A Study into Prolonging Wireless Sensor Network Lifetime during Disaster Scenarios

by

Ansar Jamil

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Abstract

A Wireless Sensor Network (WSN) has wide potential for many applications. It can be employed for normal monitoring applications, for example, the monitoring of environmental conditions such as temperature, humidity, light intensity and pressure. A WSN is deployed in an area to sense these environmental conditions and send information about them to a sink. In certain locations, disasters such as forest fires, floods, volcanic eruptions and earth-quakes can happen in the monitoring area. During the disaster, the events being monitored have the potential to destroy the sensing devices; for example, they can be **sunk in a flood, burnt in a fire, damaged in harmful chemicals, and burnt in volcano lava etc**. There is an opportunity to exploit the energy of these nodes before they are totally destroyed to save the energy of the other nodes in the safe area. This can prolong WSN lifetime during the critical phase. In order to investigate this idea, this research proposes a new routing protocol called Maximise Unsafe Path Routing Protocol (MUP) routing using IPv6 over Low power Wireless Personal Area Networks (6LoWPAN). The routing protocol aims to exploit the energy of the nodes that are going to be destroyed soon due to the environment, by concentrating packets through these nodes. MUP adapts with the environmental conditions. This is achieved by classifying four different levels of threat based on the sensor reading information and neighbour node condition, and represents this as the node health status, which is included as one parameter in the routing decision. High priority is given to a node in an unsafe condition compared to another node in a safer condition. MUP does not allow packet routing through a node that is almost failed in order to avoid packet loss when the node fails. To avoid the energy wastage caused by selecting a route that requires a higher energy cost to deliver a packet to the sink, MUP always forwards packets through a node that has the minimum total path cost. MUP is designed as an extension of RPL, an Internet Engineering Task Force (IETF) standard routing protocol in a WSN, and is implemented in the Contiki Operating System (OS). The performance of MUP is evaluated using simulations and test-bed experiments. The results demonstrate that MUP provides a longer network lifetime during a critical phase of typically about 20% when compared to RPL, but with a trade-off lower packet delivery

ratio and end-to-end delay performances. This network lifetime improvement is crucial for the WSN to operate for as long as possible to detect and monitor the environment during a critical phase in order to save human life, minimise loss of property and save wildlife.

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List of Abbreviations

6LoWPAN IPv6 over Low power Wireless Personal Area Networks.

BH Back-up Cluster Header.

CCA Clear Channel Assessment.

CH Cluster Head.

CPU Central Processing Unit.

CSMA/CA Carrier Sense Multiple Access Collision Avoidance.

CTS Clear-To-Send.

DAO Destination Advertisement Object.

DAO-ACK Destination Advertisement Object Acknowledgement.

DGRM Directed Graph Radio Medium.

DIO DODAG Information Object.

DIS DODAG Information Solicitation.

DODAG Destination Oriented Directed Acyclic Graph.

DSSS Direct Sequence Spread Spectrum.

ETX Estimation Transmission Count.

FFD Full Function Device.

GPS Global Positioning System.

ICMP Internet Control Message Protocol version 6.

IEEE Institute of Electrical and Electronic Engineering.

IETF Internet Engineering Task Force.

IP Internet Protocol.

IPv4 Internet Protocol version 4.

IPv6 Internet Protocol version 6.

IR Infra-Red.

LLN Low Power and Lossy Network.

LPM Low Power Mode.

LR-WPAN Low-Rate Wireless Personal Area Network.

MAC Medium Access Control.

MCU Micro Controller Unit.

MEMS Micro-Electromechanical Systems.

MP2P Multipoint-to-Point.

MRHOF Minimum Rank Objective Function with Hysteresis.

MTU Maximum Transmission Unit.

MUP Maximise Unsafe Path Routing Protocol.

OF Objective Function.

OS Operating System.

P2MP Point-to-Multipoint.

P2P Point-to-Point.

PAN Personal Area Network.

PHY Physical Layer.

QoS Quality of Service.

RAM Random Access Memory.

RDC Radio Duty Cycle.

RFD Reduced Function Device.

RPL IPv6 Routing Protocol for Low Power and Lossy Networks.

RSSI Received Signal Strength Indicator.

RTS Request-To-Send.

SNR Signal-to-noise ratio.

SRAM Static Random Access Memory.

TCP Transport Control Protocol.

UAV Unmanned Ariel Vehicles.

UDGM Unit Disk Graph Medium.

UDP User Datagram Protocol.

WSN Wireless Sensor Network.

Chapter 1

Introduction

1.1 Background

A WSN is defined as a large collection of small wireless devices called sensor nodes that can organise themselves into an ad-hoc network. They have constraints of energy, processing and communication resources [75]. These wireless devices are deployed in close proximity to the phenomenon to gather information about the physical world and send it to a sink or base station. This technology is suitable for environmental data collection systems that enable a user to monitor environmental conditions effectively from a distance. Several studies have been carried out to integrate WSNs with the Internet which will provide more functionality such as requesting data, sending notifications, and monitoring sensor readings via email [44] and the web [17].

Sensor nodes can be attached with many different types of sensor, such as magnetic, seismic, infrared, thermal, acoustic, visual and radar, which are able to monitor a wide variety of ambient conditions [29]. In addition, the self-organising feature makes WSN technology suitable to be deployed in many applications such as agriculture, animal tracking, the military, petroleum pipeline monitoring, patient-health monitoring and forest fire monitoring systems. The deployment of a WSN needs to be done carefully to meet the desired performance of an application. This is because a WSN has many constraints compared to a traditional computer network.

Sensor nodes in a WSN have two obvious resource limitations in terms of energy sources and memory storages. The sensor nodes have a limited amount of energy because they are reliant on batteries as an energy source. Once sensor nodes are deployed in an area, their batteries cannot be replaced or recharged easily. Therefore, the battery charge must be conserved to extend the life of the individual sensor node and hence the entire network. The sensor nodes have a

small amount of memory and storage space for program codes. For example, a MICAZ node has an 8-bit, 7.37 MHz CPU with only 4 kB SRAM and 128 kB program Flash memory. Other than this, a N740 Nano-Sensor node has an 8-bit MCU with 128 kB Flash and 8 kB RAM. The size of the developed program codes for the sensor nodes must also be quite small.

Normally, WSNs use unreliable connectionless communication when delivering a packet from a node to the sink to avoid the energy wastage from dedicated routes in connection-oriented communication. WSNs provide their best effort to deliver a packet to the sink successfully. Due to the unreliable wireless communication link, a packet may get corrupted due to channel errors. This unreliable wireless communication link is highly probabilistic and asymmetric. It depends on the transmission power and the distance travelled by a packet [106]. Other than this, a packet can also become corrupted due to transmission interference, which occur when two nodes within the same coverage area transmit packets simultaneously. In both cases, the packet transfer fails and the sender node needs to retransmit the packet. If the number of retransmissions has reached the maximum value, the sender node simply drops the packet. A packet may also be dropped due to congestion at a highly congested node. It is very important in a WSN to have appropriate mechanisms to handle these situations in order to reduce the probability of packet loss.

1.2 Problem Statement

A WSN is suitable for use in a wide area of applications. A WSN is deployed to fulfil a specific task, which may be different for each application: for example, detecting forest fire, monitoring soil humidity, monitoring room temperature, and tracking wild animals. Each application has specific requirements in terms of security level, Quality of Service (QoS) and the type of data collected. Thus, a WSN should be designed specifically to meet the individual application requirements. In order to achieve this, a large number of communication protocols and network solutions should be examined in the process of constructing an optimal WSN infrastructure before practical deployment [30]. The main challenge is to achieve an acceptable network performance for a desired task, given the limitations and constraints of WSN technology.

A major issue which has been frequently emphasised in many research studies in this field is the problem of limited energy. It is important for the WSN to be available throughout the intended time of deployment. For example, in critical situations, a WSN must always be ready to detect any critical event. If the sensor network becomes non-functional, the network can no longer detect and monitor

the critical event. This situation can cause many unwanted events to happen, such as loss of human life, property, public infrastructure and valuable wildlife when the critical event becomes uncontrollable. It is crucial for researchers in this field to develop new protocols that are able to prolong the network lifetime of a WSN. Since network lifetime is directly influenced by energy, the power efficiency often turns out to be a major performance metric. In the WSN, the power consumption of a sensor node can be divided depending on each component: sensing, communication and data processing. Among these components, the communication components have the highest energy consumption, which includes the activities of transmitting and listening for a packet.

Besides this, the two performance metrics that should be considered during the deployment of the WSN are the packet delivery ratio and end-to-end delay. It is expected that the WSN to have a high packet delivery ratio performance in order to provide sufficient information to achieve the monitoring aims. If the node is located further away and does not have a direct link of communication with the sink, the network must deliver it using multihop communication. This is a challenging task because the WSN has an unreliable communication link with limited bandwidth, which is heavily influenced by its lossy environment [106, 13]. This problem with the communication link can be solved by implementing the hop-by-hop basis of data transfer, where for each successful transmission the receiving node must send an acknowledgement message to the sender node. Because of this, the end-to-end delay performance in the WSN becomes unpredictable. The WSN must be able to deliver the packet as soon as possible because, for certain applications, the data is only valid for a short period of time.

1.3 Objectives

A common application of a WSN is environment monitoring. Here, a WSN is deployed in an area to sense environmental conditions, such as temperature, humidity, light intensity and pressure, and collect the sensed information. In certain deployment areas, sudden disasters such as forest fires, floods, volcanic eruptions and earth-quakes can happen during monitoring. During such a disaster phase, the events being monitored have the potential to destroy the sensing devices; for example, **they can be sunk in a flood, burnt in a fire, damaged in harmful chemicals, and burnt in volcano lava etc**. There is an opportunity to exploit the energy of these doomed nodes before they are totally destroyed to save the energy of other nodes and prolong network lifetime during the disaster phase.

In order to investigate this idea, the present research proposes the Maximise Unsafe Path (MUP) routing protocol. MUP aims to exploit the energy of these

dying nodes by concentrating packets through the nodes before they are totally destroyed in order to save the energy of the other nodes, to provide a longer network lifetime during disaster situations. MUP is also expected to provide a similar packet delivery ratio and end-to-end delay performance. MUP is designed specifically for normal monitoring applications. MUP adapts its routes to the environments by using sensing information from the sensors, which is included as one of the parameters during the selection of routes in the networks. The research work is focused on the development and evaluation of MUP based on IEEE 802.15.4 beaconless operation and 6LoWPAN architecture, which becomes the popular choice for various monitoring applications.

1.4 Scopes

The scope of the research is divided into three technical phases which include the design of MUP, a simulation study of MUP and an experimental study of MUP in WSN test-beds.

1.4.1 Design of MUP

The MUP design concept consists of three functional modules that include routing management, neighbourhood management and critical event detection modules. These functional modules cooperate to prolong the network lifetime of the WSN during disaster situations.

One approach for developing MUP is by reusing an existing routing protocol. MUP is designed as an extension to the IPv6 Routing Protocol for Low Power and Lossy Networks (RPL) [100], an IETF standard routing protocol in WSN. The implementation and development of the MUP design is based on the ContikiRPL platform [48], which is the implementation of RPL in the Contiki OS. The routing management module is implemented by introducing a new Objective Function (OF). The critical event detection is developed as a new module. The neighbourhood management module uses the existing Neighbour Discovery available in RPL. Here, two implementations of MUP are proposed: MUP-single and MUP-adapt.

The characteristics of MUP have been studied to ensure that the implementation is carried out correctly and that the routing protocol performs as expected. This step is very important before intensive measurement to determine the performance of MUP via simulation.

1.4.2 A Simulation Study of MUP

In the development of MUP, COOJA is selected as the design and evaluation tool. COOJA is a simulator for the Contiki OS which enables cross-level simulation, i.e. simultaneous simulation at many levels of the systems [71]. It is flexible and extensible in that all levels of the system can be changed and replaced, including the sensor node platforms, the operating system software, the radio transceivers, and the radio transmission models. MUP is simulated based on the Contiki OS which includes 6LoWPAN functionality. In addition,Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) is chosen as the Medium Access Control (MAC) layer protocol. For the physical layer, the simulation uses the sensor node model which is based on the IEEE 802.15.4 physical layer standard. Other than this, the simulator has a built-in plugin to include any disaster scenario. Since the forest fire scenario is selected as an example of disasters, the plugin loads the scenario that consists of temperature increment information for each node in the network into the simulation. The performance of MUP, such as network lifetime, energy consumption, packet delivery ratio, packet loss and end-to-end delay, is studied and compared with RPL.

1.4.3 An Experimental Study of MUP in WSN Test-beds

MUP is tested in WSN test-beds to determine the routing performance in the real environment. The WSN test-beds consist of sensor nodes which are called N740 Nano-Sensor, manufactured by the SENSINODE LTD company. The sensor node is user programmable and operates at 2.4 GHz frequency using an 8051 MCU, an 8-bit MCU with 128kB Flash and 8kB RAM [83]. The Contiki OS which is used in the simulation can be programmed into the sensor node. In the experiment, two different sizes of WSN testbeds are established consisting of 10 sensor nodes (small testbed) and 25 sensor nodes (large testbed) distributed on the field. Each node sends data periodically to the sink. Based on the captured data, the performance of MUP in the experiment is determined and compared with the simulation.

1.5 Significance of the Research Work

MUP is designed for normal monitoring applications. MUP is able to prolong the network lifetime of a WSN during the disaster phase. It is very important for the network to keep functioning for as long as possible, especially to detect and monitor any disaster events. These disaster events are unpredictable and can happen anywhere at any time in the network. For example, in forest fire detection and monitoring systems, the network must be available to detect any

fire happening and send an alert to fire fighters as soon as possible. The forest fire can be put out easily even with a small squad of fire fighters with just basic equipment. If the network is not available, an undetected fire can grow larger until the stage where it becomes uncontrollable, which is too risky for fire fighters to handle and may endanger their life. Thousands of hectares of valuable forest will be burnt in a fire. This forest can consist of a diversity of small and large trees, which are places where many animal species live. To make things worse, the fire could cause loss of civilian life, houses, properties and other facilities in the affected area.

1.6 Thesis Contributions

The contributions of the thesis are outlined as below:

1. Study a new idea for prolonging the network lifetime in WSN. In certain deployment areas, disasters such as forest fires, floods, volcanic eruptions and earth-quakes can happen in the monitoring area. During the disaster phase, the events being monitored have the potential to destroy the sensing devices; for example, **they can be sunk in a flood, burnt in a fire, damaged in harmful chemicals, and burnt in volcano lava etc**. There is an opportunity to exploit the energy of these nodes before they are totally destroyed to save the energy of the other nodes in the safe area. This can prolong the WSN lifetime during the disaster phase. In order to study this idea, a new routing protocol is proposed called the Maximise Unsafe Path (MUP) routing protocol.

2. Design and development of the MUP routing protocol. MUP is a new routing protocol in WSN. It is designed to be used in normal monitoring applications. The main objective of MUP is to prolong the network lifetime of WSNs and still provide comparable network performances during the disaster phase. In order to achieve this, MUP exploits the energy of unsafe nodes that are going to be damaged soon, to save the energy of the other nodes in the network by routing packets through the unsafe nodes. The main feature in MUP is the ability to adapt alongside the environment, which is achieved by taking consideration of the environmental conditions in the routing decision. A new parameter is introduced in the MUP routing design to represent the environmental threat to a sensor node, which is called health status. Determination of health status is based on the available information from the sensor reading and the neighbour nodes' condition. MUP uses the health

status and total path cost information as parameters to make routing decisions. First, a MUP node finds neighbours with the lowest total path cost. If two or more neighbours are found, the node selects from them based on their health status by giving the highest priority to the neighbour in an unsafe condition rather than other neighbours in a safe condition. If they are still tied, the routing algorithm remains with the current best neighbour as the forwarding node. In order to avoid packet loss when a neighbour is just damaged, the node removes the almost failed neighbour as its forwarding node. MUP routing is designed for 6LoWPAN network. MUP is implemented as an extension to RPL.

3. Study of MUP in simulation and experiment. A forest fire scenario is taken as an example of a disaster situation. The simplest circular shape of the forest fire growth model for a flat terrain without wind is used in both the simulation and the experiment. When a node becomes exposed to fire, a linearly growing offset is added to the node's temperature value. In the simulation, the characteristics and performance of MUP are studied in perfect and lossy network conditions. After that, the simulation findings are verified by experiment. In the experiment, MUP is tested using a WSN test-bed, which is deployed on a field. Through this study, the findings demonstrate that MUP prolongs the network lifetime of the WSN during the disaster phase when compared to RPL. The findings also indicate that MUP suffers a lower packet delivery ratio and end-to-end delay performance when compared to RPL.

1.7 Thesis Organisation

This thesis consists of eight chapters. Chapter 1 serves as an introduction to the thesis. It covers topics such as the statement of the research problem, the objectives of the research, the scope of the research and the significance of the research.

Chapter 2 provides the relevant background about the WSN, IEEE 802.15.4 and 6LoWPAN. The chapter introduces the applications of the WSN, the constraints in the WSN, the routing challenges in the WSN and the routing categories in the WSN.

Chapter 3 describes the MUP routing protocol design which is based on RPL. MUP introduces two new modules which are the OF and the critical event detection module. The OF module defines how nodes select and optimise routes within the network based on the routing algorithm. The critical event detection module

is very important to determine node health status, which represents the environmental threat to the sensor node. Other than these modules, MUP continues using the available modules in RPL such as the neighbour discovery mechanism and the routing update mechanism.

Chapter 4 describes the Contiki OS that is selected as the operating system for sensor nodes in both simulation and experiment. This chapter also explains the COOJA simulator, the simulation tool for developing and designing MUP. It includes an explanation of the forest fire scenario that has been introduced in the simulation. The basic network configuration is also described in detail in this chapter. In addition, this chapter defines the performances metrics used in the simulation and experiment.

Chapter 5 describes the simulation results and the analysis for MUP. It includes the performance for both implementations of MUP: MUP-single and MUP-adapt. For performance comparison, this chapter includes the simulation results and the analysis for SAFEST and RPL.

Chapter 6 describes the hardware implementation of MUP and RPL using N740 Nano-Sensor. Both routing protocols have been tested in two different sizes of WSN test-beds consisting of 10 nodes (small test-bed) and 25 nodes (large test-bed). In order to achieve multi-hop communication, the transmission range of each node is limited to its adjacent neighbours. Experimental results from the hardware implementation are compared with the simulation results.

Finally, Chapter 7 concludes the thesis with a summary of the work that has been done, along with suggestions for future work.

Chapter 2

Background and Related Work

2.1 Introduction of WSN

Recent advancement in micro-electromechanical systems (MEMS) technology, wireless communications, and digital electronics have enabled the development of low-cost, low-power, multi-functional sensor nodes that are small in size and communicate in short distances [2]. These small sensor nodes, which consist of sensing, data processing, and communicating components, leverage the idea of sensor networks based on the collaborative effort of a large number of nodes [2]. Also, the low cost of the sensors makes it possible to have a network of hundreds or thousands of these wireless sensors, thereby enhancing the reliability and accuracy of the data and the area coverage as well.

WSN networks are affected by many challenging issues such as sensor nodes deployment, data processing and routing, data security, fault tolerance, data aggregation and connectivity [4, 16]. These challenges arise primarily due to the large number of constraints such as limited energy, bandwidth, memory and computational speed [77].

2.2 Architecture of WSN

Figure 2.1 shows the WSN architecture. The main entities that build up the WSN architecture are described below [90]:

- *The sensor nodes*: These are small devices that form the sensor network. The main functionalities of a sensor node are sensing the phenomenon within its coverage area, forming a network by communicating with other nodes over a wireless medium and routing the sensor reading data to the user via a base station or sink.

- *The base station (sink)*: **The base station communicates with the user via satellite communication or internet**. The base station is located close to the sensor network area. The data collected from each sensor node is sent to the user by a multi-hop communication method (due to the low power of the sensor nodes) through the base station.

- *Phenomenon*: This is an entity that is of interest to the user. The sensor node has the capability to sense the phenomenon and also to do simple analysis on it before sending the data to the user.

- *The user*: **A person that is interested in collecting data about a specific phenomenon in order to monitor or measure its behaviour**.

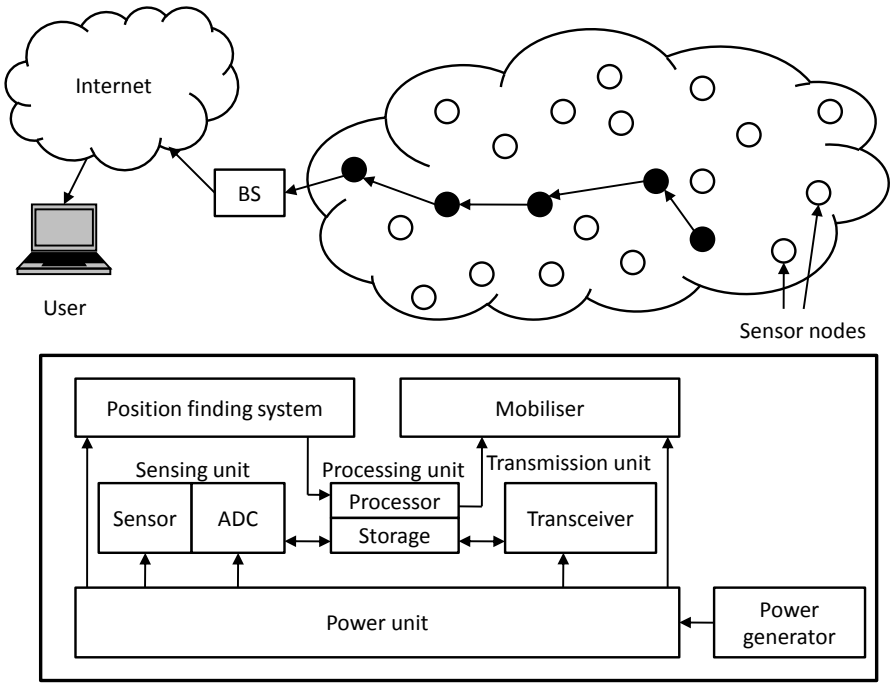

Figure 2.1: WSN architecture [2].

2.2.1 IEEE 802.15.4 Specification

IEEE 802.15.4 is a standard which defines the Physical Layer (PHY) and MAC sub-layer specifications for Low-Rate Wireless Personal Area Network (LR-WPAN) [41]. This standard was not specifically developed for WSN, but WSN can be built up from the LR-WPAN. The IEEE 802.15.4 protocol targets **low power consumption, low data rate and low cost wireless networking which meet the requirement of the WSN.**

Based on the IEEE 802.15.4 standard, a LR-WPAN can support two different types of device: the Full Function Device (FFD) and the Reduced Function Device

(RFD). The FFD is a device that supports three operation modes; one of these acts as a Personal Area Network (PAN) coordinator. A PAN coordinator identifies its own network such that other devices may be associated. A LR-WPAN must include at least one FFD acting as a PAN coordinator. An FFD can also act as a coordinator that provides synchronisation services through the transmission of beacons but does not create its own network. Other than this, an FFD can just be a simple device which does not implement the previously mentioned functionalities. The RFD is a device operating with the minimal implementation of the IEEE 802.15.4 protocol. An RFD supports simple applications such as environment sensing using temperature, light or infra-red sensors, which do not require the device to send large amounts of data.

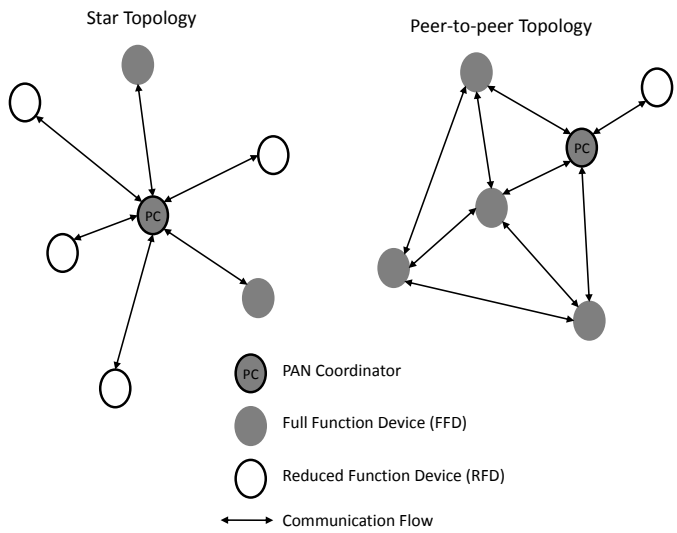

Figure 2.2: Star and peer-to-peer topology [41].

There are two basic types of network topology specified in the IEEE 802.15.4 standard: the star topology and the peer-to-peer topology. Both topology examples are shown in Figure 2.2. In the star topology, a node operates as the PAN coordinator. The PAN coordinator selects a PAN identifier which is not currently used by any other network. Each of the devices, either FFD or RFD, joining the network can communicate with other devices, and must send its data through the PAN coordinator. The PAN coordinator becomes the centre of communication among the devices in the network. This means that the PAN coordinator may be mains powered because of the power consuming tasks of the PAN coordinator in the star topology, while the other devices are more likely to be battery powered.

In the peer-to-peer topology, a device must be selected as the PAN coordinator, a decision which is based on, for instance, the first device to communicate on the channel. The communication paradigm in the peer-to-peer topology is decentralised. This means that each of the devices can communicate directly

with the other devices in its radio communication range. This topology provides networking flexibility, but it requires an additional complexity for providing an end-to-end connectivity between all the devices in the network. The peer-to-peer topology operates in an ad-hoc manner, and implements multi-hops communication to transfer data from any device to any other device. However, these functions must be defined at the network layer which is not considered in the IEEE 802.15.4. In contrast with the star topology, the resource usage is fairer in the peer-to-peer topology since the communication process does not rely on a particular node [50].

Table 2.1: Physical layer description in IEEE 802.15.4 [41].

Property	Range
Raw data rate	868 MHz: 20 kb/s; 915 MHz: 40 kb/s; 2.4 GHz: 250 kb/s
Range	10-20 m
Latency	Down to 15 ms
Channels	868 MHz: 1 channel; 915 MHz: 10 channels; 2.4 GHz: 16 channels
Frequency band	Two PHYs: 868 MHz/915 MHz and 2.4 GHz
Addressing	Short 16-bit or 64-bit IEEE
Temperature	Industrial temperature range −40 to +85 °C

The IEEE 802.15.4 physical layer offers three operational frequency bands: 868 MHz, 915 MHz and 2.4 GHz. There is a single channel between 868 and 868.6 MHz, 10 channels between 902 and 928 MHz, and 16 channels between 2.4 and 2.4835 GHz as shown in Figure 2.3. The operating frequency bands are defined with specific data rates, which are 20 kb/s at 868 MHz, 40 kb/s at 915 MHz and 250 kb/s at 2.4 GHz. Lower frequencies are more suitable for longer transmission ranges due to lower propagation losses. However, high data rate transmission provides higher throughput, lower latency and lower duty cycles. All these frequency bands are based on a modulation technique called the Direct Sequence Spread Spectrum (DSSS). The specification of IEEE 802.15.4 physical layers are summarised in Table 2.1.

The MAC sub-layer of the IEEE 802.15.4 protocol provides an interface between the physical layer and the higher layer protocols of LR-WPANs. It has many common features with the MAC sub-layer of the IEEE 802.11 protocol, such as the use of CSMA/CA (a channel access protocol), and the support of contention-free and contention-based periods. However, the standard does not include the request-to-send (RTS) and clear-to-send (CTS) mechanism to reduce the probability of collisions, which are more likely to happen in low data rate networks. Figure 2.4 shows a structure for the operational modes for the MAC sub-layer of IEEE 802.15.4. The MAC protocol supports two operational modes that may be

selected by the coordinator as described below:

1. *Beacon-enabled mode*: **The coordinator generate becons periodically to synchronise the attached devices and to identify the PAN. The first part of a superframe is a beacon frame,** which also embeds all data frames exchanged between the nodes and the PAN coordinator. Data transmissions between the nodes are also allowed during the superframe duration.

2. *Non beacon-enabled mode*: **The devices can simply use unslotted CSMA/CA to send their data**. A superframe structure is not used in this mode.

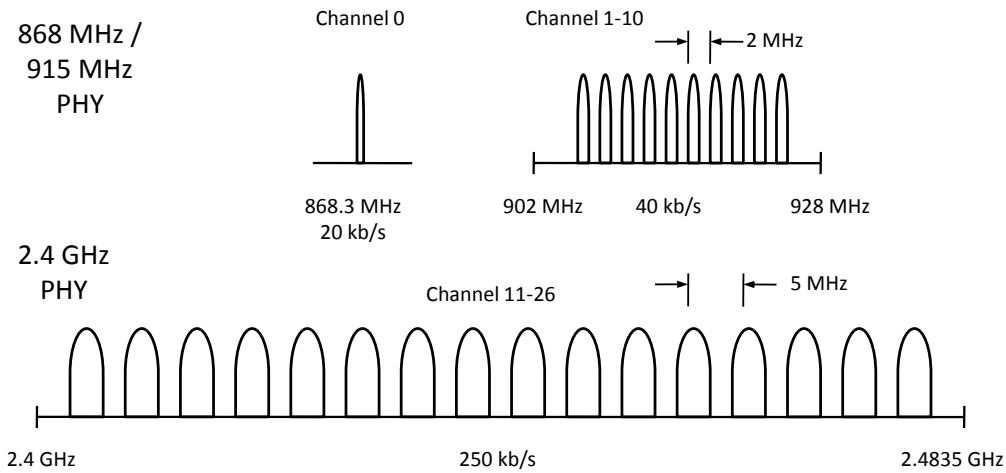

Figure 2.3: Operating Frequency Bands in IEEE 802.15.4 [50].

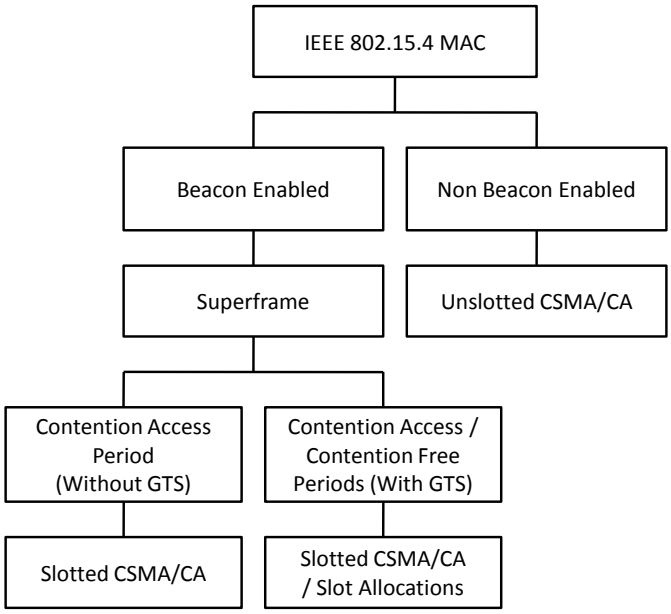

Figure 2.4: Operational modes for MAC sub-layer of the IEEE 802.15.4 [50].

2.2.2 6LoWPAN

The Internet Protocol version 6 (IPv6) is designed to supersede Internet Protocol version 4 (IPv4) and enable the Internet to scale for decades to come. IPv6 expands the IP address from 32 to 128 bits. This means that IPv6 provides about 2^{128} or approximately 3.4×10^{38} address spaces which is significantly more than the IPv4 with 2^{32} or 4, 294, 967, 296 address spaces. Since there is a need to assign thousands of sensor nodes with IP addresses to enable simple interconnectivity to the other IP networks, including the internet [53], IPv6 becomes the best choice for WSN. In addition, the stateless address auto-configuration simplifies the configuration and management of IPv6 devices by enabling sensor nodes to assign themselves meaningful addresses. These features make IPv6 better suited for WSN, especially for large scale deployment.

As described in section 2.2.1, IEEE 802.15.4 is a standard designed specifically for long-lived applications that require numerous low-cost nodes, and has constraints of limited capability of the links and MCU. The data rate is limited to 250 kb/s in the 2.4 GHz band and 20 or 40 kb/s in other frequency bands. The frame length is limited to 128 bytes to ensure a reasonably low packet error. Other than this, it is known to have limited buffering capabilities. The IEEE 802.15.4 defines short 16-bit link addresses in addition to 64-bit addresses to reduce the header overhead and memory requirement. The communication range is short due to its low transmit power. The associated microcontroller typically has about 8 kB of data RAM and 64 kB program ROM.

Because of these resource constraints, supporting IPv6 over WSN presents several challenges. One of them is that IPv6 datagrams are not fit for WSN. The IEEE 802.15.4 frame is one-tenth of the size of the IPv6 minimum MTU requirement, which makes datagram fragmentation and compression essential for efficient operation. It starts from a maximum physical layer packet size of 127 bytes. For the worst case, the link header requires about 46 bytes (25 bytes of physical layer overhead and 21 bytes of overhead in media access control using AES-CCM-128), which leaves 81 bytes for the IPv6 payload. The IPv6 header requires 40 bytes, which leaves 41 bytes. Other than this, the transport layer header must be deducted from the remaining 41 bytes which leaves a very short payload. If UDP is used (which requires 8 bytes header), this leads to 33 bytes for the payload. If TCP is used (which requires 20 bytes), this leaves 21 bytes for the payload.

The adaptation layer must be provided to comply with the IPv6 requirements of a minimum MTU. It is expected that most applications of IEEE 802.15.4 will not use such large packets, and small application payloads in conjunction with the proper header compression will produce packets that fit within a single IEEE

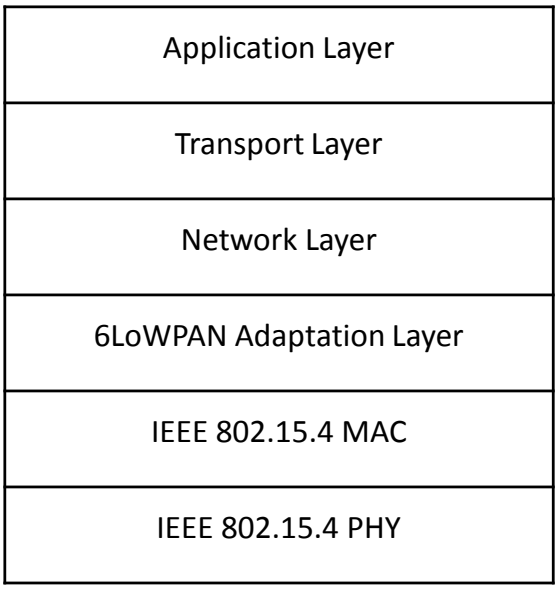

Figure 2.5: 6LoWPAN adaptation layer.

802.15.4 frame [53]. For certain applications, it is quite likely that the packet size requires a small number of fragments. The 6LoWPAN [65] defines the format of how the IPv6 is carried in the IEEE 802.15.4 frames and specifies key elements in the adaptation layer. The 6LoWPAN adaptation layer is illustrated in Figure 2.5. The key concept applied throughout the 6LoWPAN adaptation layer is that it uses stateless compression, which elides the adaptation, network and transport layer header fields by compressing them down to a few bytes. 6LoWPAN has three primary elements:

- **Header compression**: IPv6 header fields are eliminated from a packet when the adaptation layer can derive them from the link-level information carried in the IEEE 802.15.4 frame or based on simple assumptions of shared context.
- **Fragmentation**: IPv6 packets are fragmented into multiple link-level frames to accommodate the IPv6 minimum MTU requirement.
- **Layer-two forwarding**: To support layer-two forwarding of IPv6 datagrams, the adaptation layer can carry link-level addresses for the ends of an IP hop. Alternatively, the IP stack might accomplish intra-PAN routing via layer-three forwarding, in which each IEEE 802.15.4 radio hop is an IP hop.

Similar to IPv6, the 6LoWPAN adaptation layer makes use of header stacking. There are three types of sub-headers which are supported by the 6LoWPAN: *mesh addressing header*, *fragmentation header* and *compression header*. The header

stack is simple to parse and support stateless compression. Each type of sub-header is added only when needed. The fragmentation header is not added for small datagrams, which indicates that a single frame carries the entire payload. Similarly, the mesh header is not added when 6LoWPAN frames are delivered over a single hop radio, since the path source and destination are identical in the link layer header. Figure 2.6 shows typical header stacks and detail for each sub-header.

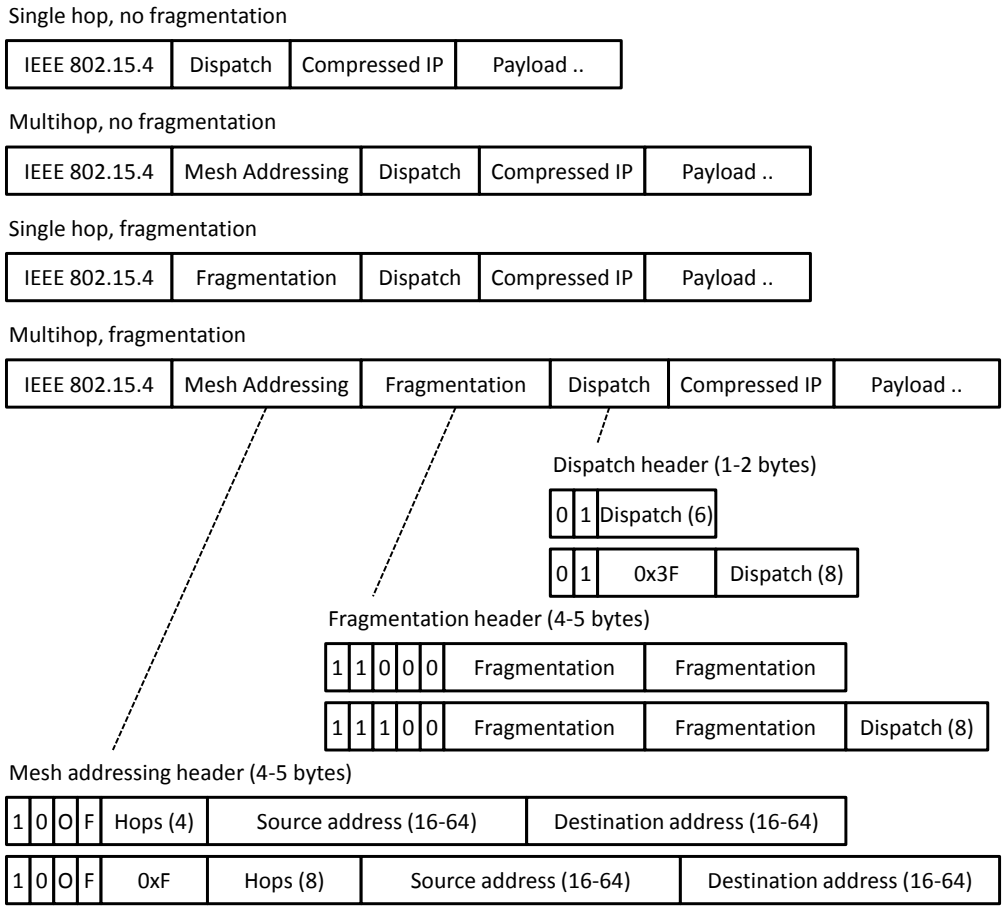

Figure 2.6: 6LoWPAN header stack [40].

2.3 Applications of WSN

The applications of WSN can be categorised into military, environment, home, agriculture and commercial areas [2]. Examples of WSN implementation for military purposes include monitoring, tracking and surveillance of borders; in industry it can be used for factory instrumentation; in a large city it can monitor traffic density and road conditions; in engineering it can monitor building structures; in the environment it can monitor forests, oceans, precision agriculture etc. The next section will explain some examples of the implementation of WSN in real

applications.

2.3.1 Forest Fires Applications

Forest fires present a challenge for forest management because they have the potential to be at once harmful and beneficial. On the one hand, forest fires can **destroy large amounts of timber resources and threaten communities**. On the other hand, forest fires are a natural part of the forest ecosystem and are important for maintaining the **diversity and health of the forest**. In Canada, the forest fire season runs from April through to October. The majority of fires covering the largest areas happen in June, July, and August. During a typical year there are over 9,000 forest fires, burning an average of 25 million hectares [ha] or 25 000 km^2 [19]. The number of fires and the area burned can vary dramatically from year to year. Table 2.2 shows the total number of forest fires and the size of the area burned in 2013. The weekly forest fire occurrence for the same year is illustrated in Figure 2.7. Two-thirds of all forest fires are caused by people, while lightning causes the remaining third. Yet, the lightning fires account for over 85% of the area burned in Canada [19]. This is because the lightning-caused fires usually occur at remote areas which are difficult to reach with fire suppression equipment. However, human-caused fires usually start close to communities, where they are reported quickly and are dealt with by local fire crews.

Table 2.2: Statistics of Forest Fires for the Canadian Forest Fires in 2013 [19]

Metric	2013	10 years avg	% Normal
Number	5,780	6,113	88%
Area (ha)	3,647,589	1,875,617	185%

Traditionally, look-out towers located at high points were used to detect forest fires. A person looks for fires using special devices, such as the Forest Fire Modelling Osborne fire finder [32], to determine the location of the forest fire. However, this approach has a few drawbacks due to the unreliability of human observation and the threat to life for forest fire personnel. Because of this, automatic video surveillance systems [21, 51] have been developed and introduced as part of forest fire detection systems. Automatic surveillance systems mainly use cameras and infrared (IR) detectors installed on top of towers. These systems are not suitable for monitoring large areas of forest. For this reason, aeroplanes or Unmanned Aerial Vehicles (UAV) are used for monitoring large forests [107, 12]. In addition, more advanced forest fire detection systems are based on satellite remote sensing.

These existing forest fire detection systems cannot function efficiently during all types of weather conditions. Their success depends on the time of the day,

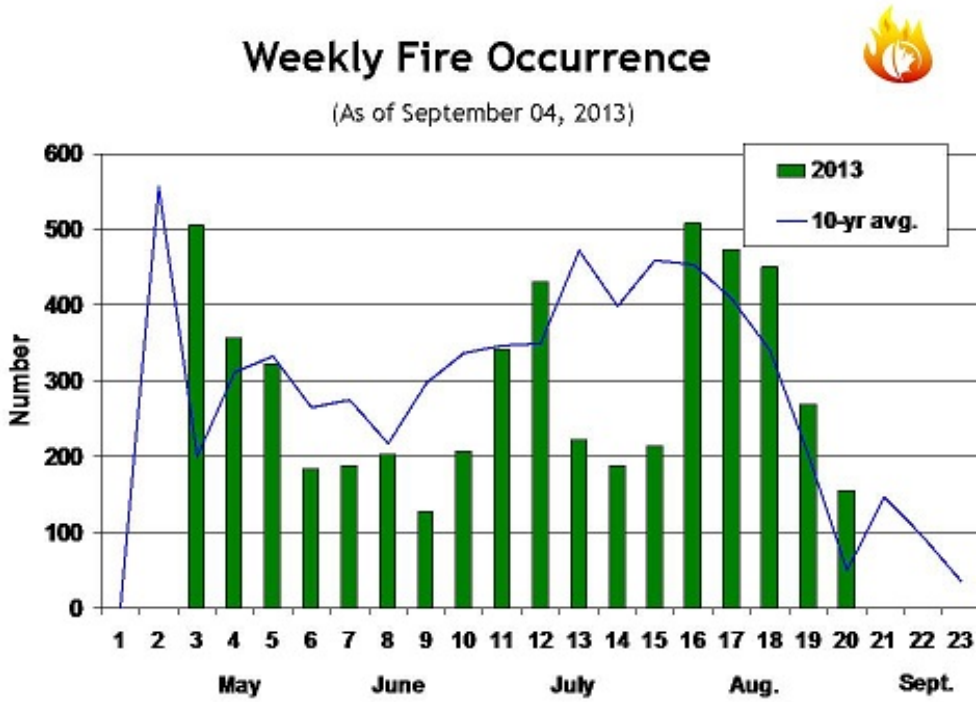

Figure 2.7: Weekly number of Forest Fires in 2013 [19]

the existence of a line of sight and other visibility constraints [43]. WSNs can potentially provide solutions to these problems. If the system can be supported by WSNs, it can make a promising framework for a forest fire detection system. The current sensing modules of WSNs can sense a variety of phenomena including **smoke, temperature and relative humidity** which is helpful in forest fire detection systems. When no fire occurs, the sensor nodes send data in an infrequent manner such as one packet per day, in order to save their energy. If fire is detected, a sensor node must send data rapidly i.e. within a minute or even a second to monitor the unpredictable behaviour of the fire [5]. Moreover, the self-organising feature of sensor nodes to create a network means that the WSN can be easily deployed in a forest.

The most important goals in forest fire surveillance are: the quick and reliable detection and the accurate localisation of the fire [22]. Most forest fires are caught in the early stages before they have chance to grow. In Canada, only 3% of all the forest fires that start each year grow to more than 200 ha in area. However, these fires **cause** for 97% of the total area burned across the country [19]. A WSN can provide timely detection of the forest fire because it is located in close proximity to the phenomenon. Furthermore, a WSN can provide information about the location of the fire, fire growth, and the environmental conditions which are needed by the fire-fighting management [85]. By having this information, fire-fighting staff can

be guided to the critical area to suppress it quickly by utilising the necessary fire-fighting equipment. As a result, there will be a reduction in the number of forest fires that become uncontrolled.

There has been a considerable amount of work carried out to deploy WSNs in forest fire detection systems. Researchers from Civil and Environmental Engineering, University of California [23], have designed a system for wildfire monitoring using WSN and have evaluated the system in a real experiment during prescribed test burns near San Francisco, California. In the experiment, the system was established using 10 sensor nodes with GPS capability which collected **temperature, barometric pressure and humidity data**. The collected data was sent to a base station to be stored on a database server, which could be accessed using a browser-based web application or any other application capable of communicating with the database server. The experiment showed that most of the motes in the burned area were capable of reporting information about the fire event, fire front spreading, increasing temperature, decreasing barometric pressure and decreasing humidity during the fire growth before they became burnt.

FireWxNet [35], a multi-tiered portable wireless system, is introduced for monitoring forest fire environments. The main objective of the system is to support the fire fighting community in safely viewing the fire and measuring the weather conditions to determine the behaviour of the fire rather than its detection. The system uses a tiered structure which consists of directional radios to provide long distance communication, a sensor network to provide environmental data, and web-enabled surveillance cameras to provide visual data. Data gathered from the sensor nodes and the web-enabled cameras are aggregated at a base station which has the capability of providing long distance communication using satellite technology. The sensor network measures **temperature, wind speed, wind direction and relative humidity** periodically every half an hour. However, the cameras monitor the fire zones continuously.

Another forest fire surveillance system based on WSN has been developed to monitor the South Korea Mountains. This system is called Forest-Fires Surveillance System (FFSS) [86]. The developed FFSS consists of WSNs, middleware and a web application. The sensor nodes are attached with the temperature, humidity and smoke sensors. The WSN uses a flat routing protocol based on the minimum cost path forwarding method to deliver data to the sink. The middleware program and the web application analyse the collected data and produce the fire risk level. The FFSS is able to provide a real-time alarm when a forest fire occurs.

2.3.2 Military and Safety Applications

WSN can be used in the military for a number of purposes such as monitoring or tracking enemies and force protection [55]. Unlike the commercial WSN, a tactical military sensor network has different priority requirements for military usage. Especially in the remote large-scale network, topology, self-configuration, network connectivity, maintenance, and energy consumption are the challenges [16].

An example of WSN deployment for military application is the Sensor Information Technology (SensIT) program [52]. This program was sponsored by the Information Technology Office (ITO) and was conducted by the Defence Advanced Research Projects Agency (DARPA). The primary goal of the SensIT program is to develop new software for distributed micro-sensors. The SensIT team pursued two key research and development thrusts. The first thrust is the development of new networking techniques. In the battlefield context, sensor devices or nodes should be ready for rapid deployment, in an ad-hoc fashion, and in highly dynamic environments. The second thrust is networked information processing, for example how to extract useful, reliable, and timely information from the deployed sensor network. This implies leveraging the distributed computing environment created by these sensors for signal and information processing in the network, and for dynamic and interactive querying and tasking the sensor network. The SensIT software was tested in the field, with the assistance of the United States Marine Corps and other service entities.

The Remotely Monitored Battlefield Sensor System (REMBASS) [68] is another implementation of a WSN in a military application. REMBASS is a ground-based battlefield surveillance system designed to detect, locate, classify, and report personnel and vehicular activities in real-time within the area of deployment. It uses remotely monitored sensors placed in position along likely enemy avenues of approach. These sensors respond to infrared energy, magnetic field changes and seismic-acoustic energy to detect enemy activities. The collected data is processed by the sensor nodes to provide detection and classification information, which is sent to the system monitoring set (SMS) wirelessly using radio communication. The messages are demodulated, decoded, displayed, and recorded to provide a time-phased record of enemy activity. REMBASS can be used to complement other manned/unmanned surveillance systems such as ground surveillance radar, unmanned aerial vehicles and night observation devices.

Smart Dust is envisioned to combine sensing, computing, and wireless communication capabilities in an autonomous, dust-grain-sized device [45]. A dense network of Smart Dust should then be able to unobtrusively monitor real-world processes with unprecedented quality and scale. The researchers in [80] had pre-

sented and evaluated a prototype implementation of a tracking system to find the exact location of real-world phenomena (using a toy car as an example) with Smart Dust. The toy car is equipped with an omnidirectional infra-red (IR) light emitter consisting of eight IR LEDs, which is mounted on top of the car. Accordingly, the sensor nodes are equipped with an omnidirectional IR light detector consisting of three IR photo diodes. The system includes techniques for node localisation, time synchronisation, and for message ordering specifically tailored for large networks of tiny Smart Dust devices.

2.3.3 Environmental Applications

Some environmental applications of sensor networks include: **monitoring the environmental conditions that affect crops and livestock; tracking the movements of birds, small animals, and insects; biological, earth, and environmental monitoring in marine, soil, and atmospheric contexts; chemical/biological detection; irrigation; macro-instruments for large-scale earth monitoring and planetary exploration; precision agriculture; meteorological or geophysical research; bio-complexity mapping of the environment; forest fire detection; flood detection; and pollution study** [2].

Habitat monitoring: A WSN architecture was proposed for habitat monitoring on Great Duck Island (GDI), a small island located 15 km south of Mount Desert Island, Maine [59]. The WSN architecture was designed for monitoring the nesting environments and behaviours of Leachs Storm Petrel. In the actual deployment, a WSN was established consisting of 32 Mica nodes. The network monitored underground nesting burrows and surface micro-climates for biologists and ecologists. The data, consisting of temperature, humidity, occupancy, and pressure, was used to correlate nesting patterns with micro-climates. Live data from the sensors can be viewed on the web.

Landslide Detection: The Calita [81] is a WSN infrastructure for landslide monitoring. In May 2009, the infrastructure was deployed in the Emilia Romagna Apennines. The deployment exploited 13 Crossbow Micaz motes with TinyOS software and covered a surface of about 500 m^2. Nodes are embedded with accelerometer sensor boards for capturing slope movements, and environmental boards for the monitoring of ambient parameters like temperature, pressure, humidity and light depth. The sensor nodes send the collected data to the base station, which is cable-connected to a laptop. The laptop sends the data by exploiting File Transfer Protocol (FTP) over a Universal Mobile Telecommunications System (UMTS) connection to the server; the data can be viewed via

a Web graphical user interface. Another landslide detection system using WSN has been designed and deployed at the Anthoniar Colony, Munnar, Idukki (District), Kerala (State), India [78]. The system provides information about the soil condition using selected geophysical sensors: pore pressure transducers, soil moisture sensors, geophones, stain gauges and tilt-meters. The geological sensors were placed inside a sensor column and connected to the wireless sensor node via a data acquisition board. The pilot deployment consists of two sensor columns with ten sensors, deployed in the field along with six wireless sensor nodes.

Flood monitoring: Flooding is a disaster that can cause loss of life, and damage to buildings and other structures including bridges, sewerage systems, roadways, and canals. The cost of damage caused by flooding is dependent on the warning time given before a flood event, making flood monitoring and prediction critical to minimising the cost of flood damage. The GridStix system [39] is an example of the implementation of a WSN in a flood monitoring system. The GridStix sensor platform uses powerful embedded hardware, heterogeneous wireless networking technologies and next generation grid middleware to implement an adaptable WSN. This allows nodes not only to send data to remote fixed grids but also to perform local grid computations to improve the support for flood monitoring and provide more timely warnings to local stakeholders in a range of formats including on-site audio/visual warnings, a public Web site and SMS alerts. For evaluating the system under real world conditions, fifteen GridStix nodes based on the Gumstix embedded computing platform are deployed to perform flood monitoring on a 3 km stretch of the River Ribble in the Yorkshire Dales, UK, which is prone to flooding for much of the year. All of these nodes are equipped with pressure-based depth sensors and a subset is equipped with ultrasound-based flow measurement equipment and cameras for image-based flow measurement. In addition, each node is equipped with 802.11bg1 and Bluetooth network hardware, which are used to provide an ad-hoc communications infrastructure. A single node is equipped with a GPRS uplink and a DVB satellite down-link. Each node is attached with a power solar array to address the energy issue caused by power-consuming devices, which continually powers a GridStix system even during the dark, British winter months.

Active volcano monitoring: A research group from Harvard University began collaborating with volcanologists at the University of North Carolina, the University of New Hampshire and the Instituto Geofísico n Ecuador in order to study active volcanoes. This group was amongst the first to investigate the use of a WSN for the purpose of geophysical studies. In 2004, they deployed a small WSN on Volcán Tungurahua in central Ecuador as a proof of concept using three nodes equipped with microphones collecting continuous data from the erupting volcano

for three days [98]. August 2005, they deployed a larger and more capable network on Volcán Reventador in northern Ecuador [99]. The network consisted of 16 sensor nodes, with each of the sensor nodes equipped with a microphone and seismometer, collecting seismic and acoustic data on volcanic activity. The nodes relayed data via a multi-hop network to a gateway node connected to a long-distance FreeWave modem, providing radio connectivity with a laptop at the observatory. A GPS receiver was used along with a multi-hop time-synchronisation protocol to establish a network-wide timebase. Over the three weeks of the deployment, the network captured 230 volcanic events.

2.3.4 Agriculture Monitoring Systems

The Precision Agriculture Monitor System (PAMS) is an intelligent system which can monitor the agricultural environment of crops and provide services to farmers [57]. The system has been deployed successfully in many places in the Shaanxi province of China such as Yangling, Ansai Apple Park, etc. The main objective of the system was to improve crop output by managing and monitoring the crops' growth period. Examples of monitored environment factors include: air temperature and humidity, soil temperature and moisture, carbon dioxide concentration and illumination intensity. Information about these environmental factors is sent to the control unit to be analysed. The system sends an alarm message to the user when it has detected an abnormal situation affecting the crops growth. Besides this, the system can prevent water wastage.

Another example of a WSN implementation in precision agriculture is the LOFAR-agro project [54]. This project is the first large-scale experiment in precision agriculture in the Netherlands. The project concerns protection of a potato crop against phytophthora, a fungal disease that can spread easily amongst plants and destroy a complete harvest within a large region. The development of the fungus and its associated attack on the crop depends strongly on the climatological conditions within the field. In particular, the humidity and temperature within the crop canopy are important factors in the development of the disease. To monitor these critical factors, a potato field was instrumented with a WSN. A close monitoring of the micro-climate can reveal when the crop is at risk of developing phytophthora and allows the farmer to treat the field, or parts of it, with fungicide only when absolutely needed. This precise treatment saves time, reduces costs, and limits the use of environmentally unfriendly substances as opposed to traditional treatment based on information from a remote weather station.

2.3.5 Commercial Building Applications

WSN could be used in commercial building applications. One example of these applications is a structural health monitoring system designed to seek, detect, and localise damage within buildings, bridges, ships and aircraft. Structural health monitoring is the collection and analysis of the structural response to ambient or forced excitation. Wisden [101] is one example of the implementation of a WSN in structural health monitoring. Wisden collects structural response data from a multihop network of sensor nodes, and displays and stores the data at a base station. In terms of hardware, Wisden used Mica-2 motes with a 16-bit vibration card designed specifically for high-quality vibration sensing. The researchers deployed 10 nodes of Wisden on a test structure resembling the frame of a hospital ceiling. The structure was repeatedly hit with a 2-by-411 for 20 s. The system collected data and displayed it at the base station successfully. Another deployment has also been carried out to further evaluate Wisden system performance. In this deployment, a 14 MicaZ node WSN was deployed on a large seismic test structure used by civil engineers [73]. The experiment indicates that Wisden can deliver time-synchronised structural vibration data reliably across multiple hops with low latencies.

A group of researchers from the University of California has successfully implemented WSN for structural health monitoring on a bridge [74]. They have designed, implemented, deployed and tested a WSN on the 1280 m (4200 feet) long main span and the south tower of the Golden Gate Bridge (GGB). Ambient structural vibrations are reliably measured at a low cost and without interfering with the operation of the bridge. In the GGB WSN deployment, 64 nodes are distributed over the main span and the tower, collecting ambient vibrations synchronously at 1kHz rate. The sampled data is collected reliably over the 46-hop network.

2.4 Constraints in WSN

A WSN has many constraints compared to a traditional computer network. Due to these constraints which are discussed below, the deployment of a WSN needs to be managed carefully to meet the desired performance which depends on the requirements of the applications. The constraints are classified into two categories: sensor node constraints and networking constraints [11].

References

[1] Adel Ali Ahmed and Norsheila Fisal Fisal. Secure real-time routing protocol with load distribution in wireless sensor networks. *Security and Communication Networks*, 4(8):839–869, 2011.

[2] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. Wireless sensor networks: a survey. *Computer Networks*, 38(4):393 – 422, 2002.

[3] Ian F. Akyildiz, Tommaso Melodia, and Kaushik R. Chowdhury. A survey on wireless multimedia sensor networks. *Computer Networks*, 51(4):921 – 960, 2007.

[4] J.N. Al-Karaki and A.E. Kamal. Routing techniques in wireless sensor networks: a survey. *Wireless Communications, IEEE*, 11(6):6 – 28, dec. 2004.

[5] Martin E. Alexander. Calculating and interpreting forest fire intensities. *Canadian Journal of Botany*, 60(4):349–357, 1982.

[6] I. Banerjee, S. Chakrabarti, A. Bhattacharyya, and U. Ganguly. An energy aware routing design to maximize lifetime of a wireless sensor network with a mobile base station. In *Advances in Computing, Communications and Informatics (ICACCI, 2014 International Conference on*, pages 2135–2141, Sept 2014.

[7] M. Bhardwaj, T. Garnett, and A.P. Chandrakasan. Upper bounds on the lifetime of sensor networks. In *Communications, 2001. ICC 2001. IEEE International Conference on*, volume 3, pages 785 –790 vol.3, 2001.

[8] A. Boukerche, R.W.N. Pazzi, and R.B. Araujo. HPEQ a hierarchical periodic, event-driven and query-based wireless sensor network protocol. In *Local Computer Networks, 2005. 30th Anniversary. The IEEE Conference on*, pages 560 –567, November 2005.

[9] Azzedine Boukerche and Anahit Martirosyan. An energy efficient and low latency multiple events' propagation protocol for wireless sensor networks with multiple sinks. In *Proceedings of the 4th ACM workshop on Performance*

evaluation of wireless ad hoc, sensor,and ubiquitous networks, PE-WASUN '07, pages 82–86, New York, NY, USA, 2007. ACM.

[10] Azzedine Boukerche, Richard Werner Nelem Pazzi, and Regina Borges Araujo. A fast and reliable protocol for wireless sensor networks in critical conditions monitoring applications. In *Proceedings of the 7th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems*, MSWiM '04, pages 157–164, New York, NY, USA, 2004. ACM.

[11] David W. Carman, Peter S. Kruus, and Brian J. Matt. Constraints and approaches for distributed sensor network security (final). *DARPA Project report,(Cryptographic Technologies Group, Trusted Information System, NAI Labs)*, 1:1, 2000.

[12] David W. Casbeer, R.W. Beard, T.W. McLain, Sai-Ming Li, and Raman K. Mehra. Forest fire monitoring with multiple small UAVs. In *American Control Conference, 2005. Proceedings of the 2005*, pages 3530–3535. IEEE, 2005.

[13] Alberto Cerpa, Jennifer L. Wong, Louane Kuang, Miodrag Potkonjak, and Deborah Estrin. Statistical model of lossy links in wireless sensor networks. In *Proceedings of the 4th International Symposium on Information Processing in Sensor Networks*, IPSN '05, Piscataway, NJ, USA, 2005. IEEE Press.

[14] Jae-Hwan Chang and L. Tassiulas. Maximum lifetime routing in wireless sensor networks. *Networking, IEEE/ACM Transactions on Networking*, 12(4):609 – 619, August 2004.

[15] Yunxia Chen and Qing Zhao. On the lifetime of wireless sensor networks. *Communications Letters, IEEE*, 9(11):976 – 978, November 2005.

[16] Chee-Yee Chong and S.P. Kumar. Sensor networks: evolution, opportunities, and challenges. *Proceedings of the IEEE*, 91(8):1247 – 1256, August 2003.

[17] W. Colitti, K. Steenhaut, N. De Caro, B. Buta, and V. Dobrota. REST enabled wireless sensor networks for seamless integration with web applications. In *IEEE 8th International Conference on Mobile Adhoc and Sensor Systems (MASS), 2011*, pages 867–872, 2011.

[18] W. Colitti, K. Steenhaut, B. Lemmens, and J. Borms. Simulation tool for wireless sensor network constellations in space. In *International Conference on Ultra Modern Telecommunications Workshops, 2009. ICUMT '09*, pages 1 –5, October 2009.

[19] Canadian wildland fire information system : National wildland fire situation report. http://cwfis.cfs.nrcan.gc.ca/en_CA/datamart, 2013.

[20] Douglas S. J. De Couto, Daniel Aguayo, John Bicket, and Robert Morris. A high-throughput path metric for multi-hop wireless routing. *Wireless Networks*, 11(4):419–434, July 2005.

[21] Eric Den Breejen, Marcel Breuers, Frank Cremer, Rob Kemp, Marco Roos, Klamer Schutte, and Jan S De Vries. Autonomous forest fire detection. In *Proc. 3rd Int. Conf. on Forest Fire Research*, pages 2003–2012, 1998.

[22] Kosmas Dimitropoulos, Kivanc Kose, Nikos Grammalidis, and Enis Çetin. Fire detection and 3D fire propagation estimation for the protection of cultural heritage areas. In *ISPRS Technical Commission VIII Symposium*, volume 38, pages 620–625, 2010.

[23] David M. Doolin and Nicholas Sitar. Wireless sensors for wildfire monitoring. In *Proc. of SPIE Symposium on Smart Structures and Materials*, San Diego, CA, USA, March 2005.

[24] S. Dulman, T. Nieberg, Jian Wu, and P. Havinga. *Trade-off between traffic overhead and reliability in multipath routing for wireless sensor networks*, volume 3. March 2003.

[25] A Dunkels, B. Gronvall, and T. Voigt. Contiki - a lightweight and flexible operating system for tiny networked sensors. In *Local Computer Networks, 2004. 29th Annual IEEE International Conference on*, pages 455–462, Nov 2004.

[26] Adam Dunkels. Rime - a lightweight layered communication stack for sensor networks. In *European Conference on Wireless Sensor Networks (EWSN)*, January 2007, Delft, The Netherlands.

[27] Adam Dunkels, Fredrik Österlind, Nicolas Tsiftes, and Zhitao He. Software-based on-line energy estimation for sensor nodes. In *Proceedings of the 4th workshop on Embedded networked sensors*, EmNets '07, pages 28–32, New York, NY, USA, 2007. ACM.

[28] M. Dwijaksara, Doyoung Chung, Y. Park, Jangseong Kim, and Kwangjo Kim. Secure, fast rebuilding, and energy efficient routing protocol for mission-critical application over wireless sensor networks. In *Proceedings of the Symposium on Cryptography and Information Security, Kokura, Japan*, pages 25–28, 2011.

[29] Deborah Estrin, Ramesh Govindan, John Heidemann, and Satish Kumar. Next century challenges: scalable coordination in sensor networks. In *Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking*, MobiCom '99, pages 263–270, New York, NY, USA, 1999. ACM.

[30] Jin Fan and D.J. Parish. Using a genetic algorithm to optimize the performance of a wireless sensor network. In *The 8th Annual Postgraduate Symposium, The Convergence of Telecommunications, Networking and Broadcasting, Liverpool John Moores University, 28th-29th June*, 2007.

[31] E. Felemban, Chang-Gun Lee, and E. Ekici. MMSPEED: multipath multispeed protocol for QoS guarantee of reliability and timeliness in wireless sensor networks. *Mobile Computing, IEEE Transactions on*, 5(6):738–754, 2006.

[32] J. Fleming and R.G. Robertson. Fire management tech tips: The osborne fire finder. Technical report, Technical Report 0351 1311-SDTDC, USDA Forest Service, 2003.

[33] Omprakash Gnawali. The minimum rank with hysteresis objective function. RFC 6719, September 2012.

[34] E.B. Hamida and G. Chelius. Analytical evaluation of virtual infrastructures for data dissemination in wireless sensor networks with mobile sink. In *Proceedings of the First ACM workshop on Sensor and actor networks*, pages 3–10. ACM, 2007.

[35] Carl Hartung, Richard Han, Carl Seielstad, and Saxon Holbrook. Firewxnet: A multi-tiered portable wireless system for monitoring weather conditions in wildland fire environments. In *Proceedings of the 4th international conference on Mobile systems, applications and services*, pages 28–41. ACM, 2006.

[36] Tian He, John A Stankovic, Chenyang Lu, and Tarek Abdelzaher. SPEED: A stateless protocol for real-time communication in sensor networks. *International Conference on Distributed Computing Systems*, 0:46, 2003.

[37] Wendi Rabiner Heinzelman, Joanna Kulik, and Hari Balakrishnan. Adaptive protocols for information dissemination in wireless sensor networks. In *Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking*, MobiCom '99, pages 174–185, New York, NY, USA, 1999. ACM.

[38] W.R. Heinzelman, A. Chandrakasan, and H. Balakrishnan. Energy-efficient communication protocol for wireless microsensor networks. In *System Sciences, 2000. Proceedings of the 33rd Annual Hawaii International Conference on*, page 10 pp. vol.2, January 2000.

[39] Danny Hughes, Phil Greenwood, Gordon Blair, Geoff Coulson, Paul Grace, Florian Pappenberger, Paul Smith, and Keith Beven. An experiment with reflective middleware to support grid-based flood monitoring. *Concurrency and Computation: Practice and Experience*, 20(11):1303–1316, 2008.

[40] J.W. Hui and D.E. Culler. Extending IP to low-power, wireless personal area networks. *Internet Computing, IEEE*, 12(4):37–45, 2008.

[41] *IEEE Std 802.15.4-2011, IEEE Standard for local and metropolitan area networks - Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)*, 2011.

[42] Chalermek Intanagonwiwat, Ramesh Govindan, and Deborah Estrin. Directed diffusion: A scalable and robust communication paradigm for sensor networks. In *Proceedings of the 6th Annual International Conference on Mobile Computing and Networking*, MobiCom '00, pages 56–67, New York, NY, USA, 2000. ACM.

[43] Sinan Isik, Mehmet Yunus Donmez, Can Tunca, and Cem Ersoy. Performance evaluation of wireless sensor networks in realistic wildfire simulation scenarios. In *Proceedings of the 16th ACM international conference on Modeling, analysis & simulation of wireless and mobile systems*, pages 109–118. ACM, 2013.

[44] Christine Jardak, Krisakorn Rerkrai, Aleksandar Kovacevic, Janne Riihijarvi, and Petri Mahonen. Design of large-scale agricultural wireless sensor networks: email from the vineyard. *Int. J. Sen. Netw.*, 8(2):77–88, August 2010.

[45] Joseph M. Kahn, Randy Howard Katz, and Kristofer S.J. Pister. Emerging challenges: Mobile networking for "smart dust". *Communications and Networks, Journal of*, 2(3):188–196, Sept 2000.

[46] Konstantinos Kalpakis, Koustuv Dasgupta, and Parag Namjoshi. Efficient algorithms for maximum lifetime data gathering and aggregation in wireless sensor networks. *Computer Network : The International Journal of Computer and Telecommunications Networking*, 42(6):697–716, August 2003.

[47] Intae Kang and R. Poovendran. Maximizing static network lifetime of wireless broadcast ad-hoc networks. In *Communications, 2003. ICC '03. IEEE International Conference on*, volume 3, pages 2256 – 2261 vol.3, May 2003.

[48] Jeonggil Ko, Joakim Eriksson, Nicolas Tsiftes, Stephen Dawson-Haggerty, Andreas Terzis, Adam Dunkels, and David Culler. ContikiRPL and TinyRPL: Happy Together. In *Proceedings of the workshop on Extending the Internet to Low power and Lossy Networks (IP+SN2011)*, Chicago, IL, USA, April 2011.

[49] Takuma Koga, Kentaroh Toyoda, and Iwao Sasase. Priority based routing for forest fire monitoring in wireless sensor network. *Journal of Telecommunications & Information Technology*, 2014(3), 2014.

[50] Anis Koubâa, Mário Alves, and Eduardo Tovar. IEEE 802.15.4 for wireless sensor networks: a technical overview. *IPP-HURRAY Technical Report (TR-050702)*, 2005.

[51] E. Kuhrt, J. Knollenberg, and V. Mertens. An automatic early warning system for forest fires. *Annals of Burns and Fire Disasters*, 14(3):151–154, 2001.

[52] S. Kumar and D. Shepherd. SensIT: Sensor information technology for the warfighter. In *Proc. 4th Int. Conf. on Information Fusion*, 2001.

[53] N Kushalnagar, G Montenegro, C Schumacher, et al. IPv6 over low-power wireless personal area networks (6LoWPANs): overview, assumptions, problem statement, and goals. *RFC4919, August*, 10, 2007.

[54] K. Langendoen, A. Baggio, and O. Visser. Murphy loves potatoes: experiences from a pilot sensor network deployment in precision agriculture. In *Parallel and Distributed Processing Symposium, 2006. IPDPS 2006. 20th International*, page 8 pp., april 2006.

[55] Sang Hyuk Lee, Soobin Lee, Heecheol Song, and Hwang-Soo Lee. Wireless sensor network design for tactical military applications : Remote large-scale environments. In *Military Communications Conference, 2009. MILCOM 2009. IEEE*, pages 1–7, Oct 2009.

[56] P. Levis, T. Clausen, J. Hui, O. Gnawali, and J. Ko. The Trickle Algorithm. RFC 6206 (Proposed Standard), March 2011.

[57] Shining Li, Jin Cui, and Zhigang Li. Wireless sensor network for precise agriculture monitoring. In *Intelligent Computation Technology and Automation*

(ICICTA), 2011 International Conference on, volume 1, pages 307 –310, march 2011.

[58] S. Lindsey and C.S. Raghavendra. PEGASIS: Power-efficient gathering in sensor information systems. In *Aerospace Conference Proceedings, 2002. IEEE*, volume 3, pages 3–1125 – 3–1130 vol.3, 2002.

[59] Alan Mainwaring, David Culler, Joseph Polastre, Robert Szewczyk, and John Anderson. Wireless sensor networks for habitat monitoring. In *Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications*, WSNA '02, pages 88–97, New York, NY, USA, 2002. ACM.

[60] A. Manjeshwar and D.P. Agrawal. TEEN: a routing protocol for enhanced efficiency in wireless sensor networks. In *Parallel and Distributed Processing Symposium., Proceedings 15th International*, pages 2009 –2015, April 2001.

[61] A. Manjeshwar and D.P. Agrawal. APTEEN: a hybrid protocol for efficient routing and comprehensive information retrieval in wireless sensor networks. In *Parallel and Distributed Processing Symposium., Proceedings International, IPDPS 2002, Abstracts and CD-ROM*, pages 195 –202, 2002.

[62] Cecilia Mascolo and Mirco Musolesi. SCAR: context-aware adaptive routing in delay tolerant mobile sensor networks. In *Proceedings of the 2006 international conference on Wireless communications and mobile computing*, IWCMC '06, pages 533–538, New York, NY, USA, 2006. ACM.

[63] V. Michopoulos, Lin Guan, G. Oikonomou, and I. Phillips. DCCC6: Duty cycle-aware congestion control for 6lowpan networks. In *Pervasive Computing and Communications Workshops (PERCOM Workshops), 2012 IEEE International Conference on*, pages 278 –283, March 2012.

[64] Vasilis Michopoulus. *Congestion and medium access control in 6LoWPAN WSN*. PhD thesis, Loughborough University, 2012.

[65] Gabriel Montenegro, Nandakishore Kushalnagar, J Hui, and D Culler. Transmission of IPv6 packets over ieee 802.15.4 networks. *Internet proposed standard RFC*, 4944, 2007.

[66] S.D. Muruganathan, D.C.F. Ma, R.I. Bhasin, and A.O. Fapojuwo. A centralized energy-efficient routing protocol for wireless sensor networks. *Communications Magazine, IEEE*, 43(3):S8 – 13, March 2005.

[67] Donggeon Noh, Dongeun Lee, and Heonshik Shin. Mission-oriented selective routing for wireless sensor networks. In *Communications and Networking in*

China, 2007. CHINACOM '07. Second International Conference on, pages 809 –813, aug. 2007.

[68] Federation of American Scientists. AN/GSQ-187 REMBASS. Internetfromhttp://www.fas.org/man/dod-101/sys/land/rembass.htm., July 2011.

[69] George Oikonomou and Iain Phillips. Experiences from porting the contiki operating system to a popular hardware platform. In *Distributed Computing in Sensor Systems and Workshops (DCOSS), 2011 International Conference on*, pages 1–6. IEEE, 2011.

[70] World Meteorological Organization. World: Highest temperature. http://wmo.asu.edu/world-highest-temperature, July 2014.

[71] F. Österlind, A. Dunkels, J. Eriksson, N. Finne, and T. Voigt. Cross-level sensor network simulation with cooja. In *Proceedings of The 31st IEEE Conference on Local Computer Networks, 2006*, pages 641 –648, November 2006.

[72] Fredrik Österlind, Joakim Eriksson, and Adam Dunkels. Cooja timeline: a power visualizer for sensor network simulation. In *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*, pages 385–386. ACM, 2010.

[73] Jeongyeup Paek, K. Chintalapudi, R. Govindan, J. Caffrey, and S. Masri. A wireless sensor network for structural health monitoring: Performance and experience. In *The Second IEEE Workshop on Embedded Networked Sensors (EmNetS-II), 2005*, pages 1 – 10, May 2005.

[74] Shamim N. Pakzad, Gregory L. Fenves, Sukun Kim, and David E. Culler. Design and implementation of scalable wireless sensor network for structural monitoring. *Journal of Infrastructure Systems*, 14(1):89–101, 2008.

[75] R.W.N. Pazzi and A. Boukerche. Mobile data collector strategy for delay-sensitive applications over wireless sensor networks. *Computer Communications*, 31(5):1028–1039, 2008.

[76] Han Peng, Zhou Xi, Li Ying, Chen Xun, and Gao Chuanshan. An adaptive real-time routing scheme for wireless sensor networks. In *The 21st International Conference on Advanced Information Networking and Applications Workshops, 2007, AINAW '07*, volume 2, pages 918–922, 2007.

[77] M. Petrova, J. Riihijarvi, P. Mahonen, and S. Labella. Performance study of IEEE 802.15.4 using measurements and simulations. In *Wireless Communications and Networking Conference, 2006. WCNC 2006. IEEE*, volume 1, pages 487 –492, April 2006.

[78] Maneesha V. Ramesh. Real-time wireless sensor network for landslide detection. In *Third International Conference on Sensor Technologies and Applications, 2009. SENSORCOMM'09*, pages 405–409. IEEE, 2009.

[79] H. Rangarajan and J.J. Garcia-Luna-Aceves. Reliable data delivery in event-driven wireless sensor networks. In *Ninth International Symposium on Computers and Communications, 2004. Proceedings. ISCC 2004*, volume 1, pages 232–237 Vol.1, June 2004.

[80] Kay Römer. Tracking real-world phenomena with smart dust. In *Wireless Sensor Networks*, volume 2920, pages 28–43. Springer Berlin / Heidelberg, 2004. 10.1007/978-3-540-24606-0_3.

[81] Alberto Rosi, Matteo Berti, Nicola Bicocchi, Gabriella Castelli, Alessandro Corsini, Marco Mamei, and Franco Zambonelli. Landslide monitoring with sensor networks: experiences and lessons learnt from a real-world deployment. *International Journal of Sensor Networks*, 10(3):111–122, 2011.

[82] C. Schurgers and M.B. Srivastava. Energy efficient routing in wireless sensor networks. In *Military Communications Conference, 2001. MILCOM 2001. Communications for Network-Centric Operations: Creating the Information Force. IEEE*, volume 1, pages 357 – 361 vol.1, 2001.

[83] Sensinode. http://www.sensinode.com/. Accessed May 23, 2011.

[84] Kewei Sha, Junzhao Du, and Weisong Shi. WEAR: a balanced, fault-tolerant, energy-aware routing protocol in WSNs. *Int. J. Sen. Netw.*, 1:156–168, January 2006.

[85] Kewei Sha, Weisong Shi, and O. Watkins. Using wireless sensor networks for fire rescue applications: Requirements and challenges. In *Electro/information Technology, 2006 IEEE International Conference on*, pages 239–244, May 2006.

[86] Byungrak Son, Yong-sork Her, and J Kim. A design and implementation of forest-fires surveillance system based on wireless sensor networks for South Korea mountains. *International Journal of Computer Science and Network Security (IJCSNS)*, 6(9):124–130, 2006.

[87] M. Soyturk and D.T. Altilar. Reliable real-time data acquisition for rapidly deployable mission-critical Wireless Sensor Networks. In *INFOCOM Workshops 2008, IEEE*, pages 1–6. IEEE, 2008.

[88] Alexandru Stan. Porting the core of the Contiki operating system to the TelosB and MicaZ platforms. *Computer Science, International University Bremen, Campus Ring, Bremen, Germany*, 1:28759, 2007.

[89] Čedomir Stefanović, Vladimir Crnojević, Dejan Vukobratović, Lorenzo Niccolai, Francesco Chiti, and Romano Fantacci. Contaminated areas monitoring via distributed rateless coding with constrained data gathering. In *Proceedings of the 6th International Wireless Communications and Mobile Computing Conference*, IWCMC '10, pages 671–675, New York, NY, USA, 2010. ACM.

[90] Sameer Tilak, Nael B Abu-Ghazaleh, and Wendi Heinzelman. A taxonomy of wireless micro-sensor network models. *ACM SIGMOBILE Mobile Computing and Communications Review*, 6(2):28–36, 2002.

[91] T.T. Truong, K.N. Brown, and C.J. Sreenan. Using mobile sinks in wireless sensor networks to improve building emergency response. In *Academy Research Colloquium on Wireless as an Enabling Technology*, 2010.

[92] Tsvetko Tsvetkov. Rpl: Ipv6 routing protocol for low power and lossy networks. *Sensor Nodes–Operation, Network and Application (SN)*, 59:2, 2011.

[93] N. A. Vasanthi and S. Annadurai. Pattern based routing for event driven wireless sensor-actor networks. In *Proceedings of the 1st Amrita ACM-W Celebration on Women in Computing in India*, A2CWiC '10, pages 43:1–43:6, New York, NY, USA, 2010. ACM.

[94] Thiemo Voigt, Joakim Eriksson, Fredrik Österlind, Robert Sauter, Nils Aschenbruck, Pedro J. Marrón, Vinny Reynolds, Lei Shu, Otto Visser, Anis Koubaa, and Andreas Köpke. Towards comparable simulations of cooperating objects and wireless sensor networks. In *Proceedings of the Fourth International ICST Conference on Performance Evaluation Methodologies and Tools*, VALUETOOLS '09, pages 77:1–77:10, ICST, Brussels, Belgium, Belgium, 2009. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering).

[95] C. E. Van Wagner. A simple fire-growth model. *The Forestry Chronicle*, 45(2):103–104, 1969.

[96] John Paul Walters, Zhengqiang Liang, Weisong Shi, and Vipin Chaudhary. Wireless sensor network security: A survey. *Security in distributed, grid, mobile, and pervasive computing*, 1:367, 2007.

[97] Bernd-Ludwig Wenning, Dirk Pesch, Andreas Timm-Giel, and Carmelita Görg. Environmental monitoring aware routing: making environmental sensor networks more robust. *Telecommunication Systems*, 43:3–11, 2010. 10.1007/s11235-009-9191-8.

[98] G. Werner-Allen, J. Johnson, M. Ruiz, J. Lees, and M. Welsh. Monitoring volcanic eruptions with a wireless sensor network. In *Proceeedings of the Second European Workshop on Wireless Sensor Networks, 2005*, pages 108 – 120, jan.-2 feb. 2005.

[99] Geoffrey Werner-Allen, Konrad Lorincz, Matt Welsh, Omar Marcillo, Jeff Johnson, Mario Ruiz, and Jonathan Lees. Deploying a wireless sensor network on an active volcano. *IEEE Internet Computing*, 10:18–25, 2006.

[100] Tim Winter (editor), Pascal Thubert (editor), Anders Brandt, Jonathan Hui, Richard. Kelsey, Philip Levis, Kris Pister, Rene Struik, J. P. Vasseur, and Roger Alexander. RPL: IPv6 Routing Protocol for Low power and Lossy Networks. RFC 6550, March 2012.

[101] Ning Xu, Sumit Rangwala, Krishna Kant Chintalapudi, Deepak Ganesan, Alan Broad, Ramesh Govindan, and Deborah Estrin. A wireless sensor network for structural monitoring. In *Proceedings of the 2nd international conference on Embedded networked sensor systems*, SenSys '04, pages 13–24, New York, NY, USA, 2004. ACM.

[102] M. Younis, A. Lalani, and M. Eltoweissy. Safe base-station repositioning in wireless sensor networks. In *Performance, Computing, and Communications Conference, 2006. IPCCC 2006. 25th IEEE International*, pages 8 pp. –528, apr. 2006.

[103] Yan Yu, Ramesh Govindan, and Deborah Estrin. Geographical and energy aware routing: A recursive data dissemination protocol for wireless sensor networks. Technical report, Technical report ucla/csd-tr-01-0023, UCLA Computer Science Department, 2001.

[104] Marco Zúñiga Zamalloa and Bhaskar Krishnamachari. An analysis of unreliability and asymmetry in low-power wireless links. *ACM Trans. Sen. Netw.*, 3(2), June 2007.

[105] Yuanyuan Zeng and Guilin Zheng. Delay-bounded and robust routing protocol for emergency applications using wireless sensor networks. In *Advanced Computer Control (ICACC), 2010 2nd International Conference on*, volume 4, pages 37 –41, March 2010.

[106] Jerry Zhao and Ramesh Govindan. Understanding packet delivery performance in dense wireless sensor networks. In *Proceedings of the 1st international conference on Embedded networked sensor systems*, SenSys '03, pages 1–13, New York, NY, USA, 2003. ACM.

[107] Gouqing Zhou, Chaokui Li, and Penggen Cheng. Unmanned aerial vehicle (UAV) real-time video registration for forest fire monitoring. In *Geoscience and Remote Sensing Symposium, 2005. IGARSS'05. Proceedings. 2005 IEEE International*, volume 3, pages 1803–1806. IEEE, 2005.