flexible and economical way of monitoring environmental or industrial parameters by simply deploying a number around tens, hundreds or even thousands of nodes throughout a designated area.

Advancement of cheap micro processing chips and wireless technology, infrastructure-free ad-hoc networks have become attractive alternatives to more traditional wired sensor monitoring in terms of cost, ease of deployment, robustness and flexibility. Sensors equipped with wireless communication devices can be deployed on bridges, glaciers, oceans and rivers, landfills, agricultural sites, volcanoes, satellites in orbit or even on the Moon.

Habitat study is one of the driving applications for WSNs. Such applications usually require the sensing and gathering of bio-physical or bio-chemical information from the entities under study, such as Redwoods, Storm Petrels, Zebras, and Oysters. In many scenarios, habitat study requires relatively simple signal processing, such as data aggregation using minimum, maximum, or average operations. Hence, motes are ideal platforms for such applications **[53]**.

Prevention of Forest Fires

As a result of global warming and arson, forest fires have increased in recent years in southern Europe. The problem is particularly acute in Portugal where burned area has risen with peaks in 2003 and 2005. One of the most important means of prevention of forest fires are early detection systems. By virtue of cheap deployment and resilient nature, WSNs are well adapted to the purpose of fire detection, since they may provide early warnings of forest fires to a centralised supervision centre. Static fire detection sensors are distributed in open forests.

It must be noted that there are no "out of the box" products to fit any environmental situation. Some experiments of this kind were conducted in recent years, e.g. two projects in US California state: The San Diego State University Fire Sensor deployments in the Santa Margarita Ecological Reserve for early detection of wildfires (2005) based on a commercially available system (Figure 13), and the FireBug project a proof of concept experiment carried out by UC Berkeley under the CITRIS project (Figure 14). These experiments are a first step towards a feasible solution **[54]**.

Figure 13 - USDS Fire Sensor [55]

Figure 14 - UCB FireBug Motes [56]

Monitoring of Redwood Trees

In 2003, UC Berkeley developed micro-mote wireless sensors to monitor Redwood trees in California to ascertain the unique phenomenon of how the fog helps them to grow. Wireless sensors are perfect for environmental monitoring because they are low impact and low visibility.

Early Warning of Natural Disasters

It is absolutely vital to provide early warning systems for natural disasters such as earthquakes and tsunamis (e.g. Tōhoku, March 2011), volcanoes (e.g. Copahue, May 2013), floods (e.g. Memphis, May 2011) and tornadoes (e.g. Oklahoma, May 2013) to reduce casualties and limit damage to infrastructure, but also for the conservation of the Earth's natural resources as well as improving our knowledge of our planet.

A developing field related to both health monitoring and security is that of disaster relief. For example, the wireless sensors of the HVAC system in a collapsed multi-story building can provide victim location information to rescue workers if acoustic sensors, activated automatically by accelerometers or manually by emergency personnel, are included. Water and gas sensors also could be used to give rescuers an understanding of the conditions beneath them in the rubble. Even if no additional sensors were included, the identities and pre- and post-collapse locations of the surviving network nodes can be used to help workers understand how the building collapsed, where air pockets or other survivable areas may be, and can be used by forensic investigators to make future buildings safer **[57]**.

In 2005, Harvard University deployed a WSN on Volcán Reventador in northern Ecuador. The array consisted of 16 nodes equipped with seismo-acoustic sensors deployed over 3 km. The WSN captured 230 volcanic events, producing useful data and evaluation of the performance of large-scale WSNs for collecting high resolution volcanic data **[58]**. Similarly at the University of Cambridge, CamBridgeSens Research design, build and deploy volcano surveillance wireless sensors for carbon cycle studies to urban pollution monitoring **[59]**. Therefore, ad-hoc networks are quicker to deploy and setup than installing Internet Infrastructure and WSNs are ideally suited to detecting natural disasters alongside other proven detection technology.

Animal Tracking and Management of Fish Farms

WSNs have been deployed in Norway for tracking livestock (e.g. a herd of sheep) to prevent theft or to reduce loss by predators. Surveillance of farm animals during grazing, but also later in the production chain has several benefits for the involved parties. In particular areas of Norway the animal loss due to predator attack in the grazing season is as high as 30%. This fact has both ethical and economical consequences for the farmer and his products. In addition, food safety and tractability has in recent years gained a lot of focus in Europe (e.g. UK Horsemeat scandal, January 2013). There are extensive amounts of data that needs to be collected and in very different environments with stringent demands on system robustness, lifetime and financial cost.

In 2005, Telenor's eShepherd system **[60]** was implemented as an approach to build infrastructure that might apply in this area. By deploying a WSN it is possible to monitor the state of the animals at all times. The data collected can be used to alarm the farms of predator attacks and predator rich areas and in turn be used to document the quality of the food products based on that specific animal. Similarly, according to Prof. Darwazeh, the CISG participated in a project which tracked sheep in North Wales (2010).

Marine Animals used as Ocean Sensors

In 2006, UC Santa Cruz and Stanford University were collaborating on a project called Tagging Of Pacific Pelagics (TOPP) which is a Census of Marine Life **[61]**. Another venture was University of St. Andrews' Sea Mammal Research Unit (SMRU) on Southern Elephant Seals as Oceanographic Samplers (SEaOS) project around Antarctica. Biologists and oceanographs enlisted 23 species of apex predators to serve as ocean sensors, outfitting them with electronic tags that reported oceanographic conditions (Figure 15). The data yielded new information about the migrations and behaviour of the animals and about the North Pacific Ocean.

Figure 15 - Sealion with Ocean Sensor [62]

As shown in Figure 16, the tags capture an animal's location, swim speed, and the depth and duration of dives, as well as the temperature and salinity of the seawater and how that changes with depth. As the sealions travel along the coast diving for food, their tags transmit data back to the researchers via satellite.

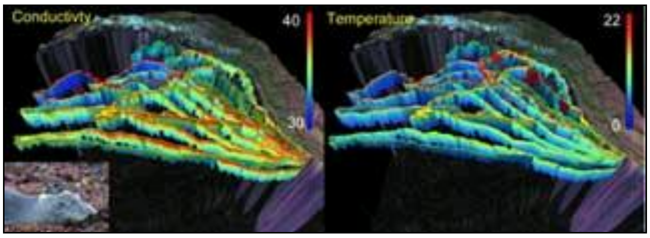

Figure 16 - TOPP/SEaOS - Sensor Data Transmitted [63]

Delay-tolerant Data Dolphin

In 2007, the University of Bologna and UCLA trialled underwater WSNs attached to dolphins. Due to the hard constraints imposed by acoustic communications and to high power consumption of acoustic modems, in Underwater Wireless Sensor Networks (UWSN), energy saving becomes even more critical than in traditional WSNs. They proposed an approach known as Delay-tolerant Data Dolphin (DDD) to apply delay tolerant networking in the resource-constrained underwater environment. DDD exploits the mobility of a small number of capable collector nodes (dolphins) to harvest information sensed by low power sensor devices, while saving sensor battery power. DDD avoids energy-expensive multi-hop relaying by requiring sensors to perform only one-hop transmissions when a dolphin is within their transmission range **[64]**.

3.3 North Sea Coastal Oceanography Sensor Network

Self-Organising Collegiate Sensor (SECOAS) is an environmental sensor technology to monitor seabed movement caused by offshore wind farming. SECOAS was a BT-led, three year DTI collaborative project that finished at the end of March 2006. The main aims of this project were, firstly, to develop a WSN for oceanography that would give unprecedented spatial resolution of a complex coastal environment, and, secondly, to develop and test lightweight techniques for pervasive ICT that would have a range of properties, including resilience, adaptation, self-configuration and responsiveness to user requirements.

Salamander (formerly Intelisys), built the sensor module that was suspended from a pyramidal cage, beneath a customised buoy. On the 60cm diameter mooring buoy was mounted a box housing data loggers, PIC microprocessors, and a low-power 173.25 MHz radio, to which a 50cm antenna was attached. Some preliminary radio trials were carried out with partners Essex University, Plextek, and Kent University.

Whilst the sensor devices were developed to be deployed off the coast, they may also be deployed as fluvial sensors. This is possible because they have a small footprint that may be further scaled down when operating in a more protected environment.

A number of unique capabilities were demonstrated by putting lightweight software on to the devices to optimise sampling rates, forwarding of data and in-situ data compression. The AI running on the low-cost, low-power microprocessors, enabled devices to be deployed without a priori knowledge of the environment to be monitored. That is, the devices exhibited adaptation to the environment in which they were deployed, in order to give the best characterisation of the environment of interest, within user-specified parameters of required lifetime and measurement priorities.

The devices were able to achieve the following:

- Share operating parameters with their neighbours, in order to refine their management of sampling rate, forwarding rate and data-compression, within available resources of battery power and bandwidth;
- Respond to differential measurement priorities, resulting in a measurement quality of service guarantee;
- Respond to further user preferences, dynamically, such as the volume of data required, or the length of the monitoring experiment, by sending short messages into the deployed sensor network;
- Demonstrate real-time data-processing, at the node level, such that a subset of data points could be forwarded that was still able to represent the key features of the shape of the curve of data, and thereby conserve battery power.

As part of two WSN trials at sea, BT gathered detailed radio and networking data. This resulted in an unexpected observation: that there was an excellent correlation between wave activity on the sea and the quality of radio communication between the wireless sensor node buoys. The sheer simplicity of the devices, whose data-gathering and communication of that data are inextricable, means that that they are very robust, because they do not have any sub-surface or other mechanical sensing elements, and the electronics consists of one simple radio microprocessor.

Figure 17 - SECOAS Buoys at Scroby Sands [65]

As illustrated in Figure 17, a number of buoys were deployed at Scroby Sands, off the Norfolk coast. The Sensor flex at the base of each buoy measured the following:

- Turbulence;
- Sediment;
- Water current;
- Salinity (used to measure salt levels);
- Water pressure (used to determine wave height).

Current oceanographic devices give detailed information about a very limited number of points, perhaps one device for every 100km or more of coastline. The technology developed for SECOAS would be cheap enough to enable sea-state monitoring devices to be distributed all around coastal waters, at short intervals, of the order of 1km. Furthermore, the sea-state information gathered would refer to the sea between buoys, as well as at the buoys themselves. So, the consequence of this technology is the ability to create an extremely rich, real-time observation tool. This real-time data could be used to enhance current state-of-the-art modelling of oceanographic processes, and to deliver rapid warnings of sea conditions to shipping and coastal residents, in the event of high seas and flood conditions.

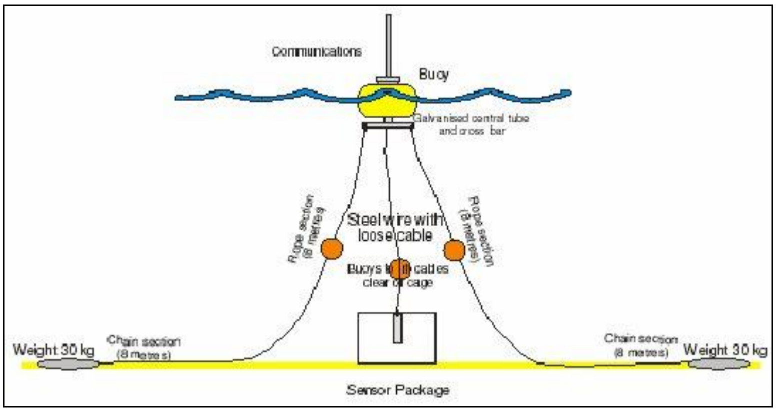

Figure 18 - SECOAS WSN Deployment [66]

Attributes of SECOAS deployment as shown in Figure 18:

- Monitor seabed movement caused by offshore wind farming;
- Radios on buoys communicate data to shore via ad-hoc network;
- Device intelligence manages battery power and bandwidth so that network collects data of greatest relevance, with appropriate priority.

The SECOAS project proved that a number of variables could be monitored by the deployment of buoys equipped with WSNs. Potential applications include monitoring off-shore wind farms to infer effects on tidal conditions, habitat, local fishing, etc. Moreover, environmental monitoring has the potential to extend WSN applications to enable early warning of a Tsunami. Also, monitoring for regulatory compliance reasons or for alerts, since most forms of utility company need to meet targets on emissions, performance, and environmental impact. Alternatively, to monitor a range of important metrics in the field in an off-the-shelf package with a modularised component system. The same core networking and O/S would be needed for humidity, temperature, gases, chemicals, etc, but with specialised plug in sensors.

Benefits of SECOAS include the sensory equipment is easily deployable, low maintenance, low cost, uses ad-hoc networks, reliable near real-time data, able to blend into an attractive environment, further buoys may be added later. Issues include the equipment being damaged by the sea, ensnared in fishermen's nets or stolen.

SECOAS Technology Dividend [67]:

- Potential for advanced flood warning;
- Coastal defence planning;
- Understanding impact of coastal developments, such as wind farms;
- Input into national and global models of climate change.

3.4 Smart Vehicles - Ubiquitous Traffic Telematics

The drive towards in-car information and entertainment systems (Telematics), which will enable cooperative vehicle and safety applications, electronic toll collection and in-car Internet access, is steadily picking up steam. This together with the rapid developments in the wireless access technologies (including WiFi), creates the possibility of large-scale ubiquitous computing applications for travellers, including real-time traffic monitoring, dynamic navigation, route weather forecast and location based services **[68]**.

- Purpose – communications for use in moving vehicles;
- Requirements and ability – operation, management and performance of ad-hoc networks;
- Security and privacy – protecting users' data in a mobile world;
- Middleware – connecting users with their information anytime and anywhere;
- Business models – multiple applications sharing common (generic) infrastructure;
- Evaluate – vehicle to infrastructure communications for improved RT congestion control;
- Down-streaming – identify appropriate strategies for the Traffimatics platform.

The Traffimatics research project was part-funded by the DTI (2004-06) and was led by BT in partnership with Nottingham Trent University (NTU), Influx Technology and Shadow Creek Consulting. As depicted in Figure 19, Traffimatics explored ways to send information from one vehicle to another, Telematics to benefit drivers, traffic control centres and emergency services. The Traffimatics project is about enabling the connected car vision – a vision where vehicles communicate information to other vehicles or to the intelligent transport infrastructure (vehicle-to-vehicle and vehicle-to-infrastructure). This is made possible by the formation of two networks, an internal network within each individual vehicle that can read potentially useful data from the vehicle, and an external network made up by a number of moving vehicles, connected by wireless LAN technology, that can pass on that information.

The research was used to build a prototype. Such information is the basis for a plethora of value-added services to benefit the drivers, the passengers and transport planners. These services could range from safety applications such as informing vehicles behind of an unexpected traffic hazard ahead (e.g. icy roads in winter) to traffic information services offering automatic re-routing to automated road user charging.

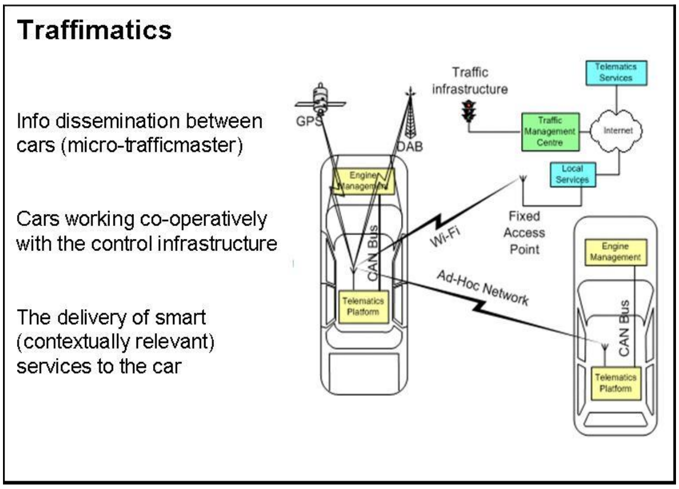

Figure 19 - Traffimatics WSN Architecture [69]

Traffimatics Project Aims

- To produce an open, cost effective Telematics communications platform;
- To integrate seamlessly with other ubiquitous computing environments (e.g. car industry) and emerging infrastructure;
- To be self-managing, requiring no driver involvement and to evolve with technology and end-user demand;
- To demonstrate the ability to support innovative applications that will deliver real benefits to the vehicle user, and society.

Traffimatics Overview

- Intercept vehicle status data via Controller Area Network (CAN) bus;
- Analyse status with location context to deduce intentions or recognise problems (e.g. traffic hotspots or accidents);
- Communicate information and warnings to other road users and the infrastructure operators (e.g. traffic management, emergency services, city councils);
- Receive and analyse information: present relevant advice to the driver in a useful way;
- Test-beds were deployed in Nottingham City Centre and at Adastral Park.

Figure 20 - Traffimatics Car [70]

To enable the connected car vision the Traffimatics project looked at the information flow from the vehicle to the transport infrastructure. As Dr. George Bilchev (Figure 20) explained, this information flow involves several steps as follows: "1. extracting sensor data from the vehicles; 2. analysing the raw data and communicating relevant events to other traffic participants; and 3. presenting the data to traffic controllers or other interested parties" **[71]**.

Former BT Research Director, Mike Carr, commented: "Traffimatics examines how the combination of standard in-vehicle networks and sensors, cheap wireless LAN technologies and web services can be combined to disseminate important data from a vehicle to help improve traffic control, road safety and other useful and inexpensive motoring services to drivers. These might include real-time traffic and weather information, or back-seat entertainment, such as access to the web or online inter vehicle chat" **[72]**.

Traffimatics also points to other benefits of joined-up communication on the roads, including to society and the environment. Better information on the volume and type of traffic will help governments implement road toll schemes where they will be most effective. The use of such Information Networking (IN) should help to reduce accidents and control congestion, re-route traffic, shorten journey times and ensure optimum fuel consumption resulting in lower pollution levels (fewer carbon monoxide emissions) for the environment, not to mention raise revenue for the government.

The WSN prototype solution, which is based on open standards, was cost-effective to build, because it used off-the-shelf components and open-source software to implement an on-board platform. It also includes traffic control applications such as a parking-space finder, and a system that can detect traffic jams, road congestion and obstacles on the road, all based on data related to the vehicle's position.

Car-2-Car Communication Consortium

Following on from the achievements of the Traffimatics project, as illustrated in Figure 21, the C2CCC are developing state-of-the-art technology for intelligent networked vehicles for the car industry. The consortium members include leading car manufacturers: VW/Audi, BMW, Daimler, Fiat, Honda, Opel, Renault, and Volvo. They are looking at ad-hoc networking to provide vehicle-to-vehicle and vehicle-to-infrastructure data about the EU traffic networks.

Figure 21 - Smart Vehicle WSN Traffic Scenarios [73]

The mission and the objectives of the Consortium are as follows:

- The development and release of an open European standard for cooperative Intelligent Transport Systems (ITS) and associated validation process with focus on inter-vehicle communication systems;
- To be a key contributor to the development of a European standard and associated validation process for vehicle-2-roadside infrastructure communication being interoperable with the specified inter-vehicle communication standard;
- To provide its specifications and contributions to the standardisation organisations including in particular ETSI TC ITS in order to achieve common European standards for ITS;
- To push the harmonisation of Car-2-Car Communication standards worldwide;
- To promote the allocation of a royalty free European wide exclusive frequency band for Car-2-Car applications;
- To develop realistic deployment strategies and business models to speed-up the market penetration;
- To demonstrate the Car-2-Car system as proof of technical and commercial feasibility.

Ultimately, there are more benefits if all manufacturers enable the following:

- Car-to-car and car-to-infrastructure ad-hoc networking;
- Traffic infrastructure integration;
- Novel application areas.

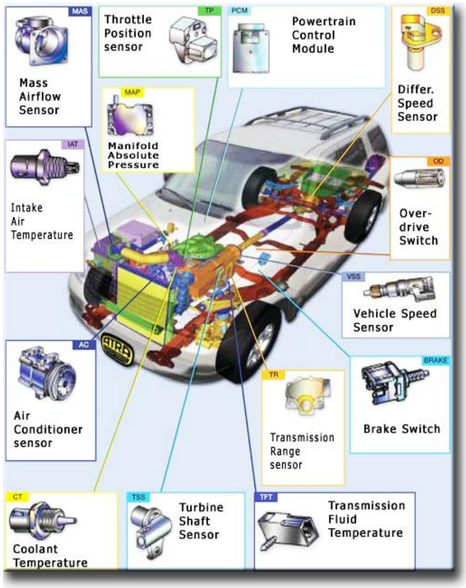

Figure 22 - Vehicle Sensors [74]

As depicted in Figure 22, vehicle manufacturers use many different types of sensors as standard (e.g. vehicle speed sensor, coolant temperature sensor, etc).

Smart vehicle technology is applicable to motorcycles, emergency vehicles, highway maintenance vehicles, HGVs and not just the preserve of cars. The main aim is to eradicate all fatal accidents and perhaps even all accidents. In fact, today’s innovation and differentiation becomes tomorrow’s expectations, standardised components or incorporated into Road Safety Law.

Smart car innovations using sensors include the following:

- Auto-drive (e.g. Google self-driving cars and RobotCar);
- Auto-brake (e.g. Toyota’s automatic brake system assisted by GPS);
- Auto-park (e.g. Ford’s ‘active park assist’ for parallel parking);
- Proximity sensors or cameras (e.g. Audi, BMW, Mercedes);
- External airbags (e.g. Volvo’s external vehicle protection (EnVeloP) system);
- Rain detection for auto-windscreen wipers (e.g. Peugeot).

Google’s self-driving cars are based on Lexus RX450h and Toyota Prius models. Each is fitted with sensors and a camera on the top. Nevada’s Department of Motor Vehicles said they were as safe as human drivers **[75]**. Similarly, RobotCar by Oxford University is based on a Nissan Leaf electric car and uses an onboard laser sensor **[76]**.

Cooperative Vehicle-Infrastructure Systems (CVIS)

Intelligent CVIS are the next big challenge in automotive electronics and ITS. Intelligent Co-operative Systems that are based on Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I)

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communications hold the promise of great improvements both in the efficiency of the transport systems and in the safety of all road users. CVIS partners include: the DoT, TfL, Highways Agency, BAE Systems, Imperial College London, Mapflow, Vodafone, Volvo and Renault. Intelligent Co-operative Systems increase the 'time horizon', the quality and reliability of information available to the drivers about their immediate environment, the other vehicles and road users, enabling improved driving conditions leading to enhanced safety and mobility efficiency. Co-operative Systems also offer increased information about the vehicles, their location and the road conditions to the road operators and infrastructure, allowing optimized and safer use of the available road network, and better response to incidents and hazards **[77]**.

Sensor networks have a wide variety of applications, from monitoring environmental data, to observing natural phenomena, and from various target tracking to even prevention of terrorist attacks. By embracing recent sensor network technology, many practical applications, both highway and non-highway related, can be discovered. Other potential developments include prevention of car collisions, pedestrian safety and lane-maintenance. All are very interesting sensor-network research topics that will improve the safety and efficiency of our highways for the future **[78]**.

BT Trackit

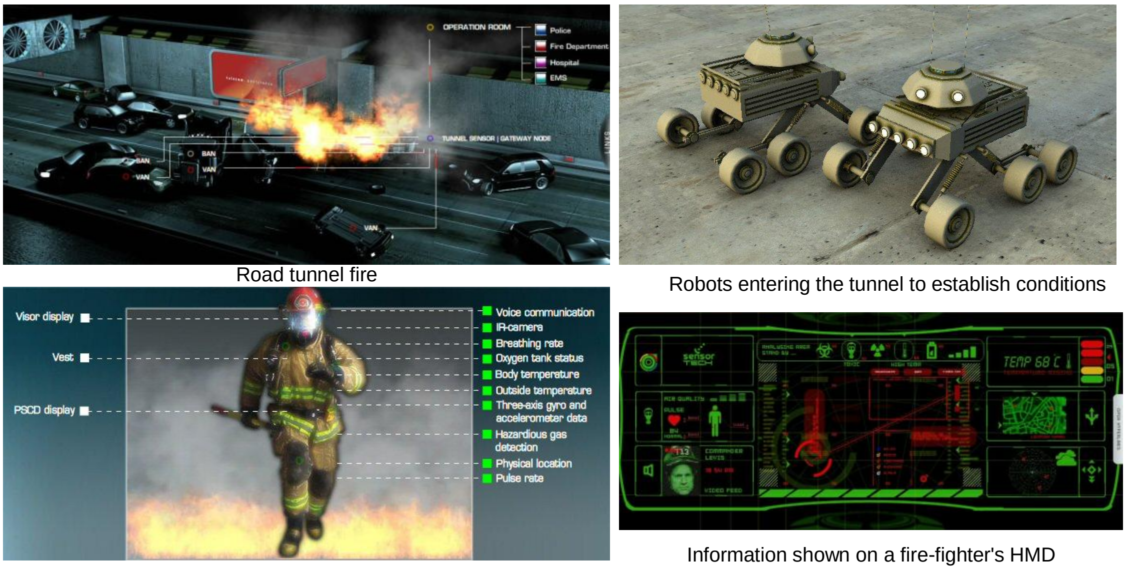
BT Redcare is an innovative product and service business, developing M2M based solutions offering secure wireless data and Telematics. BT realised that vehicle tracking was a significant growth area, both for security and to enable companies to automate activities such as vehicle expenses, logistics, etc. As shown in Figure 23, the first in-car security service that BT Redcare developed was called Trackit, a GPS vehicle tracking system and anti-theft solution, which enables BT to pin-point the exact location of a vehicle in the UK and 27 European countries.

Figure 23 - Trackit Vehicle Tracking System [79]

Trackit provides the highest level of vehicle security monitoring for fleets of lorries and emergency services vehicles, through a driver identification tag, coupled with satellite tracking and BT's own Secure Operation Centre (SOC) **[80]**. Trackit can remotely and safely immobilize a car when moved without the owner's consent, while at the same time providing remote alarm and location data to speed its recovery **[81]**. Trackit is easy to use, because when the ignition is switched on, the Trackit system searches for the unique identification tag. It uses the latest in tracking technology, combining wireless, in-car electronics and satellite navigation to enable the speedy recovery of stolen vehicles. The local police and the BT SOC are then alerted to ensure the safe recovery of the vehicle. No further action is required by the driver and once they are identified as the authorised driver, the system is disarmed **[82]**.

Reconfigurable Ubiquitous Networked Embedded Systems (RUNES)

The author attended the RUNES project summer school at UCL (refer to Appendix J). The compelling “Fire in a Road Tunnel” video (Figure 24) shows the potential of transportation WSNs with the deployment of bots within a multi-vehicle collision accident scenario. RUNES vehicles may alert each other as well as traffic control authorities and emergency services to ensure the nearest hospitals are on standby to deal with casualties.



Road tunnel fire

Robots entering the tunnel to establish conditions

Information shown on a fire-fighter's HMD

Fire-fighter equipped with a body area network

Figure 24 - Fire in a Road Tunnel Scenario [83]

The goals of the RUNES project were as follows:

- Build well-founded middleware systems that are:
  – Scalable (heterogeneity, numbers);
  – Adaptive;
  – Auto-configurable.
- Ensure middleware is robust and predictable;
  – Control and security.
- Build tools that allow for:
  – Application development;
  – Assessment of usability;
  – Application debugging.
- Assess our developments in:
  – Real-world scenarios;
  – Emulation of large scale systems.

The RUNES middleware provides abstractions to simplify both application and system development. As illustrated in Figure 25, the middleware is built around Component Frameworks (CF), which are reusable and dynamically-deployable software architectures. Highly modularised and customisable services and application specific mechanisms can be built as compositions of components and/or CFs. These have been validated in the context of the "Fire in a Road Tunnel" scenario and deployed on devices ranging from PCs to PDAs to tiny sensor devices running the Contiki OS.

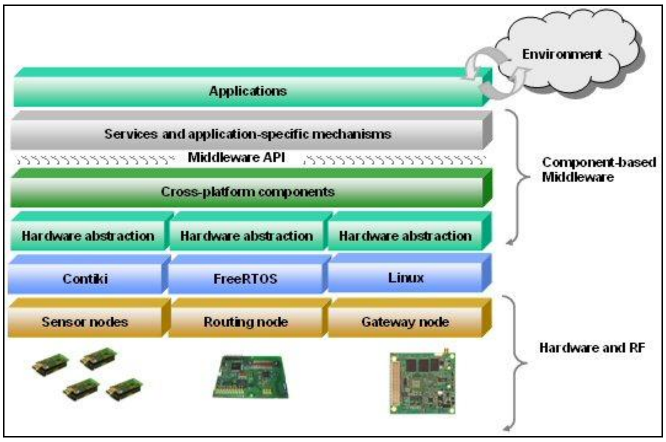


Figure 25 - Contiki WSN Architecture [84]

Smart Vehicles, Devices and Robots

Despite global recession and US national debt, DARPA continue to invest heavily in sensory R&D, mote technology and applications by funding WSN projects at leading universities including UCLA, MIT, UC Berkeley, Virginia Tech, and UA Huntsville. DARPA's program, called Tactically Exploited Reconnaissance Node (TERN) after a family of seabirds, seeks a faster, less expensive way to use smaller ships as mobile launch and recovery sites for long-endurance drones **[85]**. The MCANAE summer school combined WSNs with robotics and featured radio controlled drones, which are packed with sensors (refer to Appendix J).

DARPA funded remote-controlled drones known as Autonomous Underwater Vehicle (AUV) or Unmanned Aerial Vehicle (UAV) are deployed predominantly for military applications. UAVs are used as a safety precaution against impending danger, but for Virginia Tech, AUV Maritime Robot drones are utilised for a more educational purpose. With six drones on hand, the university is working with the pilotless helicopters to perform vital research. Remaining on the ground, engineering faculty and students from Virginia Tech control the aircraft carriers with a remote, allowing for autonomous flight. They inspect the contraption in midair, aiming to improve the technology associated with drones and "develop specific applications," describes The Roanoke Times. Their goal is to improve the study of agricultural disease as well as the assessment and mapping of "special environments" like that of forests and explosion locations **[86]**.

Distributed sensor modelling and anomaly detection can be used in a wide variety of sensor network and mobile robot applications, such as detecting the presence of intruders, detecting sensor failures, detecting anomalous human motion patterns, detecting unexpected chemical signatures, and so forth **[87]**.

The University of Aberystwyth worked on an unmanned, remote controlled boat which uses software and sensors to steer, sail and operate the rudder. They were vying to be first to cross the Atlantic **[88]**.

Honda's humanoid robot ASIMO comprises of multiple sensors and is capable of mimicking human behaviour such as charting a route; recognising moving objects, faces and gestures; distinguishing sounds; and even climbing stairs **[89]**.

Sensors are ubiquitous in affordable smart devices such as mobile phones and tablet computers (e.g. accelerometer, GPS) and in video game consoles (MEMs). Furthermore, WSNs lend themselves to being integrated with immersive Virtual Environments (VE) and augmented reality, e.g. for safer and more secure offices and stadia (intelligent buildings), all linked in a digital world.

3.5 Intelligent Buildings

WSNs may be deployed for remote home automation or to monitor buildings or infrastructure such as bridges, or by utility companies for underground infrastructure condition monitoring (e.g. PIPES) or automated meter reading (AMR).

Building Awareness for Enhanced Workplace Performance

BOP (formerly known as BAEWP) was a £1 million, two-year (2007-2009), multidisciplinary project, funded by the DTI. It investigated how pervasive computing, using WSNs, can be used to create an understanding of the creative workplace - 'Making Sense of Space'. The consortium consisted of the following partners: ARUP Foresight; BT Research; Imperial College; Central Saint Martins (CSM), University of the Arts London; Brunel University; AP Futures; Artificial Tourism; Maoworks; and Spy.

BOP Overview

- Monitor users behaviour using sensors - social interactions between work colleagues for the purpose of improving working conditions and designed office spaces;
- Workplace trials using bespoke sensor motes attached to desks or deployed in meeting rooms, near real-time processing on Dell Latitude X1 laptop;
- Measure creative performance ('performativity');
- Passive polling;
- Simulations and various sensor deployments in London and at Adastral Park.

BOP aimed to develop a system for monitoring the use of buildings and to use this system to understand how people interact with buildings. The system was independent from the fabric of the building allowing it to be readily reconfigured and giving the opportunity for the impact of design changes in the building to be measured and assessed. Data from the system can be analysed in real-time and fed back to users in ways that enhance their creativity, innovation, performance and comfort.

As the project literature explains, BOP conceives human, technological and building performance as being integrated in an open system that underpins productivity in the knowledge workplace. BOP gathered quantitative and qualitative data about the physical environment, the use of space and the mood of the work force. The WSN captures tangible environmental factors, for example, light levels, heat levels, noise levels and people's presence, and workforce reports on intangible factors, such as perceptions of personal energy levels, sense of well-being, stress and feelings of connectedness with others **[90]**. In practical terms this meant that the consortium deployed a 20 node WSN capturing environment data, activity based sensors and prototyped several different polling devices **[91]**.

Although Pervasive computing is in its commercial infancy, BOP was the first project to use WSNs to get a better understanding of the fit between built environments and the organisations and people who use them. Current industry best practice for monitoring energy use or workplace productivity is highly labour-intensive. BOP aimed to design a faster, more effective system, a foundation for grasping human-built environment interaction systems.

BOP developed new sensory user interfaces for gathering and reporting data. The new, non-intrusive interfaces provide a compelling alternative to online or paper-based Post Occupancy Evaluation (POE) questionnaires and express outcomes as audiovisual feedback directly into the workplace environment.

BOP provides feedback data to an audience that includes the workforce as well as managers. It is envisaged that knowledge shared with the workforce will empower and energise teams and individuals in the more flexible forms of organisation which are emerging, by providing them with the information they need in a timely and engaging fashion.

BOP - control and monitoring systems for buildings rely on an extensive installed infrastructure to provide predetermined information solely to building managers. Pervasive computing technologies have the potential to provide more flexible systems that can be readily reconfigured both in location and in terms of the parameters measured. Leading to improved disaster management since emergency services familiar with building layout plans and construction materials (e.g. asbestos in the ceilings, stairways, location of fire exits). Also, sensors already deployed for sprinkler system, so usable after customised sensor mote additions.

WSN Architecture

Four different WSN platforms were deployed in the whole BOP project to facilitate the variety of sensors used - Crossbow motes, Arduinos, Bengt Polls and Beasties. Data fusion for all the devices took place at a centralized MySQL server where each data logger would push data in order to provide a pseudo-synchronous view of the WSNs. To achieve the link between the base stations and the centralized database, bespoke software was developed to forward data to the database. A web-based query interface was used to interact with the database and perform queries on filtered data based on location variables. Using the Bricks architecture, a user (or an application) can seamlessly query multiple sensors that are part of the same location or the same location subgroup. Bricks will automatically process the values from all the sensors that logged data, hiding the complexity of the underlying WSNs and providing a persistent interface for the end-user. The Beastie used an architectural description language implementation called Tesserae **[92]**.

Beasties were used in partnership with ARUP architectural engineers as part of the BOP installation in Central Saint Martins College of Art Innovation Centre. The BOP project used WSNs to non-invasively monitor people performing creative work in an office environment and thus provide a way to evaluate the design of their office environment and how it affected creativity. Beasties were used to measure two types of information. One set were fitted with temperature, light, and multiple-echo ultrasound sensors, the output of which was fed into a modified self-organising feature map, running locally on the Beastie, which allowed it to pick out various states of the room (such as “dark”, “light”, “in use”). A second set of Beasties monitored thermal people counters to count people moving between various parts of the building. Both of these sets of Beasties sent their data back to base stations for aggregation and further processing. In use, the Beasties proved extremely reliable and survived the entire four week trial without failure, unlike the other types of commercial WSN device that were deployed at the same time **[93]**.

Central Saint Martins College of Art Innovation Centre deployment in 2007 **[94]**:

- Vibrations, motion, environmental sensors;
- Novel polling stations;
- Meeting rooms, offices, informal areas;
- Self-Organising NN deciding state:
  - 6-10 states a day;
  - Day, night, empty, occupied, meetings, social, creative/uncreative?
- “One of the biggest heterogeneous sensor network deployments in the world”.

BOP - Data Analysis

The author assisted Dr. Jane Tateson with data analysis of the BOP meeting room observation trials on the 5th Floor of Orion building at Adastral Park. As shown in Table 3, BOP observations were conducted by the author in October 2007 within three meeting rooms. The rationale was to observe how the meeting room activities on a particular day (e.g. number of occupants, equipment used, type of meeting, etc) compared with the sensor data captured by the mote deployed in each of these meeting rooms for the BOP trial.

The Orion meeting room trials resulted in patterns of an active meeting (a person standing / using whiteboard - usually infers larger groups); or a passive meeting (participants seated while discussing or single person using the telephone); and the number of participants in the room could be inferred from the noise levels monitored. Unsupervised clustering was carried out to ascertain how many states the room was in. If feedback was attained from the room occupants via POE, then some supervised learning was carried out. The raw data was processed into statistics of various types that was then used as input data for the supervised and unsupervised learning.

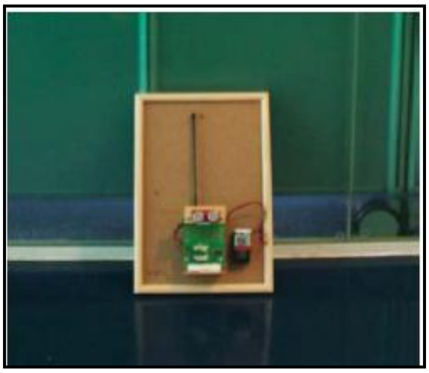


Figure 26 - Customised Beastie Mote Deployed in Orion [95]

Custom-built motes based on Imperial College's ultrasound Beastie and known as "BT Proximity Ultrasounder" sensors (Figure 26) were used to avoid recording private meetings. In addition, the author was responsible for ensuring that the motes deployed in meeting rooms always had adequate power by changing the (AA type) batteries every other day.

Table 3 - BOP - Meeting Room Observations [96]

Time	Meeting Room (5th Floor, 1,3&4)	No. of Occupants	Meeting Activity	Type of Meeting (detected by mote)
10:10am	5/01	6	seated with laptops, door closed	Passive
	5/03	2	seated with laptops, door closed	Passive
	5/04	0	empty, light on	n/a
10:30am	5/01	6	seated with laptops, door closed	Passive
	5/03	2	seated with laptops, door closed	Passive
	5/04	3	seated, door closed	Passive
10:38am	5/04	3 exit, 3 enter	Transition	n/a
10:50am	5/01	4	1 standing, 3 seated, door closed	Active
	5/03	2	seated with laptops	Passive
	5/04	3	2 standing, door closed	Active
11:15am	5/01	0	empty, light on	n/a
	5/03	2	seated, door closed	Passive
	5/04	3 exit	transition, light on, door closed	n/a
11:41am	5/01	0	empty, laptop in room	n/a
	5/03	2	1 standing at white board, door closed	Active
	5/04	0	empty, light on, door open	n/a
11:43am	5/04	1	seated using phone, door closed	Passive
12:00	5/01	1	seated using laptop, door closed	Passive
	5/03	1	seated using laptop and headphones door closed	Passive
	5/04	0	empty, light on	n/a
12:30	5/01	1	seated using laptop, door closed	Passive
	5/03	0	empty, light on, laptop in room	n/a
	5/04	0	empty, light off	n/a
12:39	5/04	1	seated using phone, light on, door closed	Passive
13:24	5/01	1	seated using laptop, door closed	Passive
	5/03	1	seated using laptop	Passive
	5/04	1	seated using phone	Passive
13:31	5/04	1 exits	transition, light on, door closed	n/a
13:50	5/01	1	seated using laptop, door closed	Passive
	5/03	2	seated using laptops, door closed	Passive
	5/04	0	empty, light on	n/a
14:20	5/01	0	empty, light on	n/a
	5/03	2	1 standing with laptops	Active
	5/04	3	seated with laptops, door closed	Passive
14:42	5/01	2	seated no laptops, door closed	Passive
	5/03	2	1 standing with laptops, door closed	Active
	5/04	5	seated with laptops, door closed	Passive
16:07	5/01	0	empty, light on	n/a
	5/03	3	seated with laptops	Passive

	5/04	0	empty, light on	n/a
16:38	5/01	1	seated using phone, door closed	Passive
	5/03	3	seated using laptops, door closed	Passive
	5/04	0	empty, light off	n/a
17:12	5/01	0	empty, light on	n/a
	5/03	1	seated using laptop and phone, door closed	Passive
	5/04	0	empty, light off	n/a
17:39	5/01	0	empty, light off	n/a
	5/03	1	seated using laptop, door closed	Passive
	5/04	0	empty, light on	n/a
18:15	5/01	0	empty, light off	n/a
	5/03	1	standing using mobile and laptop, door closed	Active
	5/04	0	empty, light on	n/a

As discussed (see WSN Architecture, p.68) bespoke algorithms were developed by the BOP consortium for the WSN deployment at CSM. The Orion meeting room trials conducted by the author were much simplified to serve as proof of concept (i.e. to test customised sensors, room acoustics, attitudes/objections of attendees towards the monitoring devices, etc). Figure 27 depicts a simulated graph of the accuracy of the trials conducted by the author.

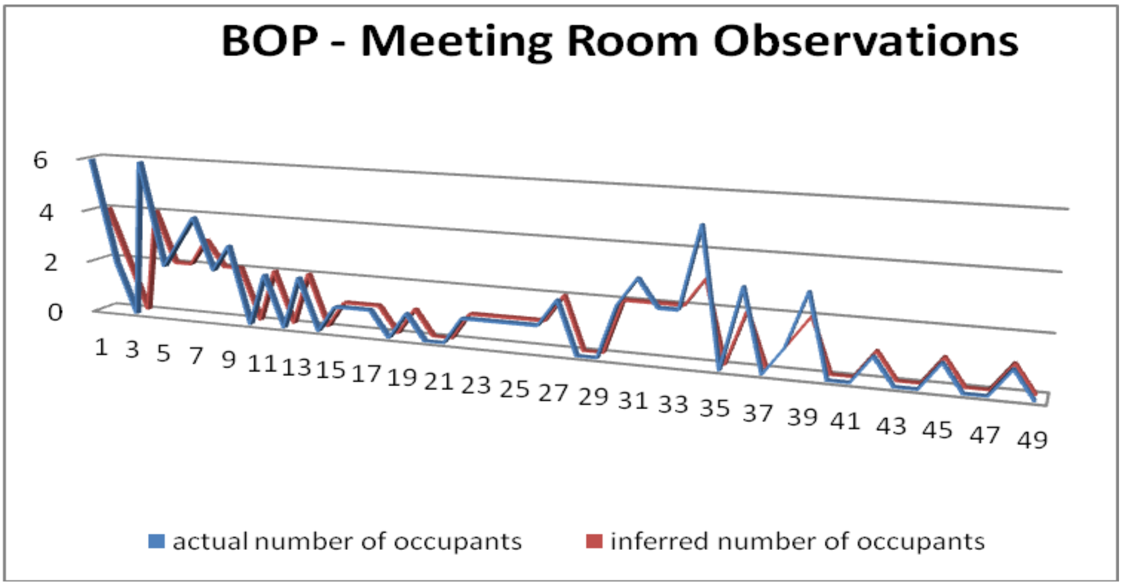


Figure 27 - BOP Meeting Room Observations Graph [97]

Figure 27 shows greater accuracy with lower numbers of occupants. This is because the ultrasound mote (shown in Figure 26) relies on noise detected to count the number of occupants. For example, an active meeting with several occupants sitting and one occupant standing to present, is likely to result in less noise being detected and therefore erroneously fewer occupants being detected.

BOP - Data Sample Observations (Figure 28)

- Some of the columns have been omitted to enhance readability;
- Timestamp is unique for each sensor reading/stream to maintain data integrity;
- Time elapsed in minutes gives the frequency of the sensor events captured;
- Real-time keeps an accurate recording of the actual date and time of the sensor event captured;
- Packet length is always 12 to ensure sensor data is transmitted in the correct format and not truncated, e.g. this would show zero if the batteries were spent;
- Sensors deployed on this particular mote were light, temperature and ultrasonic 1, 2 and 3;
- Light maintains the values from 245 to 246, so there is minor loss of brightness from the fluorescent lighting tubes installed in the suspended ceiling;
- Room temperature is maintained at 22°C, which is as expected since the room has automated air conditioning and heating;
- Ultrasonic 1 maintains the values from 37 to 38;
- Ultrasonic 2 maintains the values from 80 to 82;
- Ultrasonic 3 sensor data readings vary between a steady 188 and maximum of 204.

In conclusion, the customised ultrasound motes used for the Orion meeting room trials were successful in their objective. Motes were fairly easy to customise, configure and deploy. There were no objections made by BT people or visitors using the meeting rooms. Battery power was adequate for the purpose and consistent sensor data was captured for analysis. However, the Orion trials are not representative of the more advanced and extensive building monitoring WSN deployments conducted by the BOP consortium. The BOP trials conducted at CSM used the Beastie node counting sensor (thermal people counters, p.68) and developed a bespoke count algorithm.

Figure 28 shows a fifty row sample of sensor data captured within one of the Orion meeting rooms during the BOP observation trials conducted in October 2007 by the author.

Timestamp	Time elapsed in minutes	Real time	packet length should be 12	Light	Temperature	Ultrasonic1	Ultrasonic2	Ulrasonic3
0A3A0669	2859.581483	10/10/2007 11:16	12	246	22	38	81	188
0A3A06EE	2859.5837	10/10/2007 11:16	12	246	22	38	81	188
0A3A0754	2859.5854	10/10/2007 11:16	12	246	22	38	81	188
0A3AFA8B	2860.623117	10/10/2007 11:17	12	245	22	38	81	188
0A3AFAF6	2860.6249	10/10/2007 11:17	12	245	22	38	81	188
0A3AFB6E	2860.6269	10/10/2007 11:17	12	245	22	38	81	188
0A3BEEC3	2861.665117	10/10/2007 11:18	12	246	22	38	81	188
0A3BEF67	2861.66785	10/10/2007 11:18	12	246	22	38	81	188
0A3BF00B	2861.670583	10/10/2007 11:18	12	246	22	38	81	188
0A3CE37E	2862.7093	10/10/2007 11:19	12	246	22	38	81	188
0A3CE41F	2862.711983	10/10/2007 11:19	12	246	22	38	81	188
0A3CE4BD	2862.714617	10/10/2007 11:19	12	246	22	38	81	188
0A3DD827	2863.753183	10/10/2007 11:20	12	246	22	38	81	188
0A3DD8C7	2863.75585	10/10/2007 11:20	12	246	22	38	81	188
0A3DD950	2863.758133	10/10/2007 11:20	12	246	22	38	81	188
0A3ECCA9	2864.796417	10/10/2007 11:21	12	246	22	38	81	204
0A3ECD14	2864.7982	10/10/2007 11:21	12	246	22	38	81	204
0A3ECD92	2864.8003	10/10/2007 11:21	12	246	22	38	81	204
0A3FC0E5	2865.838483	10/10/2007 11:22	12	246	22	38	81	188
0A3FC192	2865.841367	10/10/2007 11:22	12	246	22	38	81	188
0A3FC234	2865.844067	10/10/2007 11:22	12	246	22	38	81	188
0A40B6F1	2866.888283	10/10/2007 11:23	12	246	22	38	81	199
0A40B758	2866.89	10/10/2007 11:23	12	246	22	38	81	199
0A40B7C4	2866.8918	10/10/2007 11:23	12	246	22	38	81	199
0A41AB60	2867.9312	10/10/2007 11:24	12	246	22	38	81	195
0A41AC5F	2867.93545	10/10/2007 11:24	12	246	22	38	81	195
0A41ACC7	2867.937183	10/10/2007 11:24	12	246	22	38	81	195
0A42A008	2868.975067	10/10/2007 11:25	12	246	22	38	82	196
0A42A07A	2868.976967	10/10/2007 11:25	12	246	22	38	82	196
0A42A106	2868.9793	10/10/2007 11:25	12	246	22	38	82	196
0A439488	2870.018267	10/10/2007 11:27	12	246	22	38	81	199
0A439521	2870.020817	10/10/2007 11:27	12	246	22	38	81	199
0A4395AF	2870.023183	10/10/2007 11:27	12	246	22	38	81	199
0A4488FB	2871.06125	10/10/2007 11:28	12	246	22	38	81	199
0A448985	2871.06355	10/10/2007 11:28	12	246	22	38	81	199
0A4489F5	2871.065417	10/10/2007 11:28	12	246	22	38	81	199
0A457D48	2872.1036	10/10/2007 11:29	12	246	22	38	81	199
0A457DDF	2872.106117	10/10/2007 11:29	12	246	22	38	81	199
0A457E68	2872.1084	10/10/2007 11:29	12	246	22	38	81	199
0A4671AB	2873.146317	10/10/2007 11:30	12	246	22	37	80	188
0A467222	2873.1483	10/10/2007 11:30	12	246	22	37	80	188
0A4672AE	2873.150633	10/10/2007 11:30	12	246	22	37	80	188
0A4765F6	2874.188633	10/10/2007 11:31	12	246	22	38	82	203
0A4766A2	2874.1915	10/10/2007 11:31	12	246	22	38	82	203
0A476742	2874.194167	10/10/2007 11:31	12	246	22	38	82	203
0A485AB4	2875.232867	10/10/2007 11:32	12	246	22	38	81	199
0A485B94	2875.2366	10/10/2007 11:32	12	246	22	38	81	199
0A485C1A	2875.238833	10/10/2007 11:32	12	246	22	38	81	199
0A494F55	2876.276617	10/10/2007 11:33	12	246	22	38	81	199
0A494FBF	2876.278383	10/10/2007 11:33	12	246	22	38	81	199

Figure 28 - BOP Sensor Data [98]

Related Work

There are many other examples of where sensors are used in an 'intelligent building'. However, these have traditionally been wired installations (e.g. standard building management systems, such as HVAC). WSNs offer several significant advantages over such systems in terms of ease and cost of deployment and flexibility and live data streams.

Functioning as part of the Building Management System (BMS), proximity sensors have been used in offices such as Orion building, for a number of years to automatically switch off lights at the end of a working day, in order to make energy (environmental) and cost (utility bill) savings.

3.6 Intelligent Infrastructure

Personalised Information from Prioritised Environmental Sensing (PIPES)

PIPES was a three year DTI collaborative project from 2006-09 and concerned underground infrastructure condition monitoring. The Modern Built Environment is underpinned by communication and utilities infrastructures. There is a need to monitor and maintain the physical media (e.g. pipes, cables, and supporting structures such as tunnels, ducts and manholes). The PIPES project aimed to develop a system which provides timely, relevant information on infrastructure integrity to a range of interested users. Integrating monitoring data with communication infrastructures will make logistics more efficient **[99]**.

The PIPES project consortium consisted of the following partners:

- BT - Project Lead, Sensors and Communications, AI, BT test site (7 acre) and deployment;
- Cambridge University - Radio propagation from underground infrastructure;
- Imperial College - Computing architecture;
- Severn Trent Water - Domain knowledge, data, leak research test site (Lake House), deployment tests;
- Salamander (formerly Intelisys) - Products in water industry, down-streaming route.

PIPES aimed to develop a system of low-cost wireless devices that could:

- Locate mains water leaks fast and accurately in Severn Trent Water's supply network;
- Provide BT with real-time information on environmental damage, maintenance and illegitimate access to assets such as cables, ducts and support infrastructures (BT's "Poles & Holes");
- Cost effective monitoring of physical media;
- Nottingham leak repair **[100]**.

PIPES predictive and preventative maintenance for utilities saves precious resources, reduces potentially dangerous gas leaks or electrical faults, good for the environment as well as business (As exemplified in Figure 29).

The objectives of PIPES were as follows **[101]**:

1. Locate mains water leaks cheaply and accurately:
    - Fix leaks more quickly to meet regulation targets and reduce maintenance costs;
    - Bypass leaks to manage supply/demand and conserve water.

2. Provide BT with real-time information on ingress and security breaches into cables, ducts and support infrastructures (e.g. manholes, distribution points).
    - Fewer faults for better customer service;
    - Better maintenance logistics to reduce maintenance costs and improve safety;
    - Infrastructure planning for timely, preventative maintenance;
    - Better monitor and deal with security issues (e.g. copper theft or terrorist sabotage).

Figure 29 - PIPES WSN Deployments [102]

Architecture - A platform that:

- Is made up of heterogeneous devices, able to exploit very simple sensor nodes (e.g. motes), higher functionality devices (e.g. PDAs), and even be integrated with high-resolution sensor systems, such as fibre sensors;
- Uses heterogeneous communication, having multiple data forwarding routes, such as 802.15.4 (e.g. ZigBee), WiFi, GSM, and wire-line, if appropriate;
- Is sensor transparent, and hence can be extended to other underground infrastructures such as oil and gas pipelines;
- Has distributed intelligence to provide robustness and adaptation to diverse environments and varying priorities.

Common Sensing

- Single sensor multiple applications;
- Low cost Bi-morph to sense vibration;
  - Accelerometers
- Simple analogue signal conditioning;
- Signal analysis in the digital domain;
  - PIPES: leak noise
  - BT: destructive versus normal use
- AI techniques to self learn “normal-behaviour”;
- Imperial College created a tuple space architecture.
- Lake House water leak simulation and detection tests (Amplitude and Sonogram plots by Severn Trent / BT)
  - Normal Flow;
  - Easy Leak;
  - Hard Leak.
- Fault finding applications for utility management (ARUP).

Future Work

- More measurements;
  - Improving AI approach
- Sensor Prototypes;
  - Sun SPOTS
  - Mobile Phone
  - PDA
  - GSM M2M Module
- Gateway Devices;
- Comparison with other off-the-shelf solutions;
- BT application;
- Architecture.

The PIPES project is an example of how BT collaborates with its clients to develop innovative technology led solutions to address their business challenges. Technology developed by BT for one purpose being applied to similar problems in other sectors. A bigger picture view should be taken to move away from the application specific approach. Also, provides future business opportunities, especially for Telcos as identified by the Eurescom survey.

Figure 30 - PIPES Simulation [103]

As depicted in Figure 30, PIPES demonstrated the need for sensor integration for a number of utility companies (BT - telecoms; Severn Trent - water and sewage). WSNs were deployed to aid infrastructure monitoring and to enable predictive maintenance. The author conducted testing and created graphics for the PIPES simulation demo programmed in Visual Basic by Dr. Chris Roadknight to show monitoring of changes (e.g. weather, temperature, vibration caused by a virtual JCB) to the underlying infrastructure at Adastral Park. For instance, noise may be detected by vibration / seismic / acoustic sensors underground. In the demo, the simulated JCB results in increasing vibration sensor readings sensed by the underground PIPES installation, which detects utilities (e.g. gas, water, sewage, telecoms, and electric cabling) and routes relevant and timely data to BT and Severn Trent Water. Similarly, sensor deployments may be used by oil and fracking companies prior to drilling potential sites.

The PIPES project outcomes are commercially sensitive, since some of the WSN intellectual property went into a fibre sensing opportunity, which led to a number of patents being filed by Dr. Jane Tateson in September 2010.

Shared Development

Since BT Research participated in PIPES and BOP consecutively, a mix of variant sensor motes were used to enable shared development expertise, thus utilising similar techniques for both WSN projects as follows **[104]**:

- Crossbow MicaZ motes;
- Arduino boards (Atmel chip) for data averaging at Severn Trent Testing Facility;
- Sun SPOT sensor motes (ZigBee 802.15.4 and Java);
- Imperial College Beasties;

- Custom built Bi-morph boards (non networking);
- Hardware deployed for BT and all partners;
- Software updates uploaded and varies according to partner requirements.

Automated Meter Reading (AMR)

AMR is increasingly being employed by utility companies such as Gazprom for energy consumption monitoring and automatic billing. Figure 31 shows the AMR solution developed by ViaTelemetry (formerly Comtech M2M). In 2005, Dong Energy (formerly NESA) deployed a wireless AMR system powered by a Freescale solution. The acquisitions illustrate the fast-moving pace of M2M technology companies.

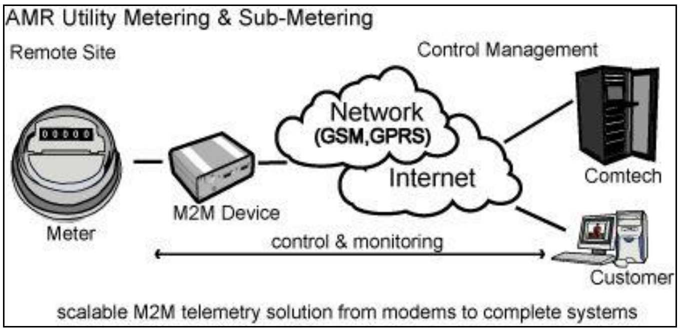


Figure 31 - Comtech AMR [105]

Energy Management

With the continuous improvement of energy efficiency representing a major drive in WSN research, the major objective of UCL's "Efficient Energy Management in Energy Harvesting WSNs: An Approach Based on Distributed Compressive Sensing" project **[106]** is to develop transformative sensing mechanisms, which can be used in conjunction with current or upcoming energy harvesting capabilities, in order to enable the deployment of energy neutral WSNs with data gathering rates that are substantially higher than the current state-of-the-art.

Oil Wells

In 2010, HP began a project with Royal Shell to use one million tiny sensors to help the company locate oil reserves. Around 50% of the oil wells drilled turn up dry, so the sensor technology such as smart dust equipped with vibration, seismic, acoustic sensors has the potential to help oil and also fracking (borehole sensors) companies understand underground resources prior to intensive drilling **[107]**.

BT Redcare Group

Redcare is a market-leading specialist in secure, monitored communications services, which help customers to benefit from automated, intelligent decisions and responses. With over 30 years of experience, Redcare is recognised as having a world leading platform for connecting, controlling and managing data, serving some of the largest organisations in the world **[108]**.

BT Redcare is positioning itself for this future as a strategic supplier offering M2M services that provide 'living intelligence' that can be shared and leveraged across the connected enterprise. Redcare specialises in M2M communication technology. This enables machines to 'talk' to each other to provide tracking and monitoring information - for example, protecting customer's valuables to improve the efficiency of a retailer's supply chain and ensuring that the emergency services can respond to accidents.

BT Redcare Group comprises of three divisions: Redcare, BT Auto-ID and Transcomm **[109]**, which operate as autonomous businesses but draw on a collective expertise to deliver the best possible solutions to all customers. The Group is responsible for developing a range of innovative M2M applications for BT Retail. The Group includes businesses ranging from Redcare fire & security, which provides 24-hour building alarm monitoring services using secure fixed and WSNs, through to Redcare machine and vision which supplies remote vending machines that manage stocks and CCTV transmission services that monitor buildings and people.

Redcare also has divisions called BT Auto-ID to help customers monitor and track goods and assets for supply chain management and is the business within BT dedicated to new Radio Frequency Identification (RFID) as well as Transcomm which is the secure wireless data solutions business of BT. Transcomm provides a wide range of wireless data applications to help organisations run their operations more profitably and efficiently by providing up-to-the minute information whenever and wherever it is needed.

M2M applications are the heart of the BT Redcare Group. M2M applications are about making machines 'talk' - they allow information from machines to be shared with people or central information systems, thereby enabling real-time control and monitoring. The net result is more efficient business operations and greater protection for assets and people.

Redcare is active notably in Vending and Car Security. Data from a population of vending machines located across the UK is constantly returned to indicate stock levels and the status of the vending machines themselves to enable Just-in-Time (JIT) management. The pattern of purchases allows predictions to be made when stock will run low and which products are Fast-Moving Consumer Goods (FMCG) **[110]**.

BT Redcare focuses on the following key areas **[111]**:

- Security – offers an all year round security service which provides continuous monitoring of a BT telephone line that links a burglar alarm system on a customer's premises to an Alarm Receiving Centre (ARC);
- Fire – The service provides building monitoring for fire prevention, security and fire alarms for over 400,000 buildings in the UK. In 2002, BS 5839-1 recommended continuously monitored Fire Detection and Alarm (FDA) systems. Redcare fire system plays a critical role in fire detection and prevention;
- Vend online is Redcare's M2M remote monitoring solution for the vending industry. It is a web-based application that communicates with vending machines to deliver up-to-date management information direct to the customer via web access, day or night. (e.g. Cadbury);
- Vision - is the link between the camera and the control room. The high quality and dependable E2E CCTV solution for both local authorities and transport. Provides surveillance, digital recording and storage (e.g. IPv6 CCTV transmission);
- BT Auto-ID - goods monitoring via RFID tracking on stock levels to ensure speedy replenishment of FMCG (e.g. M&S);
- Transcomm - is the secure wireless data solutions business of BT; providing secure Mobile Data Solutions to help organisations run their operations more efficiently. Transcomm specialises in connectivity including Mobitex/GPRS, Trackit, Emergency Services and M2M Wireless.

3.7 Building Radio Frequency Identification for the Global Environment (BRIDGE)

BRIDGE was a three year project from 2006-09 and aimed to resolve the barriers to the implementation of RFID as well as advancing the state-of-the-art on RFID in Europe. The BRIDGE consortium included the following partners and GS1 standards organisations of most European countries, China and extensive users in the retail trade, pharmaceutical supply chain, and manufacturing:

- GS1: Global Office (Coordinator);
- Universities: Cambridge; ETH Zurich; Fudan; UPC Barcelona; TUG Graz;
- Users: Carrefour; Bénédicta; Kaufhof; Gardeur; Nestlé UK; Sony;
- Solution Providers: BT; SAP; AIDA; Confidex; Verisign UK; Unisys.

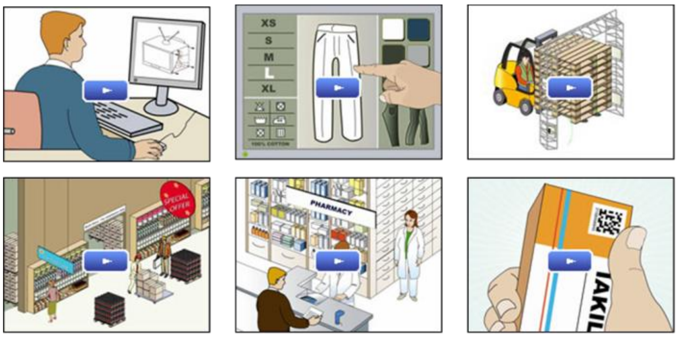


Figure 32 - BRIDGE Supply Chain Scenario [112]

As illustrated in Figure 32, RFID is primarily used for asset tracking and supply chain management, (e.g. logistics, warehousing and stock replenishment) since it saves time in locating and handling ship containers in a large port. RFID tags and readers are used extensively by retail warehousing and hospitals to locate and track pallets, boxes or packets in transit. Passive Infrared (PIR) RFID sensors are also used to secure virtually all supermarket products (e.g. food packages, Blu-ray discs, clothing, electrical items) which activate an alarm if the RFID tags are not deactivated during checkout before the shopper leaves the store and passes through the RFID (reader) barrier at the store exit. Perishable goods may be tracked and monitored to ensure optimal temperatures and care is maintained during transit to maximize life span, thereby reducing waste or replacement expenditure. Also, to achieve efficient stock rotation based on best before dates on pallets, boxes or even packets (e.g. medication pills). Valuable products and expensive equipment may be tracked in warehouses to enable quick location and theft prevention of materials or products (e.g. copper theft from BT).

The main achievements of BRIDGE were as follows:

- Low cost readers and smart shelves, building blocks for a practical deployment in the retail supply chain were developed and prototyped for many sectors;

- Pilots have demonstrated the real benefits of the technology and will serve as best practices to educate prospective users;
- The BRIDGE discovery services activity met its ambition of building RFID-tagged object search functionality comparable to Internet search engine content. This investment in discovery services was recognised by industry as the largest effort of its kind in the world;
- Although early RFID apps made abstraction of security and data protection issues that can result from a mass deployment of the technology, BRIDGE dedicated work to these security issues. This resulted in a new generation of RFID tags, readers and apps that can ensure a higher level of security and data protection than today's state-of- the-art solutions;
- BRIDGE was present at many European and international events to disseminate the knowledge gained and to create the momentum that should lead to a more competitive European industry in this new RFID sector;
- The BRIDGE supply chain scenario trialled the SWE 1.0 specifications.

As described later in Chapter 5, BT's SAPHE project was SWE-enabled. Similarly, BT's BRIDGE project trialled a SWE installation for their supply chain scenario, which is depicted in Figure 33. Therefore, it is possible for projects as diverse as SAPHE and BRIDGE to share sensor data and to enable data fusion and inferencing, especially if they employ SWE specifications, e.g. Sensor Observation Service (SOS) and Windows Notification Service (WNS).

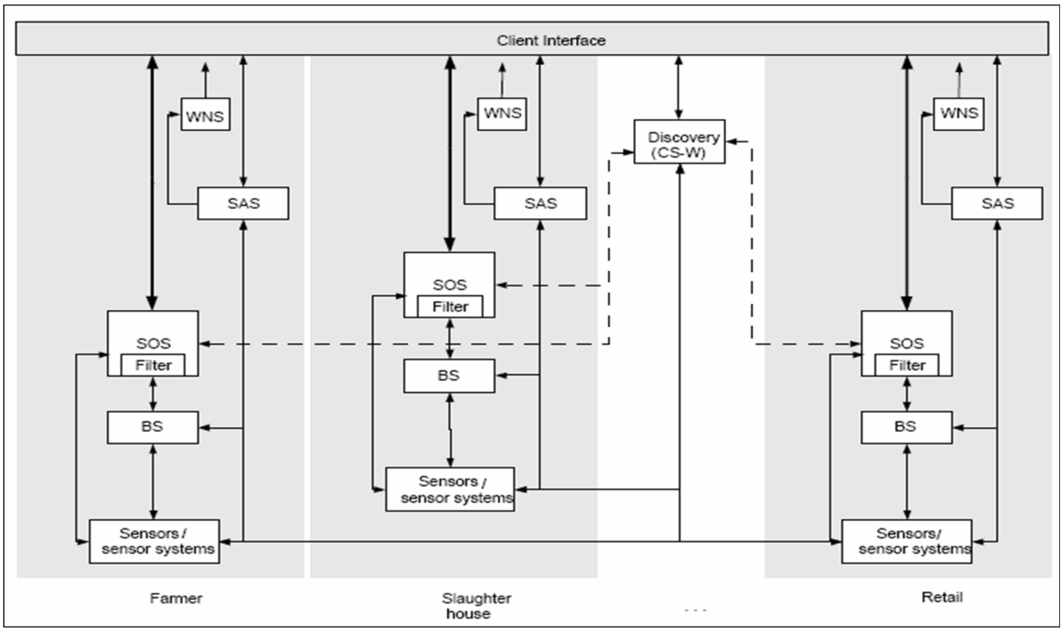


Figure 33 - SWE-enabled BRIDGE Supply Chain [113]

3.8 Summary and Conclusion

Chapter 3 provided an indication of the capabilities of BT WSN projects and similar external projects, which cover ever expanding domains for WSN applications. Just as the bubble diagram illustrates (Figure 1), sensors and WSNs are increasingly pervasive and becoming ubiquitous throughout society. The sensory technology is already being utilised by a myriad of applications ranging from healthcare and environmental monitoring to intelligent buildings and smart vehicles. The demand for practical and smart services coupled with the advances in related technological components drive and enable innovative and cost effective solutions to be designed and deployed in all domains. All projects exemplified real-world WSNs in action, which use various ad-hoc networks to capture and make inferences from key sensor data.

The author contributed to a number of BT Research's WSN projects across a range of domains. The BOP project and related Orion meeting room trials were presented in Chapter 3. The Sensor Virtualization project (detailed in Chapter 4) and Applying SWE to the SAPHE Telecare project (the focus of Chapter 5). During this time, the author gained valuable experience in all the stages of WSNs, from design and deployment, to sensor data capture, data analysis and evaluation of applications. In addition, surveying (Eurescom's P1555 study) state-of-the-art WSNs external to BT. As far as the author is aware, this thesis is the only publication to document all of BT Research's WSN endeavours, to describe the author's contribution to these projects, in addition to providing comprehensive resources on these projects as well as external WSN projects.

CHAPTER 4 Enabling the Sensor Web

4. Introduction

This chapter introduces the Open Geospatial Consortium (OGC) and defines their Sensor Web Enablement (SWE) initiative, which includes SensorML from VAST **[114]**. Additionally, BT Research's Generic Architecture is explained. Considerable business benefits may be realised especially by Telcos by developing and deploying intelligent WSNs. For example, in the OGC's SWE activity, members are defining, testing, and documenting a consistent framework of open standards for exploiting web-connected virtual sensors and sensor systems of any type in the physical world. SWE presents a myriad of opportunities for adding a real-time sensor dimension to the Internet and the Web.

4.1 Sensor Virtualization

Under the umbrella of BT Research's M2M and Information Networking themes, the Sensor Virtualization project was an important deliverable and commenced in 2007. At the hub of the activities was the Generic Architecture. Sensor Virtualization initially investigated how the SWE standards from the OGC could help streamline the creation of sensing / monitoring M2M applications. In particular, it focussed on the web services enabled open sensor APIs and the semantic modelling of observed data (e.g. observations and measurements). The task aimed to achieve a sensor / device virtualization framework under which adding new sensors and devices to the pervasive M2M platform is as seamless and decoupled from the applications using these sensors / devices as installing drivers in an operating system (such as Microsoft Windows). In addition, the SNG produced a number of technical papers detailing the installation and our experiences with SWE components, such as SOS and SensorML **[115]**.

The author as a member of the SNG and led by Dr. George Bilchev, started the research with the objective to create a framework that allows useful components (hardware and software) to be reused by various monitoring projects as well as the creation of a shared sensor information space where data from various deployments could be better utilised. In particular, the SNG evaluated if the SWE concept could fulfil these requirements. We found that the Sensor Observation Service (SOS) **[116]** combined with the observations and measurements (O&M) **[117]** specification provide a flexible mechanism for describing and querying sensor data thus proving a useful candidate technology for building shared sensor information spaces. The value of such sharing could be seen when multiple applications are then built on top of a shared infrastructure and 'infostructure' (the shared information space) **[118]**.

Prior to considering SWE for building a Generic WSN Architecture, the SNG conducted a thorough evaluation of the Nortel Networks' Sensor Dispatch System (SDS). Unfortunately, due to a confidentiality agreement between BT and Nortel, no further details may be provided of this trial. Following on from the Nortel SDS evaluation, it was the author's recommendation to evaluate CEP engines via Esper trials, since it had the functionality required, without the high usage costs of other vendors.

However, the SWE framework seemed flexible, therefore the SNG began researching the OGC standards and SWE specifications. In January 2007, the author attended an OGC event, “Best Practice Makes Perfect with Open Geospatial Standards”, hosted by the British Geological Survey (BGS) in Nottingham.

4.2 OGC SWE / SANY Workshop

In March 2007, the author and Dr. Gavin Churcher were present at the OGC SWE three-day workshop at the Institute for Geoinformatics at the University of Muenster, Germany **[119]**. The workshop was run in collaboration with the SANY (Sensors Anywhere) IST 6th Framework project and provided a basic level of training on SWE standards and an overview of the SANY project **[120]**.

The OGC working group on SWE has the aim of publishing standards that enable sensors to use services to publish their data and to ensure that they are discoverable using simple HTTP protocols. SWE resides at the lower middle layers of the OSI model stack and is not directly concerned with sensor ad-hoc networking and data aggregation, nor with data fusion and application layers. Its goal is to provide the mechanisms where network-connected sensors can publish their data, and the mechanisms for applications to consume that data. SWE relies on two OGC XML-based standards, Sensor Model Language (SensorML) and Observations & Measurements (O&M). SensorML is used to describe the sensors and their capabilities, and O&M is used to describe the sensor data readings in terms of an event.

The workshop was chaired by Dr. Ingo Simonis from OGC Europe and editor of the OGC SWE specifications **[121]**. He had an active role in co-authoring the Sensor Planning Service (SPS), Sensor Alert Service (SAS), Web Notification Service (WNS) and the SWE architecture. Ingo provided an overview of the SWE architecture and a brief introduction to how the different services interoperate.

Alex Robin of Sensia Software presented as co-author and one of the leading developers of SensorML **[122]**. Arnulf Christi of Open Source Geospatial Foundation (OSGeo) provided an introduction to open source development **[123]**, while Arne Broring presented an overview of the OX-Framework. Finally, Denis Havlik gave an overview of the objectives of the SANY (Sensors Anywhere) project.

The majority of the workshop consisted of presentations that described the various services. The practical work was kept to a minimum but most usefully demonstrated an early implementation of a number of SWE services by 52° North which was available for download and demonstration purposes under the GPL Open Source license **[124]**. The framework provides the following Java-implemented services:

- Sensor Observation Service – a service that allows a sensor to publish data, and an application to query said published data;
- Web Notification Service – a protocol transducer to send events to different media (e.g. to send an SMS notification);
- Sensor Alert Service – a service that can be set to trigger an HTTP notification based on a number of preconditions for a sensor's readings;
- Sensor Planning Service – a goal-orientated approach to controlling a sensor to enable specific readings (e.g. commands to fly a drone into an area to achieve readings there).

The software was used to control the orientation of a remote camera (SPS) and to trigger notifications from a weather station to both email addresses and SMS.

The workshop was well attended by approximately forty people, half of which were directly involved in the SANY project, and representing a broad number of European states. During discussions, several organisations exemplified how they currently use WSNs within their specific fields, ranging from agriculture (Netherlands), oceanography (Hamburg) and river authorities (Europe) to utility companies (UK) and the military **[125]**.

Following the SANY workshop, the author advised the SNG to enlist SWE developers from 52° North to assist in applying SWE to BT's ongoing Telecare project, Smart & Aware Pervasive Healthcare Environment (SAPHE). In November 2007, Dr. Ingo Simonis and 52° North delivered a SWE workshop at Adastral Park to demonstrate how the SWE specifications could be applied to the SAPHE project architecture. This was a useful exercise and the findings were published at ISWPC 2008.

4.3 Sensors Anywhere (SANY)

SANY's remit was to play a role in the development of OGC standards to provide a framework for WSNs and their applications, of which SWE is a key part. Whilst SWE provides an event messaging and discovery layer, the SANY project focused on end-to-end solutions including data fusion services and the application layer. There is a tight integration between the SANY project members and the OGC SWE standards group, with many key members involved in both activities.

The SANY consortium was led by Dr. Denis Havlik (ARC) **[126]** and the project focuses on interoperability of in-situ sensors and sensor networks and integration of heterogeneous:

- Sensors;
- Data;
- Services.

The goal for the SANY architecture is to provide a quick and cost-efficient way to reuse data and services from currently incompatible sensors and data sources in future environmental risk management applications.

The objectives of SANY were to deliver the following:

- Standard SOA for environmental sensor networks. SANY services were self-describing and capable of seamless "plug and measure" and sharing ("virtual networks");
- Reference implementations of re-usable sensor and domain-agnostic services, including decision support and generalised data fusion services;
- Three innovative risk management applications covering the areas of air pollution, marine risks and geo hazards.

By developing a standard open architecture and a set of basic services for all kinds of sensors, sensor networks, and other sensor-like services, the SANY integrated project supports and enhances both GMES (Global Monitoring for Environment and Security, a major European space initiative) and GEOSS (Global Earth Observation System of Systems) in the area of in-situ sensor integration. Though the SANY work enhances interoperability for monitoring sensor networks in general, the application focus is on air quality, bathing water quality, and urban tunnel excavation monitoring. The project outcomes were published in the SANY book, which is entitled, "An Open Service Architecture for Sensor Networks" and is freely available as a PDF **[127]**.

4.4 Open Geospatial Consortium (OGC)

The OGC is defined on their website as "an international industry consortium of 476 companies, government agencies and universities participating in a consensus process to develop publicly available interface standards. OGC® Standards support interoperable solutions that 'geo-enable' the Web, wireless and location-based services and mainstream IT. The standards empower technology developers to make complex spatial information and services accessible and useful with all kinds of applications" **[128]**. Aside from membership, the OGC publish technical specifications and best practice papers which are freely downloadable from their portal by the general public. The OGC's offerings include OpenGIS® standards, SensorML, Web Services (OWS) and SWE specifications.

There are hundreds of millions of Internet-connected sensors on, in and around the Earth, and the number is growing rapidly. Standardization is the key requirement for communicating information about sensors and sensor data and for comparing and combining information from different sensors. The OGC's Sensor Web Enablement (SWE) standards meet this requirement in the most complex as well as very simple applications. Sensor location is usually a key piece of sensor or sensor data information, and SWE standards make it easy to integrate this information into thousands of geospatial applications that implement the OGC's other standards **[129]**.

BT Research became an associate member of the OGC in 2007 as recommended by the author. Membership enabled participation in key initiatives, such as SWE. Leading members of OGC include familiar BT partners, such as Oracle, MIT, and UCL. Other notable international members are; NASA, ESA, Boeing, BAE Systems (aviation and defence), Google, Autodesk (2D & 3D design, digital content creation), MapInfo (GIS), ESRI, Intergraph (security, government, military, and industry), Hitachi, Mitsubishi, University of Nottingham (Centre for Geospatial Science), University of Leeds, IEEE, GRSS, eSpatial, GeoConnections, Ionic, NCAR, Autodesk **[130]**.

SWE Common

SWE Common is a way of describing structure and encoding of data, i.e. "self-describing" datasets. It allows for data in encodings other than XML (ASCII / Binary), e.g. to reduce bandwidth when transmitting video. It provides semantics for data elements by referencing dictionaries such as definitions provided by external dictionaries or ontologies can be used for (describing and encoding) streaming and multiplexed data **[131]**. SWE Common was created by Dr. Michael Botts and Alexandre Robin at the University of Alabama in Huntsville in 2003-2004. Inspired by the early work of Simon Cox on Observation and Measurements, SWE Common became a standalone SWE component during OWS-3 in 2005. It is used within multiple parts of the SWE framework (e.g. SensorML, O&M, SPS, SOS, SAS) **[132]**.

Sensor and Process description language is very generic and uses SWE Common:

- Mixture of hard/soft-typed approaches;
- Enables description of structure;
- Encodes values independently;
- Allows for referenced and inline data **[133]**.

OGC Web Services Phase 8 (OWS-8)

The latest OWS-8 demonstration video explains that the OGC interoperability program promotes OpenGIS Standards. The ongoing futuristic videos focus on geospatial data, Web connected sensors and open interfaces demonstrate the scenarios where OGC standards may be implemented. As stated in the narrative, "Lives and property depend on information flowing smoothly from one system to another. Most of the information is geospatial. It's all about location, place and time" **[134]**. Furthermore, Geographical Information Systems (GIS), earth images, GPS tracking and other geospatial data and services can now plug into the World Wide Web through open interfaces, thus enabling diverse systems to interconnect and greatly improving the following:

- Data discovery;
- Information integration;
- Situational awareness;
- Decision support.

OGC OpenGIS services

Most of the OGC standards depend on a generalised architecture captured in a set of documents collectively called the Abstract Specification, which describes a basic data model for representing geographic features. Atop the Abstract Specification members have developed and continue to develop a growing number of specifications, or standards to serve specific needs for interoperable location and geospatial technology, including GIS. As illustrated in Figure 34, the OGC mainly focuses on earth observation standards and GIS satellite imaging specifications, which feature high resolution vector images, and may be overlaid to create a rich representation or hybrid view of real-world information **[135]**.

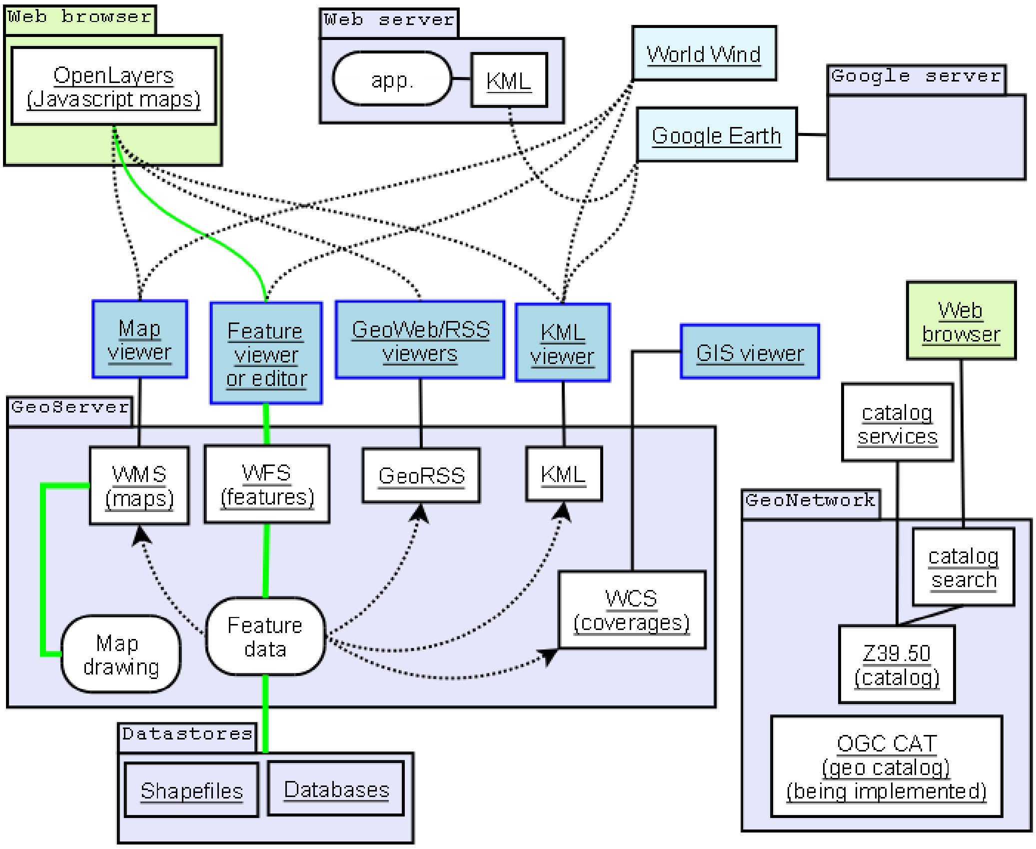


Figure 34 - Relationship between Clients/Servers and OGC Protocols [136]

By means of traditional services of the OGC you can request sensor data, but only in a limited manner:

1. A map of the air temperature can be requested from a Web Map Service (WMS) for a certain area of interest and point in time;
2. Raster data like satellite images or results of dispersion models can be accessed via the Web Coverage Service (WCS);
3. Vector data, say way points from vehicle tracking might be provided by a Web Feature Service (WFS).

However, a generic framework for sensor data integration into Spatial Data Infrastructures (SDI) was missing. Thus it was imperative to extend the SDI specifications by a framework for integrating sensors into SDIs. Therefore, the OGC founded the SWE initiative to develop specifications for access to and control of sensors and WSNs via the Internet **[137]**.

Outside of the home, the location-aware capabilities of WSNs are suitable for a diverse collection of consumer-related activities, including tourism and shopping. In these applications, location can be used to provide context-specific information to the consumer. …the tourism guide, the user is provided only information relevant to his present view; …the shopping guide, the user is provided with information relevant to the products before him, including sale items and special discounts and offers. Therefore, a kind of augmented reality is possible **[138]**.

4.5 Sensor Web Enablement (SWE)

The concept of Sensor Webs was coined in the 1990's: millions of connected on-line sensors monitoring the physical world, the sensor capabilities being described using metadata so they can be published and understood by anyone with web access and appropriate authentication. This model is similar in concept to the World Wide Web where a standard web browser can access this vast information space due to the adoption of key standards such as HTTP, HTML and XML. In 2001, a data modeling language for sensors, SensorML, was introduced into the OGC which led to the SWE working group. The group was tasked to produce a framework of open standards for Web connected sensors and all types of sensor systems. The SWE standards draw from a number of existing OGC standards from SensorML to Observations & Measurements and propose a number of services that use the HTTP protocol for access. The services are able to self-describe the data they represent and the access mechanisms they provide **[139]**.

Version 1.0 of the Sensor Observation Service (SOS) was published as an OGC OpenGIS Implementation Standard in October 2007. Of particular interest to SAPHE are the proposed standards for SOS and SAS. Together they provide the ability to store data that can be accessed and queried by an external application and to detect simple conditions that can then generate an alert, published to the external network and various application subscribers.

The role of the SOS is to translate incoming sensor data into a data model that represents the sensor and the data as a series of observations of a particular feature of interest. This translated representation is then archived until an external client makes a request for data, providing a number of parameters that act as filters. The parameters for the SOS include the ability to specify a time constraint, for example, between two time periods, or after a time point, and the identification of the particular sensor cluster. In the case of multiple sets of data from a sensor cluster, the observed property (phenomenon) can be specified along with the features of interest. Once the request for data has been made, the application client receives a set of Observations and Measurements which encapsulate the sensor data in the data model. Sensor data can also be streamed into an SAS where a similar transformation occurs. An external application is able to specify conditions for data as it arrives at the SAS. When the data meets those conditions an event is sent to the application using the publisher/subscriber methodology. The conditions that can be applied in the current proposal for the SAS are limited to specifying whether a sensor data value is less than (or equal to), greater than (or equal to), equal to, not equal to a value, or between two values. For example, an application could specify that an alert should be sent when a PIR sensor detects movement, or when a temperature sensor reports a value over 40ºC which could be critical for certain medicines.

SOS -> Access sensor data, consistent for all kinds of sensor, returns O&M e.g. event time, FoI, observed property, procedure used (often a sensor).

At the time of the author's experiments in 2007-08, SWE version 1.0 was released as an open set of "Issue 1" standards having been through many drafts and practical evaluations using prototype deployments **[140]**. The main standards of SWE 1.0 were as follows:

1. Observations & Measurements (O&M) - Standard models and XML Schema for encoding observations and measurements from a sensor, both archived and real-time;
2. Sensor Model Language (SensorML) - Standard models and XML Schema for describing sensors systems and processes associated with sensor observations; provides information needed for discovery of sensors, location of sensor observations, processing of low-level sensor observations, and listing of taskable properties, as well as supports on-demand processing of sensor observations;
3. Transducer Model Language (TransducerML) - The conceptual model and XML Schema for describing transducers and supporting real-time streaming of data to and from sensor systems;
4. Sensor Observation Service (SOS) - Standard web service interface for requesting, filtering, and retrieving observations and sensor system information. This is the intermediary between a client and an observation repository or near real-time sensor channel;
5. Sensor Planning Service (SPS) - Standard web service interface for requesting user-driven acquisitions and observations. This is the intermediary between a client and a sensor collection management environment;
6. Sensor Alert Service (SAS) - Standard web service interface for publishing and subscribing to alerts from sensors;
7. Web Notification Services (WNS) - Standard web service interface for asynchronous delivery of messages or alerts from SAS and SPS web services and other elements of service workflows.

Within the SWE initiative, the enablement of such sensor webs and networks is being pursued through the establishment of several encodings for describing sensors and sensor observations, and through several standard interface definitions for web services. As shown in Figure 35, OGC members are building a unique and revolutionary framework of open standards for exploiting Web-connected sensors and sensor systems of all types: traffic monitoring (e.g. bridge stress gauges); satellite and airborne earth imaging devices; environmental monitoring (e.g. air pollution, flood gauges); stored sensor data; Webcams; industrial process monitoring; mobile heart monitors **[141]**.

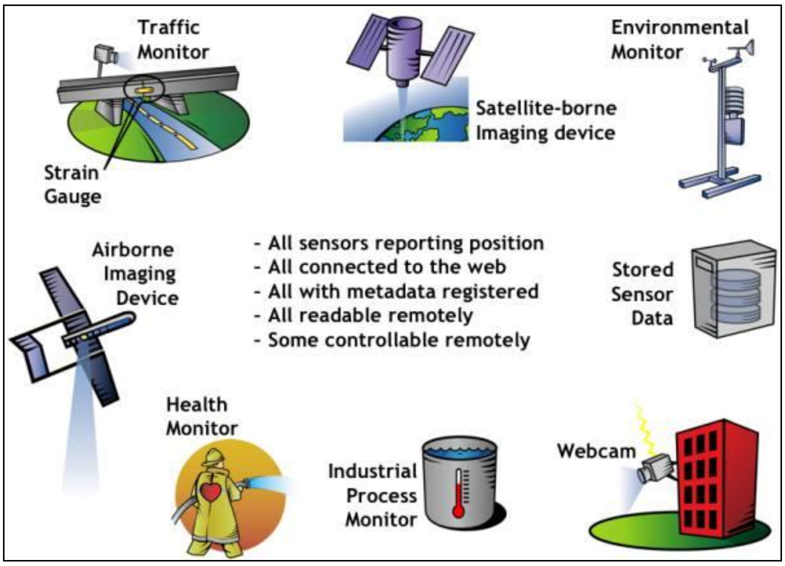


Figure 35 - SWE Discovering Sensors & Sensor Systems [142]

SWE Services

The goal of SWE is to enable all types of Web and/or Internet-accessible sensors, instruments, and imaging devices to be accessible and, where applicable, controllable via the Web. The vision is to define and approve the standards foundation for 'plug-and-play' Web-based sensor networks **[143]**.

SWE 2.0 services enable the following functionality:

- XML / SOAP over HTTP;
- RESTful;
- Provide rich data - trust users to filter;
- Pre-organisation of data;
- All services are "self-descriptive" - SOS/SPS: spatial/temporal features, observed feature, phenomenon, sensor, etc **[144]**.

Critical applications that will benefit from SWE include:

- Homeland security;
- Disaster management;
- Emergency services management;
- Military.

The Sensor Web

The term 'sensor web' has morphed into sometimes being associated with an additional layer connecting sensors to the World Wide Web. The SWE initiative of the OGC defines service interfaces which enable an interoperable usage of sensor resources by enabling their discovery, access, tasking, eventing and alerting. By defining standardised service interfaces, a sensor web based on SWE services hides the heterogeneity of an underlying sensor network, its communication details and various hardware components, from the applications built on top of it. OGC's SWE initiative defines the term ‘sensor web’ as an infrastructure enabling access to sensor networks and archived sensor data that can be discovered and accessed using standard protocols and application programming interfaces. Through this abstraction from sensor details, their usage in applications is facilitated. The Sensor Web aims to enable different operating systems Java (Sun SPOT), Tangos (Xbow), Contiki and others to interface and operate as a unified system rather than a number of disparate systems.

Discovery of sensors relies on accurate and timely catalogue registration (up-to-date so sensors remain discoverable) whereas control of sensors depends on their primary purpose and related security constraints. The Internet infrastructure enables the sensor web to become feasible, however, security and privacy provide boundaries to restrict access to certain sensors and their data. For example, weather data is freely publishable (due in some part to low accuracy rates) as opposed to military sensor system data or medical sensor data, which are highly classified, or sensitive patient data respectively. Therefore, the concept of the sensor web enabling discovery, tasking and alerting of **all** sensors and sensor systems of all different types regardless of size, capabilities or location is unlikely according to the author, because of the necessary barriers.

However, as sensor network deployments grow and mature there emerge a common set of operations and transformations. These can be grouped into a conceptual framework called the Sensor Web. Sensor Web combines cyber infrastructure with a SOA and WSNs to provide access to heterogeneous sensor resources in a deployment independent manner. The Open Sensor Web Architecture (OSWA) is a platform independent middleware for developing sensor applications. OSWA is built upon a uniform set of operations and standard data representations as defined in the SWE Method by the OGC. OSWA uses open source and grid technologies to meet the challenging needs of collecting and analysing observational data and making it accessible for aggregation, archiving and decision making **[145]**.

Integration of Observations from a Variety of Sensors

The SWE user desires the ability to discover and integrate observations from any sensor that meets their needs. The Sensor Web desires and vision are listed as follows **[146]**:

Sensor Web Desires

- Quickly discover sensors (secure or public) that can meet user needs – location, observables, quality, ability to task;
- Obtain sensor information in a standard encoding that is understandable by user and their software;
- Readily access sensor observations in a common manner, and in a form specific to user needs;
- Task sensors, when possible, to meet user specific needs;
- Subscribe to and receive alerts when a sensor measures a particular phenomenon.

The Sensor Web Vision

- Sensors will be web accessible;
- Sensors and sensor data will be discoverable;
- Sensors will be self-describing to humans and software (using a standard encoding);
- Most sensor observations will be easily accessible in real-time over the web;
- Standardized web services will exist for accessing sensor information and sensor observations;
- Sensor systems will be capable of real-time mining of observations to find phenomena of immediate interest;
- Sensors will be capable of issuing alerts based on observations, as well as be able to respond to alerts issued by other sensors;
- Sensors and sensor nets will be able to act on their own (autonomous);
- Software will immediately be capable of geo-locating and processing observations from a newly-discovered sensor.

OpenGIS Sensor Web Enablement

The following web services, encodings and client are based on open standards and standards bodies such as the W3C, OGC, ETSI, OData, ISO, IEEE, and OASIS. "Just as http:// is the dial tone of the World Wide Web, and HTML / XML are the standard encodings, the spatial web is enabled by OGC standards **[147]**. For example:

"High-level" OGC Services supporting sensor data **[148]**:

- Web Map Service (WMS) – request map (e.g. visualizations of geo data);
- Web Coverage Service (WCS) – request binary gridded or aggregated data (e.g. raster graphics);
- Web Feature Service (WFS) – request feature data (e.g. vector graphics).

Sensor Web Enablement Framework – Schema:

- SensorML – models and schema for describing sensor characteristics (geo-location, response);
- Observation & Measurement (O&M) – models and schema for encoding sensor observations.

Sensor Web Enablement Framework – Services:

- Sensor Observation Service (SOS) – access sensor information (SensorML) and sensor observations (O&M);
- Sensor Planning Service (SPS) – task sensors or sensor systems;
- Web Alert Service (SES) – asynchronous notification of sensor events (tasks, observation of phenomena);
- Sensor Registries – discovery of sensors and sensor data;

Sensor Web Enablement Framework – Probable Additions:

- TransducerML (TML) – XML protocol for streaming data clusters from transducers (sensors, transmitters, actuators). Combined with SensorML, so TML discontinued in SWE 2.0;
- Common Alert Protocol (CAP) – developed by international emergency management community for XML publishing of events.

4.6 SWE-enabled Applications

During the author's research he recognised that the SWE framework may lead to a more effective method of controlling sensors in specific applications **[149]**. As shown in Figure 36, this section identifies the characteristics of WSN applications which have benefited from applying SWE specifications. A number of these projects are outlined below, references are provided for the other applications.

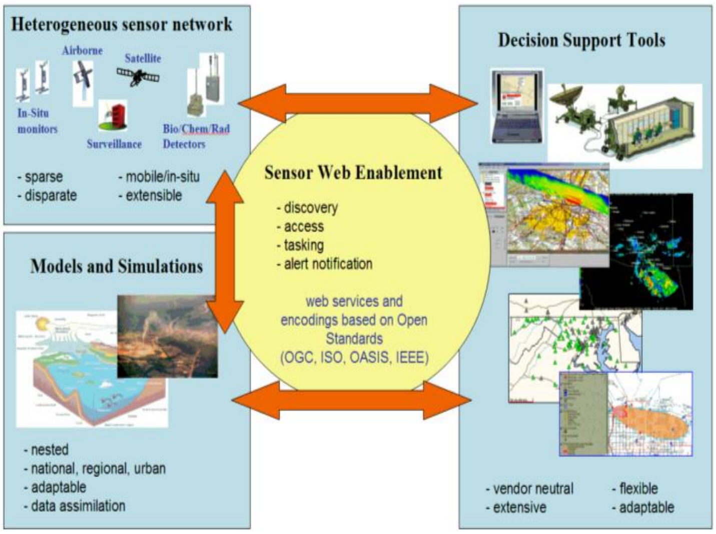


Figure 36 - SWE-enabled Applications [150]

Advanced Fire Information System (AFIS)

AFIS Web Fire Mapper monitors the spread of wildfires in South Africa. AFIS employs the SWE specifications and is an Internet-based mapping tool that delivers locations of active fires in near real-time. As illustrated in Figure 37, for selected regions/countries the user can view an interactive map showing active fires for a specified time period, combined with a choice of GIS layers and satellite imagery. AFIS combines in-situ measured sensor data (e.g. from weather stations) and remote sensing data to detect wild fires in South Africa. As soon as the power supply infrastructure (power lines or pylons) is endangered, an automatic notification of responsible persons is triggered so that damage to transformers can be prevented **[151]**.

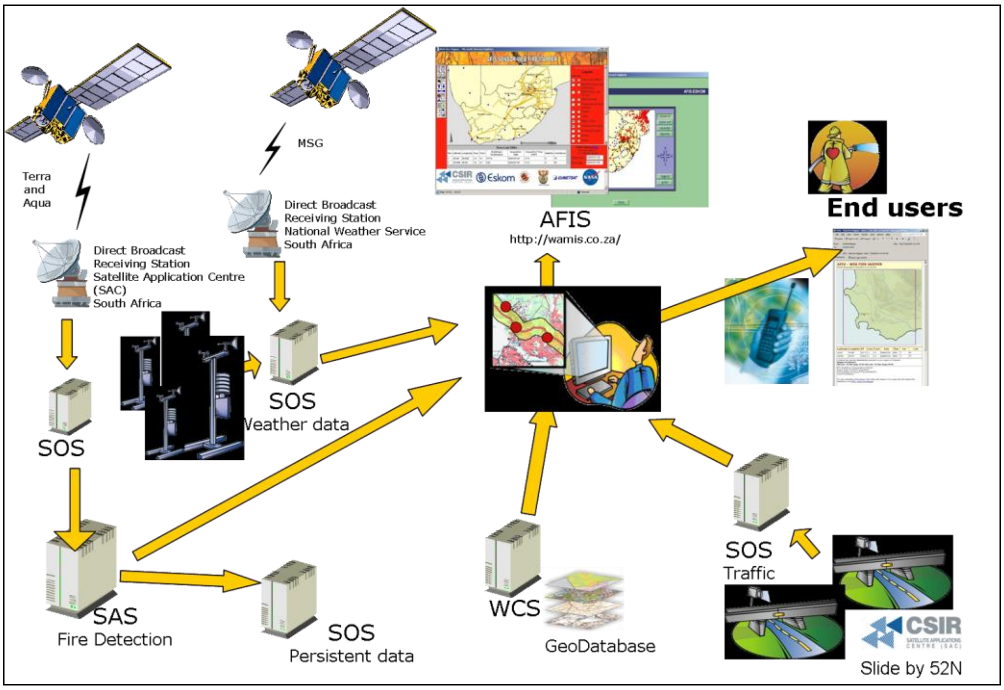


Figure 37 - AFIS - Sensor Web Fire Mapper Architecture [152]

Key actions of the specifications are summarised below:

Fusion of satellite / weather data / GeoDatabase / traffic data

-> compiled by experts at data centre and sent to AFIS / end user

SOS used for satellite / weather / traffic / persistent / data

SAS used for fire detection (AFIS)

WCS used for location data (GeoDatabase)

WNS used to send alerts to end users (web browser or mobile phone)

OOSTethys (Marine)

OOSTethys are using SWE to conduct Ocean Science Interoperability Experiments (OCEANS IE) in order to implement an earth-observing "system of systems". Ocean Observing System Architecture has developed software components to leverage oceanographic research. As shown in Figure 38, the aim has been to integrate heterogeneous ocean observing systems such as the application oriented Integrated Ocean Observing System (IOOS) and the research-oriented Ocean Observatories Initiative (OOI) by utilizing SWE and other standards.

OOSTethys partners develop, test and implement easy-to-use, open-source, OGC-compliant software, and have created a working prototype of networked, interoperable, real-time data systems. The goal of the ocean-science community is to develop capabilities that will advance and support initiatives such as the IOOS, ORION, GEOSS, etc. OOSTethys is a provider-to-user data systems framework, using interoperable standards, such as SWE's SOS to enable discovery and use of data. Software toolkit generates SensorML on-the-fly by getting the capabilities of sensors.

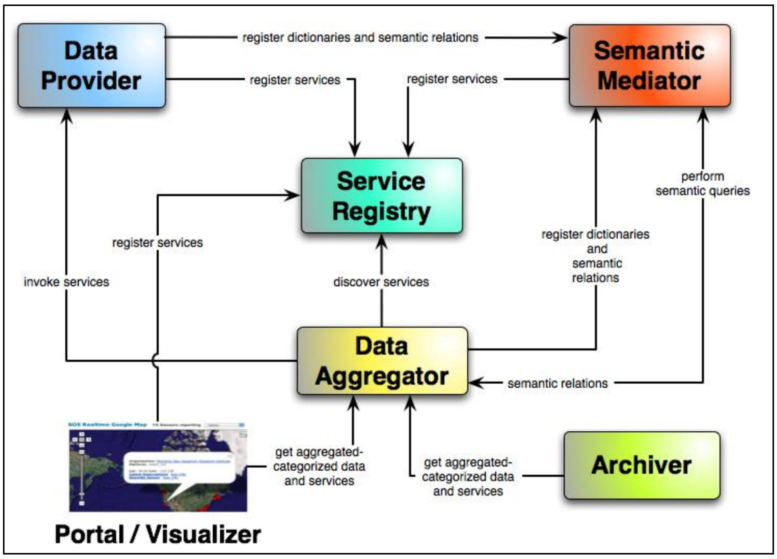


Figure 38 - OOSTethys - Ocean Observing System Architecture [153]

Earth Observation by NASA

NASA Sensor Web application employs SWE-enabled Earth Observation (EO) technologies. EO-1 aims to understand how physical phenomena (e.g. volcanic eruptions) evolve over time (Figure 39). To achieve this purpose, multiple sensor observations over the duration of the event are required. A Sensor Web approach offers the ability to trigger the imaging of these transient events via in-situ sensors and global-coverage, lower-resolution, on-orbit assets to capture higher temporal, spatial and spectral resolution images.

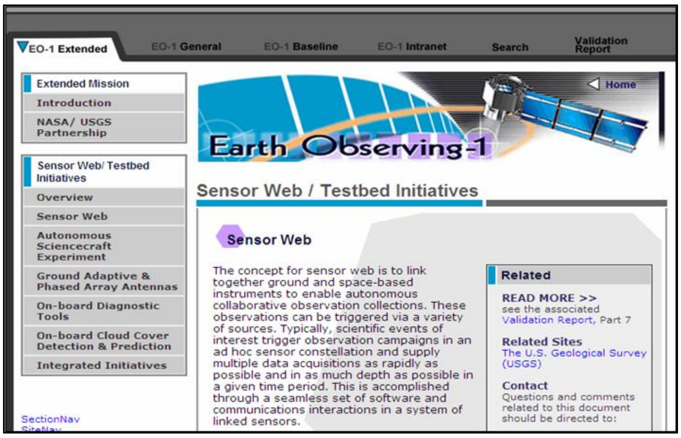


Figure 39 - NASA Sensor Web [154]

Galileo Satellite by ESA

The European Space Agency’s Galileo is a Global Navigation Satellite System (GNSS) and the European competitor to the US Global Positioning System (GPS). The Galileo project promises to bring a range of location-based services to many industries. Combining sensor data, geospatial databases and a geospatial context can provide a foundation for future industry. “The final constellation of Europe’s Galileo satellite navigation system will consist of 30 satellites” **[155]** and **[156]**.

CSIR Meraka Institute

ICT for Earth Observation (ICT4EO) Research Group is focused on the potential of SWE and has demonstrated a SWE-enabled robotic camera. The Sensor Web is an emerging technology trend that promises to revolutionise Earth Observation **[157]**. Their research is relevant in the context of Global Earth Observing System of Systems (GEOSS) / South African Earth Observation Strategy (SAEOS) architecture. Meraka are working closely with the OGC and the outcome of SWE will be a global network of interoperable sensors and sensor networks (The Sensor Web). The Sensor Web proves viability of advanced spatial data infrastructure (SDI) **[158]**. Meraka's research is directed at developing intelligent middleware to harvest meaningful information from the Sensor Web. They have investigated how semantic reasoning and knowledge representation can be used to configure the Sensor Web to observe particular phenomena.

Corridor Sensor Web

A simplified technology demonstrator of a sensor web has been created by Meraka. A sensor web is an advanced SDI that combines data from multiple sensors and sensor networks to provide feedback to users and sensors. Built by University of KwaZulu-Natal postgraduate students and researchers, it comprises a LEGO mobile robot (built with off-the-shelf components), active radio frequency ID tags with heat sensors along the corridor, which relay signals to readers placed higher up on the walls and a computer (20m away). As depicted in Figure 40, the corridor sensor web uses an open source, standards-compliant software platform and proprietary development tools by Wavetrend Technologies. The demonstrator shows the effectiveness of a sensor web, albeit on a small scale. "A campus sensor web will allow us to investigate sensor web applications such as intelligent traffic-transport systems in a relatively closed and controlled environment".

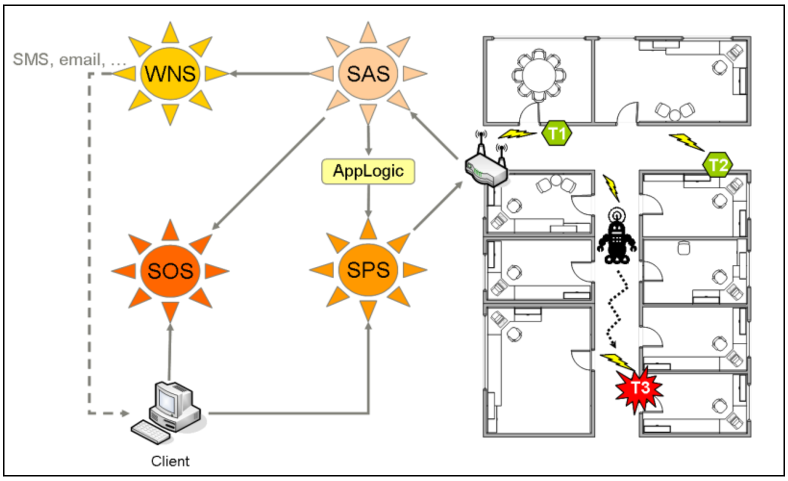


Figure 40 - Corridor Sensor Web [159]

Further Examples of SWE-enabled Projects and Applications

- The SANY project was described earlier in this chapter and incorporated SWE into their architecture that is designed to "provide a quick and cost efficient way to reuse data and services from currently incompatible sensor and data sources" **[160]**;
- Open Standards for Urban Operations GUARD Program (OWS-4) **[161]**;
- Sensor Network Application: Water Catchment Flow Monitoring **[162]**;
- SLEWS - A Sensor-based Landslide Early Warning System **[163]**;
- Location Services, Multi-Modal Tracking and Navigation for emergency response **[164]**;
- GeoSWIFT architecture for ISIES (Intelligent Sensorweb for Integrated Earth Sensing). A Sensor Web for a better crop yielding prediction. All data from open standard-based geospatial web services **[165]**;
- GeoCENs 3D Sensor Web Browser (uses NASA WorldWind open-source e.g. WMS) and GeoCENs 2D Browser - mix n match sensors n data **[166]**;
- Rockyview Well Watch - SWE permits access to same information via two different systems (front-end schemas). OGC specs such as SOS used behind the scene, enables searchable well sensors, e.g. owners upload well readings to monitor water levels, conserve resources, check illegal use, location protected, etc) **[167]**;
- The Igliniit (Trails) Project - Inuit (Eskimo) hunters document life on the trail to map and monitor arctic change **[168]**;
- SWE Loves Android - SOS client for Android smart devices (e.g. choose server and access sensor location and data via Android mobile) **[169]**;
- DLR (German Aerospace Center, Oberpfaffenhofen): Tsunami Early Warning & Mitigation Center **[170]**;
- PULSENet Applications: Atmospheric/Air Quality - Fire Monitoring/Smoke Forecasting **[171]**;
- SAIC Global SensorWeb Client - General SWE client **[172]**;
- PUCK - IEEE 1451 - SOS, Lead by Tom O'Reilly (MBARI) **[173]**;
- Simple SensorML and Semantics, Lead by Carlos Rueda (MBARI) **[174]**.

4.7 New Generation SWE 2.0

To recap, BT Research's Sensor Virtualization project began in 2007 and all the SWE service and encoding specifications were released as version 1.0 in summer 2007. New Generation SWE 2.0 was released in March 2011, therefore a comparison of the SWE 1.0 and 2.0 frameworks is provided to highlight which key specifications have been upgraded or discontinued since the previous version.

SWE Standardization

The main OGC Standards in the SWE framework are as follows **[175]**:

- O&M - The general models and XML encodings for observations and measurements;
- PUCK Protocol Standard - Defines a protocol to retrieve a SensorML description, sensor 'driver' code, and other information from the device itself, thus enabling automatic sensor installation, configuration and operation;
- SensorML - Standard models and XML Schema for describing the processes within sensor and observation processing systems;
- Sensor Observation Service (SOS) - Open interface for a web service to obtain observations and sensor and platform descriptions from one or more sensors;
- Sensor Planning Service (SPS) - An open interface for a web service by which a client can 1) determine the feasibility of collecting data from one or more sensors or models and 2) submit collection requests;
- SWE Common Data Model - Defines low-level data models for exchanging sensor related data between nodes of the OGC SWE framework;
- SWE Service Model - Defines data types for common use across OGC SWE services. Five of these packages define operation request and response types;
- The Pub/Sub Standards WG is working to produce a version 1.0 implementation standard that clearly defines a standard way to enable publish/subscribe functionality for OGC Web Services. This will be applicable to sensors.

Table 4 compares SWE 1.0 and 2.0 specifications to highlight key improvements **[176]** and **[177]**:

Table 4 - Comparison of SWE 1.0 and 2.0

Advantages of SWE 1.0:	Disadvantages of SWE 1.0:	Resolved in SWE 2.0:
SWE exposes sensor data and allows reuse for multiple applications, hence connecting diverse sensor networks. SWE approach to sharing sensor objects is good.	Security is not within the scope of SWE. Security layers - transactions was unavailable. SWE is part of system, security must be addressed separately. SOS lacks access control. Encryption required for sensitive data. Improved security external to SWE (e.g. IPv6, E2E security)	Major changes to SWE 2.0 Information Model and Service Model. Added support in SWE Common Data for disparate messages, nil values, extensions (e.g. security tagging, UncertML) and required tagging to semantic definitions. SOAP implementation supporting security and web notification.
Extensible – current approach of getting a basic level first and a	At the time of writing, registration of sensors (CS-W) could not be	Sensor registry upgraded, discovery of sensors supported by Sensor

process where extensions can be adopted.	done as that part of the work was not completed, but WIP.	Instance Registry (SIR) and Sensor Observable Registry (SOR). SWE standards are more precise and testable.
Integration of sensor data and encodings.	Not necessarily real-time and certainly not "RT integration".	SWE 2.0 specs provide functionality to integrate sensors into Spatial Data Infrastructures (SDI). Improved specs and encodings e.g. EML supports CEP (EPL for CEP) (e.g. Aviation) CEP has potential to enable data fusion aspect for projects (e.g. SAPHE, BRIDGE) which SWE alone does not provide.
Interoperability - reusing existing architecture/technology, interoperable WS & data encoding models (e.g. developing open standards applicable to environmental monitoring networks (e.g. SANY).	Lack of tool-kits for development purposes. Not surprising since many specs had barely been ratified, while others were in draft.	SWE 2.0 enhanced functionality. Extended tool-kit to aid interoperability more suited to building BT's vision of a reusable Generic Architecture. More consistent use of SWE Common Data and SWE Common Services throughout SWE standards.
Some of the implementations of SWE (e.g. 52° North specs) are open source.	The standards are not open source and may be proprietary (OGC).	More WSN projects are adopting SWE specs for applications. Refer to SWE-enabled Apps, p.95.
OGC compliant - standard interfaces and encodings compliant with standards – uses and builds upon existing OGC standards.	Many standards may relate and subject to being ratified or change.	Introduction of SWE Service Model (SWES) specification which defines a common model consisting of basic types for requests and responses and Capabilities document of SWE services. SWE Common data model extracted from SensorML.
SensorML (XML schemas) – rich description language which is self-describing since it is used to describe the semantics, tolerances, ranges, units, etc.	SensorML may not be required before applying other SWE standards, such as SOS and SAS. (e.g. SAPHE use case)	SensorML supported and simplified profile for discovery. Better support for inheritance and configuration in SensorML. TML discontinued.
OX-Framework used for visualizations. Integration - GML/KML viable alternatives to visualize data.	Visualization performed by graphical apps not SWE framework, since SWE won't work on its own, it's part of larger system.	52° North Sensor Web Community develops various client apps for different SWE services. Most are built on top of the generic OX-Framework, which facilitates the accessing and utilization of OWS. It provides adapter plug-in for various OGC services. Client projects include: - Rich OX Client - Sensor Web Client - ArcGIS SOS Extension - uDig Plugin - SOS for R.
Scalability - replicate any sensor system.	Requires much knowledge and time, so has to be worth the effort.	Specs and encodings upgraded to improve scalability. Conformance classes allow for partial uptake and implementation.
SWE apps can be retro-fitted to provide SWE services.	Geographically static nature of FoIs – people are mobile. 1.0 static only – no mechanism to allow location of FoI to be associated with another sensor providing location details.	Latest WSN projects using SWE framework and "easily" able to upgrade to SWE 2.0. Mobile sensors supported in SWE 2.0.
	Proprietary feeder framework had to be used to integrate sensor data into SOS.	Major improvements to SOS. SPS enables tasking of sensors. Better support for data streaming.

	SOS request/response pattern not sufficient.	
	SAS not evaluated because not stable implementation	SAS superseded by SES (Sensor Event Service) interface spec.
	SensorML underused, not required by SOS nor any tools to take advantage of model.	Sensor Interface Descriptor (SID) may influence SensorML development.
	Current status of standards, implementations, supporting tools too immature.	SWE 2.0 enhanced functionality and will enable Semantic Sensor Web in future.
	Number of issues to address in specs and support by developers.	Higher level of support via OGC / 52°N / iGSI developers & websites.
Publish/subscribe and OGC Web Services is currently done by OWS pub/sub standards WG at OGC.		Working towards common pub/sub functionality across all OWS, using established IT standards to realise the pub/sub functionality as appropriate.

Due to the number of non-compatible communities of sensor types, with stovepipe solutions for discovery, accessing observations, receiving alerts, and tasking sensor systems. Interoperability is expensive due to incompatible encodings and services. To realise the vision of a ‘plug-and-play’ web-based sensor network, the following functionality is required:

- Discovery of sensors and sensor data that meet applications’ or users’ immediate needs;
- Determination of sensors’ capabilities and quality of measurements;
- Access to sensor parameters that allow software to process observations automatically;
- Access to real-time measurements and time series in standardized encodings;
- Tasking of sensors and simulations to acquire observations of interest;
- Subscription to and publishing of alerts to be issued by sensors based upon certain criteria (Event based notification) **[178]**.

SWE Future (i.e. SWE 3.0)

- Development of Service interfaces and encodings;
- Integration of Security layers;
- Integration of Visualization components;
- Integration of Catalogue / Registry;
- Data Fusion / Processing / Analysis;
- OGC compliance, interoperability, testing & evaluation (CITE). The development team evaluate OpenGIS specification conformant interfaces and products to implement them **[179]**.

4.8 The Design of a Generic Sensor Network Architecture

For over a decade, BT Research has had a rich history of success in the research, design and deployment of sensor network and their supporting infrastructure. As described in Chapter 3, through a number of innovative collaborative projects covering a wide range of application domains from healthcare (Telecare and SAPHE); smart vehicles (Traffimatics); environmental monitoring (SECOAS); intelligent buildings (BOP); utility infrastructure monitoring (PIPES); and RFID supply-chain management (BRIDGE).

Each project delivered a bespoke and highly optimised solution for sensor hardware, sensor software, data formats and communication protocols. These highly specialised solutions have made it difficult for other projects to re-use the components and also to combine sensed data into a shared information space ('infostructure'). This approach however, is also widely seen in the marketplace where many companies offer highly specialised single point sensor solutions. This 'optimised' solution approach has driven interest in the application of more generic open architectures to permit more re-use of sensors and their observations. Developments in IP-based technologies such as Sensor Web Enablement (SWE) and their real world applications were investigated by the SNG.

Due to the number of WSN projects requiring similar architecture solutions, the author under BT Research began to examine generic architectures which could be reused on diverse WSN projects ranging from healthcare to RFID. Rather than continuing to design bespoke solutions for every individual project, the idea was to design a reusable architecture which enables 'plug-in' elements and interfaces with a number of diverse sensor networks and enables data fusion **[180]**.

The author learned that projects such as AFIS and SANY had adopted OGC standards to achieve their objectives. Typically, each project would require a unique end-to-end solution using sensor hardware, interfaces and communications specific to the requirements of the project. The ongoing experience of these projects has led to activities in the design of sensor-orientated architectures that enable new ventures to be established with a minimum of overhead and the reuse of sensors and their observations in a variety of applications.

This led to the SNG's interest in SWE from the OGC as a possible component for the virtualization of sensors as part of BT's strategy for building a more generic sensor network architecture with reusable components for diverse sensor network projects. In particular, the author investigated the SWE standards for the Sensor Observation Service (SOS), Sensor Alert Service (SAS) and SensorML and how they may be applied to one of our existing sensor network projects, SAPHE.

It is useful to understand how WSNs relate to the Generic Architecture work also carried out. As discussed in Chapter 3, BT Research contributed to numerous WSN projects with stove-piped (vertical) solutions, hence the requirement to explore the Generic Architecture (horizontal) approach. The author realised that each of BT Research's WSN projects was employing a highly customised stove-piped solution, which required considerable investment that could not be further utilised in other applications. Moreover, individual standalone WSN applications are not interoperable (backwards compatible) with earlier or future developments. Instead of a standalone WSN solution, WSNs may be integrated and interoperable. This enables aggregation and correlation of sensor data across a number of diverse projects from smart vehicles to healthcare and environmental monitoring to intelligent buildings, enabling infrastructure and sensor data to be shared and reused.

Recent advancements in Internet-centric / IP-dependent technologies coupled with emerging standards such as SWE have led to BT's interest in the design of architectures to ensure a minimal overhead in new projects and the growth of new applications that benefit from incremental investment due to component re-use.

The key reasons why a Generic Architecture for pervasive sensing is required are as follows **[181]**:

- To speed up the development of new sensing projects;
- To shorten the gap between trials and commercial deployment;
- To achieve economies of scale (on the information management level);
- To enable massive scale deployments (SWE) facilitating sensor data aggregation and integration (data fusion) amongst multiple and diverse WSN projects;
- To seamlessly integrate and to enable interoperability with other enterprise systems.

The SNG began our research with the objective to create a framework that allows useful components (hardware and software) to be reused by various monitoring projects as well as the creation of a shared sensor information space where data from various deployments could be better utilised. In particular, we evaluated if the SWE concept could fulfil these requirements. We found that the Sensor Observation Service (SOS) combined with the Observations and Measurements (O&M) specification provide a flexible mechanism for describing and querying sensor data thus proving a useful candidate technology. The value of such sharing could be seen when multiple applications are then built on top of a shared (smart) infrastructure and "infostructure" (shared information space) **[182]**.

Over recent years, BT has collaborated in a number of projects by providing expertise of sensor hardware and interface and networking infrastructure in several heterogeneous domains, such as the unobtrusive monitoring of the health and wellbeing of elderly people in their own homes. Remote monitoring of these individuals with the automatic ability to learn everyday behaviour profiles and raise an alert when deviations from these profiles occur. The Telecare project, a collaboration with Liverpool City Council, began in 2004 with the aim of trialling non-intrusive sensors that relied on vibration, light and infrared to monitor elderly residents in their homes.

Telecare utilised architectures that were designed and implemented for the specific tasks in the remit of that project which is typical of projects previously undertaken. Whilst a bespoke solution will always match the requirements of a specific project, there is little scope for another application to utilise its data directly, or indeed to discover and understand the capabilities and the scope of the observations collected. The use of emerging OGC standards from the SWE working group are indicative of a shift in this direction. Using a modular approach, components are used to discover, access and control a myriad of Web-connected devices as diverse as flood gauges to airborne earth imaging devices.

The author explored architectural design that would virtualize the interface to a sensor enabling a middleware layer featuring rich processing functionality. Components and functionality under consideration included Complex Event Processing (CEP), the introduction of geospatial reasoning and converged communications. This functional layer would then be able to interface with applications, providing a rich base of sensor observations, analytics and the reactive control based on publish/subscribe models.

During EuroSSC 2007 the author continued to examine the SWE standards and to develop the generic sensor network architecture with a poster entitled, “Recent Developments in the Design of Sensor Network Architectures”, which provided an overview of a number of BT Research sensor network projects and how they may be able to share sensor data, thus enable data fusion, via a conceptual architecture. Refer to Appendix I.

Figure 41 shows the typical architecture components for one of BT’s WSN projects. The sensors and WSNs interface with custom proprietary code, written specifically for a single standalone (stove-piped) application. Therefore, it is not possible to re-use the components for additional WSN project applications or to combine several applications in this typical architecture. BT Research requires architectures to shorten the gap between research and exploitation (i.e. mass scale deployment) and to shorten the time in which a new WSN project is completed (i.e. with the help of re-usable components).

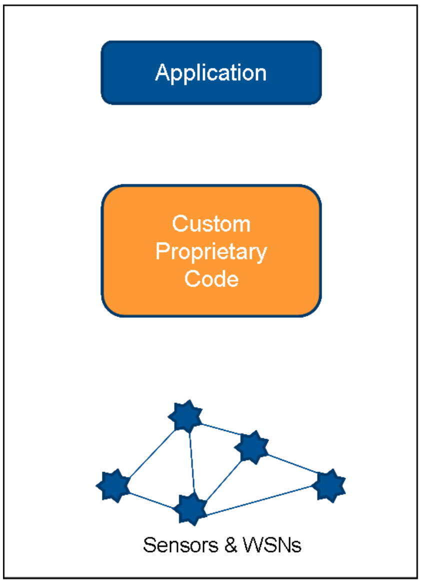


Figure 41 - Typical Architecture [183]

Figure 42 builds on these factors and evolved to a generic (horizontal) architecture, which enables a number of diverse projects to be "plugged" into it with only minimal changes required. The SNG identified the essential components of the middle layer which consists of Complex Event Processing (CEP); Geographical Information System (GIS) / context; converged communications; security and Digital Rights Management (DRM). Sensor Virtualization was enabled by the SWE framework which interfaces with sensors and WSNs. That is using SWE common specifications (encodings and web services) to acquire sensor capabilities and data. Since sensors and WSNs are registered in the Catalogue Service for Web (CS-W) and therefore discoverable online.

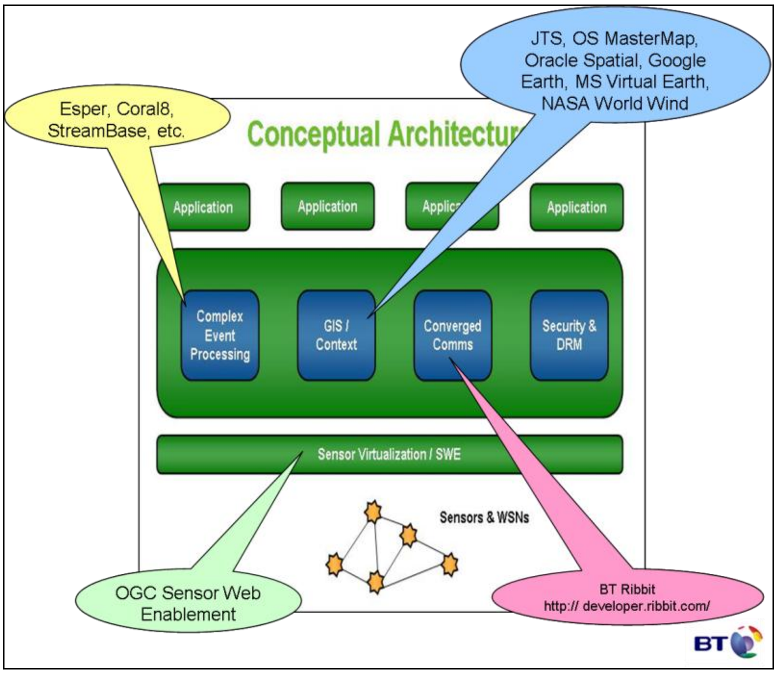


Figure 42 - Conceptual Generic Architecture [184]

Figure 42 was developed by the author during the Sensor Virtualization project and depicts the recommended framework (SWE); CEP engines (Esper or Coral8 or StreamBase); GIS / context visualization applications (Google Earth, MS Virtual Earth, NASA World Wind); Converged Communications developer toolkits (BT Ribbit 21CN SDK 'hybrid communication tools'). These were trialled by the author and Dr. Gavin Churcher, as specified for the components above. Collectively, they facilitate access, analysis and visualization of data, reduce the time to develop new applications and facilitate innovation.

4.9 Eco System Architecture

Figure 43 depicts an Eco System for a generic architecture, which is important because it interfaces with specific WSN applications. For example, SAPHE (BSN location); Traffimatics (vehicle location); BOP (building temperature, security status); PIPES (utility meter readings); BRIDGE (RFID tag data); weather station (real-time data). Other Eco Systems will be competitors to the BT system. Sensors and WSNs feed into the data layer, while live queries or archive data is handled by a CEP engine or stored in DBMS for persistence. Processing is performed at the Information Networking (IN) layer, where raw data is filtered and is transformed into knowledge or business intelligence.

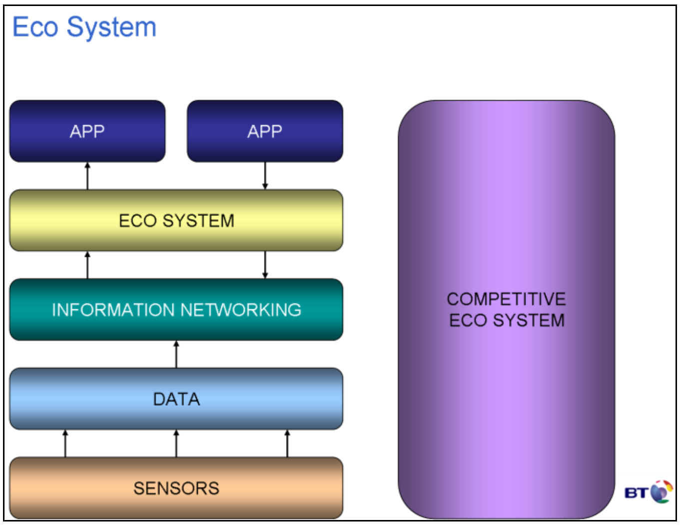


Figure 43 - Eco System Architecture [185]

4.10 Context Architecture

As illustrated in Figure 44, the Generic Architecture research evolved after the author worked briefly with Dr. Eliane Bodanese and Mo Haghighi at Queen Mary, University of London (QMUL) **[186]**. The Networks Group were also surveying the SWE framework as a component for their research into context architectures for WSNs **[187]**.

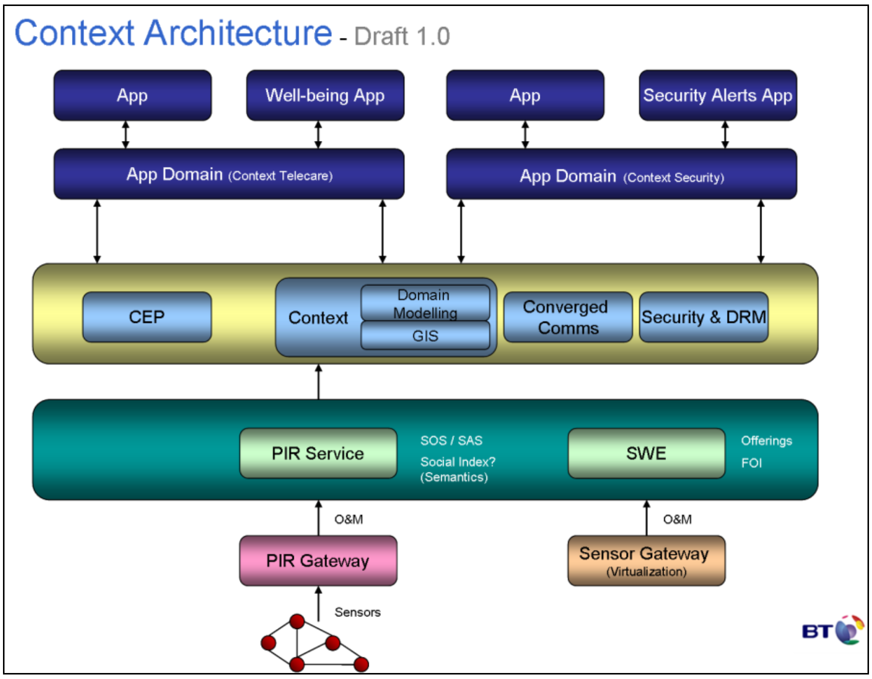


Figure 44 - Context Architecture [188]

WSNs are inextricably linked to geospatial issues such as GIS, location-based services and context-aware capabilities, i.e. the location of the sensors may be pertinent during a WSN data monitoring experiment. For instance, a sensor board may include an accelerometer and Global Positioning System (GPS). Therefore, that is the reason why BT's Sensor Virtualization project included context awareness, in addition to the Generic Architecture. Moreover, the reason why the OGC, primarily concerned with GIS began the SWE WG to incorporate the sensor element to their extensive framework.

Value is added to the information by using 'context awareness', which comes from detecting, storing, processing and integrating situational and environmental information gathered from sensor tags and/or sensor nodes, whether static sensors or mobile sensors Features of Interest (FoI). For instance, context awareness may relate to where the FoI is located; whether it is moving (e.g. BSN or Traffimatics) or stationary (e.g. UCB FireBug mote deployed in a field or SECOAS buoy anchored off-coast); whether it is hot or cold, etc.

For example, a group of sensor nodes or a person (SAPHE service user hence BSN) or vehicle or livestock or resources (hence RFID tracking) to ascertain where the data originates from (e.g. via GPS). For example, mobile sensors are dynamic not static, unlike static weather station sensors or UCB FireBug motes deployed in the fields of California, or static sensor motes attached to Redwood trees or SECOAS buoys anchored to the seabed.

Therefore, sensor positions may be visualized on Google Maps. Sensors enhance GIS systems as evangelised by Ed Parsons (Geospatial Technologist of Google) **[189]**, Robin Mannings' "Whereness" (BT Research) **[190]**, and Jon Bryant (BT GIS Group).

Location / Whereness include the following considerations:

- Efficient and adaptive multi-modal, multi-sensor information fusion (i.e. primary sensing versus secondary correlated inputs sensing);
- Distributed detection, estimation with constraints (power, bandwidth, etc);
- Distributed WSN performance characterization and metrics **[191]**.

As illustrated in Figures 43 and 44, the author designed Generic and Context Architectures for WSNs to attain reusable interoperable solutions and lower costs for Telcos. The rationale for the architecture components is described in the following section.

Based on the Open Systems Interconnection (OSI) Model Layers, which are defined as follows **[192]**:

7. Application layer: Provides different services to the application;
6. Presentation layer: Converts the information;
5. Session layer: Handles problems which are not communication issues;
4. Transport layer: Provides end-to-end communication control;
3. Network layer: Routes the information in the network;
2. Data Link layer: Provides error control;
1. Physical layer: Connects the entity to the transmission media.

The following layers of the Context Architecture (Figure 44, p.108) are explained below:

Logical Node / Application Layer:

- Application Domain (Context Telecare) Well-being App and App Domain (Context Security) Security Alerts App;
- Potentially any WSN application projects which may "plug-in" to the reusable and generic context architecture;
- Other example App domains include Telematics (smart cars); BOP (smart buildings); BRIDGE (RFID supply chain management); PIPES (predictive maintenance for a utility company); SECOAS (environmental monitoring), etc.

Middleware:

- CEP engines (EsperTech/SAP's Sybase CEP/StreamBase) execute real-time queries on sensor data streams (or feeds), store and archive sensor data for future queries;
- Persistence is handled by the CEP engine or DBMS (as detailed in Chapter 6);
- Domain Modelling represents the key concepts, vocabulary, relationships of entities and attributes, encapsulates entity methods of object oriented models within the problem domain;
- Geographic Information System (GIS) enables location-based services (LBS) such as Google Earth or Map.
- Converged Communications enable hybrid services such as fixed-line, mobile, email, SMS, chat, Web Services, LBS, client-server apps;
- Security / Digital Rights Management (DRM) ensure secure and trusted connection, privacy and content provider rights safe-guarded/protected from theft/duplication/breach of copyright.

Physical Node / Connectivity Layer:

- Sensors and WSNs connect via Passive Infrared (PIR) Gateway and Sensor Gateway directly to SWE (Java) Web Services (Sensor Observation Service / Sensor Event Service) and Encodings (SensorML / CS-W / O&M) / Semantic Web (social index).

Application and System Design

The Application Domain provides the context which enables domain modelling or GIS such as exact location or system capabilities and boundaries. The end system or Application Domain within a Telecare or Security context that is performing the final processing of the information and taking action, or presenting information to human operators. Such applications might be supply chain and inventory management (e.g. BRIDGE), road congestion tolling (e.g. Traffimatics), building security and safety (e.g. BOP) or environmental monitoring (e.g. SECOAS). In addition to the BT Research projects, specific application propositions will require unique technical and social research to enable them to succeed.

There are a number of questions to answer, such as which applications and devices will drive pervasive computing and M2M communications? What are the examples of successful business critical M2M implementations? Are two approaches needed, an application driven approach and a research driven approach? The design/selection of network parameters/topologies for different applications - monitoring patients on life support is more mission critical than the whereabouts of a pallet of baked beans in a warehouse. How does one scale, design, middleware, grow a network. Where is the intelligence in the system? (e.g. towards the edge, within the network, distributed, centralised or a hybrid of these). How does one identify a trend until you aggregate all the information together into one system? Considerations such as energy-efficient designs for sensor management and end-to-end services for multiple interested parties is the over-arching design goal for WSNs. That is, from one infrastructure, many forms of information can be gathered for many different kinds of user requirements (e.g. threshold alarms, comprehensive infrastructure view, real-time data fed into bigger management systems). The information should be reliable, secure, and appropriate in terms of precision, quantity, timeliness and in terms of the end-user device to which it is delivered.

User Friendliness and Componentisation

Designers may assume they know best about designing the ideal WSN, generally real users will want to use the system in unexpected ways. If WSN technology is ever going to be deployed universally, it will probably have to be developed so a teenager could build an application fairly easily, within a few hours. This may require a simple drag-and-drop-style GUI to enable rapid assembly of a working system. To enable such ease of use, researchers may need to identify the key system components, and make them stand-alone. However, one may need to distinguish between retail markets (home and SME use) and corporate infrastructures where a large system is deployed and users subscribe to services on it.

How does one monitor a WSN to ensure it is running ok? Does a heartbeat signal negate distributed computing? Is high available equipment needed towards the edge to stop the need for a heartbeat signal? It may require cost analysis of sensing versus sending an engineer out (e.g. sensing the fill level of a fire extinguisher may be automated, but a six monthly check is required to assess the physical state). Finding suitable trade-offs between accuracy, coverage, and resource consumption, etc. This could have a bearing on the scale and topology of a deployed network.

Architecture and Devices

The main question is how to structure the system, where to put interfaces, and where to deploy functionality in the system. This includes defining common functions and the standard interfaces for devices and applications. Also included is the balance between a generic system and one tailored for the requirements of particular applications. This will include how much processing capability to provide on the devices and in the network in order to improve scalability. In theory, any BT WSN project whether Telecare (Well-being app) or Security (Alerts app) is “pluggable” into the Generic Architecture.

Devices are the objects in the physical world connected to a communications network. Devices include sensors, cameras, motors, robots, vehicles, goods and asset tags, alarms, lights, heaters etc. Such devices combined form more complex machines such as buildings or transportation systems. Devices are involved in receiving information from the physical world, or controlling physical resources. Devices which provide information services to humans such as computers, televisions and phones are not included in this definition. The use of such devices to receive M2M services is considered to be an application. Computers and phones used for specific automation tasks such as an application platform for home automation, in-car Telematics platforms, or mobile phone tracking are included within our scope. Problems include power management, localised processing, support for remote management including configuration and updates, security and key management and shared resource control.

Connectivity

The connectivity layer provides the data connection between devices, and between devices and other applications. This will include the OSI model layers from the physical network until the session control for both the core networks and the myriad of local access networks. Problems may include power management of radio networks, multicast, routing, congestion and quality. Although the connectivity is provided by gateways, hubs, switches and routers, some network connectivity must be implemented on the physical device itself, and this is still considered to be in the connectivity layer. Research into the connectivity layer includes the development of high-density radio networks, ad-hoc multi-hop mobile networks and delay tolerant networks. It is imperative to consider the networking options available for the connection of devices, and the impact that the connectivity will have upon system capabilities.

Middleware and Persistence

Middleware is defined as the shared computing resources and services to support multiple applications. The middleware may be operated as a hosted value-added network by companies such as BT, or may be distributed between application operators and devices as a common interoperability layer. The (set of) middleware may provide structured data, routing of information, storage, generic processing capabilities (e.g. aggregation, filtering, min/max, blurring/blending), contextual (e.g. spatial/temporal) and semantic models, process enaction, information and device searching, management capabilities and security and privacy management. A selection of these different systems must act in concert for a particular M2M solution. The capabilities provided in the middleware are defined by the requirements and common characteristics in the applications, the devices, and in the data and nature of operations to be performed. Early M2M systems will necessarily have a narrow application scope to facilitate deployment and to reduce costs.

How does one retain data and information? The middleware and devices must be able to retain information to meet the current demands of the applications such as real-time queries, calculating averages, responding to historical queries. In contrast, one must be careful about information retention for security and privacy, and in order to be able to manage the scalability of system caches and data stores.

Scalability and Management

Can the system architecture deal with the huge amounts of data from the physical world? Part of the answer to this question is the design of systems to process information as early as possible. However, the management of complexity that this introduces has its own scalability problems in terms of diversity instead of load. Every additional capability an engineer brings into the system has its own weaknesses in terms of overload. How does one ensure that a processing capability on a particular sensor is not overloaded? Scalability is a system requirement that is in a fine balance with the requirements of the individual applications (e.g. one could aggregate data from the devices to improve scalability, yet this might conflict with the real-time requirements of an application) **[193]**.

Connecting a few sensors/devices together, ensuring they are 'listening' and sending at the right times, ensuring they use resources effectively is a difficult task. Achieving this for thousands/millions of devices will require increasing levels of 'hands off' support, self configuration and optimization. Embedding this kind of support in a trusted way is a key challenge. Simulations, models and real-world test-beds will start the process of defining the impact of scaling these systems up. Management of sensors/devices, reduce deployment and maintenance costs (e.g. remote management, fault management and diagnostics, long battery life). The WSN system should not need to be re-engineered based on the addition or substitution of sensors. The devices should not need to know in advance which sensors will be attached. Ideally wireless programming and remote, networked software/firmware upgrades will be enabled. A further consideration is placing additional sensors into a network securely, allocating addressing and naming configuration.

Context Aware Sensing

Network problems are not only about efficiency of sensing and communication, but what to sense and what to do with data sensed. A functional sensing device can perform many roles even using the same set of sensors (e.g. an infrared sensor can act as a variety of information producers including security, healthcare, and communications). When dealing with a few devices, hand configuration is feasible. As the number of devices increases and consequently the networking rises then decisions on how devices should be used becomes complex. Also, how feasible will it be to change a devices behaviour once it is 'in the field' by uploading policies or even code **[194]**.

Data Processing and Analysis

CEP is used to aggregate and correlate sensor data acquired from either diverse WSN project. How do the middleware and devices support delegated processing from the applications? Can the network detect composite events on behalf of an application? Can engineers perform aggregation and filtering to reduce the load on the network and deliver the information as the application desires? One problem is how to express Complex Event Processing queries and decompose them to allow re-use between different applications with similar requirements. Where is the most efficient place to run such processing? Nearer to the device reduces load and allows specific capabilities. Later in the network and middleware allows fusion of data from more different devices. Processing capability in the middleware can also aid privacy by blurring the accuracy of the information or blending it with other sources **[195]**.

Generating data is simple, but how does one generate better quality data and efficiently process data into meaningful information and knowledge. How much processing should be done in the network and how much by the end user? What tools could be developed to aid this. Should this boundary be dynamically adjustable depending on the current status or sequence of events? Characterisation of failure modes and recovery as a result of hardware outage/replacement, interference, DoS attack, etc.

Management of information (e.g. distributed, address or location mapping between sensors, and functionality i.e. temperature, pressure, grouping, etc). Data processing is related to sensing, because it can affect the sensing rate. Attempting to characterise a phenomenon from current measurements will influence how that phenomenon is measured in future. How this data processing is distributed through the WSN and through other more powerful networks, should probably be application or user specific. However, with a flexible sensor networking platform, the extent of data processing at various levels within the fixed and sensor networks (device/cluster head/gateway/end-user), should be flexible/adaptable/specifiable. Data fusion is related, and could take place (aggregation) within one WSN, or amongst networks owned by different parties. Hence standards will be important. If data is not brought back to a central repository will it be possible to mine the data for unexpected trends. Are AI tools or CEP required to identify data trends? How does one handle geographic distribution, varied security levels and heterogeneity relating to sensors and the GRID? **[196]**.

Control and Monitoring

The problem of control has several dimensions, firstly how are the devices controlled, secondly, how does one control the physical world? How can one discover which devices are available (e.g. SWE Registry) and have suitable models of how they can be used? If the devices are shared between different applications of even organisations, how does one protect our physical operations from attack, and allow sharing of these resources? Another dimension to control is the configuration and management of the devices themselves. In evolution we consider the upgrading and re-use of devices, whereas in monitoring we consider how we can control the information feed from the device. Can the information requirements of the applications be met while preserving the device battery life and the owner's security policies?

How does one build systems to deliver the information required by applications? There are underlying problems of knowing what data is available and how to route the data efficiently towards where it is required. As the devices and data available change, together with rapid changes in the requirements of the applications, we need to design a network that can automatically adapt. Solutions exist in the fields of publish/subscribe and event messaging networks, and also in work on large-scale data collection and processing. However, such systems traditionally do not provide many of the additional capabilities that one might require, e.g. how might one build a publish/subscribe system to serve real-time applications?

Resilience

Are M2M systems dependable? Although they may never be totally reliable, we need to provide a measure of assurance to the applications. How likely are individual sensors or data feeds likely to fail, and how will it affect the application? Are there substitute sensors and how does this affect the meaning of the information? By building models of the system architecture we can answer some of these questions and begin to correlate data automatically in order to clean and improve the data quality. Can we rapidly detect the failure of system elements and automatically recover? Can we utilise some of the same mechanisms used to detect failure to improve security by detecting the injection of inaccurate data? At a higher level we can consider the resilience of the business processes. With better visibility of current state of the world, we can build processes that adapt instead of ones which regularly fail with carefully crafted exception handling.

Tools and Simulation

As M2M markets become more mature, developing and deploying cost-effective M2M solutions becomes a complex process. In such complex systems how do we know that new deployments or evolutionary changes will operate as we expect? How will development tools evolve? How do we test our new applications or middleware capabilities? System design methodologies are not well developed for such complex heterogeneous systems. Ideally we might simulate the behaviour of our application, yet this requires detailed models of the devices available and realistic data. In smaller retail deployments of M2M we must provide the facilities for designers to easily build and deploy systems including GUIs and tools to facilitate their build and operation. Suitable WSN design and simulation tool solutions will necessitate quality assurance.

Communication and Networking

Wireless standards include GSM, GPRS, WiFi, Bluetooth, ZigBee, ADSL, etc. How are decisions to be made about what technology should be used and how it is interfaced? Many WSNs have fixed nodes - they get scattered over a terrain, installed in a house, etc. What about sensors belonging to a network where the nodes are mobile and are free to wander from one area to another. E.g. WBAN or BSNs where sensors on people in a community travel to another area, car sensors, tagged goods, etc. Converged Communications enable multiple communications to be utilised (e.g. SMS, email, Twitter).

How does the network handle failure modes and recovery as a result of hardware outage/replacement, interference, attack, etc? The WSN communication should be integrated with the sensing – not seen as independent. The frequency of sensing will depend on how fast and with what level of certainty the sensed data can be communicated or stored. Communication amongst sensor nodes (or mediated via a gateway) can cause new learned operating behaviours to propagate through the network and can also be used to inform on context, thereby refocusing the sensing frequency of one or more parameters, for a time, depending on what is being observed elsewhere. Communication should be able to operate flexibly, choosing network pathways according to available hardware and technologies, e.g. multi-hop sensor-to-sensor, WiFi, GPRS, ZigBee etc., as well as according to the priority of the information and the user requirements. Power saving and network load balancing will also be important.

In terms of interoperability, a metadata exchange may be the only way to inform nearby devices of available interfaces and resources. Significant challenges also remain at the MAC layer, i.e. finding a device that's ready to listen 'now', without interfering with others, rather than relying on predefined, inflexible communication schedules. Consider applications which are best solved by wireless versus using cable. Is mobility the key or is it power? Where does a network become IP and where does the hub/gateway sit? Mission critical systems e.g. Hospitals - how reliable is a piece of wire compared to wireless? Is ZigBee too complex for simple systems? How many systems really require a super lightweight sensor? Is smart dust going to deliver anything useful in BT's research timeframe (~5 years?) Are wireless systems really the way to go for many in-building systems where a cable already exists, e.g. mains signalling?

Security and Privacy

Public-key based schemes may not be suitable for WSNs due to the limited computational abilities of the sensor nodes. Pre-distribution of secret keys for all pairs of nodes is not viable due to the large amount of memory required. Levels of security within WSNs will have to be inherently lightweight. However, there may be ways in which the typical data-gathering topology of a WSN (many-to-one) can help to prevent security breaches, compared with a many-to-many topology. In any case, whether gateway nodes are involved or not, appropriate levels of security will need to be offered, and these will almost certainly vary depending on the user and the application. In some cases, the need for urgent, emergency information may override normal privacy concerns, therefore a context aware security strategy may be important. The following must be considered: key distribution issues; security systems for ultra simple nodes; perhaps one way data transmission.

Security is required in many M2M applications. Security and DRM ensure data integrity and safeguard from hacking (e.g. false packets injected into the network or using a time stamp to prevent packets from being replayed at a later date or time). Confidentiality needs to be protected to preserve the economic value and advantage of the information. Companies need to be able to secure their operational information from competitors, and allow access to selected partners or be able to trade information within an economic market. Who can gain access to data, and also who can submit data? Data integrity is also important since the processes operating in the M2M system are critical to the business. In more open information sharing systems one needs similar security mechanisms to preserve user privacy and to build trust in the information available, leading to increased application value. By providing adequate privacy protection one can encourage participation and increase the levels of information available and the value of applications. An example of an M2M platform where privacy to encourage participation is essential is transportation systems since location is monitored.

Interoperability

Increasingly the devices and applications will be operated by different parties who wish to share data or co-ordinate their activities. Part of the problem is the definition of standard interfaces to allow the sharing to take place. Another is managing the security and integrity of the system. Along with different operators of devices and applications, one can also consider that the different middleware functions may be federated, e.g. Microsoft's recent evolution of their identity management solution and within Liberty Alliance. Other capabilities may also be federated. Allowing routing and processing to take place on nodes that are not trusted requires new security techniques including the use of Trusted Computing Platforms. Another aspect to interoperability is standards. How will data standards such as SensorML and M2MXML develop? How will initiatives such as Sensor Web Enablement, OGSA

(Grid) OSGi, and UPnP play a part in the development of M2M systems? For instance, Passive Infrared (PIR) service may interface with the Sensor Observation Service (SOS) and perhaps some kind of Social Index ontology is available from the Semantic Web.

Understanding

How do we use the data harvested / aggregated / available from numerous devices? We must be able to transform such data into meaningful information. Contextual models can provide one mechanism for relating data. Models of space and time allow the application to 'understand' the data in those contexts. It is possible for the application to ask for an event 'A' followed within five seconds by event 'B', or to ask for events within a geographical area. Models of trust or resilience can help us assess the quality of the data we receive. Further semantic information can aid the application in navigating the data available in a similar way to the Semantic Web. An application running in a car might be able to ask about congestion along the M6, without ever knowing exactly which sensors and devices have contributed to the answer.

Standards

For large scale systems to exist they need common standards or a large number of protocol conversion units will be needed both for communications and data conversion. What's the best solution? Choice of standards, levels of standardization etc. Which of the following initiatives will play a key role? Is BT monitoring the right standards activities?

- Sensor web enablement (SWE) initiative;
- Observations & Measurements (O&M) or SensorML – encoding language to describe sensor models. Metadata representation of sensor data and sensor capabilities;
- Machine-to-Machine eXtensible Markup Language (M2MXML) – data exchange language/protocol, interoperability among sensor nodes **[197]**;
- SensorGrid – integration of sensor networks and the grid architecture (OGSA open grid services architecture) **[198]**;
- UPnP – Universal plug and play **[199]**.

Power

How can devices be powered currently, what are the options in the future? Is battery power really viable for large scale M2M system? Having a system with 100,000 battery powered sensors will become unmanageable if the batteries have to be changed every 1-2 years. The environmental impact would also be large. How does this affect application possibilities? Is this a challenge for BT or should they take a watching brief?

Sensing

Sensing and communication are inextricably linked. Dr. Chris Roadknight's work involved the user specifying fitness functions for the nodes, without specifying precise operating behaviours. This removes the need for the network user to attempt to know in advance the behaviour of the phenomena being observed. Sensing can fairly easily be carried out in response to the sensor measurements themselves (e.g. how fast a measurement is varying) which is important for determining how valuable a given data point is. In future, it would be beneficial to add current context (cross-checking with other measured parameters, both on the device, locally and network-wide) and the recent behaviour of the phenomenon being measured, to give a more sophisticated measure of the importance of a given measurement. PIR Gateway serves as an interface and filter between the sensors and the PIR service; Sensor Gateway (Virtualization) enables actual and virtual sensors to be handled by the architecture.

M2M

Most of what is described above seems to assume a human end-user, rather than a machine. Although system behaviour and performance will need to be logged, especially in the early stages, to confirm that all is working well, there is no reason why the endpoints of the data-gathering could not be actuators. Indeed, this may well be the biggest market for WSNs. As such, WSNs could lead to the re-design of many management systems for large infrastructures, such as power and water supply, distributing the control, e.g. supply, through the network, much closer to the consumer (as in power networks, where even ordinary householders can sell energy back to the National Grid). This may mean that sensor devices have to operate subject to many different influences, with feedbacks at many different levels, before autonomous (distributed and real-time optimised) control of a critical infrastructure is possible.

Evolution

Companies need to ensure that investment in devices and services returns the maximum value. Part of this is to ensure that such devices and infrastructure can service more than one application. As new applications emerge, the system must be capable of meeting these new requirements. Flexible systems may be designed from the outset, however, cost decisions will dictate flexibility. Therefore the facility to perform upgrades is essential. One aspect to the problem is how to introduce new devices and middleware capabilities and have the applications adapt to their use without significant re-engineering. Another aspect is being able to upgrade devices that are currently in live operation. This problem covers the design of the device, but also how to manage the disruption to the live applications **[200]**.

Summary

The author has outlined some of the top-level technical challenges that must be overcome in building M2M system architectures, whether generic or context aware. Although much, often fragmented research has already been performed, there are still complex challenges ahead in deploying the next generation of M2M solutions.

4.11 Sensor Visualization

This section assesses frameworks for visualising sensor data. Furthermore, the applicability of alternative frameworks for WSN applications, for realising a web of sensors or 'Sensor Web' are outlined as viable alternatives to the OX-Framework. For example, Microsoft Research's SenseWeb project, which visualizes sensors and enables data fusion.

Data derived from a weather station's sensors may be displayed in an Internet browser or incorporated into a mash-up (e.g. Google Earth or Map depicting the exact location of a weather station). For a BT demonstration, the location of virtual environmental sensors deployed on a river bank were visualised on Google Earth. This is effective and provides context for the sensor data being streamed by the application from the data sink of the sensors in the field to the gateway of the laptop capturing and collating the sensor data **[201]**. Refer to Appendix G.

OX-Framework

The OGC Web Service Access Framework (OX-Framework) was developed by OGC and 52° North for visualising SWE applications. It handles service management and XML schemas. The client displays a number of schemas depicting weather stations in Cape Town, South Africa. As depicted in Figure 45, line graph variables, time variation curves, barometric pressure, etc **[202]**.

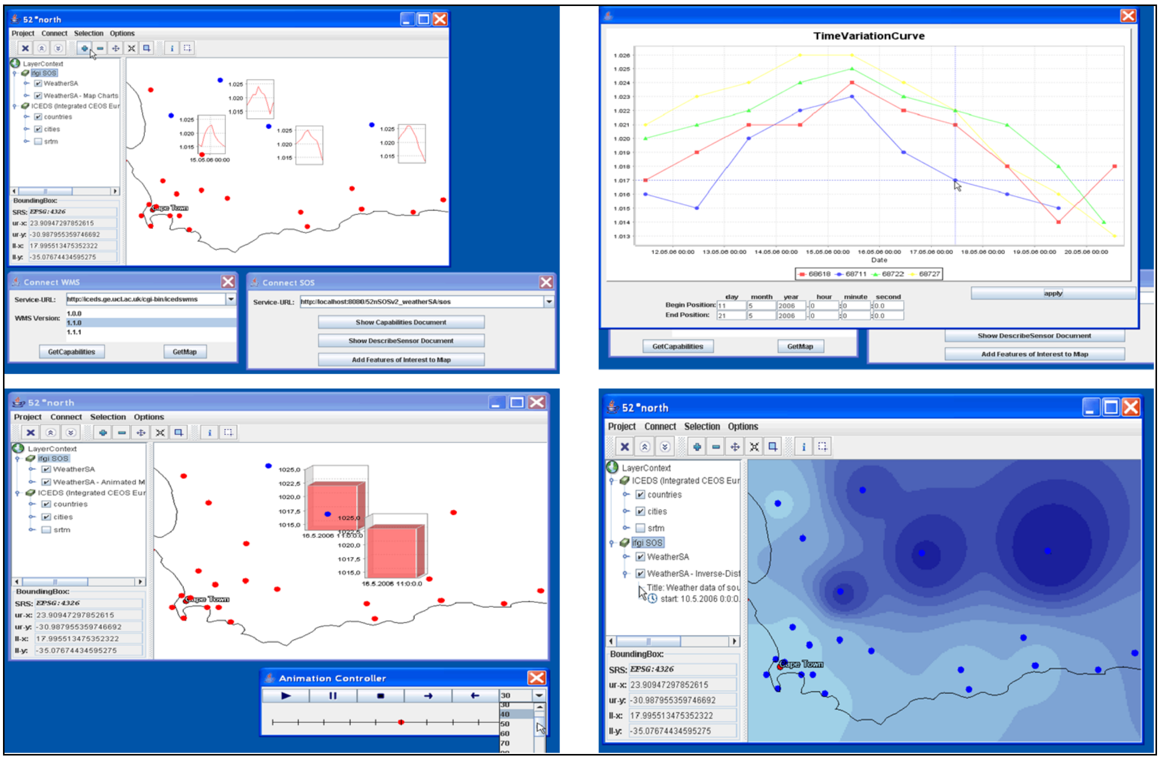


Figure 45 - OX-Framework Visualizations [203]

Weather Station Sensors:

- Data easily accessible due to low accuracy (around 50%);
- No privacy issues because not personal data but freely available;
- Unlike healthcare (sensitive sensor data);
- Relatively inexpensive and easy to set up;
- Useful for most activities especially nautical and outdoor pursuits.

The OX-Framework is a multi modal client framework. It enables the management of all service types offered within 52° North. This generic framework invokes, manages and visualizes these services independently from a specific User Interface (UI). It also offers developers a customizable and extendable system of cooperating classes supplying a reusable design which is applicable for client and server applications.

Alternatively, a Java Swing Front-end client is used to explore sensor data captured by weather stations in South Africa. For example, sensor data such as time, temperature, wind speed, pressure. As shown in Figure 46, the user has added three Web Map Service (WMS) layers, zoomed into the region of South Africa and added Features of Interest (FoI) i.e. weather stations provided by the ‘Weather’ Sensor Observation Service (SOS). FoI are drawn as red dots on the map. After zooming into the region around Cape Town and selecting some weather stations (blue dots), the user can choose between various renderers to visualise the weather observations. Before rendering starts, the user specifies parameters of ‘GetObservation’ request which will be sent to the ‘Weather’ SOS. As a result, time series or animated charts will be rendered on the map.

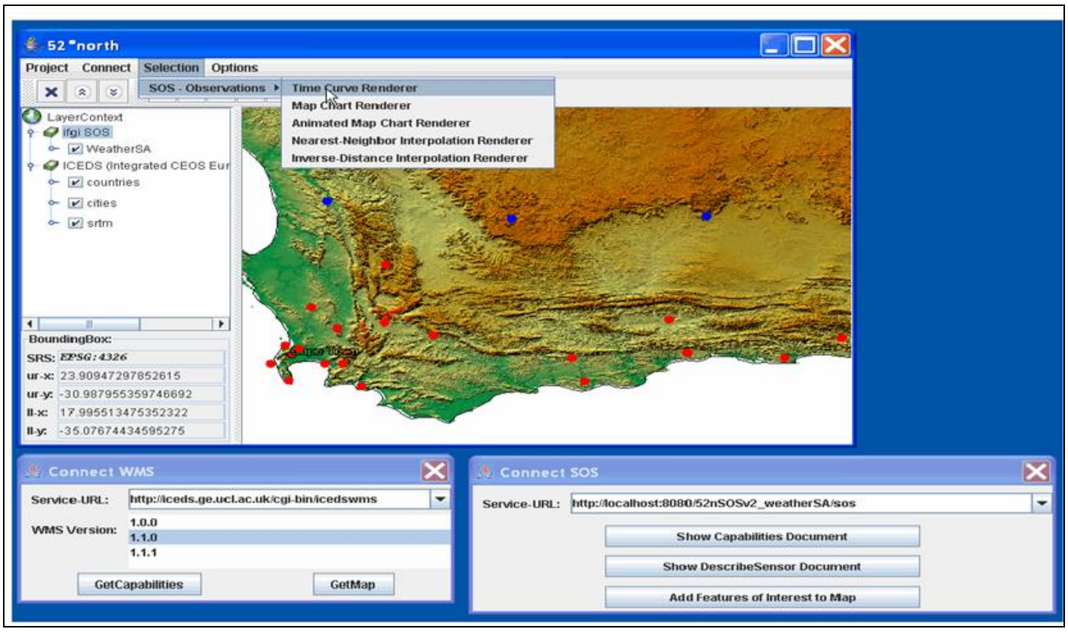


Figure 46 - Java Client Visualization [204]

Taken from the authoritative source of the IfGI and 52° North leading developers of NG SWE 2.0 specifications **[205]**, other middleware systems for building Sensor Web infrastructures based on SWE are as follows:

- GeoSWIFT 2.0 - optimizes scalability by introducing peer-to-peer based spatial query framework;
- PULSENet framework - reuses and amends the open source components of the 52°North SWE-based Sensor Web;
- NASA Sensor Web 2.0 - SWE combined with Web 2.0 technology. Mash-up functionality is realised by incorporating the representational state transfer (REST) approach to access data.

Non-standardised approaches for building a Sensor Web are as follows:

- Hourglass – provides architecture for connecting sensors to applications. It offers discovery and data processing services and focuses on maintaining the quality of service of data streams;
- Global Sensor Network (GSN) – flexible integration of sensor networks to enable fast deployment of new sensors. Central concept of virtual sensor abstraction with XML-based deployment descriptors in combination with data access through plain SQL queries. GSN provides distributed querying, filtering and aggregation of sensor data as well as dynamic adaptation of a system during runtime;
- Sensor Network Services Platform (SNSP) – defines a set of service interfaces usable as an API for WSNs. Similar to SWE, the approach follows a top down view on WSNs independent of a particular implementation or hardware platform. It offers (non-standardised) service interfaces for data querying and sensor tasking, but also auxiliary services for locating, timing, and a concept repository;
- SOCRADES (Service-Oriented Cross-Layer Infrastructure for Smart Embedded Devices) – comprises multiple services providing functionality such as data access, eventing or discovery.

Agent-based systems for establishing Sensor Web infrastructures are as follows **[206]**:

- IrisNet (healthcare) – envisions a global Sensor Web by focusing on data collection and query answering. Therefore, it introduces organizing agents to store sensor data in a hierarchical, distributed database and sensing agents which collect the sensor data;
- Sensor Web Agent Platform (SWAP) – combines the paradigms of a service oriented architecture and multi agent systems. By building on the SWE framework, the proposed architecture improves the integration of arbitrary sensors into workflows on the application level. This is done by introducing a three tier architecture comprising sensor, knowledge and application layer. Different kinds of agents residing on the three layers provide certain functionality and facilitate the development of new applications and the integration of sensors with applications **[207]**.

Centralised Sensor Web Portals are as follows:

- SensorMap with its underlying SenseWeb infrastructure;
- SensorBase;
- Pachube;
- Sensorpedia.

Such Sensor Web portals offer APIs to the public for registering sensors, uploading sensor data, as well as querying inserted data. Once registered, the discovery of sensors is also supported. However, a controlling or tasking of sensors, as provided by the SPS service, is usually not possible. Except for Sensorpedia, which supports the SOS as a data source, none of the portals leverage SWE standards. The centralized approach of the portals is the main difference to the decentralized approaches of Sensor Web Infrastructures. Metadata of registered sensors as well as uploaded sensor data are hosted by the centralized portal instead of separate service components within enterprise architectures. This may be unsuitable for use cases with needs for full control over deployment and administration set up or strict data privacy regulations.

Specific subtypes of such Sensor Web portals are platforms which are specialized for certain sensor types or domains. Examples include the following:

- Weather Underground – allowing people to register their home weather station and contribute their measured data to weather forecast computations;
- EarthCam – links the video feeds from thousands of Web cameras.

AR Weather Cam

The Augmented Reality Weather Cam is a software framework for service management to create a mash-up of a webcam image and additional spatial and textual data. The additional data could be geo-data retrieved from a rain radar. The main idea of the AR weather cam is to combine a real-world image with sensor data which is visualised in the sky part of the camera image. Since the AR weather cam can be automatically steered into the weather direction, (i.e. the direction where the weather comes from), users can be helped to judge how far away certain weather events from the actual stand point of the camera are **[208]**.

Sensor Map by SenseWeb

SenseWeb is a peer produced sensor network that consists of sensors deployed by contributors across the globe. It allows developing sensing applications that use the shared sensing resources and Microsoft Research's sensor querying and tasking mechanisms. As illustrated in Figure 47, Sensor Map is one such application that mashes up sensor data from SenseWeb on a map interface, and provides interactive tools to selectively query sensors and visualize data, along with authenticated access to manage sensors.

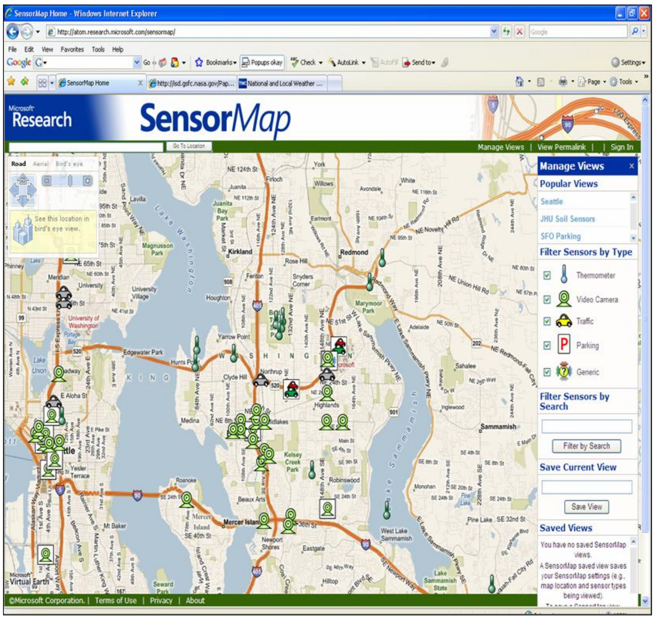


Figure 47 - Sensor Map [209]

Data sources for Sensor Map have included the following:

- Swiss Experiment - Interdisciplinary Environmental Research (some sensors protected from public);
- SEAMONSTER project;
- Soil sensor data from JHU - Life Under Your Feet;
- Parking space data from a US city;
- Traffic conditions and traffic camera images from Washington DoT;
- Weather data from Weather.com;
- Temperatures from a WSN deployed in an office building;
- Lake Metabolism data from North Temperate Lakes;
- User data.

4.12 Summary and Conclusion

Chapter 4 introduced BT Research's Sensor Virtualization project and demonstrated the OGC's Sensor Web Enablement (SWE) specifications. It recalled the author's participation in the Sensors Anywhere (SANY) Workshop, exemplified other key SWE-enabled applications and identified shortcomings in standalone WSN projects. SWE 1.0 was compared with New Generation SWE 2.0 specifications and the requirement for the SWE framework to enable mobile sensor Features of interest (FoI) was identified. Chapter 4 also detailed the Design of a Generic Sensor Network Architecture which resulted in the development and implementation of parts of the architecture as a prototype for WSNs to realise a smart and reusable architecture for a number of BT projects. Finally, Sensor Visualization was explored, including the OGC's OX-Framework, Google's Map / Earth and Microsoft's SensorMap.

Under BT Research, the author has explored a number of different WSN architectures using components from SWE, to enable these and future projects to move away from the stove-piped (vertical) solutions seen to date, and move to more flexible architectures (horizontal) that allow sensors and their infrastructure to be used by multiple heterogeneous solutions via a shared infrastructure and 'infostructure' (shared information space).

The research conducted by the author and the SNG helped BT to identify which standards and specifications comprising the OGC SWE framework were successfully used by external WSN projects to implement their applications. Also, which related initiatives or frameworks may also be considered useful components for building the reusable and generic architecture.

Although, the generic architecture concept was a collaborative deliverable of BT Research, the author developed the Conceptual Generic Architecture (Figure 42), Eco System (Figure 43) and Context Architecture (Figure 44). Similarly, the author introduced the SWE framework to BT colleagues to serve as a feasible component.

CHAPTER 5 Applying SWE to SAPHE

5. Introduction

Chapter 5 introduces Smart & Aware Pervasive Healthcare Environment (SAPHE) the most recent Telecare project which BT Research led from 2006-09 **[210]**. It details the author's practical experiences of using a generic, open architecture with a real world sensor network application, adapting SAPHE to the more generic architectural principles embodied in SWE and away from the traditional stove-piped solution. The SWE initiative is an opportunity to assess whether a single unified architecture and data model can speed the design and deployment of new WSN projects. This is not a theoretical exercise but a real deployment of the SWE technology in parallel with existing work providing a real and direct comparison to the two approaches. BT Research collaborated with 52° North to apply the SWE framework to SAPHE. BT Research's experiences with applying and trialling the SWE specifications, originally appeared in the author's publications (p.35).

5.1 Smart & Aware Pervasive Healthcare Environment (SAPHE)

Building on the expertise acquired during the Telecare project described in Chapter 3, SAPHE is a collaborative research project co-funded by the UK's Technology Strategy Board (formerly DTI), involving Imperial College, BT, Philips UK, University of Dundee, Cardionetics and Docobo. The project commenced in March 2006 and continued for three years. It aimed to develop a holistic monitoring solution to support the care and self-care of people with long-term health conditions with the placement of a number of sensors around the home and on the patient that monitor both the immediate environment in the home along with physiological traits. A 20 user trial of the solution took place in 2008 in partnership with Liverpool Primary Care Trust, Social Services and Liverpool Direct Limited.

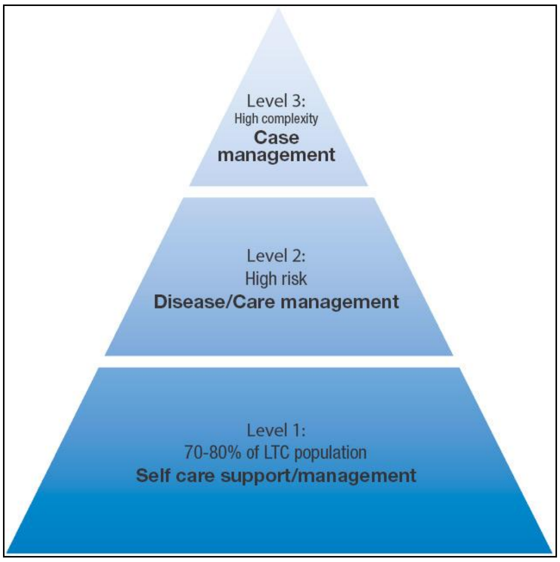


Figure 48 - NHS & Social Care Long Term Conditions Model [211]

In terms of the stratification defined by the National Health Service (NHS) and Social Care Long Term Conditions Model (Figure 48), SAPHE broadly targets users in level 2 and level 3, who may typically receive a specialist service provided by community matrons and multi-disciplinary teams. The desire is to support these users, providing a new tool for professional care, encouraging greater self-care, and preventing them from ascending the pyramid to become high intensity users of unplanned secondary care.

The SAPHE vision brings together physiological, environmental and activity monitoring, through the use both of sensors worn by the user and of non-invasive sensors deployed within their home. The body-worn sensors continue to operate while the user is away from home, performing periodic uploads via GPRS. Collected data is analysed to provide continuous risk assessment and early notification of changes, supporting preventative care. Output from the system is provided to the user themselves, family members, informal carers and care professionals, with the delivery mechanisms and content tailored to each, as depicted in Figure 49.

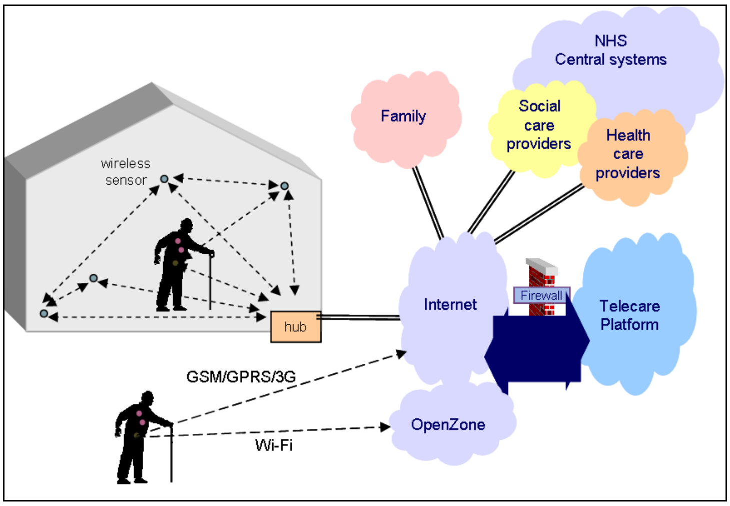


Figure 49 - Telecare In-home and Mobile WSN [212]

The final SAPHE system architecture (2010) is outlined in Figure 50. The in-home and body-worn sensor systems are shown on the left-hand side. Three different wireless technologies are used among the various sensors: ZigBee, Bluetooth and a proprietary ultra-low power radio. The fixed in-home sensors comprise low-resolution cameras, passive infrared motion detectors, vibration, contact and temperature sensors; ZigBee was chosen as a suitable technology for these devices. The SAPHE deployment of a mix of mains powered (camera) and battery powered (all other) sensors throughout the home lends itself to a mesh configuration, while the anticipated data rate falls within the ZigBee envelope. Power consumption estimations based on commercially available ZigBee modules suggest that a lifetime of greater than one year is achievable for the battery powered devices. Bluetooth is the predominant wireless standard for many standard, off-the-shelf medical devices, including blood pressure monitors and weighing scales. Bluetooth is supported in SAPHE in order to allow the use of such devices. The ultra-low power radio used for the body-worn sensors is optimised for low data rates and a range of up to 2 metres on the body, with a higher bit energy efficiency than ZigBee or Bluetooth. The body-worn sensor suite includes Electrocardiogram (ECG), SpO2 (oxygen saturation) and accelerometers.

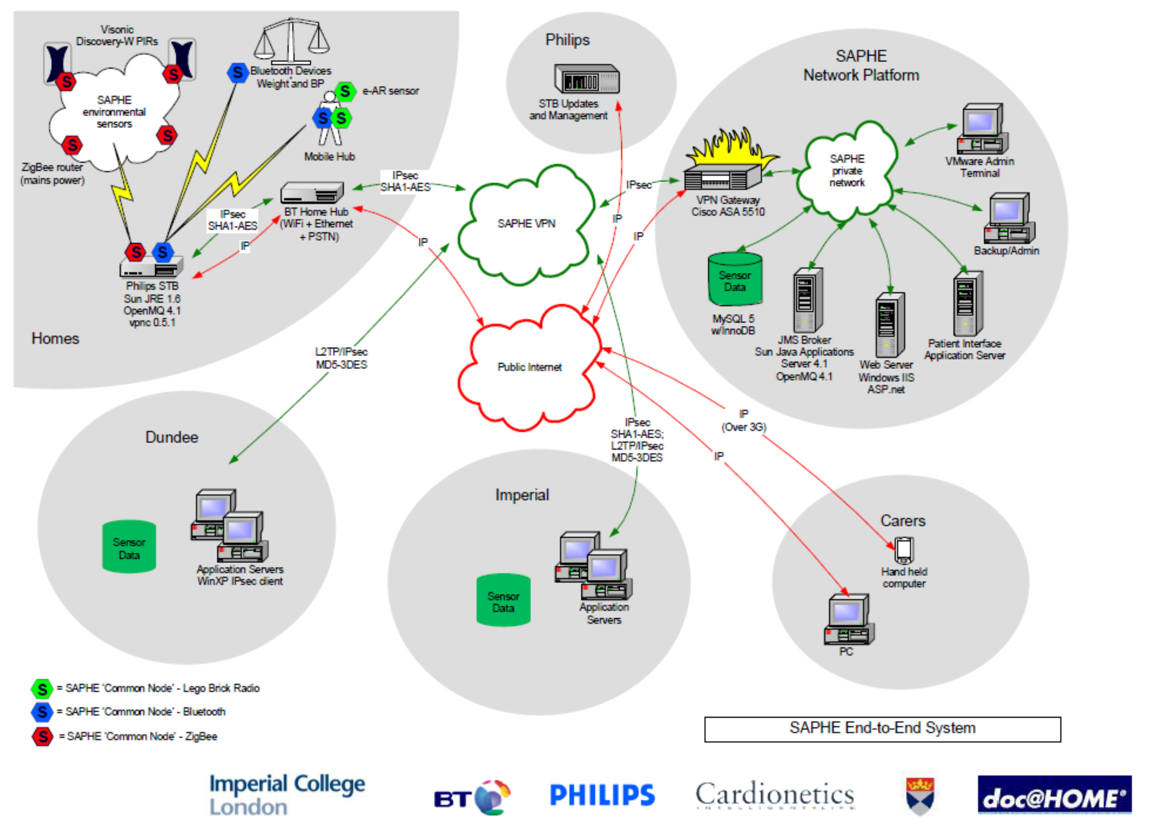


Figure 50 - SAPHE High Level Architecture [213]

The SAPHE trial infrastructure is built around a Java Message Service (JMS) middleware. A protocol was developed by the SAPHE consortium whereby each "common node" provides to the system an XML-encapsulated description of the data it offers, and outputs the data in an encoding which is transported unchanged by the middleware (in the case of an off-the-shelf Bluetooth device, this description and encoding must be provided at the receiving hub rather than by the device itself). Client modules, including the various data analysis components within the system, read the XML description in order to understand the format of any particular data feed. Certain modules require real-time feeds, so that notifications can be raised to carers or other parties in a timely manner, should any immediate cause for concern be detected. Other modules can operate on historical data; for example, interactive tools which provide data visualization or long-term trend analysis. Those clients requiring real-time data obtain it by subscribing to the middleware directly, while others can make use of a database where all raw sensor data is archived. The protocol and data encoding used, however, are particular to SAPHE and do not consider interoperation with other systems outside of the trial.

5.2 Encoding SAPHE as a SWE Service

The SAPHE project provides us with the opportunity to apply a more generic and open approach by extending certain parts of the existing architecture with SWE protocols and service components. This would present a standard and self-describing mechanism for access to relevant sensors and their observations which could then be accessed by other applications and layers. Two key aspects are the repackaging of SAPHE data in accordance with SWE models and formats, and the deployment of selected SWE web services. The SWE initiative consists of a range of specifications detailing services and data formats which, until relatively recently, have been continuously evolving. In 2008, many had stabilised at V1.0 and software implementations were being updated to the latest specifications. With this high degree of change, the author decided that the optimum way forward for the SWE/SAPHE implementation was to host a workshop with a selected open source software supplier and jointly implement the skeleton framework required. This would also require the SNG to create a stable snapshot of the SAPHE system together with sensor feeds that could be encoded and stored within the SWE framework. Two questions needed to be answered, firstly what SWE software and hence partner would be used and secondly what aspects of the SAPHE system would be used in the test use case.

The International Geospatial Services Institute (iGSI) and 52° North were chosen to participate in the workshop. Both parties are actively involved in the SWE initiative but more importantly they have a maturing open source implementation of the Sensor Observation Service (SOS); a key component required for the SWE/SAPHE work and their location in Europe would be beneficial for any follow on work. The SAPHE solution was work in progress with many of the sensors, gateways etc. still to be built. However, the author required a stable reliable flow of sensor data in order to build the skeleton system and it was decided to create a virtual SAPHE system, built upon the actual SAPHE architecture but using simulated sensor feeds to achieve these aims. The sensor simulators would not generate random data but act as a proxy for actual data gathered off-line from real sensors. Refer to Appendix D for SOS Installation Resources.

As illustrated in Figure 51, a simplified physical view of the test deployment was implemented by the use of virtual machines, each running an element of the final system. Virtual Machine 1 has a range of sensor data and sensor simulators which proxy the data in the correct format and temporal profile into the ActiveMQ broker running on Virtual Machine 2. Virtual Machine 3 registers with the ActiveMQ broker to receive the sensor data feeds. At the time, the 52° North implementation did not include the interface to insert observations using the Sensor Observation Service itself – this part of the interface is optional according to the specifications. Instead, a separate application was utilised that received observations and inserted them directly into a database that was then accessed by the SOS when it received a request from a client. This application to insert observations is known as the “dbFeeder” application.

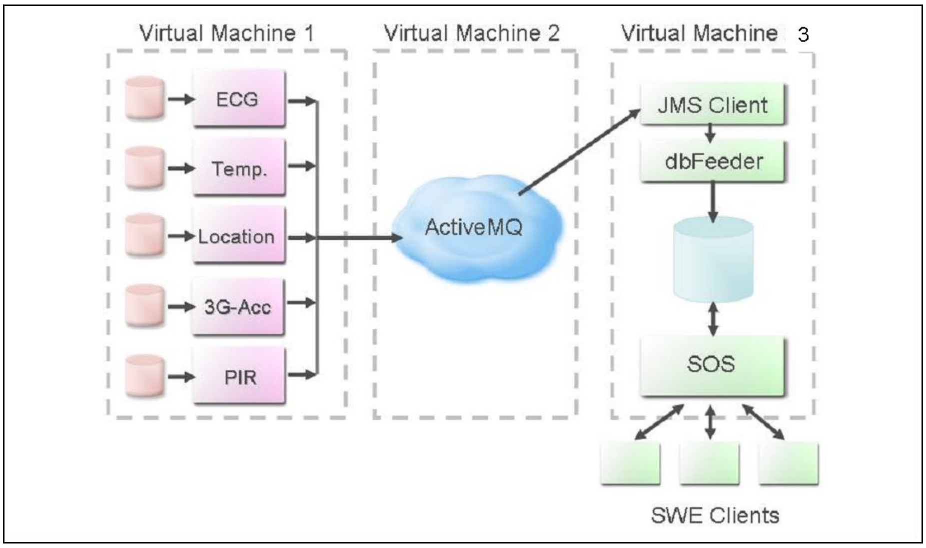


Figure 51 - SAPHE to SWE Physical View [214]

Rather than real-time sensor data, simulated data was available for the following sensors: relating to the body, ECG (heart rate), body temperature, GPS location, and accelerometer. Ambient sensors of the house included the Passive Infrared (PIR) and low resolution camera sensors. The process of creating our Sensor Observation Service began with the definition of the data model that comprises our simplified SAPHE system. This was defined by the categories of data being offered by the service, physiological data about people and ambient environmental readings from their houses. Our implementation would provide access and query for these two sets of data, known as “offerings”. The “features of interest” for our system were then defined as the person and the house, matching the physiological and the ambient observations that could be made, respectively.

The trial system incorporated simulated data from a single person and his house, thus there were two features of interest in our system: a client identified as “Bill”, and “Bill’s house”. The process of defining the data model continued with the definition of the sensors, known as “procedures”, and the observations provided by the service. These observations were defined as aggregated data records reporting, for example, an accumulation of ECG heart-rate readings over a time period.

5.3 Generating SensorML for SAPHE

This section firstly outlines the OpenGIS Sensor Model Language Encoding Standard (SensorML) which is one of the OGC’s Sensor Web Enablement (SWE) suite of standards. Secondly it outlines how the author generated SensorML for the SAPHE project.

Over the past decade, the geospatial technology world has laid groundwork for making geospatial data, geo processing services, and sensors a fluid part of the WWW. Prior to SWE, there was an increasing requirement to describe the capabilities of sensors in a detailed schema, hence SensorML was created by Dr. Mike Botts, the leader of VisAnalysis Systems Technologies (VAST) in 2001. VAST Research

[215] was part of the Earth System Science Center at The University of Alabama in Huntsville (UAH). They performed applied R&D on scientific visualization and analysis, as well as standard web-based technologies. As depicted in Figure 52, SensorML provides standard models and an XML encoding for describing any process, including the process of measurement by sensors and instructions for deriving higher-level information from Observations and Measurements (O&M). VAST recently disbanded after almost twenty years, however, the SWE-related work continues under Botts Innovative Research **[216]**. Also, SensorML is supported in SWE 2.0.

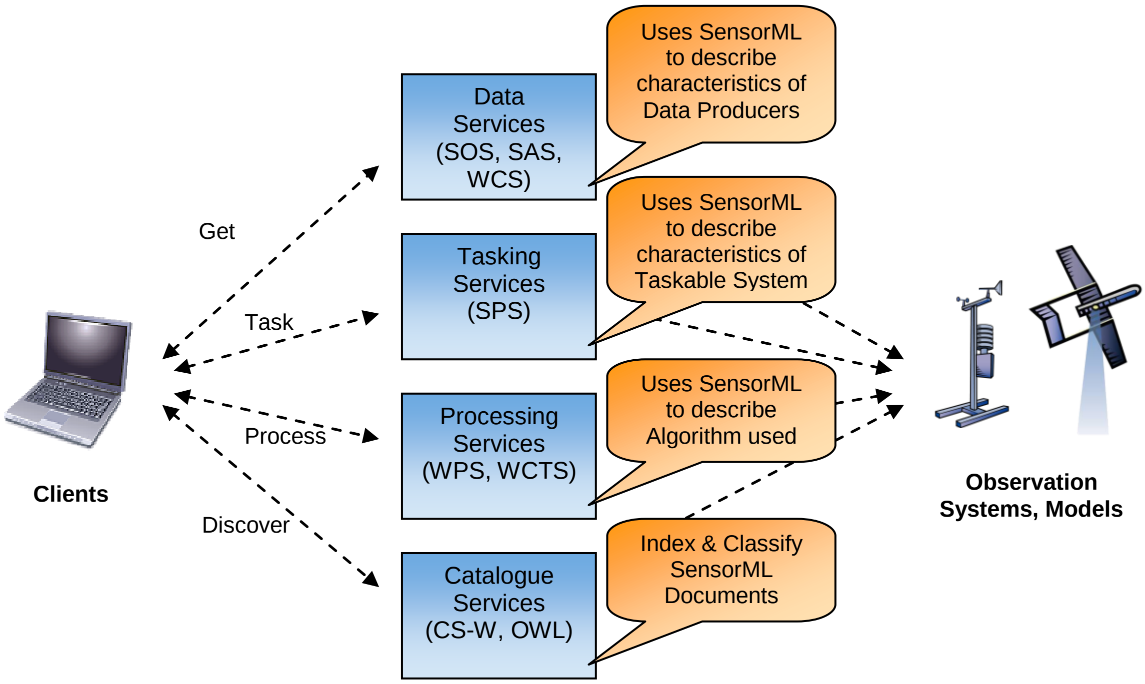


Figure 52 - SensorML Schema [217]

SensorML specifies models and XML encoding that provide a framework within which the geometric, dynamic, and observational characteristics of sensors and sensor systems can be defined. There are many different sensor types, from simple visual thermometers to complex electron microscopes and earth observing satellites. These can all be supported through the definition of atomic process models and process chains. Within SensorML, all processes and components are encoded as application schema of the Feature model in the Geographic Markup Language (GML) **[218]**.

As described above, the SAPHE project provides a scenario where SWE or sensor virtualisation may be applied. SWE was used to virtualize sensors and their observations through to the middleware layer and its additional capabilities. SAPHE system sensor capabilities may be accurately modelled using SensorML, which provides standards for describing data, sensor characteristics and processing algorithms (XML schema). XML tags are a standardised format and are advantageous because system data may be represented uniformly, e.g. less verbose than alternative data formats and easily integrated into other systems.

OGC partners, including Botts Innovative Research, 52° North and OOSTethys provide software tools to create and manipulate SensorML sensor data. As illustrated in Figure 53, a simple generator such as “SmlMor” driven by OOSTethys and MMI Ontology Registry may be used to generate SensorML for projects such as SAPHE. More recently, alternative SensorML generators and editors are available online from the OGC’s SWE software resources **[219]**. For example, “Pines” is an open source tree-based editor for viewing, creating, and modifying SensorML instances **[220]**.

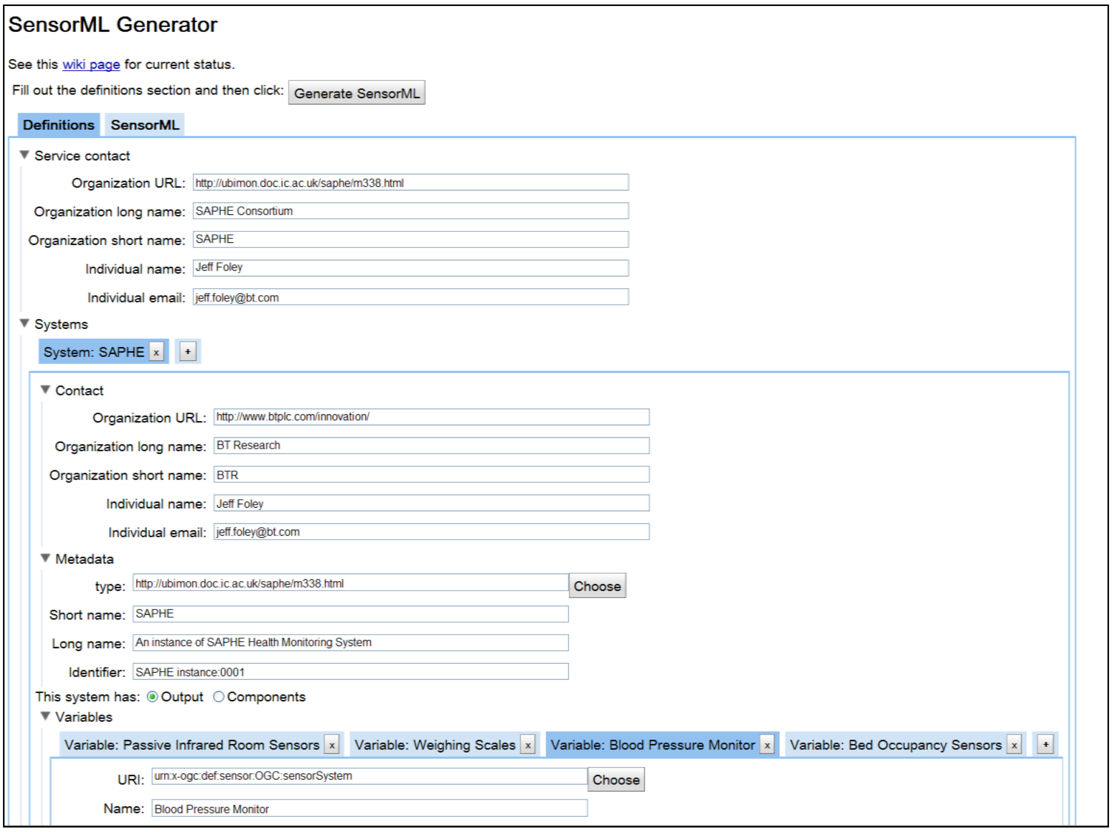


Figure 53 - SensorML Generator [221]

Figure 54 shows a screenshot of the SAPHE project data SWE-enabled as SensorML by the author. Capabilities and related data may be captured for each sensor which the system comprises of. Figure 54 exemplifies PIR, weighing scales, blood pressure monitor, and bed occupancy sensor. However, all of the SAPHE (in-home and mobile body-worn) sensors may be mapped into SensorML and includes the following:

- Contact switches;
- Vibration sensors;
- ECG recorder (chest);
- Accelerometer;
- SpO2 (ear);
- Location (GPS-enabled mobile).

```
<?xml version="1.0" encoding="UTF-8" ?>
- <sml:SensorML xmlns:oost="http://www.oostethys.org/schemas/0.1.0/oostethys" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:sml="http://www.opengis.net/sensorML/1.0.1"
  xmlns:xlink="http://www.w3.org/1999/xlink" xmlns:gml="http://www.opengis.net/gml" xmlns:swe="http://www.opengis.net/swe/1.0.1" xsi:schemaLocation="http://www.opengis.net/sensorML/1.0.1
  http://schemas.opengis.net/sensorML/1.0.1/sensorML.xsd" version="1.0.1">
 - <sml:member xlink:href="SAPHE instance:0001">
  - <sml:System>
   - <sml:identification>
    - <sml:IdentifierList>
     - <sml:identifier name="Long Name">
      - <sml:Term definition="http://mmisw.org/mmi/20080520/obs.owl#longName">
          <sml:value>An instance of SAPHE Health Monitoring System</sml:value>
        </sml:Term>
       </sml:identifier>
     - <sml:identifier name="ShortName">
      - <sml:Term definition="http://mmisw.org/mmi/20080520/obs.owl#shortName">
          <sml:value>SAPHE</sml:value>
        </sml:Term>
       </sml:identifier>
     - <sml:identifier name="Identifier">
      - <sml:Term definition="http://mmisw.org/mmi/20080520/obs.owl#identifier">
          <sml:value>SAPHE instance:0001</sml:value>
        </sml:Term>
       </sml:identifier>
     </sml:IdentifierList>
    </sml:identification>
   - <sml:classification>
    - <sml:ClassifierList>
     - <sml:classifier name="System Type">
      - <sml:Term definition="http://www.w3.org/1999/02/22-rdf-syntax-ns#type">
          <sml:value>http://ubimon.doc.ic.ac.uk/saphe/m338.html</sml:value>
        </sml:Term>
       </sml:classifier>
     </sml:ClassifierList>
    </sml:classification>
   - <sml:contact xlink:arcrole="" xlink:title="BTR">
    - <sml:ResponsibleParty>
       <sml:individualName>Jeff Foley</sml:individualName>
       <sml:organizationName>BT Research</sml:organizationName>
     - <sml:contactInfo>
      - <sml:address>
          <sml:electronicMailAddress>jeff.foley@bt.com</sml:electronicMailAddress>
        </sml:address>
       </sml:contactInfo>
     </sml:ResponsibleParty>
    </sml:contact>
   - <sml:location>
    - <gml:Point>
       <gml:coordinates cs="" />
     </gml:Point>
    </sml:location>
   - <sml:outputs>
    - <sml:OutputList>
     - <sml:output name="pointDataRecord">
      - <swe:DataArray>
         <swe:elementCount />
       - <swe:elementType name="SimpleDataArray">
        - <swe:DataRecord>
         - <swe:field name="Passive Infrared Room Sensors">
          - <swe:Quantity definition="urn:x-ogc:def:sensor:sensorType">
              <swe:uom code="Detection of movement within range of sensor" />
            </swe:Quantity>
           </swe:field>
         - <swe:field name="Weighing Scales">
          - <swe:Quantity definition="urn:x-ogc:def:sensor:sensorType">
              <swe:uom code="kg" />
            </swe:Quantity>
           </swe:field>
         - <swe:field name="Blood Pressure Monitor">
          - <swe:Quantity definition="urn:x-ogc:def:sensor:OGC:sensorSystem">
              <swe:uom code="mm Hg" />
            </swe:Quantity>
           </swe:field>
         - <swe:field name="Bed Occupancy Sensors">
          - <swe:Quantity definition="urn:x-ogc:def:sensor:sensorType">
              <swe:uom code="number of bed exits, first time in bed, last time out of bed" />
            </swe:Quantity>
           </swe:field>
          </swe:DataRecord>
         </swe:elementType>
        </swe:DataArray>
       </sml:output>
     </sml:OutputList>
    </sml:outputs>
   </sml:System>
  </sml:member>
</sml:SensorML>
```


Figure 54 - SAPHE System SWE-enabled as SensorML [222]

SensorML proved to be a useful way of representing, aggregating and integrating real-life and near real-time SAPHE sensor data. SensorML usually uses .xml or .xsd file extensions and may be rendered by standard Internet browsers. In Figure 55, the author used “XMLSpy” by Altova for the purpose of inspecting and editing SensorML sensor data.

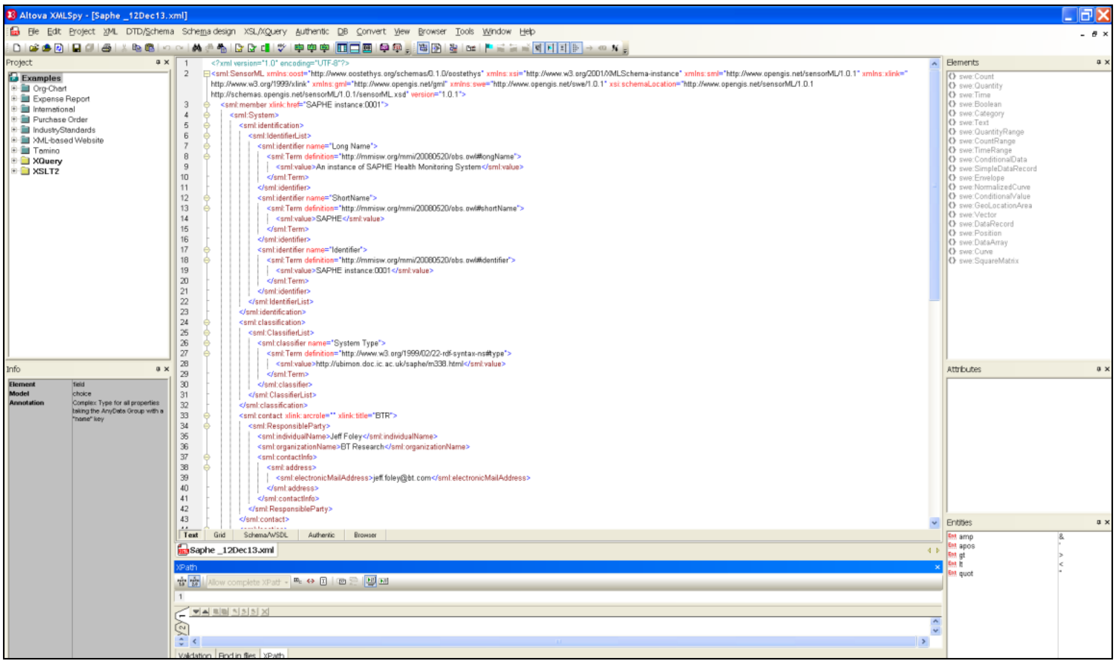


Figure 55 - Altova XMLSpy view of SAPHE SensorML [223]

Finally, Botts Innovative Research provides the "SensorML PrettyView Uploader" (Figure 56) which enables the user to upload SensorML files in order to generate a table view and also to perform validation of the XML file.

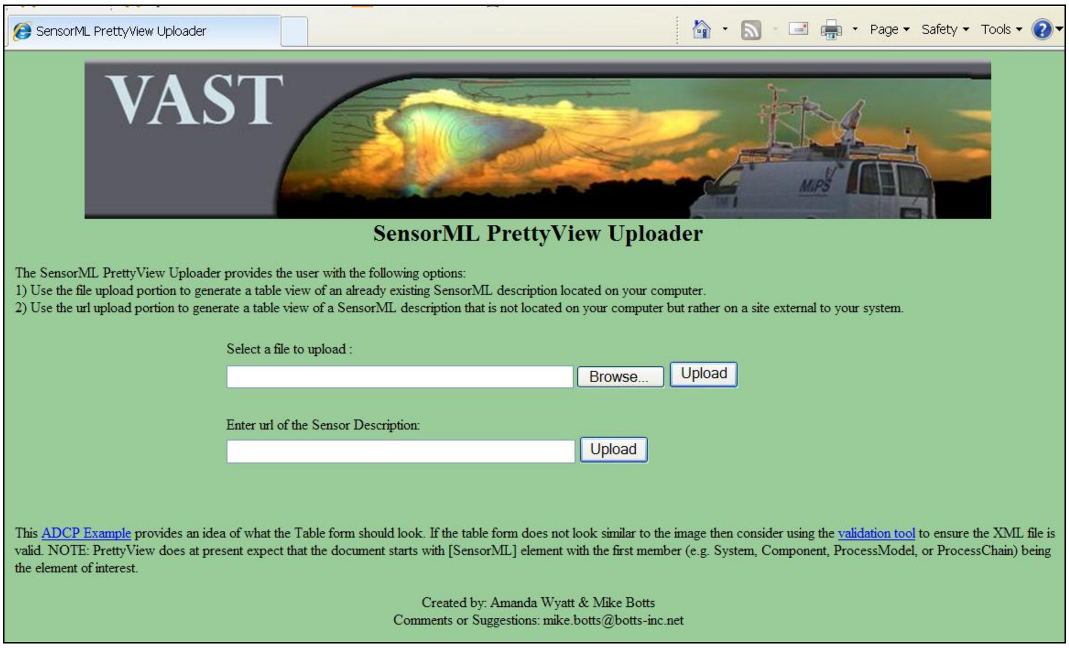


Figure 56 - PrettyView Uploader [224]

To summarise, here are the advantages of using SensorML as explained by the OGC experts. In the past, disparate sensors with independently developed support systems lead to:

- Data archiving / distribution in numerous incompatible formats;
- Incompatible processing software (stovepipe systems);
- Need for experts to exploit the data of each sensor;
- Hard to know what sensor or data is available (lack of catalogue);
- Need a standard / generic way of doing all this (Standards for describing data, sensor characteristics and processing algorithms);
- SensorML provides more than one way to describe a System;
- Information on a System can be split in several documents **[225]**;
- Describe sensors / sensor systems / processes;
- Support Geolocation;
- Provide performance characteristics and executable process chains **[226]**.

SensorML is simply used as metadata or a more powerful / complex process chain as follows:

- Metadata of the sensor system;
- Definition of position;
- Interface definition to access inputs and outputs;
- Inputs / Outputs - list of signals flowing to and from the particular sensor;
- Collection of physical and non-physical sub-processes **[227]**.

5.4 SWE 1.0 Reviewed

A key advantage of the SWE approach is the self-describing mechanism provided by the SOS service. A call to the method, *GetObservation* provides a rich description of the capabilities of the service, which includes the properties of the phenomena measured of the features of interest, their geographical extents and with additional, standardized calls, a rich understanding of the sensors involved. This goes beyond the current approach being taken by the SAPHE consortium where such information is defined explicitly and is hard-coded specifically into the applications that will use the system. An advantage of using the standardized Observation and Measurements (O&M) schema to represent data from the sensors is the ability to provide a variety of encoding formats including the aggregation of several readings into a single entry in O&M. The entry itself provides a description of how the readings can be interpreted, leading to a flexible design choice of how to represent the data, whilst providing a mechanism by which domain-agnostic applications can process that data. O&M encoding of data also provides rich meta-data including the spatial location of the observation, and through standardized calls through the SOS, a full domain-agnostic description of the system. During the process of creating a

Sensor Observation Service for SAPHE, the author discovered a number of issues directly relating to the current set of specifications that define this service.

The SOS does not directly provide support for streaming data to clients, and certain clients within the SAPHE system require a real-time feed, for example when real-time alerts are triggered by incoming data. This is easily accomplished with a JMS middleware but to simulate this functionality using only the SOS all such clients would have to poll regularly for time-limited windows of data using HTTP POST, an approach which the author believes would not be scaleable. So called "out-of-band" data is supported, however, whereby the SOS response to a *GetObservation* request will specify a link to an external resource from where the actual data may be obtained. This link could, for example, be used to identify a particular JMS topic, although in using the out-of-band mechanism the interface between sensor and client provided by the SOS is bypassed and the two are no longer decoupled, sacrificing a major advantage. At the time of the workshop there was no stable implementation or the resources to develop a Sensor Alert Service (SAS) which may have addressed some of these issues.

A further issue relevant to SAPHE is that of access control. The author makes use of (provider-specific) capabilities in the middleware to restrict destination access to certain clients. In this way one controls who can obtain data associated with a particular service user. Since the SOS interface provides no means of access control at present, sensitive data would have to be inserted in an encrypted form and external key-management procedures applied.

One important issue that will need to be addressed in future extensions of the specification is the geographically static nature of features of interest (FoI). Currently a feature of interest is defined with a geographical location or geographical extent, which is ideal for environmental monitoring. For example, a water gauge sensor is able to measure the height of water for a particular feature of interest at a defined location, for example at a certain point along a river. When the sensor is moved to a different location, it will in effect be providing readings for a different feature of interest that has a specified, fixed location. In the SAPHE system, the features of interest, i.e. the people from whom we are measuring physiological phenomena, are mobile. There is currently no mechanism built into the specifications that allow the location of the features of interest to be associated with another sensor providing location information. This association must be done at the application level, which limits the usefulness of using the SOS to provide readings that are geographically constrained.

5.5 Key Challenges in SAPHE

The final SAPHE system architecture is shown in Figure 50 (p.127). Within the home environment there are a number of sensors that use either ZigBee or Bluetooth to communicate to the SAPHE set-top box which has the task of managing the communication from the sensors and reformatting the sensor data into a common format based on Binary XML Description Language (BinX) **[228]**. The canonized data is then sent securely to the SAPHE network platform via the Internet, using the BT

Home Hub as a gateway. Within this network the data is analyzed for significant events and other factors that can lead to an assessment of the patient's wellbeing. This information is then sent on to healthcare professionals. For example, patient data is visualised in real-time on the VPN secure SAPHE healthcare monitoring portal as a series of histograms or line graphs using Dundas Chart, which the author helped to develop and is illustrated in Figure 57.

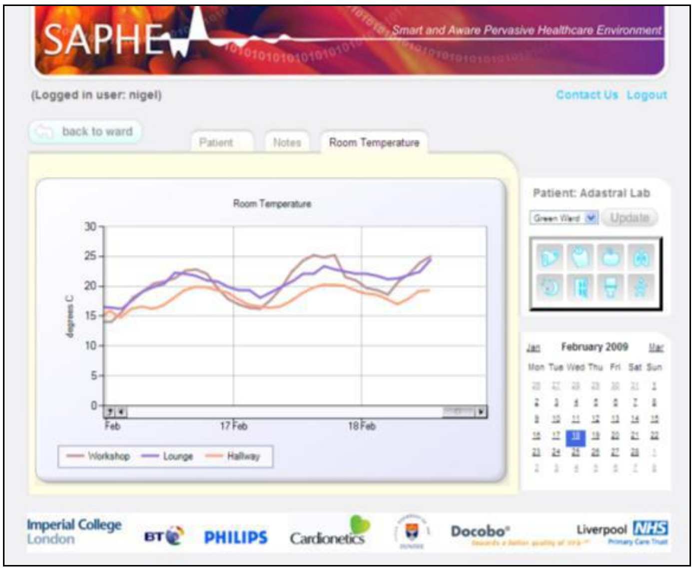


Figure 57 - Monitoring Portal Room Temperature Sensor Data [229]

The patient also wears a number of sensors in the form of a single device worn on the ear. The Sp02 device reports back blood oxygen levels, heart rate and an activity index derived from a 3D accelerometer when within range of the Set-Top Box (STB) within the home. When outside the home environment, the patient wears a mobile device that stores the body-worn sensor data until it is in range of the set-top box at which point it uploads all cached data. The mobile device is also able to communicate directly with the SAPHE network platform in the case of an emergency via a Bluetooth connection to the patient's mobile phone and GPRS connection.

The SAPHE environmental and physiological sensors and the observations they report are listed in Table 5.

Table 5 - SAPHE Sensors

Sensor	Reports	Comms	Message Frequency
Passive infrared (PIR) room sensors	Detection of movement within range of sensor	ZigBee	Up to 10,000 per 24h period
Entry/exit door sensors	door open/close event	ZigBee	Varies according to patient
Fridge door sensor	door open/close event	ZigBee	Varies according to patient
Activity sensor	activity index, SpO2 (ear) and bpm	Proprietary low-power radio	Aggregate 1 per second
Weighing scales	weight when used	Bluetooth	2 per day

Blood pressure monitor	blood pressure when used	Bluetooth	2 per day
Bed occupancy sensors	number of bed exits, first time in bed, last time out of bed	Bluetooth	Every 30 seconds

SAPHE relies on non-invasive monitoring by healthcare professionals using intelligent, low power sensors deployed around the home and/or body worn sensors, depending on the patient's condition. SAPHE enables clients to manage in their home and only alerts community matrons if urgent. Healthcare professionals access the SAPHE Web portal via a PDA to monitor the condition of their patients (aka clients) in real-time, which are classified in virtual wards as green, amber or red priority.

SAPHE targets patients who typically receive a specialist service provided by community matrons and multi-disciplinary teams. The desire is to support these users, providing a new tool for professional care, encouraging greater patient self-care and to monitor the patient in order to detect early indications that a patient's wellbeing is changing and preventative care is required. Independent monitoring of the patient and their environment can lead to early detection of worsening conditions that may either not be reported by the patient nor detected by the healthcare professional and help prevent escalation of a patient's conditions and their ability for self-care. For example, changes in sleeping patterns, mobility around and outside of the home, and eating habits can be early indicators of a worsening of a patient's condition **[230]**.

SAPHE is fundamentally different to traditional Telecare and vital signs monitoring based on event triggered responses. Instead, it is focussed on the need for a new generation of pervasive healthcare and lifestyle monitoring systems to allow for early detection and prevention of acute events. The SAPHE Project aims to open up new opportunities for the UK ICT and Healthcare sectors by combining sensing under normal conditions with intelligent trend analysis.

5.6 System Architecture Overview

The final SAPHE architecture (Figure 50) consists of three main components: ambient sensing, wearable sensing, and inferencing / decision support.

Ambient sensing – (e.g. vibration, pressure or video-based sensors) provides generic behaviour profiling and activity recognition. It is disease independent and captures information such as activity index, sleeping pattern, room occupancy, and gait and posture changes. SAPHE will use a variety of non-invasive sensors throughout the home to provide continual activity and environmental monitoring of the individual within their dwelling.

Wearable sensing – (e.g. ECG, SpO2, motion sensors) provides patient specific monitoring of key physiological indices as well as contextual information. SAPHE concentrated on the development of a common node architecture that can be used to connect almost any physiological and biochemical sensors.

The SAPHE 'common nodes' developed were as follows **[231]**:

- BP and weighing = Bluetooth;
- BSN = Ultra low power radio + body sensor;
- Home = ZigBee / 802.15.4 + environmental sensor.

The SAPHE architecture will combine on-node processing and remote long term trend analysis for inferencing. For decision support, a two tiered configuration will be used. This consists of a home gateway which coordinates local inferencing and decision support from both ambient and wearable sensors; and remote data servers and existing healthcare ICT architecture where long-term trend analysis can be performed based on individual and pooled population data.

By using wireless sensors wherever possible, the SAPHE system will help keep patients mobile and unrestricted. The proposed SAPHE system will be able to detect daily activity, recovery rate (if a patient has recently left hospital), deteriorations in a patient's condition, and assist clinicians with decisions on interventions where appropriate.

5.7 Summary and Conclusion

Chapter 5 trialled and evaluated SWE specifications for the SAPHE project to facilitate interoperability and presented the final SAPHE system architecture (Figure 50). Chapter 5 introduced SensorML from VAST and software resources for generating SensorML. It detailed encoding SAPHE healthcare sensors as a SWE Sensor Observation Service (SOS), reviewed SWE 1.0 and presented key challenges from a SAPHE perspective, in addition to featuring the SAPHE Web monitoring portal, which the author helped to develop.

The author as a member of the SNG started the research as described in Chapter 5 with the objective to create a framework that allowed useful components (hardware and software) to be reused among various WSN monitoring projects as well as the creation of a shared sensor information space where data from various deployments could be better utilised. In particular, the author evaluated if the SWE concept could fulfil these requirements. The author found that the SOS combined with the O&M specification provided a flexible mechanism for describing and querying sensor data thus proving a useful candidate technology for building shared sensor information spaces. The value of such sharing could be seen when multiple applications are then built on top of a shared infrastructure and "infostructure" (the shared information space) - for example in the SAPHE scenario a home security system could be easily modified to obtain PIR sensor data from the same deployed sensors **[232]**.

The SAPHE project provided a use case where SWE or sensor virtualization may be applied. SWE was used to virtualize SAPHE sensors and their observations through to the middleware layer and its additional capabilities. SAPHE system sensor capabilities may be accurately modelled using SensorML, which provided standards for describing data, sensor characteristics and processing algorithms (XML schema). XML tags are a standardised format and are advantageous because system data may be represented uniformly, e.g. less verbose than alternative data formats and easily integrated into other systems.

Moreover, despite being under used in SWE 1.0 and lacking tools to exploit the model, SWE-enabled data demonstrated that SensorML is a useful way of integrating the SAPHE sensor data as follows:

- SensorML provides a common interface for all sensors and a structured modelling language which provides schemas of system attributes, which the user 'drills down' on to show a greater level of detail;
- SAPHE consortium increased their understanding of how the final SAPHE architecture may interface with other standards (e.g. OGC, SensorML, XML, WS, CEP, etc) and arguably extended SAPHE capabilities beyond the scope of the project;
- Furthermore, using SWE / SensorML for SAPHE, led to a BT colleague's interest in trialling SWE 1.0 specifications for the BRIDGE project's supply chain scenario (p.82).

During the BT Workshop, SAPHE proved to be an ideal use case, in addition to increasing the author's knowledge of SWE, this initiative also helped to extend the functionality of the SWE framework. For example, mobile sensor features of interest (FoI) were required for the Body Sensor Network (BSN) aspect of SAPHE, as well as the static sensors in the patient's home environment. Therefore, the author realised that the 52° North specifications would have to be upgraded to reflect this. BT Research's collaboration with 52° North also resulted in additional publications for the SAPHE consortium (p.35).

Unfortunately, SWE and the implementation the author evaluated have not helped in defining how the sensor data is integrated into the Sensor Observation Service (SOS) in the sense that a proprietary feeder framework had to be used. The author was unable to fully evaluate the Sensor Alert Service (SAS), because it did not have a stable implementation that could be developed and used given the constraints of the workshop, therefore, the author concentrated on the provision of the SOS. The request/response pattern provided by the SOS was not sufficient for the SAPHE application and it remains to be seen whether the SAS could meet the needs of the SAPHE clients. However, the Sensor Event Service (SES) supersedes the SAS in SWE 2.0.

The author also found that the SensorML specification of the SWE framework has been underused in that the provision of an SOS did not require the existence of a SensorML model nor does it have any tools that could take advantage of the existence of such a model. To conclude, we felt that the SWE approach to sharing sensor observations is promising, but feel that the current status (SWE 1.0) of the standards, implementations and supporting tools was too immature to be readily applied to every WSN project. SWE purports to be a generic approach to WSN applications however the author's experiences highlighted a few issues to be resolved in the SWE 2.0 specifications. Refer to Table 4 - Comparison of SWE 1.0 and 2.0 (p.100-102). Refer to Appendix E for the SAPHE Project Overview.

CHAPTER 6 Complex Event Processing

6. Introduction

Chapter 6 introduces CEP to ascertain if it could be used to extend the functionality of the SWE framework. Following on from the M2M theme of evaluating components to build BT's Generic Architecture, under the IN theme, the author examined Complex Event Processing (CEP) as a candidate technology for capturing, querying and filtering sensor data obtained. CEP engines such as Esper **[233]**, Coral8 and StreamBase allow sets of rules to be defined that can aggregate and correlate complex events.

Since our understanding of our world is becoming increasingly rich and accessible as data is published by many varied sources. Harnessing this data and deriving business intelligence is crucial to many business sectors in our increasingly competitive environment **[234]**. But where is this data coming from? Sensor data is being generated by many industries at a local level typically for bespoke, stove-piped applications. Initiatives are pushing this data out into wider communities, transforming data into rich information by combining it together with other data from other fields. Combining sensor data, geospatial databases and a geospatial context can provide a foundation for future industry **[235]**. This logic may be represented as follows:

SENSOR DATA -> FILTER ALERTS -> INFORMATION -> KNOWLEDGE & INTELLIGENCE -> FEEDBACK & IMPROVE -> PREDICT FUTURE BEHAVIOUR PATTERNS

6.1 Event Driven Architecture and CEP

The author's research evolved from trialling the SWE specifications to capturing, filtering and processing potentially hundreds or thousands of sensor readings, so the author identified CEP to enable the capture and filtering of sensor data obtained.

CEP is a technology to process events and discover complex patterns among multiple streams of event data. It deals with the task of processing that event data with the goal of identifying the meaningful events within the streams, and deriving meaningful information from them. It appears to be a natural fit with the large scale and high volume data feeds promised by the M2M vision. As Service Orientated Architecture (SOA) methodologies evolve, the ability to react in a timely manner in a push-pull business environment becomes crucial **[236]**.

Event Driven Architecture (EDA) is becoming increasingly relevant to businesses because of recent advancements in software protocols (particularly IP-based) and hardware that have brought about this kind of large-scale, real-time, event driven capability. Enterprises have the desire to be able to understand their critical processes and other aspects of their complex environment and be able to react in a timely and appropriate way. This capability is often termed 'situational awareness' or 'sense-and-respond’, often used interchangeably with the emphasis on the latter being the ability to react to a situation.

One form of EDA is CEP which is able to analyse events and data from many disparate sources in order to determine patterns of behaviour or to derive a more complex event from the constituent parts. Appropriate application of CEP can reduce the information overload present and provide a level of automation and intelligence-gathering for a more productive and reactive enterprise.

CEP is inherently large-scale, applying rules that aggregate and process large volumes of events and messages. It is a technology to process events and discover complex patterns among multiple streams of event data. It deals with the task of processing multiple streams of event data with the goal of identifying the meaningful events within those streams, and deriving meaningful information from them. Within the M2M context, CEP technology appears to lend itself well to automatic aggregation and analysis needed for the large volumes of observations anticipated from the disparate sensors and other data streams in the real and virtual worlds.

What is a CEP Engine?

A CEP engine is defined by one of the major vendors, SAP’s Sybase CEP (formerly Coral8) as “A software product used to create and deploy applications that process large volumes of incoming messages or events, analyze those messages or events in various ways, and respond to conditions of interest in real-time” **[237]**. CEP offers the ability to aggregate and correlate large volumes of events (such as sensor events) through the real-time processing of continuous queries and apply event pattern matching using logical and temporal event correlation, and window views. Alternative CEP engines are available from EsperTech and StreamBase Systems.

Complex Event Processing (CEP)

- Under the IN theme, the author examined how SWE could be extended with CEP;
- CEP was investigated to ascertain its potential to harvesting project sensor data obtained and enabling data fusion for WSNs deployed within diverse domains;
- CEP has certainly proved to be feasible technology (as well as preferable to a database) to interface with sensor systems in order to handle (capture, store, archive, query, filter and process) sensor data in real-time.

Advantages of CEP:

- Ideal for aggregating and correlating thousands of sensor readings;
- Dynamic (not static like databases – “turns database concept on its head”) and real-time, complex continuous queries, pattern matching and inference, sliding window views, aggregation, causality, correlation, etc;
- Supports complex computation, process large volumes, low latency, scalable and reliable, easy to build, modify and maintain;

- Event Processing Language (EPL);
- Event Stream Processing (ESP);
- Continuous Computation Language (CCL);
- CEP data aggregation is a form of data fusion;
- Ideal for IN which may incorporate feeds from sensors and sensor systems.

Sybase CEP

SAP's Sybase products include a server configuration for running their CEP engine and a development studio for the creation and analysis of CEP behaviours. Some of the key elements pertinent to CEP technology are how Sybase has implemented features that address processing latency, data persistence, connectivity and the expressiveness and inherent extensibility of its CEP engine.

An initial analysis of the Sybase product found the following features of particular merit:

- Data input and output adaptors for connectivity;
- Extensible rules engine through Remote Procedure Calls (RPC) or User Defined Functions (UDF);
- SDK that allows the engine to be controlled programmatically and for dynamic queries to be compiled.

The practical evaluation included extending the rules engine so that geospatial functions could be called and form part of the data/event aggregation. This was achieved by using a SOAP proxy already provided by the Sybase engine and whilst using this proxy may introduce additional latency in the system, an alternative, native, route is possible.

CEP Architecture

As depicted in Figure 58, an overview of Sybase's CEP architecture (formerly Coral8) comprising the Event Processing Server which runs the rules and analytics that are formulated from within the developer interface, Coral8 Studio. Input adaptors provide a mechanism where data feeds can be virtualized and output adaptors allow aggregate/complex events and notifications to interact with dashboards, other applications and middleware.

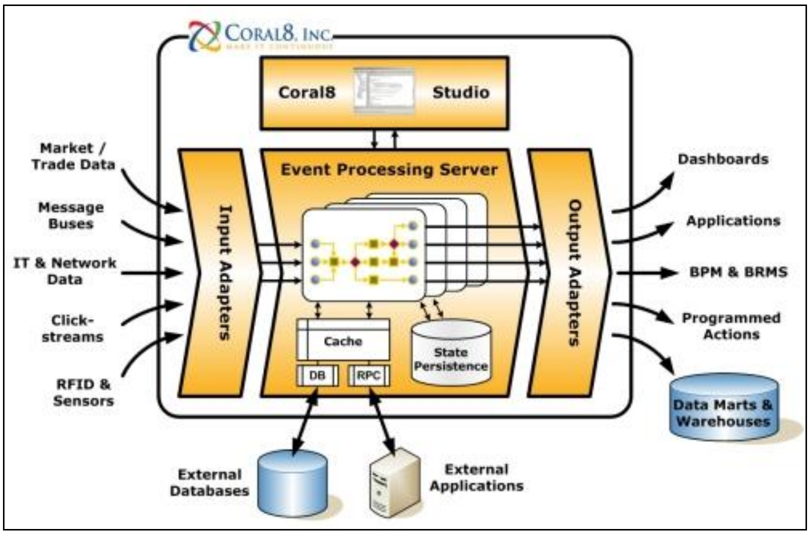


Figure 58 - CEP Architecture [238]

The Sybase CEP engine comprises a number of developer-configured streams, for the flow of data, and queries that are performed on that data. Of particular interest are the following product features:

- Native XML processing;
- Latency measurement;
- Data persistence;
- Connectivity;
- Rules engine and extensibility;
- Dash-boarding technologies.

Rules Engine and Extensibility

CEP engines typically rely on an internal rules language that performs the event aggregation, filtering and analytics necessary. The rules language used by Coral8 is the Continuous Computation Language (CCL). This is an SQL-like language that has additional features that relate to the continuous way in which queries are run. In a typical relational database, an application will run a query on the entire database, receiving appropriate results. The application must then resubmit that same query on a regular basis to obtain up-to-date results. In a CEP engine, the queries are run as the data is received, ensuring a near real-time response. Once a query is received by the engine and is active, it is run every time an event is received.

Geospatial Extension

Part of an evaluation by the author and Dr. Churcher of Coral8 CEP engine was to extend its core CCL functionality to be able to call geospatial functions directly from within the rules. Geospatial Reasoning is the capability to access and analyze all kinds of data that has a geographical or spatial context to it. Application domains relevant to BT and its customers are diverse and include Supply Chain Management, Asset Lifecycle Management, Field Force Scheduling, infrastructure and environmental monitoring, and transport sector applications such as freight management, traffic management and congestion charging.

Geospatial Reasoning offers the potential to ask richer questions about our environment, to correlate previously unrelated sensors and their observations, and fuse data with features from richer geographical data sets. Geospatial data, location-based-services and 'whereness' all play an essential part for many different lines of business in BT, from the products it offers 3rd parties to the day-to-day operation of the business.

Geospatial reasoning functionality can be provided via spatially-enabled databases such as Postgres/PostGIS and Oracle Spatial, or directly through a geospatial library available for a variety of platforms. A popular, Open Source, library is the Java Topology Suite (JTS). There is a .NET port called NetTopologySuite (NTS) which exposes the same core functionality. JTS and NTS allow a programmer to define geometric types, such as Point or Polygon, and to perform geometric functions that transform, or modify them or ask questions regarding their spatial relationship, for example, whether they intersect.

Applying Geospatial Reasoning to CEP allows the developer to introduce a spatial constraint to the data being received and derive complex events that have some geometric relationship. A simple example might centre around monitoring weather stations and deriving the risk of fire occurring in a localised area based on matching weather conditions on a local basis.

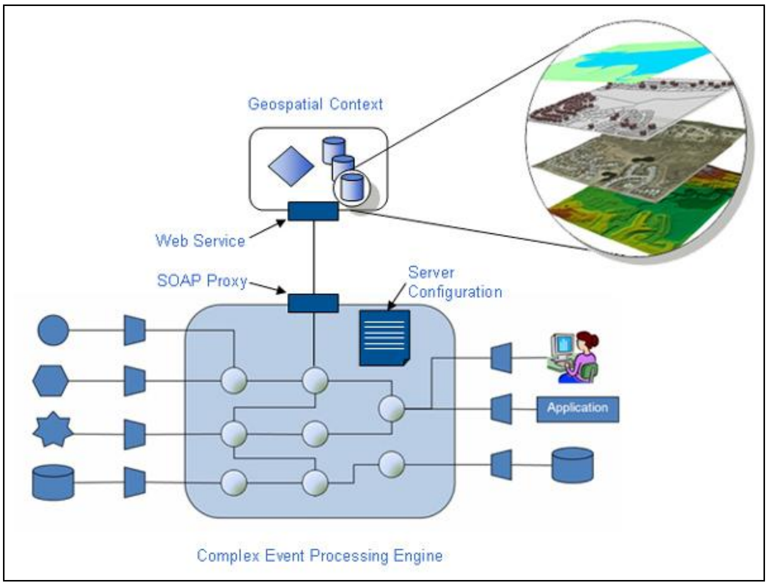


Figure 59 - Extending Coral8 with Geospatial Functions [239]

The exercise undertaken was to determine how a geospatial library such as JTS or NTS can be accessed from within the CCL rules engine of Coral8. As discussed above, Coral8 provides two main ways of extending its CCL rules engine: a User Defined Function (UDF) or Remote Procedure Call (RPC). The main advantage of a UDF is that it is managed and run as an in-process call and subsequently it typically runs with less latency than a call made with RPC. The disadvantage of using UDF is that it must be written in C/C++ with particular interface entry points. The mapping between the CCL engine and the library containing the function is defined as static XML in the server configuration file.

RPCs are also defined in the server configuration file, but can be written effectively in any language. A proxy written in C/C++ provides the ability to interface with the program or service providing the functionality. Whilst this appears to have the same disadvantages to UDF, Coral8 have provided a number of proxies for interfacing with technologies. The SOAP proxy, commonly used to interface with web services, was used to map geospatial function calls in CCL with the NTS (.NET) geospatial library. Figure 59 illustrates the overall architecture. The server configuration file specifies the mapping from a function name in CCL to the SOAP proxy and the appropriate arguments that identify the web service.

For the exercise carried out by the author and Dr. Churcher, a number of functions in the NTS geospatial library were wrapped in a web service, along with access to a Postgres/PostGIS database containing a subset of Ordinance Survey MasterMap data. A data feed from a virtual set of water gauge sensors was created and fed into a complex query that could then determine whether there were any water gauge sensors reading above a threshold level that were within a specified distance of one another. Within Coral8 Studio, the formulation and testing of the exercise was straightforward with additional benefits such as being able to identify the latency incurred by using the SOAP proxy and web service approach. Whilst the latency was greater than that anticipated by an approach using only UDF, it was felt an appropriate exercise since creating the appropriate proxies is a straight-forward engineering exercise.

6.2 Applying CEP to SWE

The limited reuse of middleware components for wireless sensor networking projects has driven interest in emerging standards from the SWE working group which offers methods to virtualize sensor data into a common, self-describing format, using access mechanisms based on HTTP. Using these standards, applications are able to discover and access different sensor offerings, automatically understand the data format used and even specify conditions in the sensor data. This section examines how an existing sensor network platform in the healthcare domain can make use of these standards and examines the possibility of extending the Sensor Alert Service (SAS) with a richer set of functions. Concepts taken from CEP engines are explored in the context of this particular healthcare platform, where it is shown that there are clear advantages to extending the standard **[240]**.

As explained in previous chapters, BT Research’s SNG had a long interest in wireless sensor networking based projects and has participated in a number of collaborations covering a wide range of domains from healthcare and assisted living through to environmental monitoring, and traffic management. Typically, these projects have required bespoke solutions where middleware reuse has been minimal. Our interest in emerging standards to address this issue has led us to investigate the use of SWE from the OGC as a possible approach for the virtualization of sensors. This would form part of our strategy for building a more generic sensor network architecture with components that could be reused in a diverse range of sensor network projects. We feel that the use of standardized middleware will help drive the acceptance of sensor network solutions as we move away from costly, bespoke solutions; a problem particularly relevant to our approach given the broad range of application areas.

The author and the SNG have investigated the SWE standards for the Sensor Observation Service (SOS) and Sensor Alert Service (SAS) and how they may be applied to one of our existing sensor network projects, Smart & Aware Pervasive Healthcare Environment (SAPHE). SAPHE is one of a number of growing industrial and academic wireless sensor network projects in the healthcare domain. The most notable being Intel IrisNet **[241]**, Hitachi Collectlo **[242]**, and A Remote Health Care System Based on Wireless Sensor Networks **[243]**.

This section reviews the previously published findings where we applied SWE to SAPHE and highlights the possibilities of extending the SAS service with more advanced filtering mechanisms, such as those found in CEP. An example CEP engine, Esper was investigated with the view that the application of CEP to the SAS service may result in a number of benefits to sensor network architectures and to SAPHE in particular. CEP is particularly relevant to SAS as it offers the ability to aggregate and correlate large volumes of events through the real-time processing of continuous queries. It is possible to apply pattern matching to asynchronous events through the use of logical and temporal event correlation, and defined 'window' views of the event streams. Current standards for defining which events are relevant to an application using SAS are severely limited to a simple definition of a property of a single event. It is not possible to correlate multiple events, a capability that has the potential to reduce bandwidth and processing overheads of edge network applications.

In the final SAPHE High Level Architecture (Figure 50), all sensor data from each patient and home environment is sent to the external, back-end servers in the SAPHE platform network which archive and check for patterns and trends in the data that are indicators of deteriorating health in the patient. The frequency of sensor communication and the overhead of BinX sent externally would indicate large volumes of bandwidth usage growing as the patient user base expands.

The architecture and protocols were already established for the SAPHE system, making use of proprietary data formats and protocols. The SWE services were created in parallel to the existing framework, an approach not untypical for sensor network platforms where such services can readily be developed as an adjunct to an existing platform; in effect, applications can be retro-fitted to provide SWE services. Our previous research shows how an SOS service could be retro-fitted to the existing framework. The exercise was a valuable one and clearly showed that there was quite a high overhead in creating a standards-based service. The cost in doing so would hopefully, with time, be mitigated through the reuse of that service by new applications, although it remains to be seen whether the cost would be simply too high for closed solutions.

The process of creating an SOS service began with the definition of the data models that represented the sensor data in terms of ‘observations’ of ‘features of interest’ that were presented in the form of ‘offerings’. There were two initial types of offering: sensor data from the ambient sensors around the house, and body-worn physiological sensor data, neatly mapping on to two features of interest being the house and the patient. Sensors and sensor clusters are known as ‘procedures’ under SWE terminology. In Table 6, a simple example of how the data model would look for a set of single sensor observations is shown:

Table 6 - SAPHE Data Model

Offering:	Physiological observations
Feature of Interest:	Patient
Phenomenon:	Heart rate
Procedure:	Cardionetics ECG Sensor
Unit:	Beats per minute

The process of creating an SAS overlaps with that of creating the SOS since the definition of the data models and the transformation from raw sensor data to these models is the same. The SWE standards do not stipulate how the services should be implemented and so an SOS and SAS can exist on the same extended platform, receiving the same sensor data and even sharing the data transformation overhead. The SAS provides a service where an external application can specify the sensor data conditions which would lead to an alert being generated and published to that subscribing application. The contents of that alert could be simple message or actual sensor data. In this discussion we consider the arrival of sensor data at a service to be an event.

The role of an SAS as defined in the current proposed specification would be of limited benefit to the SAPHE platform because of the narrow range of conditions that can be tested for in the filter schema. The SAPHE system relies on the detection of patterns in the sensor data often over differing periods of time. One main limitation of the current filter specification is the inability to aggregate sensor readings over time. The data collected from both body-worn and ambient house sensors provide a rich picture of a patient’s activity and wellbeing. The notion of wellbeing depends on the context of the individual and their own patterns of behaviour. Detecting deviation from the norm in certain behaviours, for example increased activity in the night indicative of a deteriorating sleep pattern or a drop in consumption of food and water, requires specialist applications that perform statistical analysis on large volumes of data.

An SAS functioning at the local level could still be of benefit to SAPHE if it could be extended to handle more sophisticated conditions on the sensor data. The ability to examine sensor data for patterns of behaviour and create appropriate abstract events that can be published to applications could lead to the advantages of SWE being realized in SAPHE and reduce the bandwidth needed for real-time communication of sensor data to applications.

CEP is an event processing concept that takes asynchronous, real-time, high-volume data event streams and provides a mechanism for application developers to specify correlations, aggregations and other forms of event pattern matching. The approach taken by CEP turns the traditional, database-led approach of application development upside-down. Rather than an application repeatedly compiling a query, submitting it to a database and waiting for a result, applications using CEP submit a query once. This is compiled by the engine and as data events arrive they are passed through this query. When conditions are met, the resulting data is published to the subscribing application. CEP provides a publish/subscribe view of event streams that supports complex analysis of the data stream and negates the need for an application to repeatedly poll a database.

Typically an application registers one or more queries that are similar in style to SQL but have been extended to support the correlation and pattern matching of asynchronous events. Pattern matching for instance, supports the occurrence of sequences of events meeting certain criteria, and even detect the non-occurrence of events. The versatility of CEP to specify correlations and analysis of data streams, makes it potentially a very useful component to use in the analysis of sensor data and applicable to a wide range of wireless sensor networking applications.

6.3 Esper CEP Engine

From the small number of CEP engines available we chose Esper, a Java and .NET based framework because of its extensive documentation, online community support and open source licensing. Esper supports many of the critical functions needed by CEP applications that require low-latency analysis of real-time data.

Esper supports the following key methods of analysis in CEP:

- Windows on events: sliding windows (time, length, sorted, time-ordered); tumbling windows (time, length, multi-policy, first-event);
- Grouping, aggregation, sorting, filtering and merging of event streams;
- Output rate limiting and stabilizing;
- Access to a wide range of data formats using a standardized interface language;
- Logical and temporal event correlation.

One of the basic, yet powerful ways of using a CEP engine is to define a pattern. These examples are taken from **[244]** and use the Event Processing Language (EPL) to define rules. Programmatic handlers can detect when a pattern has a match and report back to the CEP container/application. The following is an example of a time-based pattern where after event 'A' arrives it will wait 10 seconds before reporting:

```
A -> timer:interval(10 seconds)
```

More sophisticated patterns using sequences and time windows can be easily expressed, for example the following detects event 'A' followed by event 'B'. Once 'B' is found then reset the pattern:

```
every ( A -> B )
```

Patterns can be combined with SQL-style SELECT statements to create increasingly sophisticated rules, for example the following will look for the occurrence of three temperature sensor events that report a temperature of more than 50 degrees within 90 seconds of the first event, with no events reporting a reading below that threshold. This pattern is inserted into another internal stream upon which other rules can be based. Chaining of rules can lead to sophisticated pattern matching.

```
insert into TemperatureWarning select * from pattern [every
sample=Sample(temp > 50) -> ((Sample(sensor=sample.sensor, temp > 50) and
not Sample(sensor=sample.sensor, temp <= 50)) ->
(Sample(sensor=sample.sensor, temp > 50) and not
Sample(sensor=sample.sensor, temp <= 50)) ) where timer:within(90 seconds))]
```

There are a number of design patterns for applications that analyse asynchronous, real-time, high-volume event streams.

Within SAPHE there is the need for applications to abstract away from the raw sensor data and look for patterns which could indicate certain events have occurred. These events could then form the basis for further statistical analysis, contributing to a broad picture of a patient's wellbeing and the detection of early symptoms of a deteriorating situation. One factor of a patient's wellbeing relates to how sociable the patient is, for example, how often they leave their house, or whether they have visitors on a regular basis. A good example of this is automatically detecting when there is more than one person in the patient's house which can then form the basis for more sophisticated analysis. The PIR sensors in each room send data whenever movement is detected, potentially up to 10,000 events per 24 hour period per sensor. Providing the logic to look for meaningful events such as multiple occupancy or an empty house from this at a local level would negate the need to transmit the raw sensor data to the back-end applications. The logic to detect multiple occupancy may be represented as follows:

```
if a PIR sensor (PIR_A) reports movement and a different PIR sensor (PIR_B)
reports movement within 5 seconds of the first, then report multiple
occupancy
```

This simple example can be extended much further where sensors in non-adjacent rooms are triggered within a specified time-frame, or combined with other sensors such as the bed occupancy sensor and the front-door. The ability to specify a window of time from which to look for patterns in the data is essential to detect these higher-level, application specific events. CEP is adeptly suited to detect these types of events from the real-time data. CEP engines such as Esper also provide statistical analysis of patterns of events.

An SAS based on the SWE 1.0 standard could readily be implemented using a CEP engine, however it would be unable to take advantage of the level of sophistication possible in CEP, particularly the ability to analyse across a number of sensor data readings. Sensor Event Service (SES) supersedes Sensor Alert Service (SAS) in SWE 2.0. The SAPHE platform needs to perform high-level correlations and analysis of sensor data in order to calculate critical factors for a patient. Some of this correlation and analysis could be performed 'in-network' using CEP as opposed to at the 'edge'. Exposing the rich functionality of a CEP engine through an SAS would convey the advantages of both – expressiveness in pattern matching alongside access to data and its derivatives through a standard protocol. The ability to process this data in-network also has a tangible benefit to the network bandwidth and processing overhead of the edge SAPHE applications. As the application domain scales up the number of sensors and patients, placing processing close to the data source will lead to lower overheads and a more rapid response from a system that is critical to the welfare of its patients.

6.4 Summary and Conclusion

Chapter 6 focused on the integration of SWE and Complex Event Processing (CEP) in the architecture to extend SWE capabilities by applying a CEP engine to aggregate and correlate sensor data. It demonstrated the need for sensor data aggregation and integration (data fusion) amongst multiple and diverse WSN projects for the purpose of realising BT Research's Generic Architecture for WSNs. Chapter 6 introduced the concepts of Event Driven Architecture (EDA) and CEP and evaluated a number of key features provided by SAP's Sybase CEP engine (formerly Coral8) as well as the alternative by EsperTech. It presented CEP architecture, geospatial functions and exemplified Event Processing Language (EPL) queries.

Technologies such as CEP are designed to process high-volumes of sensor data with minimal latency. They provide a potential solution to the growing world of sensor data that is becoming available. Our experiences with Esper highlights that CEP is ideal for this critical and dynamic environment in contrast to a traditional database approach, where real-time processing of large volumes of data is vital. With respect to the SAPHE project, the author has proved that it is possible to retrofit existing WSN projects with SWE services.

In 2009, two OGC discussion papers were published proposing the adoption of Event Pattern Markup Language (EML) **[245]** and OpenGIS Sensor Event Service Interface Specification (SES) for SWE services. These approaches continue the discussion on the need for a more flexible and extensible method of defining which events and sequences of events are of interest to edge applications. The exercise of applying SWE to SAPHE has added to that discussion and the potential benefits of using a CEP-style aggregation/correlation engine made clear.

The Sensor Event Interface Specification (SES) **[246]** is an enhancement to the Sensor Alert Service (SAS) and introduces capabilities similar to CEP. Therefore, the SWE specifications appear to be developing in accordance with BT Research ideas for building a Generic Architecture. Furthermore, in 2011, New Generation SWE 2.0 was released, which enhances the potential to interface with CEP engines in order to attain the benefits detailed above. For example, the SES superseded the SAS; mobile sensor features of interest are now supported alongside static sensor features of interest; Event Pattern Markup Language (EML); Event Stream Processing (ESP); Event Processing Language (EPL); and Continuous Computation Language (CCL) specifications are all supported for easy integration with a CEP engine.

CHAPTER 7 Conclusions and Further Work

7. Conclusions

This thesis presented a literature review of wireless sensor networks and their use in BT WSN project applications and identified the shortcomings in standalone WSN projects (Chapters 3 and 4). As described throughout the thesis, BT Research has led a number of significant and cutting edge sensor network projects covering a wide range of domains. Often these projects led to bespoke, stove-piped solutions that fitted the needs of each project perfectly. However, the author as a member of the SNG recognised the potential benefit of opening these projects out so that data may be easily correlated with data from other WSN projects and systems to provide rich information. Under BT Research's Sensor Virtualization project, a Generic Architecture for WSNs was explored and the Open Geospatial Consortium's (OGC) Sensor Web Enablement (SWE) framework was investigated in order to enable the re-use of components.

Telecare

Telecare, considering the range and growing number of sensors monitoring each patient (client) and his or her environment, there is a recognized need to optimise the processing of sensor data in order to make informed inferences on the well-being of each patient. Support for data fusion using components from the SWE framework (e.g. Sensor Event Service) extended through concepts such as CEP may prove to be a valid approach to meeting this growing volume and complexity of data whilst providing a standard method for accessing this data.

BT Research's WSN Projects

During the SNG's extensive trials, the author's research and publications detailed the experiences with the SWE framework and evaluated how SWE services may be retrofitted to BT's WSN projects to facilitate interoperability, the SAPHE healthcare system, or alternatively, the BRIDGE supply chain scenario (Chapters 5 and 3.7).

Furthermore, during the 52° North Workshop, the author identified the requirement for extending the SWE framework to enable mobile sensor features of interest (FoI) which were compulsory for the SAPHE system. For example, the mobile heart-rate monitor body-worn sensors, in addition to the static sensors deployed within the home environment. Mobile sensor features of interest were introduced in SWE 2.0 (Chapters 4.7 and 4.10).

Whilst this finding and a number of the others have been addressed in the SWE 2.0 specifications, it does highlight a number of limitations in the SWE 1.0 framework. However, the author believes that SWE may be successfully applied to other WSN projects depending on their individual characteristics (e.g. sensors in registry; connected to the World Wide Web; sensor metadata accessible; sensors controllable; data fusion aspects, etc). A project such as Personalised Information from Prioritised Environmental Sensing (PIPES) discussed in Chapter 3, which focuses on predictive maintenance for a utility company (Severn Trent), may have the characteristics that make it a more suitable candidate for the application of the SWE 2.0 framework.

Under BT Research's Machine-to-Machine (M2M) and Information Networking (IN) themes, the Sensor Virtualization project began with the author identifying components for the Generic and Context Architectures and evaluating standards and services such as the OGC's SWE framework (p.84). During the SAPHE project, the author upgraded the SAPHE Web monitoring portal (C# programming / Dundas Chart) to enable community matrons to perform live patient data analysis (p.136, Figure 57). For the BOP project, the author conducted Orion meeting room trials with custom-built motes based on Imperial College's ultrasound Beastie and known as "BT Proximity Ultrasounder" sensors (p.69, Figure 26). The author also advised a BT colleague on how to apply elements of the SWE framework to the BRIDGE project's RFID supply chain scenario (p.82, Figure 33).

Sensor Web Enablement (SWE 1.0)

This thesis demonstrated the OGC's SWE SensorML encodings and Sensor Observation Service (SOS) (Chapters 4 and 5). The services specified by the SWE framework purport to enable the discovery, access and control of all sensors available via the World Wide Web. However, in reality there will be security restrictions regarding access and control to encrypted military sensor data or sensitive medical sensor data. However, the standardization of access to sensors and sensor data yields considerable advantages. For example, the standardized description of Observations and Measurements (O&M) as well as sensors in conjunction with standardized interfaces for accessing the data produced by them enables the implementation of applications which are capable of discovering and integrating available sensors and sensor data on the fly and in real-time - an important step for realising the Sensor Web.

This thesis reviewed how SWE services can be retro-fitted to an existing sensor network platform and highlighted what the potential benefits are in doing so. SWE enables sensor data to be virtualized, providing a common, self-describing data format and access protocol. The number of domain-agnostic toolkits becoming available indicates that the rather large overhead in creating new applications based on accessing these services can be mitigated by the re-use of data, the use of third-party analysis engines and the reductions in bandwidth and processing overhead to edge applications. The ability to access a diverse range of real-time data has the potential to lead to exciting and radically different applications including healthcare.

The author's research identified key issues and highlighted the merits of the SWE framework, especially since SWE 2.0 specifications were released in 2011 and will definitely continue to evolve offering greater potential for realising the Sensor Web. In the future, intelligent sensor deployments may help to avert the impact of industrial or natural disasters. Monitoring and predictive maintenance as used by utility companies such as Severn Trent during the PIPES project may lead to proactive leak detection via sensors and Automated Meter Reading (AMR) and targeted containment, in addition to enhanced security, theft prevention (Trackit) and RFID supply chain management (BRIDGE project).

Creating SWE services offers a number of generic advantages and some specific to this type of application where local processing could prove advantageous. SWE offers a standardized protocol for discovering and accessing sensor data which enables data to be reused in potentially new and novel ways. An application could simply repurpose sensor data for another domain, or fuse together data from several services to provide radically different applications. Standardizing on the access mechanism and the data model for the sensor data conveys advantages to the application developers as there are a growing number of 3rd party tools that facilitate access, analysis and visualization of data, reducing the time to develop new applications and facilitating innovation **[247]**.

SWE services can exist anywhere in the architecture between the sensors and the applications that utilize their data. Specific to SAPHE and similar sensor network architectures, placing the SWE services at the local level could reduce real-time bandwidth requirements. A Sensor Observation Service (SOS) archives sensor data in a common data format allowing applications to query and retrieve data as appropriate. A Sensor Event Service (SES in SWE 2.0) would be able to offer basic analysis of sensor data, publishing an alert or data fragment to subscribing applications. An application could then use the SOS to access relevant data when appropriate rather than receiving data in real-time for analysis.

Regarding the realization of the Sensor Web using SWE 1.0 specifications as a component (immature standards, security and privacy issues), but a fascinating and insightful beginning to make sensors and sensor systems interoperable, enabling discovery, access, tasking and alerting. The potential of SWE 2.0 for connecting the world of sensors (i.e. as a component of the Sensor Web or Generic Architecture) to enable universal control of all sensors remains impressive in the future, especially if Semantic Web functionality is incorporated. Especially in a sophisticated world of “Smart Cities” where SDI and GIS location-based services, Web Services, Google Maps and Earth are ubiquitous from BBC News broadcasts to company websites, Wikis and mash-ups.

SWE or CEP employed to leverage network data presents many opportunities for adding a real-time sensor dimension to the Internet and the Web, which aligned with the strategic objectives of BT Research’s Generic Architecture. As exemplified in this thesis, there are a number of diverse WSN applications utilising the SWE framework to achieve their aims, notably: AFIS; SANY; NASA; ESA; OOSTethys; Meraka; SAPHE and BRIDGE. WSNs will increasingly be deployed representing all domains and state-of-the-art International, EU and UK academic and industrial WSN projects.

Sensor Web Enablement (SWE 2.0)

In March 2011, New Generation SWE 2.0 was released and the revised specifications were adopted as standards by the OGC. Therefore, SWE 1.0 and 2.0 specifications have been compared in Chapter 4, to highlight the key improvements to the SWE services, such as interoperability between WSN applications. Chapter 4 also outlines a number of proprietary frameworks and standards including SenseWeb and Nortel SDS, but this limits the interoperability because sensor-based frameworks designed and implemented by different vendors are often incompatible. Given the author's experiences with the SWE 1.0 framework, it was certainly a useful tool to expand the SAPHE system capabilities and the BRIDGE supply chain scenario. SWE 2.0 will be an effective enhancement towards the OGC's goal of harnessing discovery, tasking and alerting of all types of sensors and sensor systems. Finally, SWE specifications, such as SensorML (2004) has been around ten years, therefore it is considered stable and mature. SWE standards are general and it has been exemplified in this thesis that they may be applied to different domains **[248]**.

Complex Event Processing (CEP)

This thesis demonstrates the need for sensor data aggregation and integration (data fusion) amongst multiple and diverse WSN projects. The author proposes the integration of SWE and CEP in the architecture to extend the capabilities of SWE by applying a CEP engine to aggregate and correlate sensor data (Chapter 6, p.141).

CEP engines were evaluated to ascertain how to facilitate data fusion by sharing sensor data amongst a number of WSN project applications across diverse WSN domains. As discussed, SWE 2.0 enables easy integration with CEP to handle sensor data aggregation and correlation to facilitate data fusion capabilities and to enable a shared 'infostructure'. The EML specification is in accordance with the findings of BT Research and the author (i.e. using a CEP engine in concert with ESP, EPL, CCL specifications) to aggregate and correlate thousands of sensor data readings from a WSN deployment.

Generic Architecture

This thesis demonstrates the development of Generic and Context Architectures for WSNs to realise a smart and reusable architecture for a number of BT WSN projects. The author developed a shared infrastructure and 'infostructure' (shared information space) and implemented parts of the architecture as a prototype (see Chapters 4.1 - Sensor Virtualization and 4.8 - The Design of a Generic Sensor Network Architecture).

Open Sensor Web Architecture (OSWA)

Similarly, the Open Sensor Web Architecture (OSWA) is a platform independent middleware for developing sensor applications and it is built upon a uniform set of operations and standard data representations as defined in the SWE Method by the OGC. OSWA uses open source and Grid technologies to meet the challenging needs of collecting and analysing observational data and making it accessible for aggregation, archiving and decision making **[249]**.

Semantic Sensor Web (SSW)

Alternatively, the Semantic Sensor Web (SSW) may address the challenges of the original SWE vision by utilising the Semantic Web technologies (e.g. SPARQL, OWL, RIF/SWRL, RDFS, XML, URI, and Unicode). These SSW technologies enable situation awareness by providing enhanced meaning for sensor observations (e.g. RDF annotations as opposed to the usual XML data) **[250]**.

Internet of Things (IoT)

Moreover, all business and consumer devices, (e.g. smart phones, tablet computers, PDA's, set-top boxes, audio and video devices, white goods), can actually be viewed as sensors at the lowest level, capable of capturing and storing sensor data, manipulating it and transferring intelligence. Furthermore, the enabling technologies were outlined to place WSNs into context; M2M; IoT; NGN; Cloud Computing, together with essential smart devices and smart homes form the backdrop of pervasive technological advancements and factor for sensors, sensor systems and WSNs **[251]**.

In the future, WSN applications will be capable of the following:

- Enabling the Semantic Sensor Web (data fusion);
- Generic / Context Architectures which enable component re-use for multiple WSN projects;
- Increasing sensor data aggregation, integration, correlation and processing power for timely intelligence via CEP or Cloud Computing;
- Pervasive and a benefit to society as much as the Web;
- Utilising the Web as a powerful platform (e.g. standard Internet browser to display OX-Framework visualizations, Sensor Map, WSN applications, etc);
- Integral to smart vehicles (Telematics) and smart cities;
- Early warning of disaster systems (e.g. Tsunami prediction) for environmental monitoring;
- Introducing a range of value-add WSN services and apps, while reducing operator costs for network and service providers.

7.1 Further Work

Despite the author leaving BT and his academic supervisor, Dr. Yang leaving UCL, the author has acquired much expertise over the last six years while working on WSN projects. The most fascinating research was conducted by the SNG (2006-09) during BT Research's M2M and IN themes, particularly the Sensor Virtualization project. Indeed, in this thesis the author has focused on what was achieved in the conference publications and the positive experiences during dissemination at a number of WSN international summer schools and with UCL peers. Therefore, the author considers this thesis to be a distinct contribution to the field of WSNs and a significant insight into the capabilities of WSN motes, followed by a literature review of the state-of-the-art BT WSN projects and similar external project applications.

The areas of future research comprise mostly practical and theoretical work that may be categorised into the main sections covered in this thesis and are as follows:

- Generic Architecture was explored and developed by the author under BT Research. Continue to build a Generic or Context Architecture prototype using reusable components including the SWE 2.0 framework to realise a shared infrastructure;
- Dr. Eliane Bodanese continues to direct QMUL PhD students exploring WSNs and SWE 2.0 specifications. QMUL trialled SWE and the Context Architecture components (p.108, Figure 44), but it was conceptual rather than a functioning system;
- Future BT Research WSN projects may be SWE-enabled. SAPHE and BRIDGE benefited from trialling the SWE 1.0 framework. Potential exists for PIPES and BOP to be SWE-enabled;
- SWE-enable WSN applications using the SWE 2.0 specifications. New projects should benefit from applying SWE 2.0 and SensorML, especially the SES, EML, ESP, EPL, CCL specifications to integrate CEP capabilities. Utilise CEP to handle data aggregation and correlation, thus enabling data fusion and a shared 'infostructure';
- Under the Google Coding Initiative, 52° North are recruiting post-graduates to speed the development of key SWE 2.0 specifications. The OGC is active in trialling the OGC Web Services (OWS-9) standards with members via their collaborative prototyping program **[252]**;
- WSNs remain a key area for future projects by PhD/EngD researchers for UCL, Lancaster University, NTU, Coventry University's Cogent Computing, University of Surrey, etc. Increasingly UK-based initiatives such as WSN workshops, presentations, student posters, demos and paper critiques organised by Sensors & Instrumentation KTN (e.g. WiSIG) and hosted by academic and industrial partners such as BT and NPL;
- All the summer schools (except RUNES) attended by the author are led by industry experts and continue to run annually. They are thoroughly recommended as invaluable resources on the developments and state-of-the-art in WSNs. Refer to Appendix J.

Appendix A Libelium's Fifty Sensor Apps for a Smarter World

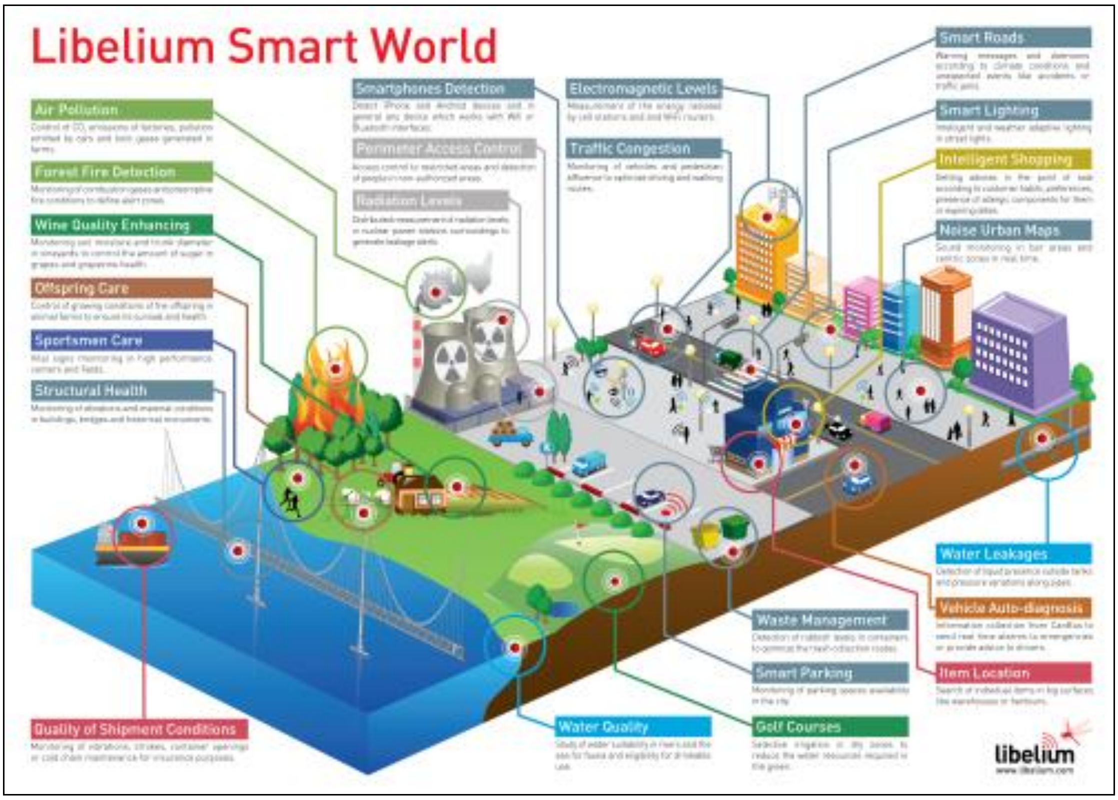


Figure A1 – Libelium's Smart World

Smart Cities

01 Smart Parking - Monitoring of parking spaces availability in the city.

02 Structural Health - Monitoring of vibrations and material conditions in buildings, bridges and historical monuments.

03 Noise Urban Maps - Sound monitoring in bar areas and centric zones in real time.

04 Smartphone Detection - Detect iPhone and Android devices and in general any device which works with WiFi or Bluetooth interfaces.

05 Eletromagnetic Field Levels - Measurement of the energy radiated by cell stations and WiFi routers.

06 Traffic Congestion - Monitoring of vehicles and pedestrian levels to optimize driving and walking routes.

07 Smart Lighting - Intelligent and weather adaptive lighting in street lights.

08 Waste Management - Detection of rubbish levels in containers to optimize the trash collection routes.

09 Smart Roads - Intelligent Highways with warning messages and diversions according to climate conditions and unexpected events like accidents or traffic jams.

Smart Environment

10 Forest Fire Detection - Monitoring of combustion gases and preemptive fire conditions to define alert zones.

11 Air Pollution - Control of $CO2$ emissions of factories, pollution emitted by cars and toxic gases generated in farms.

12 Snow Level Monitoring - Snow level measurement to know in real time the quality of ski tracks and allow security corps avalanche prevention.

13 Landslide and Avalanche Prevention - Monitoring of soil moisture, vibrations and earth density to detect dangerous patterns in land conditions.
14 Earthquake Early Detection - Distributed control in specific places of tremors.

Smart Metering
18 Smart Grid - Energy consumption monitoring and management.
19 Tank level - Monitoring of water, oil and gas levels in storage tanks and cisterns.
20 Photovoltaic Installations - Monitoring and optimization of performance in solar energy plants.
21 Water Flow - Measurement of water pressure in water transportation systems.
22 Silos Stock Calculation - Measurement of emptiness level and weight of the goods.

Security & Emergencies
23 Perimeter Access Control - Access control to restricted areas and detection of people in non-authorized areas.
24 Liquid Presence - Liquid detection in data centers, warehouses and sensitive building grounds to prevent break downs and corrosion.
25 Radiation Levels - Distributed measurement of radiation levels in nuclear power stations surroundings to generate leakage alerts.
26 Explosive and Hazardous Gases - Detection of gas levels and leakages in industrial environments, surroundings of chemical factories and inside mines.

Retail
27 Supply Chain Control - Monitoring of storage conditions along the supply chain and product tracking for traceability purposes. (e.g. RFID)
28 NFC Payment - Payment processing based in location or activity duration for public transport, gyms, theme parks, etc.
29 Intelligent Shopping Applications - Getting advices in the point of sale according to customer habits, preferences, presence of allergic components for them or expiring dates.
30 Smart Product Management - Control of rotation of products in shelves and warehouses to automate restocking processes. (e.g. Vend Online and RFID)

Logistics
31 Quality of Shipment Conditions - Monitoring of vibrations, strokes, container openings or cold chain maintenance for insurance purposes.
32 Item Location - Search of individual items in big surfaces like warehouses or harbours. (e.g. RFID)
33 Storage Incompatibility Detection - Warning emission on containers storing inflammable goods closed to others containing explosive material.
34 Fleet Tracking - Control of routes followed for delicate goods like medical drugs, jewels or dangerous merchandises. (e.g. BT Trackit)

Industrial Control
35 M2M Applications - Machine auto-diagnosis and assets control.
36 Indoor Air Quality - Monitoring of toxic gas and oxygen levels inside chemical plants to ensure workers and goods safety.
37 Temperature Monitoring - Control of temperature inside industrial and medical fridges with sensitive merchandise.

38 Ozone Presence - Monitoring of ozone levels during the drying meat process in food factories.
39 Indoor Location - Asset indoor location by using active (ZigBee) and passive tags (RFID/NFC).
40 Vehicle Auto-diagnosis - Information collection from CanBus to send real time alarms to emergencies or provide advice to drivers. (e.g. Telematics)

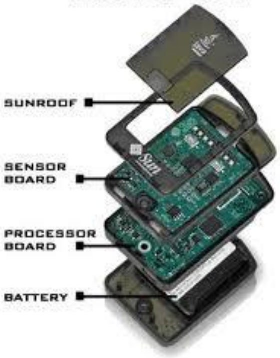
Smart Agriculture
41 Wine Quality Enhancing - Monitoring soil moisture and trunk diameter in vineyards to control the amount of sugar in grapes and grapevine health.
42 Green Houses - Control micro-climate conditions to maximize the production of fruits and vegetables and its quality.
43 Golf Courses - Selective irrigation in dry zones to reduce the water resources required in the green.
44 Meteorological Station Network - Study of weather conditions in fields to forecast ice formation, rain, drought, snow or wind changes.
45 Compost - Control of humidity and temperature levels in alfalfa, hay, straw, etc. to prevent fungus and other microbial contaminants.

Smart Animal Farming
46 Offspring Care - Control of growing conditions of the offspring in animal farms to ensure its survival and health.
47 Animal Tracking - Location and identification of animals grazing in open pastures or location in big stables. (e.g. eShepherd)
48 Toxic Gas Levels - Study of ventilation and air quality in farms and detection of harmful gases from excrements.

Domotic & Home Automation
49 Energy and Water Use - Energy and water supply consumption monitoring to obtain advice on how to save cost and resources. (e.g. AMR)
50 Remote Control Appliances - Switching on and off remotely appliances to avoid accidents and save energy.
51 Intrusion Detection Systems - Detection of windows and doors openings and violations to prevent intruders. (e.g. PIR and CCTV)
52 Art and Goods Preservation - Monitoring of conditions inside museums and art warehouses.

eHealth
53 Fall Detection - Assistance for elderly or disabled people living independently. (e.g. Telecare)
54 Medical Fridges - Control of conditions inside freezers storing vaccines, medicines and organic elements.
55 Sportsmen Care - Vital signs monitoring in high performance centers and fields.
56 Patients Surveillance - Monitoring of conditions of patients inside hospitals and in old people's home. (e.g. Telecare)
57 Ultraviolet Radiation - Measurement of UV sun rays to warn people not to be exposed in certain hours.

Appendix B Mote Manufacturers Table

MOOG CROSSBOW  Iris mote  Mica2 and MicaZ  TelosB	ORACLE Sun microsystems SunSPOT  	TEXAS INSTRUMENTS  Chipcon 
Atmel  Wireless industrial and consumer applications such as automatic metering, alarm systems and home control, as well as toys and gaming  	LINEAR TECHNOLOGY dust networks™  SmartMesh WirelessHART	SILICON LABS ember  EM351 Home/building automation & control ARM chips in all digital consumer devices/smart meters
intel   Intel Research Health apps	Millennial Net Wireless Sensor Networking...Anywhere  MeshScape GO OEM	sentilla moteiv  Tmote Sky

ARDUINO  UNO board	Digi Your M2M Expert  XBee radio	Imperial College London  Beasties
libelium  Waspmote	shimmer DISCOVERY IN MOTION  Platinum Development Kit	Ubisense RFID tags & sensors “sentient computing” and real-time location system (RTLS) technology  Smart Factory System with Series 9000 IP Sensors

Appendix C Evolution of Motes / Specifications Table

Year	Motes	Capabilities	Manufacturer / University
2010	EyesIFXv2 (EnergY-Efficient wireless Sensor) TinyOS	Hardware and software platform that is easily reconfigurable and can be used to explore the potential of collaborative sensors in self-healing networks. Apps and systems: home automation, medical sensors, security & alarm systems, building automation solutions, industrial monitoring, aircraft safety monitoring, robotics.	Infineon Technologies Processor: TI MSP430F1611 Radio: Infineon TDA5250 Ext memory: Atmel AT 45DB041B CAPSIL Project (Common Awareness & Knowledge Platform for Studying & Enabling Independent Living)
2009	Imote2 (IntelMote2)	Advanced wireless sensor node platform built around the low-power PXA271 XScale CPU and also integrates an IEEE 802.15.4 compliant radio. Design is modular and stackable with interface connectors for expansion boards on top and bottom sides, provides standard set of I/O signals, additional high-speed interfaces for app specific I/O.	Intel Research as part of Platform X
2009	SHIMMER	A wireless sensor platform designed to support wearable applications.	Shimmer Research (Sensing Health with Intelligence, Modularity, Mobility, & Experimental Reusability)
2007-09	Arduinos Bengt Polls Crossbow	Sensor network tasked with passively monitoring environment, space usage, environmental conditions and activity. Many platforms used in trial. Beastie used Tesserae an architectural description language to measure meeting room and social space usage. Data correlated using feature mapping at node level on tiny 8-bit devices, state changes propagated up network to database.	BOP project
2007-08	MSB430 ESB (Embedded Sensor Board)	Low-power microcontroller with 2k RAM, 60k flash ROM, a TR1001 radio transceiver, 32k serial EEPROM, RS232 port, JTAG port, beeper, sensors (passive IR, active IR sender/receiver, vibration/tilt, microphone, temperature).	Texas Instruments A prototype WSN device developed at FU Berlin ScatterWeb platform Contiki 2.5
2007	BTnodes	Autonomous wireless communication and computing platform based on a Bluetooth radio and a microcontroller. Demo platform for research in mobile and ad-hoc connected networks (MANETs) and distributed sensor networks.	ETH Zurich Two major research projects: NCCR MICS and Smart-Its
2007	Sun SPOT	Small Programmable Object Technology is a WSN mote. Hardware and software originally open-source. Supports IEEE 802.15.4 MAC layer, on top of which ZigBee may be built. Java IDEs (NetBeans or Eclipse) used to create apps. Java is portable over any platform (Windows; Mac OS X; Unix/Linux/GNU variants; mobile devices O/S; .Net)	Oracle Labs (Sun Microsystems) PIPES project Built on Squawk Java VM
2005-07	Beasties	Robust wireless sensor node developed at Imperial to monitor a creative workplace. Beasties ran two different types of sensor: an ultrasound/neural net based activity monitor and a thermal imager based people counter.	Imperial College BOP project

2005-07	Bi-morphs	Custom built boards (non networking) to sense vibration - accelerometer	Imperial College PIPES project
2006	Medusa MK2	Development of a Mote for Wireless Image Sensor Networks	U Stanford (WSN Labs)
2005	XBee (formerly MaxStream)	Family of form factor compatible radio modules. Based on the 802.15.4-2003 standard designed for point-to-point and star comms at over-the-air baud rates of 250 kbit/s	Digi International
2004	TelosB/Tmote Sky	Ultra low power IEEE 802.15.4 compliant Wireless sensor modules IEEE 802.15.4 compliant 250 kbps, high data rate radio TI MSP430 microcontroller with 10kB RAM Integrated onboard antenna Data collection and programming via USB interface Open-source operating system Humidity, light, temperature sensors with USB.	UCB Moog Crossbow Sentilla (Moteiv)
2004	Spec platform	Research testbed which integrated the functionality of Mica onto a single 5 mm² chip. Spec was built with a micro-radio, an analog-to-digital converter, and temperature sensor on a single chip, which led to a 30-fold reduction in total power consumption. Single-chip integration resulted in low cost sensor nodes. Integrated RAM and flash memory architecture has simplified design of mote family. The tiny footprint required TinyOS.	TinyOS developed by UC Berkeley
2004	ROBOMOTE	Representative platform of a mobile sensor node	USC
c2004	EZ430-RF2480/2500: - the EZ430-RF2480 and EZ430- RF2500	Wireless networking solutions from TI incorporate the MSP430 microprocessor and CC2480/2500 radio transceiver on each board. These kits are inexpensive mote solution.	Texas Instruments (Chipcon / National Semiconductor / Sensata)
2003	U3	Design and Implementation of a Sensor Network Node for Ubiquitous Computing Environment	U. Tokyo
c2003-04	IRIS	Latest WSN module from Xbow. Improvements over Mica range such as increased transmission range.	Moog Crossbow
2002	MicaZ Mica2Dot Mica2	Mica2/MicaZ - 2^{nd}/3rd gen wireless sensor networking mote family from XBow. 2.4 GHz, IEEE/ZigBee 802.15.4, board used for low-power WSNs. MicaZ module compatible with MoteWorks. Multi Year Battery Life Designed for deeply embedded WSNs	Moog Crossbow UCB / DARPA
2002	Mica	20 miniaturized wireless sensor motes sending back raw data on the microclimate of a petrel seabird colony in Maine. Mica motes may help change the way conservation biologists monitor wildlife habitat.	UCB Intel Research Moog Crossbow
2002	PicoNode I, II, III	Energy Aware Routing for Low Energy Ad Hoc Sensor Networks	UC Berkeley (BWRC)
2001	Smart Dust	Wireless sensor chips miniaturised to the size of "aspirin" tablets or "dust"	UCB / DARPA
2000	µAMPS - Power Aware Wireless Microsensor Networks Cricket	Highly integrated, flexible sensor node based on 2 dedicated chips (COTS systems on chip) StrongARM SA1110 32-bit, 206MHz, RISC processor, 3 acoustic sensors attached to each node for estimation of direction of target	MIT / DARPA
2000	SpotON	An Indoor 3D Location Sensing Technology Based on RF Signal Strength	U. Washington
2000 1999	MicaDot René	After WeC, René and Dot were built with upgraded microcontrollers.	Moog Crossbow UCB / DARPA

1999	WeC	Built with a small 8-bit, 4MHz Atmel microcontroller (512 bytes RAM, 8KB flash memory), consumed 15 mW active power, 45 µW sleeping power. WeC had a simple radio supporting a data rate up to 10 Kbps, with 36 mW transmitting power, 9 mW receiving power.	UCB / DARPA Moog Crossbow
1999	COTS RF	RFID tags and sensors, MEMs RF	UC Berkeley Sensor & Actuator Center (BSAC)
1998	WINS	Wireless Integrated Network Sensors	UCLA Rockwell Science Center
1996	LWIMs	Low Power Wireless Integrated Microsensors	UCLA
1971	ALOHAnet Project	First public demonstration of a wireless packet data network	U. Hawaii
1970	Packet Radio Network (PRNET)	Packet radio network protocols	DARPA

Evolution of Motes / Specifications Table Sources:

E. Omiyi, K. Burr, Y.Yang, "Current WSN Platforms and Testbeds: A Short Survey", Dept of Electronic & Electrical Engineering, UCL, 2008

M. Johnson, M. Healy, P. van de Ven, M.J. Hayes, J. Nelson, T. Newe, E. Lewis, "A Comparative Review of WSN Mote Technologies", Dept of Electronic & Computer Engineering, University of Limerick, Ireland, IEEE, 2009
http://www2.warwick.ac.uk/fac/sci/eng/research/sensors/mbl/database/ieeesensors09/PDFs/Papers/331_6128.pdf

http://www-micrel.deis.unibo.it/sitonew/research/Ami/doc/wsnAccademicheCommerciali.pdf
(Ing. D. Brunelli - An Overview on WSNets)
http://robotics.eecs.berkeley.edu/~pister/SmartDust/ (Smart Dust)
http://www-mtl.mit.edu/researchgroups/icsystems/uamps/pubs/files/Anantha_PACC_05_00.pdf (uAMPS)
http://webs.cs.berkeley.edu/tos/ (TinyOS)
ftp://ftp.cs.washington.edu/tr/2000/02/UW-CSE-00-02-02.pdf (SpotON)
http://intranet.daiict.ac.in/~ranjan/sn/papers/kawahara-vtc-03f.pdf (U3)
http://www-robotics.usc.edu/~robomote/ (ROBOMOTE)
http://ee.ucla.edu/~pottie/papers/nae_01.pdf (WINS)
http://www-bsac.eecs.berkeley.edu/ (BSAC)
http://www.berkeley.edu/news/media/releases/2002/08/05_snsor.html (Mica)
http://www.sensorsmag.com/networking-communications/mica-the-commercialization-microsensor-motes-1070
http://en.wikipedia.org/wiki/XBee (XBee)
http://www.btnode.ethz.ch/EyesIFXv2/1 (BTnodes)
http://capsil.org/capsilwiki/index.php/EyesIFXv2 (EyesIFXv2)
http://bullseye.xbow.com:81/Products/productdetails.aspx?sid=253 (Imote2)
http://www.shimmer-research.com/products-2 (Shimmer)
http://monet.skku.ac.kr/course_materials/graduate/mc/termproject/related_study/%5BRouting%5DEAR.pdf
(PicoNode)
http://graphics.stanford.edu/projects/lgl/papers/dra_cogis-06/dra_cogis-06.pdf (Medusa MK2)
http://www.diku.dk/~leopold/work/leopold08motes_u.pdf (PicoBeacon)
http://www-mtl.mit.edu/research/icsystems/uamps/ (uAMPs)

http://nms.lcs.mit.edu/projects/cricket (Cricket)

http://www.ti.com/lsds/ti/microcontroller/16-bit_msp430/overview.page?&DCMP=D_MCU_MSP430_Top%20Performers&CMP=KNC-GoogleTI&247SEM (MSP430)

Appendix D SWE - SOS Installation Resources

This appendix describes the install process for the Sensor Observation Service (SOS).
Refer to https://wiki.52north.org/bin/view/SensorWeb/SosTutorial
or how2install_SOS.pdf for full installation details.

Following the installation

The package you will check out from the CVS repository contains an implementation of the SOS as a Java Servlet. Executing the installation steps [build] will deploy this service in your Apache Jakarta Tomcat web container as a web application (webapp).

The SOS

The SOS (Na & Priest 2005) aggregates readings from live, in-situ and remote sensors. The service provides an interface to make sensors and sensor data archives accessible via an interoperable web based interface. Four profiles are defined within the SOS specification: core, transactional, enhanced, and entire.

The 2007 release (52N-SOS-v2-01-00) implements the core profile comprising of the mandatory operations:

- GetCapabilities, for requesting a self-description of the service;
- GetObservation, for requesting the pure sensor data encoded in Observation&Measurements;
- DescribeSensor, for requesting information about the sensor itself, encoded in a SensorML instance document.

Requirements:

- Windows 2000 or higher [tested with Windows XP SP2]
- JRE/JDK 1.5 [1.5.0_06-b05]
- Apache Jakarta Tomcat 5.5 or higher [5.5.9]
- PostreSQL Version 8.1.3 [8.1.3]
- PostGIS Version 1.1.1 [1.1.1]
- CVS-Client
- Apache Ant 1.6.2 or higher [1.6.5]

Installation Procedure:

Get the programs:
Download / install Apache Jakarta Tomcat, release version 5.5, from: http://jakarta.apache.org/tomcat
Download / install PostgreSQL release version 8.1.3 from: http://www.postgresql.org/ftp/binary/v8.1.3
Download / install PostGIS release version 1.1.1 from: http://www.webbased.co.uk/mca/
Download / install Apache Ant version 1.6.5 from: http://ant.apache.org/

Get the sources:
Check out the sources from sourceforge-CVS-Repository, or use the sources provided by the 52N-SOS-v2-01-00.zip:

Host:	*fifty-two-north.cvs.sourceforge.net*
Repository:	*/cvsroot/fifty-two-north*
Module:	*SOS*
Branch:	*main*
Tag:	*rel-v2-01-00*
User:	*anonymous*
Password:	*no password required – leave it blank*

For additional instructions see: http://sourceforge.net/cvs/?group_id=122215

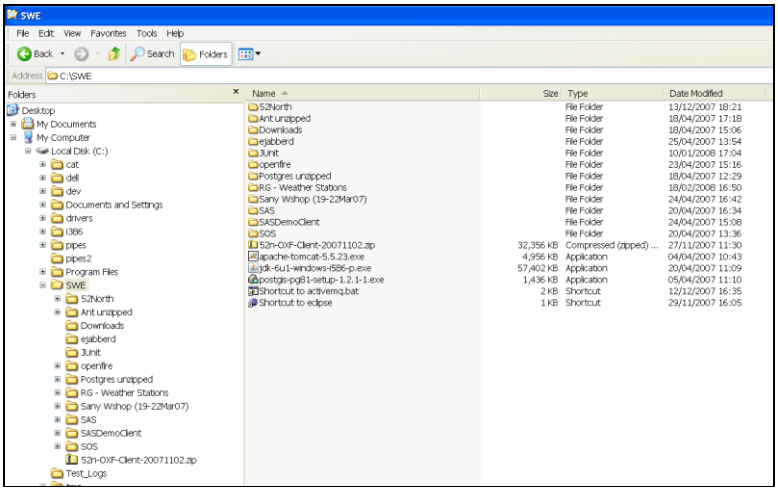


Figure D1 - Resource folders downloaded (e.g. 52° North SWE specs)

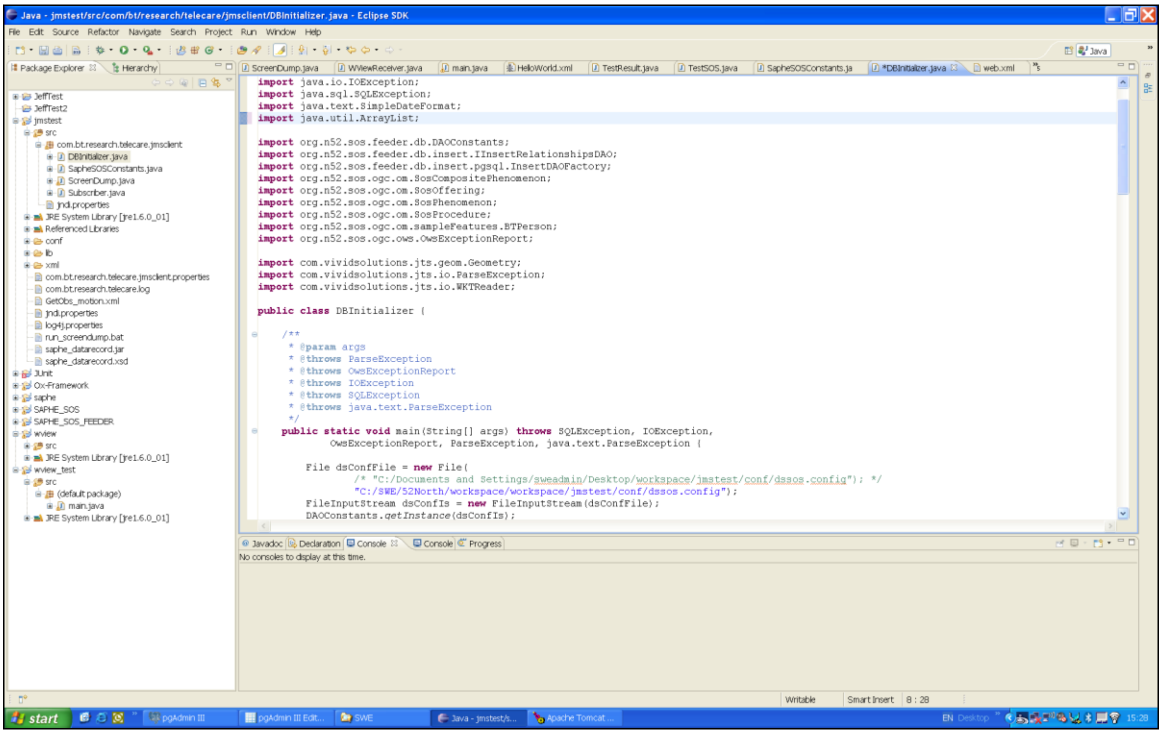
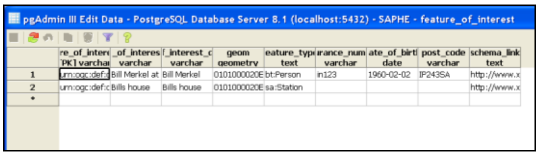


Figure D2 - Java Eclipse SDK


pgAdmin III Edit Data - PostgreSQL Database Server 8.1 (localhost:5432) - SAPHE - feature_of_interest

	re_of_intere [PK] varchar	_of_interes varchar	f_interest_c varchar	geom geometry	eature_type text	urance_num varchar	ate_of_birth date	post_code varchar	schema_link text
1	urn:ogc:def:c	Bill Merkel at	Bill Merkel	0101000020E	bt:Person	in123	1960-02-02	IP243SA	http://www.x
2	urn:ogc:def:c	Bills house	Bills house	0101000020E	sa:Station				http://www.x
*									

Figure D3 - PostgreSQL Database

Appendix E SWE 2.0 - Building Blocks

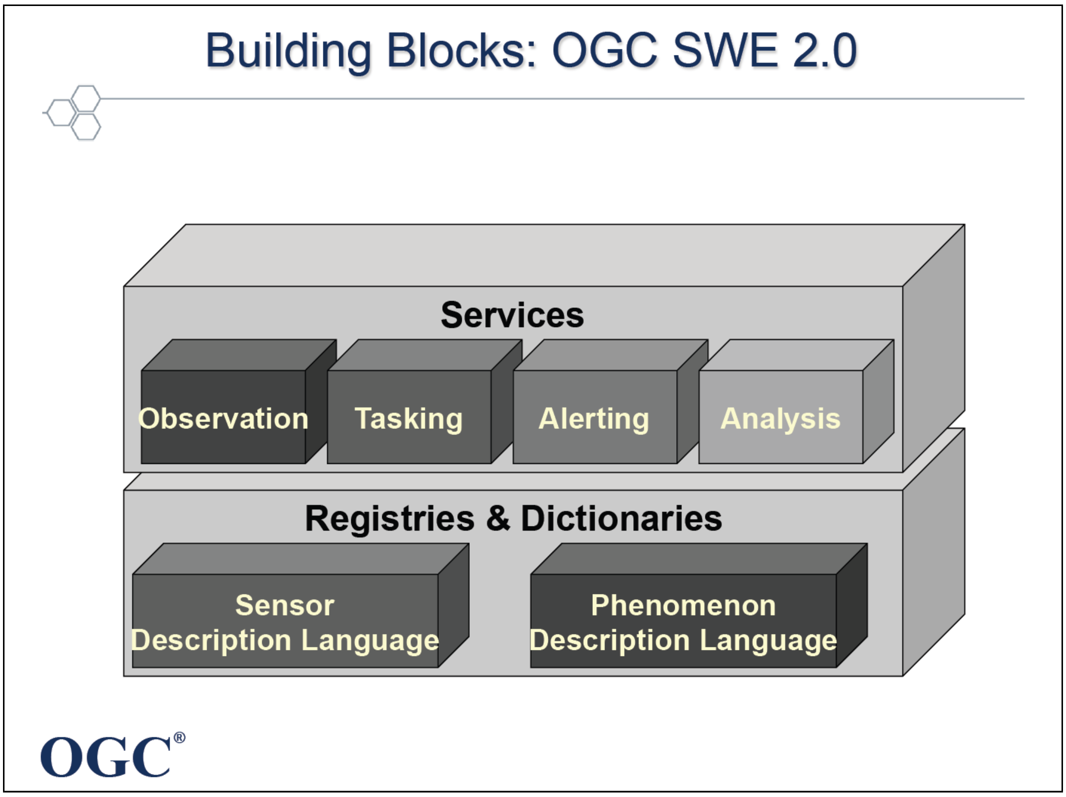


Figure E1 – SWE 2.0 - Building Blocks

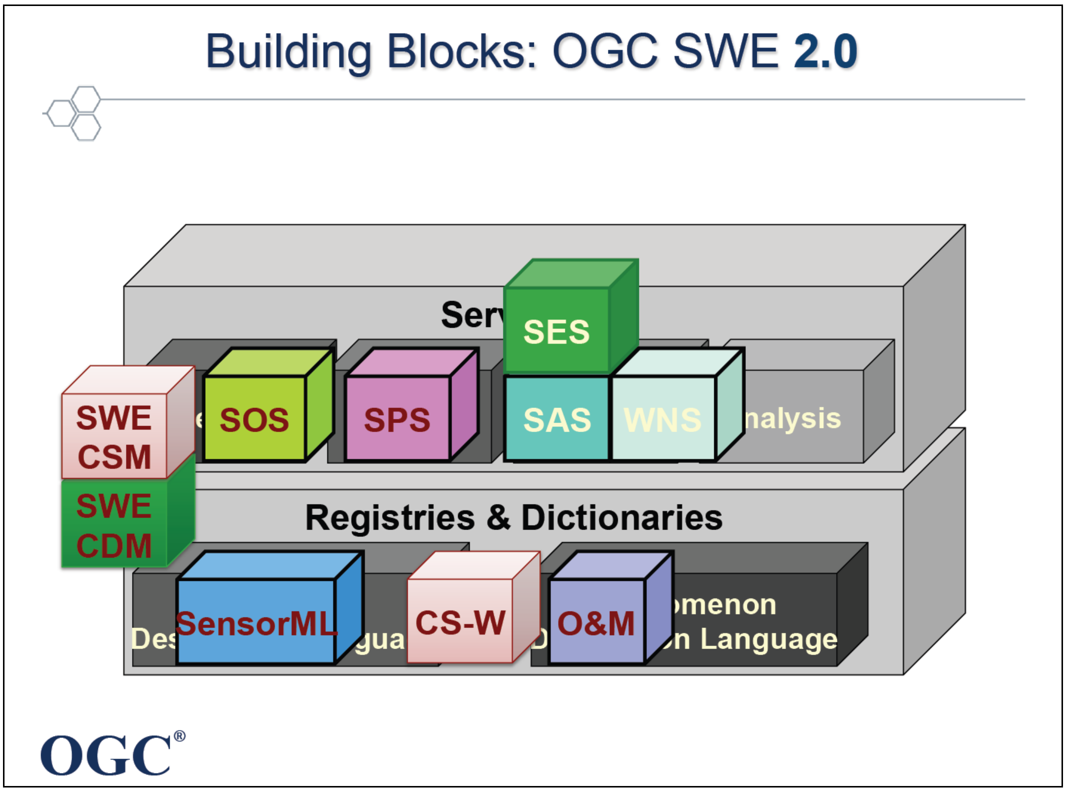


Figure E2 – SWE 2.0 - Services and Encodings

Appendix F SAPHE - Project Overview

Technology problem solved:

Creation of an integrated system that combines multiple sensor inputs (both fixed and wearable) to monitor both the activity / lifestyle and physiology of an individual within their own home; and to provide information derived from these inputs that relates to individuals' wellbeing to different stakeholder groups.

Why is the problem hard:

Complex integration of devices.

Acceptance from health providers – change in healthcare delivery.

What is unique / clever about SAPHE:

Single system for monitoring multiple facets of an individual's wellbeing.

Real world experience and engagement with Community Matrons.

How is the problem solved now:

Home care visits is the primary solution.

Technological solutions are available but are not widely adopted (especially within UK):

Chronic Disease Management solutions proving remote physiological parameter monitoring exist but generally as single disease offerings – none include activity / lifestyle monitoring as well.

Basic activity / lifestyle monitoring solutions are emerging but these do not include any physiological monitoring.

Market opportunity and competitors:

User (patient) population:

1 in 5 people have a chronic condition.

Increasing elderly population ~25% of UK population over 60 years old.

Sell to:

Consumer market

NHS

Private health and social care providers

Competitors:

CDM solution provides – e.g. iMetrikus, Health Hero

Community Alarm and Lifestyle monitoring providers – e.g. Tunstall, TyneTec

What is the opportunity timeline i.e. when will the market be looking for a solution and what factors drive this:

Now (2009).

Government, funding and other pressure will increasingly drive this over next few years.

Demographics, rapid increase in obesity, diabetes etc.

Appendix G SWE - Sensor Visualization Demonstration

For a BT demonstration by Dr. Churcher and the author, the location of virtual environmental sensors deployed on a river bank were visualised on Google Earth. This is effective and provides context for the sensor data being streamed by the application from the sensor (gateway) mote in the field to the laptop (data sink) collating the sensor data.

- The scenario consisted of a Flood Sensor – the sensor was already set up with SOS and SAS services.
- The client can browse the capabilities of the SOS by entering the URL of the service.
- The client can then ‘add’ the offering and set a notification up with the SAS.
- The offering can be displayed in Google Earth.
- The readings of the Flood Sensor are generated automatically by a script that feeds in O&M into the database (Feeder app).
- The client application allows the demonstration to be reset/started and to provide a visualisation via Google Earth.
- As sensor data is received by the SOS, the client application periodically polls the SOS service to receive an updated value (perhaps as a timeline) which is displayed in Google Earth.
- At some point the sensor sends a reading which triggers the SAS to send a notification to the client application
- The client application uses the specified phone number to send an alert as an SMS to the phone.

Client PC

- Google Earth
- Application
- start/reset demo
- enter phone number
- poll SOS FS and generate KML
- receive SAS alert
- query SOS to get GPS sensor
- interface with Web21C to send SMS

Server

- SWE SOS and SAS services

Appendix H Proposed Sensor Patent

The following two diagrams are outputs from the brainstorming sessions held at BT Adastral Park. Pervasive ICT Centre researchers explored ideas around intelligent / context aware / Semantic Sensor Web sensors. In addition, backend storage and query solutions were examined. The author created Figures H1 and H2, which were discussed to ascertain possible patents.

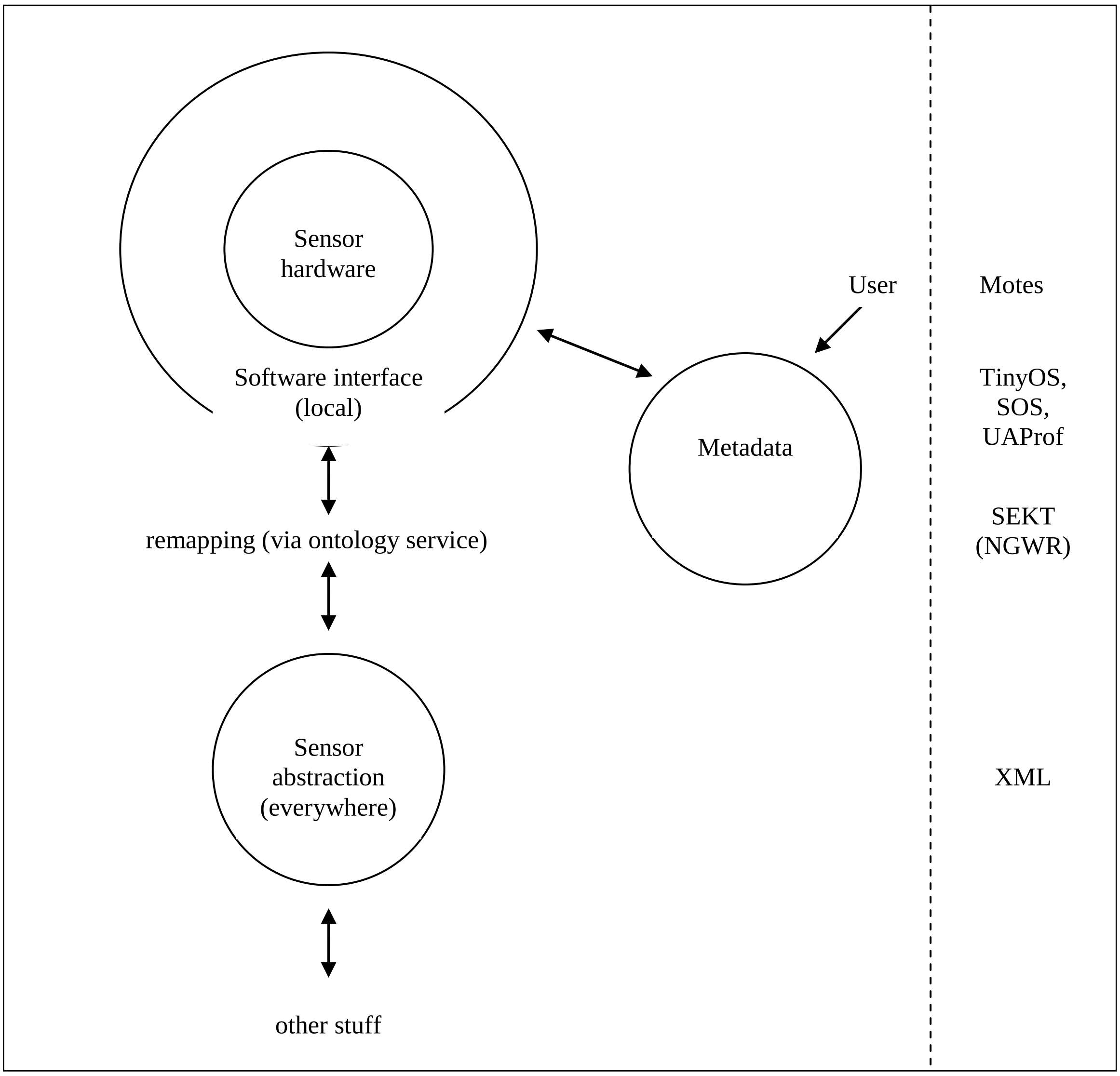


Figure H1 – Sensor Interfaces

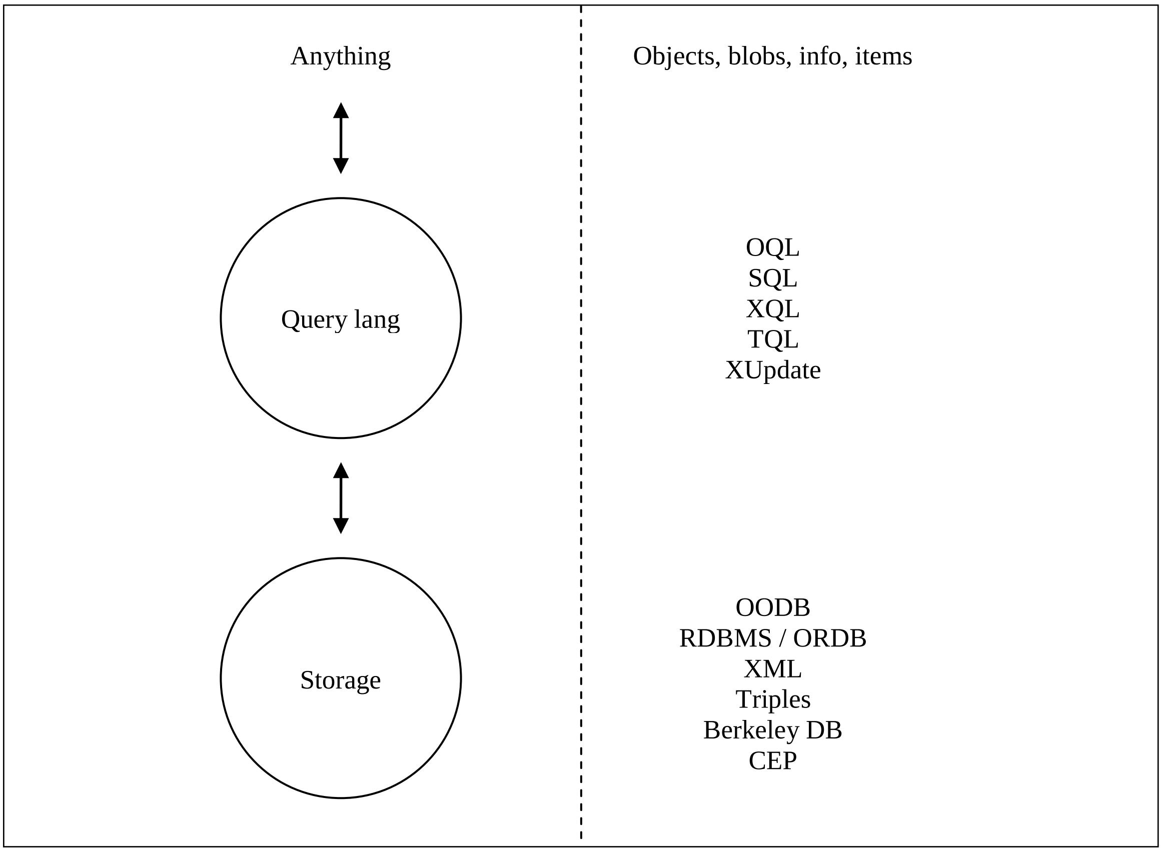


Figure H2 – Sensor Query and Storage

Appendix I EuroSSC Poster 2007

Appendix J International WSN Summer Schools and Presentations

The summer schools were ideal forums for immersing one's self while learning about innovative WSN applications and included London, Warsaw, Frankfurt and Bologna. The author explored the capabilities of Sun SPOT motes and evaluated a number of WSN installations during hands-on courses (e.g. SENIOT - Crossbow motes and Contiki COOJA; MCANAE - Sentilla Perk Kit and Java; RUNES - Crossbow motes and Contiki).

Reconfigurable Ubiquitous Networked Embedded Systems (RUNES)

FP6 Integrated Project IST (2004-07)
9-11 July 2007 at UCL
http://www.control.lth.se/project/RUNES/

Overview: RUNES integrates and extends cross layered research ranging from hardware and network communication to application usability and middleware to advanced control theory and verification tools for validation of the methods and prototypes.

Objective: Provide an architecture middleware and specialised simulation/verification tools that enables the creation of large-scale, widely-distributed, heterogeneous networked embedded systems that inter-operate and adapt to their environments.

Partners: connectBlue; CRC; Ericsson; IABG; Kodak; KTH; Lancaster University; LiPPERT; Lund University; NICTA; Politecnico di Milano; RWTH Aachen; SICS; Universita di Pisa; UCL; UC Berkeley; UC San Diego; University of Patras; University of Queensland; Victoria University.

Senzations

10-14 September 2007 at Warsaw University of Technology, Poland.
http://www.senzations.net/home

Telematics, telemedicine, environment monitoring, home applications and control, security and surveillance, industrial applications like process industry automation and agricultural applications are examples of potential applications of wireless sensor networks. Thanks to its broad range of possible applications and potential to change the way we interact with our environment, wireless sensor networks have gained a lot of attention in the research world and are becoming increasingly popular in business world as well.

The goals of the summer school were as follows:

- Survey the most relevant research domains;
- Present various perspectives and underlying technologies;
- Identify the most important challenges and research themes;

- Interact with distinguished scholars and establish contacts that;
- may lead to research collaborations in the future.

The intended audience consisted of post-graduate students, PhD students, and young researchers from universities and industrial laboratories around the world. There were around 40 participants.

Lectures: Each day featured lectures and discussions around a research theme like programming of sensor networks, integration of WSN with mobile networks, security in WSN, ZigBee vs. Bluetooth, remote health monitoring, etc.

Lecturers included: Srdjan Krco (Ericsson Ireland), Kees Lokhorst (Wageningen University), Sotiris Nikoletseas (University of Patras, Greece), Martin Ouwerkerk (Philips Research), and Konrad Wrona (SAP Research).

Monitoring & Coordination Across Networked Autonomous Entities (MCANAE)

17-22 August 2008 at Castle Ebernburg, Bad Muenster am Stein, Frankfurt, Germany.
http://www.gkmm.tu-darmstadt.de/summerschool2008/

TECHNISCHE UNIVERSITÄT DARMSTADT

Organisation: GKmM and Darmstadt University set out to survey the state of the art in several highly important sub-areas of the above research domains. The lectures and tutorials were held by renowned speakers from Sentilla, Virginia Tech, ETH Zurich, University of Tennessee, University of Illinois at Urbana-Champaign, University of Pisa, and University of Freiburg.

Description: Heterogeneous networks of sensors and unmanned vehicles open avenues for a class of novel applications. Tasks ranging from environmental monitoring to user support within emergency-response scenarios require fundamental, multidisciplinary research, typically spanning Computer Science, Electrical Engineering and Mechanical Engineering topics.

Objective: To enable the transition towards a cooperative, adaptive and responsive monitoring using networked, autonomous entities. The solutions will comprise an array of devices ranging from inexpensive, tiny, low power sensor nodes, through unmanned autonomous vehicles, and all the way up to resource rich, powerful command stations. The heterogeneity in communication mechanisms, processing capabilities and inherent mobility of the different devices has been defined to be the Mixed-Mode Environment.

The Research Training Group 1362 (funded by the German Research Foundation) combines two exciting and challenging research areas:

1. Navigation and coordination of multiple autonomous vehicles to perform a common task possibly together with a human mission manager

2. Monitoring in mixed mode environments that are characterized by the heterogeneity of their components in terms of resources, capabilities and connectivity.

The 4 components which make up the logo represent all members / areas of interest of Darmstadt University's graduate school and these are:

Antenna = (wireless) communication
Small robotic car = robotics / autonomous vehicles / control theory / ...
Eye = computer vision
UML interface signs = (distributed) middleware

- Linking sensors with robotics (UAV & AUV drones) ideal combination for harsh environments;
- Overlap WSN/robotics/computer vision/middleware;
- Networking with around 40 participants;
- Evaluation of Sentilla Perk Kit - develop, deploy and own license to sell applications;
- Overview of Research in Europe, Middle East, USA;
- Academic and commercial representatives;
- Resources (websites, presentations, papers);
- Fun! (historic walks, multi-sensorial experience, Rittermahl, wine-tasting and barbecue).

SENIOT - From Sensor Networks to Networked Intelligent Objects

26 July – 1st August 2009 at University Residential Centre, Bertinoro, Forli-Cesena (between Bologna & Rimini) Italy.
www.vs.inf.ethz.ch/seniot/index.shtml

Sponsors: CONet (Cooperating Objects Network of Excellence) EU-funded project under ICT Framework 7) and BiCi (Bertinoro International Center for Informatics)
Contributors: Talks and tutorials by renowned experts from the following organisations: Dartmouth College; SAP Research; TU Delft; University of Passau; ETH Zurich; SICS; Polytechnic Institute of Porto; University of Klagenfurt; University of Lubeck; University of Virginia; EPFL LSIR Lab

Theme: Grounded in the belief that processors, sensors, and wireless radios are becoming extremely small and inexpensive, we can foresee a world where everyday objects are globally networked and physical environments are enriched by computational power. As enabling technologies for such a smart world, sensor networks and intelligent objects have not only received much attention from researchers in recent times, but also first prototypes of such systems have been deployed. These technologies do not only provide online access to and control over the state of the real world, but enable the creation of novel real-world services.

Goal: To survey fundamentals of sensor networks and networked intelligent objects, as well as to identify novel opportunities and research directions in these areas through a series of lectures by international experts. Participants can experience the relevant technologies during hands-on courses and can present their own work during a participant's workshop. The school will provide a good opportunity to get to know other people working in the field, to meet distinguished scholars, and to establish contacts that may lead to research collaborations in the future.

Audience: 62 student participants consisting of post-graduate students, PhD students, and young researchers from universities and industrial laboratories around the world.

Selected Presentations

Please also refer to the List of Publications (p.35).

The author was invited to do presentations or online seminars during the following events:

- Papers at University College London during LCS 2010, 2009 and the Symposium 2008;
- Paper during COMSWARE at Trinity College Dublin, Ireland (June 2009);
- The Sensors & Instrumentation Knowledge Transfer Network's 5th WiSIG meeting at the NPL Auditorium in Teddington, UK (March 2008);
- As requested by Jon Bryant of BT's Global Services GIS Focus Group, Live Meeting "Overview of SWE" seminar on the BT PICT Research WSN projects and OGC aspects. Representatives attended from NPL, Vodera, and Senceive (February 2008);
- Invited by Dr. Costis Kompis (Technology Translator for the Sensors & Instrumentation KTN, and a Managing Partner of Vodera Ltd.) to present an online seminar for the Measurements & Standards (MSET) part of the KTN (December 2007);
- Poster, "Recent Developments in the Design of Sensor Network Architectures" during EuroSSC in Kendal (October 2007);
- "Applications of WSNs" during Senzations at Warsaw University of Technology, Poland (September 2007).

List of References

[1] Bubble diagram (Figure 1) developed by the author (2007-13)

[2] Open Source Geospatial Foundation (OSGeo) from SWE/SANY Workshop 2007
http://www.osgeo.org/

[3] Libelium's "Fifty Sensor Applications for a Smarter World". Refer to Appendix A
http://www.libelium.com/top_50_iot_sensor_applications_ranking/#show_infographic

[4] Dr. Carl Reed, OGC, (2008_GIS_Rockies_SWE_Presentation.ppt)
http://www.ogcnetwork.net/node/382

[5] Stephen Brobst, Teradata CTO, 'Big Sensor Data', 2010 from SWE - OGC Standard Tutorials in Seoul by Dr. Steve Liang, University of Calgary, GeoCENS, October 2012
http://www.youtube.com/watch?v=LHM-1JR-aVc

[6] Verizon and Ericsson, 2011
http://online.wsj.com/article/SB10001424052702303544604576434013394780764.html

[7] Dr. George Bilchev, BT Research, Sensor Networks Group defined by Head 2005 (Bilchev.pdf)

[8] BT TSO http://www.btplc.com/Innovation/Innovation/InternetofThings/index.htm and
BT GS http://www.globalservices.bt.com/uk/en/products/global_trace

[9] Networks Research Centre (NRC): Trevor Burbridge, Andrea Soppera, Jeff Farr;
PICT Research Centre: Richard Gedge, Chris Roadknight, George Bilchev, Paul Bowman, Jane Tateson, Ian Neild. "Machine-to-Machine (M2M): Research Challenges" 2005 (M2M_research.doc)

[10] Wikipedia, Cloud Computing http://en.wikipedia.org/wiki/Cloud_computing

[11] Kevin McNulty, CEO BT Transcomm, June 2005 (Transcomm.ppt)

[12] Networks Research Centre (NRC): Trevor Burbridge, Andrea Soppera, Jeff Farr;
PICT Research Centre: Richard Gedge, Chris Roadknight, George Bilchev, Paul Bowman, Jane Tateson, Ian Neild. "Machine-to-Machine (M2M): Research Challenges" 2005 (M2M_research.doc)

[13] Harbor Research (2010 M2M & Smart Systems Forecast Report.pdf)
http://harborresearch.com/services/research/

[14] Edgar H. Callaway Jr., "Wireless Sensor Networks: Architectures and Protocols", p.307, Auerbach Publications 2004

[15] ePerSpace Project (2004-06) http://www.ist-eperspace.org/

[16] Telefonica's (TID) Smart Home, Madrid http://www.ist-eperspace.org/deliverables/D3.2.pdf

[17] Smart Home Devices with Sensors graphic created by author for Eurescom's "Sensor Telcos - New Business Opportunities" (P1555) project 2006 http://www.eurescom.eu/?id=309

[18] Dr. Friedemann Mattern, ETH Zurich, Institute for Pervasive Computing, "Visions of the Future From the Past" (mattern-future.pdf) and "Towards the Internet of Things" (mattern-iot.pdf), SENOIT 2009 http://www.vs.inf.ethz.ch/seniot/program/index.shtml

[19] Ian Neild, Futurologist, BT Research, "BT Technology Timeline" Infographic, 2006
http://www.btplc.com/Innovation/News/timeline/statictimeline.pdf

[20] Dr. Steve Liang, University of Calgary, GeoCENS, SWE - OGC Standard Tutorials, OGC Seoul, October 2012 http://www.youtube.com/watch?v=LHM-1JR-aVc

[21] Eurescom P1555, "Sensor Telcos - New Business Opportunities" (P1555-D1.v2.2.doc; P1555-D2.v1.2.doc; P1555-D3_v1.1.ppt) 2005-06 http://www.eurescom.eu/?id=309

[22] Eurescom P1653 "M2M - Opportunities in New Service Paradigms" (D1v5.pdf) 2006 http://www.eurescom.eu/?id=280

[23] Yang Yu (Motorola Labs, USA), Viktor K. Prasanna and Bhaskar Krishnamachari (U Southern California, USA), "Information Processing and Routing in WSNs", Chapter 1 Introduction to WSNs, World Scientific Publishing Company, p.2-4, 2006 http://www.worldscientific.com/worldscibooks/10.1142/6288

[24] B.Chu, "Wireless Wildfire Sensor Networks", Computer Science & Software Engineering, University of Western Australia, WA http://www.bushfirecrc.com/managed/resource/posterproga-chu.pdf

[25] UCLA http://robotics.eecs.berkeley.edu/~pister/SmartDust/ and CENS http://research.cens.ucla.edu/

[26] UC Berkeley, June 2003, http://www.berkeley.edu/news/media/releases/2003/06/04_sensor.shtml

[27] Paul Rincon, Science Reporter, BBC News, "Smart Dust to Explore Planets", April 2007 http://news.bbc.co.uk/1/hi/sci/tech/6566317.stm

[28] Eurescom P1555 - WSN components, 2005-06 http://www.eurescom.eu/?id=309

[29] BT Ribbit http://www.ribbit.com/

[30] Dr. John Mitchell, UCL, Mobile & Communications Systems IGDP Module, October 2010 (MCS2010_Mitchell_TuePM1_wireless_LAN.pdf)

[31] Jaydip Sen, "A Survey on Wireless Sensor Network Security", Tata Consultancy Services Ltd, Wireless & Multimedia Innovation Lab, Bengal Intelligent Park, Salt Lake Electronics Complex, Kolkata, India, International Journal of Communication Networks and Information Security (IJCNIS) Vol. 1, No. 2, August 2009

[32] B. Raman, K. Chebrolu, "Censor Networks: A Critique of Sensor Networks from a Systems Perspective", Dept of Computer Science & Engineering, Indian Institute of Technology, Mumbai, India, ACM SIGCOMM Computer Communication Review, Vol.38, No.3, July 2008 (2008-censor-networks.pdf)

[33] BP Loch Rannoch (20713975 BP Senses Real World Benefits Sensor Networks Enable the Oil Company to Monitor the Condition of its Assets.pdf) RFID Journal, October 2005

[34] Yang Yu et al, "Information Processing and Routing in WSNs", Chapter 1 Introduction to WSNs, World Scientific Publishing Company, p.5, 2006 http://www.worldscientific.com/worldscibooks/10.1142/6288

[35] Prof. Ian Marshall, Lancaster University, discussion during a Wireless Sensing Interest Group (WiSIG) Meeting at NPL, March 2008 http://www.research.lancs.ac.uk/portal/en/people/ian-marshall(e2655b86-7d39-48d0-8a54-26e62b33137c).html

[36] J.Gehrke and Liu.Ling, "Introduction: Sensor Network Applications", IEEE Internet Computing, vol.10, no.2, pp.16-17, March-April 2006

[37] E. Omiyi, K. Burr, Y.Yang, "Current WSN Platforms and Testbeds: A Short Survey", Dept of Electronic & Electrical Engineering, UCL, 2008

[38] Wikipedia, adapted from Table 2.1 http://en.wikipedia.org/wiki/Sensor_node

[39] I.Akyildiz, W.Su, Y.Sankarasubramaniam, E.Cayirci, "Wireless Sensor Networks: A Survey", Elsevier Science B.V., p.9, 2002 http://www.larces.uece.br/~celestino/RSSF%20I/Wireless%20Sensor%20Networks%20a%20Survey.pdf

[40] University of Geneva (UG), Theoretical Computer Science (TCS) - Smart Dust fire detection motes deployed like 'Dandelion seeds' http://tcs.unige.ch/doku.php/web/wirelesssensornetworks

[41] I. Akyildiz et al, "Wireless Sensor Networks: A Survey", Elsevier Science B.V., p.9, 2002

[42] David Bull, BT Research, "Management of the Network" March 2006 (WSN presentation.ppt)

[43] BT Research (SECOAS) and miscellaneous WSN deployments compiled by author for the annual UCL 2008 poster day

[44] Marco Zennaro, Claro Noda, Wireless Sensor Networks Blog, 2006-13 http://wsnblog.com/

[45] BT Research, PICT Centre, Three Generations of Telecare Monitoring (Telecare_071210a.ppt)

[46] I.Neild, D.Heatley, R.Kalawsky, P.Bowman, "Sensor Networks for Continuous Health Monitoring" in BT Technology Journal, Vol. 22, No. 3, July 2004

[47] AA.Reeves, JWP.Ng, SJ.Brown, NM.Barnes, "Remotely Supporting Care Provision for Older Adults" in Wearable and Implantable Body Sensor Networks International Workshop, BSN 2006, MIT U.S. April 2006

[48] Nigel Barnes, BT Research, (Telecare_Briefing_Issue1.doc) 2010

[49] Paul Bowman, BT Research, Telecare Pilot Trial

[50] Paul Bowman, BT Research, Telecare HIC demo instructions, 2007

[51] Edgar H. Callaway, Jr., "WSNs: Architectures and Protocols", p.10, Auerbach Publications 2004

[52] BBC's "Click" Technology Programme, January 2013 http://news.bbc.co.uk/1/hi/programmes/click_online/9786277.stm

[53] Yang Yu et al, "Information Processing and Routing in WSNs", Chapter 1 Introduction to WSNs, World Scientific Publishing Company, p.14, 2006

[54] Eurescom P1555 - Forest Fires http://www.eurescom.eu/?id=309

[55] University of San Diego State (USDS) Fire Sensor http://www.utsandiego.com/news/2005/Jun/24/fire-sensors-may-prevent-devastation/

[56] University of California, Berkeley (UCB), FireBug motes http://firebug.sourceforge.net/index.php

[57] Edgar H. Callaway, Jr., "WSNs: Architectures and Protocols", p.10, Auerbach Publications 2004

[58] Harvard Sensor Networks Lab, WSN deployed on Volcan Reventador in Ecuador, 2005 (ieeeic06.pdf) http://fiji.eecs.harvard.edu/Volcano

[59] University of Cambridge, CamBridgeSens Research, volcano surveillance wireless sensors http://www.sensors.cam.ac.uk/about-us

[60] Bjorn Thorstensen, Tore Syversen, Trond-Are Bjornvold, Tron Walseth, "Electronic Shepherd: A Low-cost, Low-bandwidth, Wireless Network System", MOBISYS, 2004 http://dl.acm.org/citation.cfm?id=990094

[61] Marine Animals used as Ocean Sensors, UC Santa Cruz & Stanford University collaborated on a Census of Marine Life - Tagging Of Pacific Pelagics (TOPP) project 2006 http://www.coml.org/edu/research/present/topp/to1.htm

[62] University of St. Andrews' Sea Mammal Research Unit (SMRU) on Southern Elephant Seals as Oceanographic Samplers (SEaOS) project around Antarctica 2006

[63] Tagging Of Pacific Pelagics (TOPP) / Southern Elephant Seals as Oceanographic Samplers (SEaOS) - Sensor data transmitted graphic http://www.sanctuarysimon.org/regional_docs/monitoring_projects/100137_report.pdf

[64] Magistretti, E. ; DEIS, Bologna Univ. ; Jiejun Kong ; Uichin Lee ; Gerla, M., "A Mobile Delay-Tolerant Approach to Long-Term Energy-Efficient Underwater Sensor Networking (Dolphins)", 2007 (WCNC07-DDD.pdf) http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=4224776

[65] J. Tateson, C. Roadknight, A. Gonzalez, et al, "Real World Issues in Deploying a Wireless Sensor Network for Oceanography", Workshop on Real-World WSNs, REALWSN'05, Stockholm, Sweden, June 2005 www.cs.kent.ac.uk/projects/secoas/

[66] Dr. Christopher Roadknight, BT Research, SECOAS project deliverables, 2006 http://www.cs.kent.ac.uk/projects/secoas/

[67] Dr. George Bilchev, BT Research, "The Internet of Things" Feb 2006 (BT-IofT.ppt)

[68] Bilchev, G; Marston, D; Hristov, N; Peytchev, E; Wall, N; "Traffimatics – Intelligent Co-Operative Vehicle Highways Systems". BT Technology Journal, Vol 22, No. 3, 2004 http://www.btplc.com/innovation/journal/BTTJ/Archive/Abstract.aspx?JType=BTTJ&IDVol=22&IDArt=3&IDAbs=21

[69] Dr. George Bilchev, BT Research, Traffimatics WSN Architecture

[70] Dr. George Bilchev, BT Research, Traffimatics Ford Fiesta Car

[71] Dr. George Bilchev, BT Research, Traffimatics Final Report, Jan 2006 http://www.nextwave-interface.org.uk/centres/CCIC/final_reports/Traffimatics Final Report.pdf http://www.influxtechnology.com/telematics/technologies.htm

[72] Mike Carr, 2004 http://connection.ebscohost.com/c/articles/15080137/bt-works-traffic-networking

[73] Car-2-Car Communication Consortium http://www.car-to-car.org/

[74] BT Research, Traffimatics Vehicle Sensors graphic

[75] Google cars, May 2013 http://www.dailymail.co.uk/sciencetech/article-2317594/New-images-Googles-self-driving-cars-world.html

[76] RobotCar by Oxford University, February 2013 http://mrg.robots.ox.ac.uk/robotcar/cars.html

[77] Cooperative Vehicle-Infrastructure Systems (CVIS_TfL_London ITS World_SS71_Barton.pdf) http://www.cvisproject.org/en/about_cooperative_systems/

[78] Tim Tau Hsieh, "User Sensor Networks for Highway and Traffic Applications", IEEE Potentials, May 2004

http://ieeexplore.ieee.org/search/searchresult.jsp?searchWithin=p_Authors:.QT.Tim Tau Hsieh.QT.&searchWithin=p_Author_Ids:38199149900&newsearch=true

79 BT Transcomm Story http://www.solutionsforsales.com/content/clients/testimonials/bt-transcomm

80 BT Trackit http://www.zdnet.com/thieves-steal-bt-car-security-system-3039238661/

81 Harbor Research White Paper, "Living Intelligence in the Enterprise: Enabling a Unified M2M Experience", p.8, February 2006 (2006-06.pdf) http://harborresearch.com/

82 BT Redcare www.redcare.bt.com/

83 Reconfigurable Ubiquitous Networked Embedded Systems (RUNES) "Fire in a Road Tunnel" scenario video http://runesmw.sourceforge.net/

84 "The RUNES Middleware for Networked Embedded Systems and its Application in a Disaster Management Scenario" Paolo Costa; Luca Mottola, Gian Pietro Picco, Dept of Electronics & Information, Politecnico di Milano, Italy; Geoff Coulson, Thirunavukkarasu Sivaharan, Nirmal Weerasinghe, Dept of Computing, Lancaster University, UK; Richard Gold, Manish Lad, Cecilia Mascolo, Stefanos Zachariadis, Dept. of Computer Science, University College London, UK http://eprints.ucl.ac.uk/5615/1/5615.pdf

85 Elena Malykhina, InformationWeek, "DARPA Seeks To Launch Drones From Ships", March 2013 http://www.informationweek.co.uk/government/security/darpa-seeks-to-launch-drones-from-ships/240150024

86 Molly Greenberg, InTheCapital, "Virginia Tech Using Drones for Research: Controlling Unmanned Aircraft Carriers by Remote Control", March 2013 http://www.suasnews.com/2013/03/21648/virginia-tech-using-drones-for-research-controlling-unmanned-aircraft-carriers-by-remote-control/

87 Prof. Lynne E. Parker, University of Tennessee, Distributed Intelligence Lab (DIL) http://dilab.eecs.utk.edu/DILresearch.html

88 Robin Lovelock, University of Aberystwyth, Unmanned Atlantic Remote-controlled Boat, Snoopy Sloop, May 2012 http://www.bbc.co.uk/news/uk-england-hampshire-20651779

89 Honda's ASIMO Humanoid Robot http://asimo.honda.com/Inside-ASIMO/

90 Dr. Jane Tateson, BT Research; Julie McCann, Imperial College; Duncan Wilson, ARUP et al; "Building Awareness for Enhanced Workplace Performance", Conference, November 2007 (Bop_booklet_portrait.pdf) http://www.doc.ic.ac.uk/~asher/ubi/bop/

91 Duncan Wilson, ARUP http://www.driversofchange.com/make/research/bop-making-sense-of-space/

92 Dr. Jane Tateson, BT Research; Julie McCann, Imperial College; Duncan Wilson, ARUP et al; BOP Case Study - "Beasties in the creative workplace", Intelligent Buildings International 2009 (Beasties_creative_workplace.pdf) http://www.tandfonline.com/doi/abs/10.3763/inbi.2009.0021

93 Asher Hoskins & Julie McCann Imperial College, "Beasties: Simple Wireless Sensor Nodes", 2003 http://www.doc.ic.ac.uk/~asher/ubi/hardware/beastie.pdf

94 Dr. Christopher Roadknight, Nottingham University, "Real World Data - Real World Problems", 2010 http://ima.ac.uk/slides/cmr-23-02-2010.pdf

95 Arup_ResearchReview_2010_BOP (Fig. 6, p.57) Beastie node and Duncan Wilson's (ARUP) BOP Prototype 3 images on Flickr (BT Proximity Ultrasounder) http://www.flickr.com/photos/pseudonomad/1688545460/in/set-72157602606345745

[96] BOP Meeting Room Observations by author for Dr. Jane Tateson (18/10/2007)

[97] BOP Meeting Room Observations Graph by author showing simulated inferred occupants

[98] BOP data sample.xls from BT 10th Oct 1116 cleaned_JF2.xls by author for Dr. Tateson (10/10/2007)

[99] BT Research, Personalised Information Prioritised Environmental Sensing (PIPES) project and (PICTAR_SWE_JF.ppt)

[100] Author, BT Research, "Realising a Web of Sensors", UCL Symposium 2008 (18Sept08.ppt)

[101] Richard Gedge, BT Research, (M2M and PIPES.ppt)

[102] Dr. Jane Tateson, BT Research, PIPES - WSN example deployments

[103] Dr. Christopher Roadknight, BT Research, PIPES (Visual Basic) Simulation

[104] Author, BT Research, PIPES and BOP shared development (PICTAR_SWE_JF.ppt)

[105] ViaTelemetry AMR (formerly Comtech M2M) http://www.viatelemetry.com/learningcentre/meterreading.aspx

[106] Dr. Miguel Rodrigues, Dr. Yiannis Andreopoulos & Dr John Mitchell, University College London http://www.ee.ucl.ac.uk/research/energy-harvesting-wireless-sensor-networks

[107] John D. Sutter, CNN, "Smart Dust Aims to Monitor Everything", May 2010 http://edition.cnn.com/2010/TECH/05/03/smart.dust.sensors/index.html

[108] Eurescom P1555, "Sensor Telcos - New Business Opportunities" (D2, p.17) 2006 http://www.eurescom.eu/?id=309

[109] BT Transcomm http://www.solutionsforsales.com/content/clients/testimonials/bt-transcomm

[110] Harbor Research White Paper, "Living Intelligence in the Enterprise: Enabling a Unified M2M Experience", p.3 and p.8, February 2006 (2006-06.pdf) http://harborresearch.com/future-of-real-time-intelligence/

[111] BT Redcare http://www.redcare.bt.com/

[112] Paul Bowman, BT Research, BRIDGE (Final_report.pdf) May 2010 www.bridge-project.eu and GS1 EPCglobal standards http://www.gs1.org/epcglobal

[113] Paul Bowman, BT Research, SWE-enabled BRIDGE supply chain scenario (Final_report.pdf) May 2010 www.bridge-project.eu

[114] M. Botts, G. Percivall, C. Reed, J. Davidson, "OGC SWE: Overview & High Level Architecture", Open Geospatial Consortium Inc., 06-050r2, White Paper, July 2006 http://www.opengeospatial.org/pressroom/papers

[115] M. Botts, "Sensor Model Language for In-situ and Remote Sensors" (SensorML), OGC Inc. 02-026r4, December 2002 http://www.opengeospatial.org/pressroom/papers

[116] A. Na, M. Priest, "Sensor Observation Service" (SOS), OGC Inc., 06-009r6, 26 October 2007 http://www.opengeospatial.org/pressroom/papers

[117] S. Cox, "Observations and Measurements" (O&M), OGC Inc., 05-087r4, September 2006 http://www.opengeospatial.org/pressroom/papers

118 Author, BT Research (SWE Report_Final.doc)

119 Institute for Geoinformatics at the University of Muenster, Germany http://ifgi.uni-muenster.de/

120 SANY http://www.sany-ip.eu/ and http://www.opengeospatial.org/ogc/regions/SANY

121 Dr. Ingo Simonis, Geospatial Research & Consulting www.geospatialresearch.de/

122 Dr. Alex Robin, http://www.sensiasoftware.com/technologies and http://www.astrium.eads.net/en

123 Open Source Geospatial Foundation (OSGeo) http://www.osgeo.org/

124 52° North http://52north.org/communities/sensorweb/

125 Author and Dr. Gavin Churcher, BT Research, Highlights Report, 2nd April 2007

126 Dr. Denis Havlik (ARC)
http://www.ait.ac.at/research-services/research-services-safety-security/crisis-and-disaster-management/further-development-and-integration-of-existing-technologies/sany/?L=1

127 Sensors Anywhere (SANY)
http://www.frisia-it.de/assets/images/SANY_Book.pdf
http://www.ncg.knaw.nl/Studiedagen/07SensorWeb/Introduction_to_SANY.pdf
ftp://ftp.cordis.europa.eu/pub/ist/docs/environment/sany-fact-sheet-march-2007_en.pdf

128 Open Geospatial Consortium (OGC) http://www.opengeospatial.org/ogc

129 Sensor Web Enablement (SWE) http://www.opengeospatial.org/domain/swe

130 Author, BT Research (OGC membership.doc and OGC resources.doc)

131 Marine Metadata Interoperability (MMI) Ontologies
https://marinemetadata.org/community/teams/ont/ogcowlharmonization/ontrep

132 Christoph Stasch, Institute for Geoinformatics, University of Muenster, "SWE Common", Workshop at BT (SWE_Common_BT.ppt) November 2007

133 Luis Bermudez, OGC, Washington, September, 2011 (2011_OGC_Sensor_Web_Enablement.pdf)
http://www.ogcnetwork.net/node/382
http://www.opengeospatial.org/ogc/organization/staff/lbermudez

134 OGC Web Services (OWS) Phase 8 demonstration video
http://www.opengeospatial.org/pub/www/ows8/index.html

135 Author, BT Research (JFoley_8Aug07.ppt)

136 SEWilco, Wikipedia http://en.wikipedia.org/wiki/Open_Geospatial_Consortium

137 Michel Grothe, Jan Kooijman (Editors), Alexander C. Walkowski, "Sensor Web Enablement", Netherlands Geodetic Commission, Delft, July 2008 (45Grothe.pdf)
http://www.ncg.knaw.nl/Publicaties/Groen/45Grothe.html

138 Edgar H. Callaway, Jr., "WSNs: Architectures and Protocols", p.6, Auerbach Publications 2004

139 G. Churcher, J. Foley; "Applying CEP & Extending SWE to a Health Care Sensor Network Architecture", ICST S-CUBE, Pisa, Italy, September 2009
S-CUBE 2009 proceedings, "Sensor Systems and Software", Springer 2010
www.springer.com/computer/communication+networks/book/978-3-642-11527-1

[140] G. Bilchev; G. Churcher; J. Foley; R. Gedge; T. Mizutani, “Experiences Applying SWE to a Practical Telecare Application”, IEEE International Symposium on Wireless Pervasive Computing (ISWPC), Santorini, Greece, May 2008 http://www.iswpc.org/2008/

[141] Author, BT Research (OGC resources.doc)

[142] Sensor Web Enablement (SWE) http://www.opengeospatial.org/domain/swe

[143] George Percivall (Editor), Dr. Carl Reed, OGC, (08062r4_OGC_Reference_Model_ORM_Version_2.pdf, p.24) http://www.opengeospatial.org/pressroom/papers

[144] Luis Bermudez, OGC, Washington, September, 2011 (2011_OGC_Sensor_Web_Enablement.pdf)
http://www.ogcnetwork.net/node/382
http://www.opengeospatial.org/ogc/organization/staff/lbermudez

[145] Hai Jin, Wenbin Jiang, Huazhong University of Science and Technology, China, “Handbook of Research on Developments and Trends in WSNs: From Principle to Practice”, Information Science Reference, Hershey, New York, 2010 (OGC_SensorWeb2010Chapter20.pdf) http://www.buyya.com/papers/SensorWeb2010Chapter20.pdf

[146] Author, BT Research (SWE_Overview_Presentation.ppt)

[147] Dr. Carl Reed, OGC, (2008_GIS_Rockies_SWE_Presentation.ppt)
http://www.ogcnetwork.net/node/382

[148] A. Bröring, J. Echterhoff, S. Jirka, I. Simonis, T. Everding, C. Stasch, S. Liang, R. Lemmens, “New Generation Sensor Web Enablement”, Sensors 2011, 11, p.2652-2699 (2011_Broering_NextGenSWE.pdf)
http://arne-broering.de/#journalPapers and http://www.mdpi.com/1424-8220/11/3/2652

[149] Author, BT Research, UCL Poster 2008 - “Realising a Web of Sensors”

[150] Botts Innovative Research http://www.botts-inc.com/videos.html
University of Alabama in Huntsville (UAH) http://www.uah.edu/

[151] D. Moodley, School of Computer Science, University of Kwazulu Natal, Durban, S.Africa; A. Terhorst, ICT for EO Research Group, Meraka Institute, Pretoria, S.Africa; I. Simonis, IfGI, University of Muenster, Germany, “Using the Sensor Web to Detect and Monitor the Spread of Wild Fires”, 2006 http://researchspace.csir.co.za/dspace/bitstream/10204/1055/1/Moodley_2006_D1.pdf

[152] AFIS - Sensor Web Fire Mapper Architecture http://southernafrica.afis.co.za/

[153] OOSTethys - Ocean Science Community http://www.ogcnetwork.net/node/344

[154] NASA - Earth Observation http://eo1.gsfc.nasa.gov/new/extended/sensorWeb/sensorWeb.html

[155] ESA - Galileo Satellite
http://www.esa.int/Our_Activities/Navigation/The_future_-_Galileo/What_is_Galileo

[156] ESA http://swe.ssa.esa.int/web/guest/swe

[157] CSIR Meraka Institute http://ict4eo.meraka.csir.co.za/sites/eo/wiki

[158] ESRI “GIS Best Practices: Spatial Data Infrastructure (SDI)”, September 2010
http://www.esri.com/library/bestpractices/spatial-data-infrastructure.pdf

[159] CSIR Meraka - Corridor Sensor Web http://www.csir.co.za/enews/2008_mar/ic_01.html

[160] SANY http://www.opengeospatial.org/ogc/regions/SANY

[161] GUARD (OWS-4) http://www.opengeospatial.org/pub/www/ows4/ogc-4.swf

[162] Dr. Carl Reed, OGC, (2008_GIS_Rockies_SWE_Presentation.ppt)
http://www.ogcnetwork.net/node/382

[163] SLEWS http://www.slews.de/index_en.php

[164] Location Services http://www.opengeospatial.org/domain/mobileinternet

[165] Dr. Steve Liang, University of Calgary, GeoCENS http://sensorweb.geomatics.ucalgary.ca/ and
http://trlabs.ca/trlabs/midcom-serveattachmentguid-e10acee388f715f142dfcc5830bb0099/liang.pdf
(Spatial Sensor Web - when sensor networks meet the Geo-Web)
P.M. Teillet, et al., ISIES for improved crop and rangeland yield predictions, Canadian Journal of Remote Sensing 2007

[166] GeoCENs 3D and 2D Sensor Web Browsers http://www.geocens.ca/ and http://dev.geocens.ca

[167] Rockyview Well Watch http://rockyview.geocens.ca/

[168] Igliniit (Trails) Project http://nsidc.org/research/projects/Gearheard_Igliniit_Project.html

[169] Alain Tamayo, SWE 2011, Banff, Canada, (swe2011_submission_13.pdf)
http://www3.uji.es/~atamayo/

[170] DLR Tsunami Early Warning
http://www.nat-hazards-earth-syst-sci.net/10/641/2010/nhess-10-641-2010.pdf

[171] PULSENet
http://www.botts-inc.com/downloads/presentations/SWE_Intro_and_Status_2010.pptx
http://www.botts-inc.com/downloads/videos/PULSENetOverview.wmv

[172] SAIC Global SensorWeb Client http://www.ogcnetwork.net/SWE_Software

[173] Monterey Bay Aquarium Research Institute (MBARI) http://www.mbari.org/staff/oreilly/

[174] MBARI http://www.mbari.org/staff/carueda/

[175] OGC SWE http://www.opengeospatial.org/domain/swe#activity

[176] A. Bröring, J. Echterhoff, S. Jirka, I. Simonis, T. Everding, C. Stasch, S. Liang, R. Lemmens, "New Generation Sensor Web Enablement", Sensors 2011, 11, p.2652-2699
(2011_Broering_NextGenSWE.pdf)
http://arne-broering.de/#journalPapers and http://www.mdpi.com/1424-8220/11/3/2652

[177] Luis Bermudez, OGC, Washington, September, 2011 (2011_OGC_Sensor_Web_Enablement.pdf)
http://www.ogcnetwork.net/node/382

[178] Ubiquitous Sensor Networks (USN), ITU-T Technology Watch Briefing Report Series, No. 4
February 2008 http://www.itu.int/dms_pub/itu-t/oth/23/01/T23010000040001PDFE.pdf

[179] OGC CITE http://cite.opengeospatial.org/reference

[180] Author, "Sensor Networks: Enabling the Sensor Web and Facilitating Data Fusion", London Communications Symposium, UCL, London, September 2010
http://www.ee.ucl.ac.uk/lens/schedule.html

[181] Dr. George Bilchev, BT Research, “Towards an Architecture for Pervasive Sensing”, (BT-Lancaster.ppt) May 2007 http://www.comp.lancs.ac.uk/sensornet/Program/SensorNet%20Program.pdf

[182] Author, “Recent Developments in the Design of Sensor Network Architectures”, EuroSSC 2007 (short paper accompanying poster) http://www.comp.lancs.ac.uk/eurossc2007/index.html

[183] SNG, Typical Architecture

[184] SNG, Conceptual Generic Architecture

[185] Author, “Eco System” (Context Architecture.ppt) 2009

[186] Dr. Eliane Bodanese, QMUL http://www.elec.qmul.ac.uk/people/eliane/

[187] QMUL - Networks Research Group http://www.eecs.qmul.ac.uk/research/view/networks

[188] Author, BT Research (Context Architecture.ppt)

[189] Ed Parsons, Geospatial Technologist of Google http://www.edparsons.com/

[190] Robin Mannings, BT Research www.robinmannings.com/

[191] Author and BT Research (M2M Brainstorm Results.doc)

[192] Rachelle L. Miller, SANS Institute 2001, GSEC Practical Assignment Version 1.2e, The OSI Model: An Overview https://www.sans.org/reading-room/whitepapers/standards/osi-model-overview-543

[193] Author and BT Research (M2M_research.doc)

[194] Author and BT Research (M2M Brainstorm Results.doc)

[195] Author and BT Research (M2M_research.doc)

[196] Author and BT Research (M2M Brainstorm Results.doc)

[197] M2MXML http://m2mxml.sourceforge.net/

[198] SensorGrid http://www.cloudbus.org/reports/sensor-grid.pdf
and Open Grid Services Architecture (OGSA) http://toolkit.globus.org/ogsa/

[199] UPnP Forum http://www.upnp.org/

[200] Author and BT Research (M2M_research.doc)

[201] Dr. Gavin Churcher and author, BT Research (Demonstration Overview.ppt)

[202] Author, BT Research, SWE highlight report

[203] 52° North OX-Framework http://52north.org/communities/sensorweb/oxf/index.html

[204] Arne Bröring, 52° North, “OX-Framework: An Integrated Software Framework for OGC Web Services”, Workshop at BT, November 2007 (OX-Framework_BT_Presentation.ppt)

[205] A. Bröring, J. Echterhoff, S. Jirka, I. Simonis, T. Everding, C. Stasch, S. Liang, R. Lemmens, “New Generation Sensor Web Enablement”, Sensors 2011, 11, p.2656 (2011_Broering_NextGenSWE.pdf) http://arne-broering.de/#journalPapers and http://www.mdpi.com/1424-8220/11/3/2652

[206] A. Bröring, J. Echterhoff, S. Jirka, I. Simonis, T. Everding, C. Stasch, S. Liang, R. Lemmens, "New Generation Sensor Web Enablement", Sensors 2011, 11, p.2657 (2011_Broering_NextGenSWE.pdf) http://arne-broering.de/#journalPapers and http://www.mdpi.com/1424-8220/11/3/2652

[207] D. Moodley, School of Computer Science, Westville Campus, University of KwaZulu Natal, Durban, S.Africa; I. Simonis, IfGI, University of Muenster, Germany "A New Architecture for the Sensor Web: The SWAP Framework", 2006 http://www.ict.csiro.au/ssn06/data/swap.pdf

[208] AR Weather Cam http://www.youtube.com/watch?v=wbqic_Fau1Q

[209] Microsoft Research - Sensor Map powered by SenseWeb http://atom.research.microsoft.com/sensewebv3/sensormap/

[210] Nigel Barnes and Tom Mizutani, BT Research, SAPHE http://ubimon.doc.ic.ac.uk/saphe/m338.html

[211] G. Bilchev; G. Churcher; J. Foley; R. Gedge; T. Mizutani, "Experiences Applying SWE to a Practical Telecare Application", IEEE International Symposium on Wireless Pervasive Computing (ISWPC), Santorini, Greece, May 2008 http://www.iswpc.org/2008/

[212] Nigel Barnes, BT Research, From Telecare to Holistic Care (telecare_june09.ppt)

[213] Nigel Barnes and Tom Mizutani, BT Research, SAPHE High Level Architecture (2010) http://ubimon.doc.ic.ac.uk/saphe/m686.html

[214] G. Bilchev; G. Churcher; J. Foley; R. Gedge; T. Mizutani, "Experiences Applying SWE to a Practical Telecare Application", IEEE International Symposium on Wireless Pervasive Computing (ISWPC), Santorini, Greece, May 2008 http://www.iswpc.org/2008/

[215] Dr. Mike Botts, VAST http://www.botts-inc.net/vast.html

[216] Botts Innovative Research http://www.botts-inc.com/links.html

[217] Alex Robin, Sensia Software, SANY workshop 2007 (SWE 2006-03-20.ppt) http://www.sensiasoftware.com/

[218] SensorML http://www.opengeospatial.org/standards/sensorml
http://www.ogcnetwork.net/SensorML
http://www.botts-inc.com/SensorML_1.0.1/schemaBrowser/SensorML_SensorML.html

[219] OGC Resources http://www.ogcnetwork.net/SWE_Software

[220] Pines SensorML Editor by Xuesong Liu https://sites.google.com/site/lxspine/pine'ssensormleditor

[221] SensorML Generator by OOSTethys and MMI Ontology Registry (Carlos Rueda) http://mmisw.org/smlmor/

[222] Author, BT Research, Screenshot of SAPHE system sensors represented as SensorML

[223] Altova XMLSpy http://www.altova.com/xml-editor/

[224] SensorML PrettyView Uploader http://www.sensors.ws/SensorMLforms/upload.jsp

[225] Alex Robin, Sensia Software, SANY workshop 2007, (SensorML 2006-03-20.ppt) http://www.sensiasoftware.com/

[226] Luis Bermudez, OGC, Washington, September, 2011 (2011_OGC_Sensor_Web_Enablement.pdf) http://www.ogcnetwork.net/node/382

[227] Dr. Steve Liang, University of Calgary, GeoCENS, SWE - OGC Standard Tutorials, OGC Seoul, October 2012 http://www.youtube.com/watch?v=LHM-1JR-aVc

[228] Binary XML Description Language (BinX) http://www.smos.esa.int/BinaryXML/

[229] Author, BT Research, SAPHE - Monitoring Portal Room Temperature Sensor Data (saphe screenshots.doc) http://ubimon.doc.ic.ac.uk/saphe/m338.html

[230] G. Churcher, J. Foley; "Applying CEP and Extending SWE to a Health Care Sensor Network Architecture", ICST S-CUBE, Pisa, Italy, September 2009
S-CUBE 2009 proceedings, "Sensor Systems and Software", Springer 2010
www.springer.com/computer/communication+networks/book/978-3-642-11527-1

[231] Nigel Barnes and Tom Mizutani, BT Research, "SAPHE Vision of the Future for Telehealth"
http://ubimon.doc.ic.ac.uk/saphe/public/eopmtg/SAPHE_EOP_28-5-09_eow_v2.pdf

[232] G. Bilchev; G. Churcher; J. Foley; R. Gedge; T. Mizutani, "Experiences Applying SWE to a Practical Telecare Application", IEEE International Symposium on Wireless Pervasive Computing (ISWPC), Santorini, Greece, May 2008 http://www.iswpc.org/2008/

[233] EsperTech, "Esper Reference Documentation Version 2.2.0" http://esper.codehaus.org/

[234] Author, BT Research, GIS and Virtualization (WSN folder notes)

[235] Author, BT Research, UCL Poster 2008 - "Realising a Web of Sensors"

[236] Dr. Gavin Churcher, BT Research, October 2007 (complex-event-processing-vendor-focus.doc)

[237] Sybase CEP (formerly Coral8) "Guide to Evaluating CEP Engines"
http://www.sybase.co.uk/products/archivedproducts/coral8

[238] Sybase CEP (formerly Coral8) "Guide to Evaluating CEP Engines"
http://www.sybase.co.uk/products/archivedproducts/coral8

[239] Sybase CEP (formerly Coral8) "Guide to Evaluating CEP Engines"
http://www.sybase.co.uk/products/archivedproducts/coral8

[240] G. Churcher, J. Foley; "Applying CEP and Extending SWE to a Health Care Sensor Network Architecture", ICST S-CUBE, Pisa, Italy, September 2009
S-CUBE 2009 proceedings, "Sensor Systems and Software", Springer 2010
www.springer.com/computer/communication+networks/book/978-3-642-11527-1

[241] Gibbons, P. B. and Carp, B., Intel Research Pittsburg and Ke, Y., Nath, S. and Seshan, S., Carnegie Mellon University. "IrisNet: An Architecture for a Worldwide Sensor Web", In Pervasive Computing, December 2003 http://www.intel-research.net/Publications/Pittsburgh/101220041301_266.pdf

[242] Ando, N., Hitachi Ltd., "Sensor Information Web Service for Healthcare Management at Home Powered by Collectlo", June 2008 http://www.hitachi.com/rd/portal/story/sensor_net/02.html
http://www.gbd-e.org/pubs/Recommendations_Paper2009.pdf

[243] P. Zhang, M. Chen, Northwestern Polytechnical University, Xi'an, China. "A Remote Health Care System Based on Wireless Sensor Networks", IEEE Xplore, 2008
http://ieeexplore.ieee.org/xpl/abstractKeywords.jsp?arnumber=4537133

[244] EsperTech: Esper Reference Documentation, Version 2.2.0, http://esper.codehaus.org/

[245] T. Everding, IfGI, University of Muenster; J. Echterhoff, International Geospatial Services Institute (iGSI), "Event Pattern Markup Language (EML)", (08-132) November 2008
https://www.uni-muenster.de/forschungaz/person/11584?lang=en

[246] J. Echterhoff, International Geospatial Services Institute (iGSI); T. Everding, IfGI, University of Muenster, “OpenGIS Sensor Event Service Interface Specification (SES)”, (08-133) October 2008 https://www.uni-muenster.de/forschungaz/person/11584?lang=en

[247] G. Churcher, J. Foley; “Applying CEP and Extending SWE to a Health Care Sensor Network Architecture”, ICST S-CUBE, Pisa, Italy, September 2009
S-CUBE 2009 proceedings, “Sensor Systems and Software”, Springer 2010
www.springer.com/computer/communication+networks/book/978-3-642-11527-1

[248] Luis Bermudez, OGC, Washington, September, 2011 (2011_OGC_Sensor_Web_Enablement.pdf) http://www.ogcnetwork.net/node/382

[249] T. Kobialka, R. Buyya, P. Deng, L. Kulik, Marimuthu Palaniswami, “Sensor Web: Integration of Sensor Networks with Web and Cyber Infrastructure”, University of Melbourne, Australia, IGI Global 2010 http://www.buyya.com/papers/SensorWeb2009Chapter.pdf

[250] R. Dautov, I. Paraskakis, D. Kourtesis, Mike Stannett, South-East European Research Centre, The University of Sheffield, “Addressing Self-Management in Cloud Platforms: a Semantic Sensor Web Approach”, HotTopiCS, Prague, Czech Republic, 20 April 2013
http://icpe2013.ipd.kit.edu/fileadmin/user_upload/icpe2013/rustem.pdf

[251] IoT SIG https://connect.innovateuk.org/web/internet-of-things/
IoT and M2M http://www.linkedin.com/groups/Internet-Things-73311/about
IoT EU Council http://www.theinternetofthings.eu/

[252] OGC OWS-9 http://www.opengeospatial.org/pub/www/ows9/index.html