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Multifaceted Optimization of Energy Efficiency for Stationary WSN Applications

Pin Nie

Aalto University

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Multifaceted Optimization of Energy Efficiency for Stationary WSN Applications

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Aalto University
School of Science
Department of Computer Science and Engineering
Data Communications Software

Supervising professor
Professor Antti Ylä-Jääski

Thesis advisor
Doctor Andrey Lukyanenko

Preliminary examiners
Professor Timo Ojala, University of Oulu, Finland
Doctor Nader Moayeri, NIST Maryland, USA.

Opponent
Professor Thomas Peter Plagemann, University of Oslo, Norway

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Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Abstract

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Pin Nie

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Abstract

Stationary Wireless Sensor Networks (S-WSNs) consist of battery-powered and resource-constrained sensor nodes distributed at fixed locations to cooperatively monitor the environment or an object and provide persistent data acquisition. These systems are being practiced in many applications, ranging from disaster warning systems for instant event detection to structural health monitoring for effective maintenance. Despite the diversity of S-WSN applications, one common requirement is to achieve a long lifespan for a higher value-to-cost ratio. However, the variety of WSN deployment environments and use cases imply that there is no silver bullet to solve the energy issue completely.

This thesis is a summary of six publications. Our contributions include four energy optimization techniques on three layers for S-WSN applications. From the bottom up, we designed an ultra-low power smart trigger to integrate environment perceptibility into the hardware. On the network layer, we propose a reliable clustering protocol and a cluster-based data aggregation scheme. This scheme offers topology optimization together with in-network data processing. On the application layer, we extend an industrial standard protocol XMPP to incorporate WSN characteristics for unified information dissemination. Our protocol extensions facilitate WSN application development by adopting IMPS on the Internet. In addition, we conducted a performance analysis of one lightweight security protocol for WSNs called HIP Diet Exchange, which is being standardized by IETF. We suggested a few improvements and potential applications for HIP DEX.

In the process of improving energy efficiency, we explore modular and generic design for better system integration and scalability. Our hardware invention can extend features by adding new transducers onboard. The clustering protocol and data aggregation scheme provides a general self-adaptive method to increase information throughput per energy cost while tolerating network dynamics. The unified XMPP extensions aim to support seamless information flow for the Web of Things. The results presented in this thesis demonstrate the importance of multifaceted optimization strategy in WSN development. An optimal WSN system should comprehend multiple factors to boost energy efficiency in a holistic approach.

Keywords Energy Efficiency, Data Aggregation, Clustering, Security, XMPP

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Preface

The six years research life of my doctoral study is truly a winding road, far beyond my initial estimation of the difficulty it might be in pursuit of a Ph.D degree in Aalto University. Lack of instructions, technical frustrations, family issues and the abrupt change of my research topic caused me a lot of trouble in maintaining a high level of motivation for persisting in my research. However, the generous support from good colleagues and friends resulted in this thesis possible as a happy ending.

Since 2006 when I started my doctoral study in an industry-sponsored project on security, my supervisor Prof. Antti Ylä-Jääski and a close friend Dr. Zhirong Yang have constantly fuelled me with valuable suggestions and great patience. Their help was not limited to professional guidance, but also includes development of hobbies which helped to enhance my vision and thinking. During these years, they showed me the spirit of supportive leadership. A friend in need is a friend indeed.

Later, I got acquainted with a few friendly Finnish colleagues who demonstrated the value of *Sisu*, a nice quality of Finnish culture. Miika Komu, Timo Kiravuo and Sanna Suoranta are three outstanding examples. They spent much time and effort on shaping my stubborn nature to be more open-minded. Miika reviewed some of my papers and gave a lot of good advice. Timo and Sanna showed a positive attitude and wisdom in their teaching courses. Gestures and drawing largely overcame language barrier during our intense discussions.

I would like to express my gratitude to my instructors Dr. Jaakko Kangasharju, Dr. Tancred Lindholm and Dr. Andrey Lukyanenko. Despite the short time of our cooperation, they profoundly enlightened me in conducting strict scientific research. A small compromise in some small parameter might possibly undermine the whole experiment. In addition, Prof. Jukka Manner, Prof. Tuomas Aura and Prof. Jukka K. Nurminen provided me useful advice on correct positioning and clear description in compiling my publications. I am also thankful to all ISMO project partners. It is my good luck to work with some brilliant researchers from different areas on a multidisciplinary subject. A Chinese saying goes that a drop can obtain substantial nutrition in a big pool.

Last but not the least, I highly appreciate the great help from our lab secretary Soili Adolfsson for her kind encouragement and endless effort in organizing our daily issues. The same thanks to my co-authors, friends and parents, particularly my office mate and room mate Zhihua Jin. Your support gave me the dedication to reach the objective eventually.

Helsinki, December 11, 2012,

Pin Nie

NO PAIN NO GAIN --- 成就来之不易

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I Pin Nie and Zhihua Jin. Morph: Cognitive Clustering for Wireless Sensor Networks using Smart Materials. In *European Workshop on Structural Health Monitoring (EWSHM'10)*, Proceedings of the 5th European Workshop on Structural Health Monitoring, Sorrento, Italy, June 2010.

II Pin Nie, Juho Salminen, Lukyanenko Andrey and Antti Ylä-Jääski. Smart Trigger for Ultralow Power and Time Critical WSN Applications. In *International Conference on Internet of Things (iThings'12)*, Proceedings of IEEE International Conference on Internet of Things, Besançon, France, November 2012.

III Pin Nie, Juho Vähä-Herttua, Tuomas Aura and Andrei Gurtov. Performance Analysis of HIP Diet Exchange for WSN Security Establishment. In *International Symposium on QoS and Security for Wireless and Mobile Networks (Q2SWinet'11)*, Proceedings of the 7th ACM International Symposium on QoS and Security for Wireless and Mobile Networks, Miami, USA, October 2011.

IV Pin Nie, Zhihua Jin and Yi Gong. Mires++: A Reliable, Energy-aware Clustering Algorithm for Wireless Sensor Networks. In *International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM'10)*, Proceedings of the ACM 13th International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems, Bodrum, Turkey, October 2010.

V Pin Nie and Bo Li. A Cluster-based Data Aggregation Architecture in WSN for Structural Health Monitoring. In *International Wireless Communications and Mobile Computing Conference (IWCMC'11)*, Proceedings of the 7th International Conference on Wireless Communications and Mobile Computing, Istanbul, Turkey, July 2011.

VI Pin Nie and Jukka K. Nurminen. Integrate WSN to the Web of Things by using XMPP. *International Conference on Sensor Systems and Software (S-Cube'12)*, Proceedings of the 3rd International Conference on Sensor Systems and Software, Lisbon, Portugal, June 2012.

Author's Contributions

Publication I: The author proposed a new clustering mechanism for WSN based on smart materials. He described the principle and the advantages of this novel self-adaptive topology control in the paper. Zhihua Jin contributed to the idea development and the writing of the manuscript.

Publication II: The author proposed a new hardware trigger to integrate environment perceptibility on sensor nodes. He developed the prototype with Juho Salminen, who implemented smart trigger. The author formulated the performance gain in terms of high energy efficiency and low detection latency. Dr. Andrey Lukyanenko created the evaluation model and validated the design. Prof. Antti Ylä-Jääski supervised the research.

Publication III: The author conducted performance analysis on the security protocol HIP Diet Exchange for WSNs. He implemented the code with Juho Vähä-Herttua and evaluated energy consumption, latency and the memory overhead of HIP DEX on the real devices. Juho Vähä-Herttua also contributed to the writing. Prof. Tuomas Aura reviewed the manuscript and provided valuable suggestions. Dr. Andrei Gurtov supervised the research.

Publication IV: The author designed the original clustering algorithm. He implemented the prototype with Zhihua Jin and guided Yi Gong in the simulation. The author conducted data analysis, performance evaluation and wrote the entire manuscript.

Publication V: The author created the original architecture and guided Bo Li in the implementation. Both authors set up test cases, collected data and validated the architecture together. The first author wrote the entire manuscript.

Publication VI: The author proposed an effective method to integrate WSN to the Internet based on an open industrial standard protocol XMPP. He designed the prototype and elaborated the protocol extensions in the manuscript. The author wrote the entire manuscript. Prof. Jukka K. Nurminen reviewed the paper and provided valuable suggestions.

List of Abbreviations

AES	Advanced Encryption Standard
ASIC	Application Specific Integrated Circuit
BCH	Backup Cluster Head
CMAC	Cipher-based Message Authentication Code
CIA	Confidentiality, Integrity and Availability
CH	Cluster Head
CM	Cluster Member
DoS	Denial of Service
ECC	Elliptic Curve Cryptography
ECDH	Elliptic Curve Diffie-Hellman
E2E	End-to-End
FPGA	Field Programmable Gate Array
HIP DEX	Host Identity Protocol Diet Exchange
IETF	Internet Engineering Task Force
IMPS	Instant Messaging and Presence Service
IoT	Internet of Things
MAC	Medium Access Control
M2M	Machine-to-Machine
NiMH	Nickel-Metal Hydride battery
PDR	Packet Delivery Ratio
Pub/Sub	Publish-Subscribe Communication Paradigm
QoI	Quality of Information
RSSI	Radio Signal Strength Indicator
SIM	Subscriber Identity Module
SN	Sink Node
SHM	Structural Health Monitoring
S-WSN	Stationary Wireless Sensor Network
TDMA	Time Division Multiple Access

VANET	Vehicular Ad-hoc Network
WoT	Web of Things
XMPP	Extensible Messaging and Presence Protocol

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1. Introduction

Wireless Sensor Network (WSN) technology [62, 6, 65] has been under active research and development since the 1980s. Recent advances in microelectromechanical systems (MEMS) and radio technology have led to significant expansion of WSN applications [39, 21]. New visionary concepts such as the Internet of Things (IoT) [10], the Web of Things (WoT) [27] and Machine-to-Machine (M2M) [17] are proposed to achieve large scale interconnected networks. As a key component in IoT/WoT/M2M, WSN has received extensive attention from many sectors such as urban planning, traffic control, environmental monitoring, personal health care, disaster warning and so on.

Among numerous WSN applications, stationary WSN (S-WSN) [54] is one major category for long term usage and wide coverage. In S-WSN applications, sensor nodes are carefully positioned at or near the predetermined locations to capture the right signals and events quickly. Based on the characteristics of the object or the environment, the deployment plan is usually optimized to cover a larger area with fewer nodes. With no doubt, the longer lifespan of a WSN system can sustain the higher value it produces. Consequently, more applications and users will adopt WSN technology. However, how to improve energy efficiency for a long lifespan is a big challenge and remains an open question.

Powered by the battery, a wireless sensor node will be depleted sooner or later depending on the workload. In contrast to wired infrastructure and mobile devices, S-WSNs are supposed to work autonomously in unattended manner for months or even years before the replenishment of a new battery or nodes is required. In the applications where the deployment environment is difficult to access, there will be no replenishment at all. A number of software and hardware optimization techniques have therefore been developed to increase energy efficiency. These optimizations include low-power hardware components [4, 9], efficient scheduling and routing protocols [61, 7, 5], collaborative networking architectures [30, 38], lightweight security establishment [53, 47, 56], energy harvesting modules [48, 25] and seamless information dissemination [32, 26, 13].

Due to the variety of application environments, no single solution can extend the short active time of wireless sensor nodes to a system lifetime of years or decades without any trade-off or limits. For example, duty cycled MAC protocols have an inherent trade-off between energy preservation and system reactivity. Higher energy saving implies slower response. Energy harvesting technologies heavily rely on the deployment environment. The performance can reach optimal level only when the surrounding condition is satisfactory. Sufficient ambient light is required for solar panels, persistent wind is necessary for windmills, and vibration harvesters are only effective to a narrow vibration frequency band (i.e., resonant frequency). Moreover, the conditions of harvesting energy may differ from one node to another in a WSN. Thus, it is difficult to compensate for the battery draining from periodical sensing and data acquisition in long term S-WSN applications over a large scale.

As a result of limited effectiveness of any single solution, the improvement of energy efficiency in S-WSN is a multidisciplinary subject. Multifaceted optimization aggregates multiple techniques over several layers to achieve an optimal vertical integration on the resource constrained nodes. Many researchers believe that the hardware development on WSN will soon catch up and loosen the resource limits on these tiny devices. This is a controversial perspective because the hardware upgrade raises the cost and reduces the scalability of the whole S-WSN system. Considering that the scale of a typical S-WSN application in the global market is often counted in thousands of nodes or even in millions, one extra dollar on a single node will lead to big overall cost in mass production. Essentially, the expensive hardware violates the principle of developing low cost and low power WSN for pervasive applications. In practice, a high-end sensor node is a high-value target for theft, vandalism and attracts attacks. Furthermore, a lagging development in battery technology denotes that batteries can no longer cope with advanced hardware components that usually consume a lot of energy.

To sum up, we think that S-WSN application development cannot rely on a single technique for a better future. On the contrary, multifaceted optimization with cross-layer design is the most viable method to significantly prolong the system lifespan. The following sections describe the objectives of this thesis and summarize the author's contributions.

1.1 Objectives and Methodology

WSN applications can be mainly divided into two categories. One category is stationary WSN applications in which all sensor nodes are deployed at fixed places throughout their lifetime. A number of WSN monitoring applications belong to this category, such as environmental monitoring, structural health monitoring, building surveillance and disaster warning systems. The other category is mobile WSN (M-WSN) applications [23] in which mobile nodes are involved in certain tasks such as mobile gateway for routing and/or data gathering [52]. Mobile WSN also includes scenarios where the whole network is composed of moving nodes, e.g., VANET [41, 35]. Compared with S-WSN, M-WSN has to consider more dynamical factors (e.g., mobility models and roaming nodes) and explore opportunistic data transmission mechanisms. The energy consumption in M-WSN applications is significantly higher than in S-WSN applications due to the moving nodes and adaptive communications to deal with topology changes.

In this thesis, we studied the first category of WSN systems, namely S-WSN applications. Within this context, our objectives focused on answering three important questions for energy optimization as follows:

1. What are the key components in S-WSN applications for the optimization of energy efficiency?

2. How to optimize these key components in a generic and modular manner for scalable applications and flexible integration?

3. How to quantitatively evaluate the energy efficiency of a S-WSN system that may be used in different cases?

In order to answer the first question, we identified five general aspects of optimizing energy efficiency based on the common characteristics of S-WSN applications. Figure 1.1 illustrates our layered model on energy optimization and provides an overall picture of this thesis. The essential idea was to provide an optimal interface between cyberspace and the

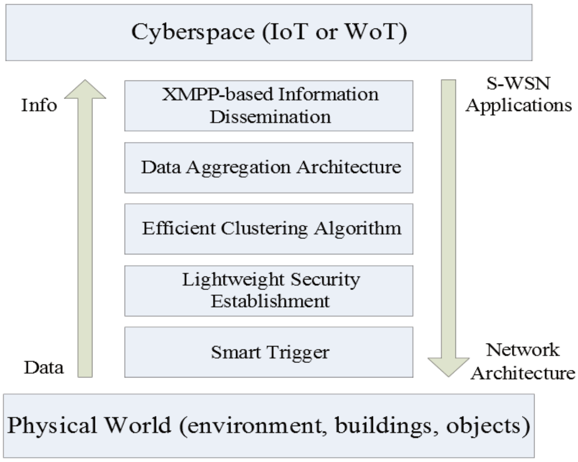

Figure 1.1. Layered model of energy optimization for S-WSN applications

physical world. This interface consists of five layers and fulfills two objectives. From the bottom up, we aggregated raw data from the sensors and extracted useful information for the applications. From the top down, we prioritized application requirements and optimized network architecture accordingly. This approach contained a continuous cycle to interpret physical objects and phenomena in an efficient network architecture overseen by the S-WSN application.

In order to answer the second question, we take scalability and flexibility into account at each layer in our design. A customized solution often achieves good performance on limited applications at a big cost. A rigid module makes it difficult to be integrated and extended in the future. Therefore, we insisted on generic and modular design in our hardware trigger and software algorithm and architecture. The five layers could be used separately or combined together. The third question posed challenges in validating our design in practice. The performance evaluation of energy efficiency should provide reference numbers to demonstrate the effectiveness of the optimization techniques. Meanwhile, we also compared with other solutions to understand the advantages and disadvantages of our design in different scenarios.

Since our research was on a multidisciplinary subject and covered five aspects, we employed multiple methods in our methodology including mathematical modeling and simulations, prototyping and implementation, practical performance evaluation, statistic data analysis, iterative refining and validation. Figure 1.2 gives an overview of our research process.

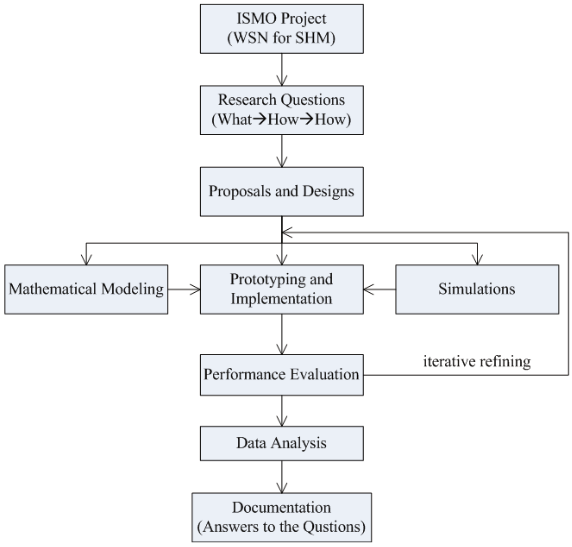

Figure 1.2. Research methodology for energy optimization in S-WSN applications

We used either mathematical modeling or network simulations to estimate the energy consumption of a large S-WSN system. Prototyping and implementation was necessary to obtain experimental measurements of energy consumption on real sensor nodes. However, due to the limited budget, this part was carried out on a small scale with a few devices. The performance evaluation validated our designs and implementations. Programming and circuit development took a long time to debug and polish. The refining process iterated until we removed mistakes and got correct data for the next step. The data analysis gives quantitative results and generates plots of energy cost for the target scenarios. By comparing the results, we reached appropriate conclusions on the lessons to be learnt and answered the three research questions above.

1.2 Contributions

This thesis is a summary of six publications which are appended at the end. The contribution of these publications is briefly described below. More details are discussed in the Chapter 3.

Publication I proposes a novel cognitive clustering mechanism for WSN by using smart materials. The idea is to use various smart materials to detect different external events and switch on/off the sensor node automatically. Based on the predefined threshold settings of the target environmental conditions, cognitive clustering creates a self-adaptive topology for WSN. Compared with the traditional duty cycled monitoring process, this reactive mechanism excels in energy efficiency and short latency in ad-hoc mode when the WSN application does not require network synchronization.

Publication II presents the prototyping and implementation of the smart trigger and demonstrates its ultra-low power consumption in both simulations and experiments. The mathematical model confirms the significant improvement of energy efficiency for S-WSN equipped with a smart trigger. This new hardware module can be developed as an external interrupt source to complement event detection.

Publication III studies a lightweight security protocol (HIP DEX) for WSN to establish a hop-by-hop secure connection between two nodes. This protocol is being standardized by IETF. Thus, our performance analysis of HIP DEX with real devices is valuable to demonstrate its actual efficiency on resource constrained sensor nodes and to reveal the potential weaknesses for further improvement.

Publication IV presents a reliable, energy-aware clustering algorithm for WSN. The clustering algorithm is based on an existing research work called *Mires* [57]. By leveraging this publish/subscribe (Pub/Sub) middleware [20, 55], we built two-level clusters in WSN to optimize the network topology. Cluster heads (CH) aggregate data from local cluster members (CM) and load measurements into fewer packets for multi-hop, long-distance transmissions to the sink node (SN). The role of CH circulates among all participants in the cluster to evenly distribute tasks and to recover from node failure. Consequently, the cluster network saves considerable energy by reducing redundant transmissions and also improves system reliability.

Publication V proposes a cluster-based data aggregation architecture in WSN for Structural Health Monitoring (SHM). This work extends the previous clustering algorithm and builds flexible data aggregation techniques in the cluster network. By performing various filters, data summary and feature extraction on CMs and CHs, we condense raw data into useful information in the network. Therefore, energy efficiency increases along with higher information throughput.

Publication VI describes a scalable and flexible XMPP sensor bot for WSN integration into the WoT. We design two lightweight XMPP extensions for sensor node representation and tasks configuration. By taking advantage of uniform XML data format and wide deployment of XMPP networks, our program bridges the gap between WSN and the Internet. This strategy enables seamless information flow and eliminates potential bottlenecks for protocol translation in the middle.

Although we aim at S-WSN applications, our contribution is not limited to S-WSN applications and can be also used in M-WSN applications, particularly for energy optimization. Modular smart trigger and generic XMPP extensions are useful tools to detect events and interface WSN systems to the IoT/WoT/M2M. Our clustering protocol and data aggregation architecture provides a general platform for WSN application development.

1.3 Structure of the Thesis

The rest of the thesis is organized as follows. Chapter 2 provides an overview of stationary WSN applications, key components for energy optimization, research challenges and practical concerns. Chapter 3 discusses the original contributions and main results of the thesis. Finally, Chapter 4 concludes with the lessons from our work and suggests possible directions for future development.

2. An Overview of Energy Efficiency in Stationary WSN Applications

This chapter provides a systematic overview of S-WSN applications, describes research challenges and addresses practical concerns that are often overlooked in theoretical study, and identifies three key components for energy optimization. We also briefly introduce our research framework project (ISMO) [2] as an example of S-WSN applications for background study. More related references are listed in our publications based on different subjects.

2.1 Stationary WSN Applications

To find out the key components for energy optimization, we should firstly study S-WSN applications [39, 54]. The common features and application requirements decide what and how to optimize in practice. In the definition of S-WSN, there are two basic properties, namely wireless and stationary. Wireless means there is no power cable attached to any sensor nodes, which are connected via wireless communication. Thus, we did not consider those WSN applications which are connected to the power grid, such as smart homes and logistics. The reason for this consideration is that the power supply is one fundamental decision factor in designing electronics and networking systems. In the WSN applications which are powered by the grid, sensor nodes are free to upgrade hardware and extend lifespan without any worry about energy shortages. Furthermore, considering that data and electricity can be carried on the same cable infrastructure (e.g., power line communication and power over ethernet), wireless becomes a weak advantage in these applications except for remote control and sensing. After all, the cost of cable installation and maintenance diminishes the benefit of wireless communication which is powered by a wired infrastructure.

The second property of S-WSN applications is the stationary nature of the network which does not contain moving nodes that can either move by themself or are attached on animals or mobile objects. However, S-WSN can be used to monitor or track moving objects such as intrusion detection and building surveillance. In addition, the deployment of sensor nodes in S-WSN applications include both 2D surface and 3D space. Thus, energy optimization should consider several factors in the actual deployment scheme, such as sensing range and transmission range. Based on the types of the monitored objects, I divided S-WSN applications into three categories and enumerated typical use cases as follows.

The first category is environmental monitoring and we consider three types of environments: land, water and urban area. Sky and outer space are not included due to the lack of sensor node deployment so far. Each type of environmental monitoring develops many applications for different purposes. Land monitoring includes disaster warning systems [51] (e.g., seismic, landslide, flood, volcanic eruption), forest fire and illegal deforestation detection [31], precision agriculture [36] (e.g., automated irrigation, fertilization and pest control) and grazing [40], atmospheric monitoring and so on. Water monitoring includes ocean current monitoring [8], tsunami warning systems, underwater acoustic monitoring, and various hydrological monitoring (i.e., water quality). Urban area monitoring includes traffic control, air quality monitoring, sewage monitoring systems and counter-terrorism surveillance in public sites. The diversity of environmental monitoring applications implies a considerable number of types of measurements that contain rich context information and favor in-network data aggregation for higher energy efficiency and information throughput. Particularly, time and location are two general conditions for data correlation in order to group various measurements and to analyze the influence and severity of the event locally.

The second category is structural monitoring [64] which includes buildings, bridges, tunnels, dams, machinery platforms, etc. The applications mainly focus on intrusion detection and building surveillance, search and rescue in emergency management, and structural health monitoring [42, 43, 37] (e.g., damage and fault detection, degradation evaluation). Figure 2.1 provides an example of an SHM application for bridge monitoring. This intelligent structural health monitoring system consists of four major components and operates at three levels to fulfill two objectives. In structural monitoring applications, images and high sampling rate time-

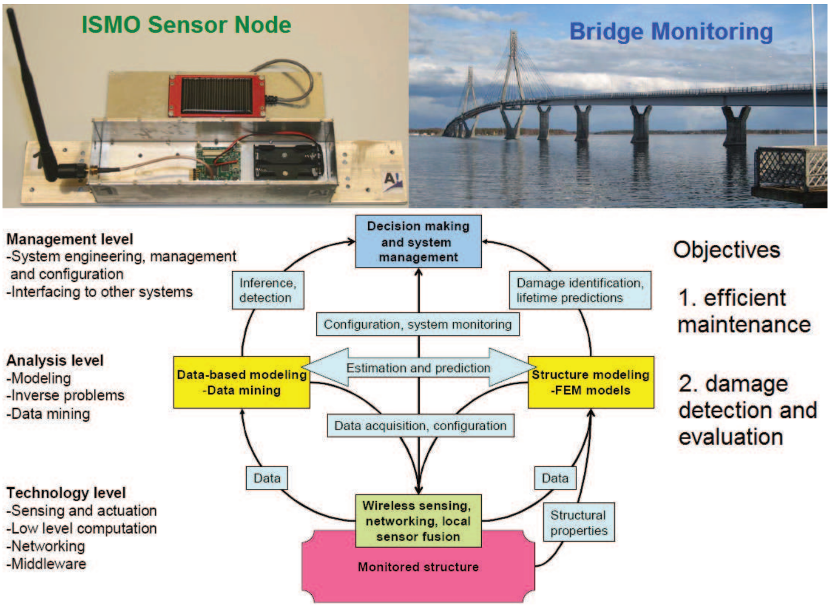

Figure 2.1. Intelligent structural health monitoring system [2]

series signals consume too much energy to be transmitted in the raw data format periodically. Hence, embedded data processing algorithms are necessary to save energy for a long lifespan. Two typical examples are feature extraction (e.g., acoustic signal analysis [63], goertzel algorithm and transmissibility on vibration signals [60], motion detection on video feeds) and filtering techniques (e.g., threshold/deviation/Quality of Information (QoI)/semantic/location filters). Furthermore, the compression (e.g., Huffman coding) of serial signals makes it more efficient to transmit chunky data. It is worth noting that time synchronization is critical to the accuracy of the results in frequency-domain analysis and the connectivity of the TDMA-scheduled multi-hop network in these S-WSN applications.

The third category is smart objects which retrofits existing infrastructure for real-time status observation to fulfill three objectives: process or management optimization, safety enhancement to prevent operational errors, and value-added features. The applications include trash bins monitoring for optimal garbage collection, smart meters for precise resources (e.g., water, natural gas, electricity) allocation, tanks or containers monitoring for on-time refilling, gate open/close alarm, queue ticketing system for service reservation and so on. Real-time responsiveness and maintenance-free operation are the core value of these applications. However, real-time may have different latency requirement depending on the application, ranging from seconds to hours. Maintenance-free operation means deploy once, run for years. Therefore, dynamic transmission based on periodical sampling is one common technique to piggyback consecutive measurements for efficient monitoring without a trade-off on real-time responsiveness.

To sum up the features and requirements of the seven promising S-WSN applications above, I created an evaluation table with five important metrics. They were system lifespan (months/years), data transport(packet/stream), response latency (seconds/minutes), network scale ($< or > 100$) and energy harvesting adoption (yes/no). The evaluation scale of the metrics is based on empirical settings and technical limits. System lifespan indicates the typical length of usage before the next maintenance or service if there is any. Data transport implies whether all measurements during one transmission period at one node can be encapsulated into a single packet or must be pipelined via data streaming. Due to the packet loss in wireless transmission, multi-hop relaying latency, packets fragmentation and limited device memory, data streaming is much more difficult than sending separate packets to achieve high reliability in the implementation. The packet payload size is limited to the maximum MAC frame size [24], including mandatory packet headers. Response latency implies the maximum allowable delay of the measurement delivery. It is a direct indicator of real-time, safety-critical applications. Network scale suggests an appropriate network topology for the S-WSN application. A network of less than a hundred nodes can either use master-slave and single-hop star topology for small scale applications to simplify routing and synchronization issues, or employ multi-hop structured architecture (e.g., tree, mesh or cluster) for large scale applications to extend coverage. When the network size exceeds a hundred nodes, network partition with multiple sink nodes should be planned to avoid single point of failure and to build security compartments. Moreover, heterogenous wireless technologies should be combined to achieve optimal bandwidth at different levels and efficient network management. Finally, energy harvesting shows the possibility to replenish the battery through the ambient environment. Solar panel and piezoelectric are two major energy sources in our consideration for their adequate power output.

From the evaluation table 2.1 of seven promising S-WSN applications, we can see outdoor scenarios usually require a long lifespan and consist of many nodes. These are typical assumptions in large-scale persistent

S-WSN Applications	System Lifespan	Data Transport	Response Latency	Network Scale	Energy Harvest
disaster warning	years	packet	seconds	>100	yes
smart objects	years	packet	minutes	>100	no
traffic control	months	stream	minutes	>100	no
intrusion detection	months	stream	seconds	<100	no
precision grazing and agriculture	months	packet	minutes	<100	no
structural health monitoring	months	stream	minutes	<100	no
atmosphere and water monitoring	years	packet	minutes	>100	yes

Table 2.1. Evaluation of seven promising S-WSN applications

monitoring applications due to the difficulty and high cost of accessing the environment regularly. In contrast, urban applications and precision agriculture can leverage regular maintenance every season to replenish batteries. Smart objects are exceptional because its purpose is to optimize existing infrastructure, not add an extra burden of cost and maintenance. Data streaming is required for high sampling rate time-series data collection and/or image-assisted applications. Alternatively, other applications may integrate various sensors on every single node to provide diverse measurements in small packets. This policy increases contextual information for events detection with less battery consumption. For non safety-critical S-WSN applications, response latency is rather loose and can tolerate long delay. One decisive factor in these cases is to make a comparison with the manual observation schedule. If the measurement delivery is much faster (e.g., tenfold) than the manual work, the allowable delay in the S-WSN solution can be in hours or even days. In contrast, safety-critical S-WSN applications do not compromise life risk with any excessive latency. Network scale and energy harvest are limited to the application environment. In general, energy harvesting technology is still too immature to provide reliable energy supply in a harsh environment.

Since the S-WSN applications are largely influenced by budget and intention, the evaluation of the seven S-WSN applications considered common situations in facility applications. Thus, network scale approximates to utility scale, and not just for experimental work. There may be exceptional scenarios in energy harvesting adoption, for example, the traffic control system may attach solar panel on sensor nodes to compensate for battery depletion. However, dust and dirt in urban areas will significantly reduce the energy harvesting efficiency. Thus, we do not take energy harvesting as a widely feasible solution in this case. Nevertheless, WSN is undergoing rapid development, and my evaluation remarks are based on the current state-of-the-art and subject to changes in the future.

2.2 Research Problems and Practical Concerns

S-WSN is a highly multidisciplinary subject including electrical engineering, communication and networking, computer science, software engineering, data mining, etc. Thus, numerous research problems raise in optimizing energy consumption from different perspectives. Here is a short list of active research topics in five major areas from the bottom up:

- Hardware: dynamic voltage scaling and energy recycling in CPU design, dedicated circuits for specific computing (e.g., ASIC and FPGA), low voltage memory, passive transducers, energy harvesting modules and security modules.

- Radio: duty cycle scheduling of active/sleep modes, quick wake-up, frequency channel hopping, transmission power control, adaptive error correction and coding techniques.

- Network: efficient routing protocols, structured network topologies, in-network data aggregation and packet header compression.

- Software: distributed algorithms and parallel computing, battery-aware parameter configuration, adaptive resource allocation, tiny programs (e.g, OS and protocol stack).

- System: power-aware middleware [29], web integration, model-driven data acquisition.

By no means is this list exhaustive, it is simply a snapshot of what is happening and where energy optimization is likely to move forward in S-WSN application development. Meanwhile, a proper selection of energy optimization techniques should consider application-specific characteristics. For example, indoor S-WSN applications which usually feature dynamic environment and multipath routing [49] can achieve a higher packet delivery ratio (PDR). For outdoor large-scale S-WSN applications, it is better to adopt location-aware routing [5, 7] to avoid routing loops and enhance directional route discovery. Note that in S-WSN applications, location information can be preloaded into the program. Thus, the GPS module is not necessary. Despite extensive research, theoretical studies often overlook some important practical concerns in the real world. These ignored factors lead to a huge gap between the projected system lifespan on the paper and the actual duration in practice. I list four major practical concerns in S-WSN applications. They are battery issues [59], antenna deployment, hardware fatigue limits, and moisture condensation.

Battery draining is not linear and its rated capacity can hardly be fully used due to the high cut-off voltage of the electronics, inefficient on-board voltage regulator and thermal effect in electrochemical reaction. Particularly for a tiny low-cost sensor node, premature battery exhaustion is a common fact that results in significant energy loss and a shorter lifetime. When selecting a suitable battery in S-WSN applications, five evaluation metrics should be considered: rechargeability, capacity, voltage supply, discharge stability (i.e., temperature effect) and price. It is extremely difficult to determine a S-WSN system lifespan based on the estimation of battery capacity and discharge characteristics in that application. The reason is that too many factors are interconnected and interact with each other at runtime. For example, higher temperatures lead to lower internal resistance and increase usable battery capacity at the cost of rising self discharge rate and higher heat dissipation. On the contrary, lower temperature causes higher internal resistance and voltage loss. But the battery sustains longer over sleeping cycles in cold conditions with a smaller self discharge rate. In addition to ambient temperature, networking parameters also exert a strong influence, such as sample rate, transmission power and schedule [45].

Nevertheless, opportunities are hiding behind the challenges. Considerable energy gain can be achieved by taking battery issues into account in the design. For example, intermittent short transmissions with optimal transmit power leverage battery recovery effect and obtain a much longer operational lifetime than continuous streaming at full transmit power. Given the current state-of-the-art in battery technology, it is better to schedule periodical transmission for outdoor long-term S-WSN applications during noon time when the daily temperature reaches a peak and use non-rechargeable lithium-ion batteries [19]. A rechargeable battery connected with energy harvesting module is optional at a higher price.

For indoor maintainable S-WSN applications, it is better to use rechargeable alkaline batteries (e.g., NiMH) for a lower cost-performance ratio. We must emphasize that battery takes a big proportion in the total cost of a sensor node and causes severe environmental problems due to the large volume of waste.

The second practical concern is antenna deployment. A good radio antenna increases the efficiency and performance of WSN communications, whereas a poor antenna degrades the capabilities of the transceiver, regardless of how good it is. Thanks to the static network topology in S-WSN applications, it is possible to install a directional antenna and signal booster for the nodes at certain positions (e.g., corners, ends and ceilings) to enhance radio communication. This is the most efficient method to increase communication range at a low energy cost. Typical scenarios include extending transmission in tunnels, compensation for high signal attenuation in forests and greenhouses, gateway nodes at the top of bridge towers. Meanwhile, optimal antenna height should be calculated based on the actual environment and adopted radio frequency to leverage ground effect of radio transmission, especially for omnidirectional antenna [34]. A rule of thumb is that doubling the antenna height will provide an average of 6 dB of effective propagation gain in a non-line-of-sight environment, extending communication range significantly. However, a well-balanced placement of the sensor node must also favor sensor proximity to the monitored object or environment for good measurements.

In addition, it is worth noting that hardware fatigue and moisture condensation two more practical concerns that should be taken into account. Otherwise, the node may fail much earlier than expected. For example, flash memory has limited write/erase cycles of about 10^5 times. Thus, it should be used to keep binary code and constant settings for scheduled updates, rather than as a temporary data buffer for daily use in long-term S-WSN applications. Instead, EEPROM with 10^6 times of write/erase cycles is a valid option for onboard data storage. Due to the tiny size and compact packaging, moisture condensation can easily occur in the sensor node and burn the circuit out, especially when deployed outdoors with significant temperature and humidity variance between daytime and night. Temperature differences observed in Helsinki in some outdoor trash bins can exceed 50°C within a single day. Therefore, a waterproof casing or air vent should be considered in dealing with the harsh application environment.

2.3 Key Components for Energy Optimization

From the S-WSN applications study and research challenges above, we can see that the optimization of energy efficiency is a very complicated task involving many considerations. Therefore, it is critical to identify key components for energy optimization. We determine three general components that can benefit all S-WSN applications. They are local data processing, lightweight security and seamless information flow. Essentially, the first component aims at increasing useful information throughput, i.e., bits per second per joule. *Local* means on the node and between nodes in the network, e.g., CH and CM in the cluster network or parent node and child node in the tree topology. *Data processing* mainly includes feature extraction, measurement filtering, data aggregation [22, 50, 15], semantic correlation [16] and information compression. As a result, there are total of ten possible way of combining two computation locations and five processing methods. Considering numerous processing algorithms and network architectures, I limit our discussion to general rules that can be widely adopted. I therefore list five general rules to distribute data processing methods at two different locations as below. More details are explained in the publications Publication IV and Publication V.

1. Feature extraction must be implemented on the node for high sampling rate time-series data collection and/or image-assisted S-WSN applications. It prevents overloading of data buffering and transmission on the node.

2. Measurement filtering must implement at least two general filters on the node: a threshold filter to narrow the signal or measurement spectrum of interests and a deviation filter to highlight abrupt changes.

3. Data aggregation should consider seven types of arithmetic operations at the aggregating nodes (e.g., parent nodes in tree topology or CHs in cluster topology) : average, maximum, minimum, sum, append, count and difference. It can provide limited statistical analysis to evaluate the quality of measurements and remove errors.

4. Semantic correlation should consider at least two conditions: temporal correlation on the node and spatial correlation at the aggregating nodes.

Both correlations help to remove outliers in the measurements by cross-checking related data.

5. Information compression should consider either lossy or lossless data compression depending on the application requirement. In general, fixed length binary representation has an advantage over variable strings for two main advantages: it is shorter and deterministic.

These five rules are derived from two concerns in achieving reliable energy optimizations. Firstly, computing intensive tasks should be performed on the node to eliminate communication variance between two different nodes. Secondly, useful information should be extracted from the raw data level by level according to the network architecture. The ratio of the data amount received at the SN to the data amount measured and transmitted by all nodes in one duty cycle decides the energy efficiency of the whole S-WSN system within a bounded latency of data delivery. Obviously, the smaller value of this ratio, the higher energy efficiency of the system. Note that the maximum (i.e., worst case) value of the ratio is not necessarily 1 due to the relaying data traffic in multi-hop routing. In all circumstances when hardware capability is fixed, the balance of energy optimization techniques should be carefully placed between the system lifespan and measurement accuracy and latency. Over-engineered power management may cause excessive delay and a sacrifice in measurement accuracy.

In S-WSN applications, wireless network topology [14] can be generally categorized into four types: star, tree, cluster and mesh. Star topology has limited range and only supports small network scale. Tree topology usually leads to a high signaling overhead in order to maintain its shape and connectivity. Mesh networking can achieve reliable routing and network reachability. However, it is difficult to build flexible data aggregation schemes in mesh networks due to the lack of regional control in this fully decentralized model. In contrast, cluster topology [3, 33] is a hybrid model of extended star topology and three-level tree topology. It gains the advantages of both sides. As a result, we selected cluster topology and combined it with data aggregation for easy network management and efficient data transmission. Considering the many trade-offs in energy optimization, we propose and implement a reliable clustering protocol and a cluster-based data aggregation architecture. A more detailed description is elaborated in the Publication IV and Publication V.

The second component is a lightweight security establishment which is a binding factor of the system lifespan. A vulnerable S-WSN system is even worse than none. Once the S-WSN application is compromised, it may provide misleading data and corrupt the back-end database, which may compromise other systems or crash analysis processes and models. Therefore, we consider security as a paramount component in energy optimization. The network topology in S-WSN applications is static and often initialized under the operator's supervision. Hence, we should use a whitelist to establish secure connections with neighboring nodes at the beginning, and a blacklist to mitigate DoS attack through collaborative detection. Security re-association (e.g., renewing keys or shared secrets) can be either scheduled at a certain interval or triggered by a specific command from the operator. Considering the long data acquisition phase in S-WSN applications in an unattended environment, it is critical to encrypt data to prevent eavesdropping. From a performance perspective, hardware encryption (e.g., AES) and efficient cryptographic operations (e.g., ECC) should be applied. More detailed protection against various attacks is discussed in the Publication III.

The third component, seamless information dissemination, focuses on reducing protocol translation and reusing existing infrastructure. Protocol translation is a potential bottleneck in network architectures and a nest of bugs in the implementations. Apparently, the less gateways and proxies in the middle of end-to-end (E2E) communication, the smoother information flows with fewer interruptions, and the lower energy cost per bit in distributing information. Therefore, a unified data representation and exchanging protocol is necessary to enable seamless information dissemination. XMPP provides a standard method for instant messaging and presence service (IMPS) which is appropriate for disseminating large amount of small data packets in real-time. In order to fit XMPP into S-WSN applications, we extended XMPP specifications and developed an XMPP sensor bot to speak a common language in WoT on behalf of the sensor nodes. More details of this work is presented in the Publication VI. Notice that a competing standard protocol called *Constrained Application Protocol* [67] is not discussed in this thesis due to its premature status. It is controversial whether such a HTTP-alike communication protocol would suit longterm stationary WSN which features intermittent reachability scheduled in duty cycles.

2.4 Summary

In this chapter, we reviewed three core subjects of this thesis. Firstly, we evaluated S-WSN applications to understand the requirements for adopting WSN technology. Secondly, we listed a few active research topics and practical concerns to show the complexity and challenges in achieving high performance and efficient operation on resource constrained sensor nodes. Thirdly, we highlighted three major components for energy optimization in all S-WSN applications. By following these three subjects, we can see why energy is a critical issue in S-WSN applications, how difficult and complicated to deal with this issue, and what our solution consists of. In the next chapter, we described our contributions in detail regarding the five-layer model 1.1.

3. Multifaceted Optimization of Energy Efficiency

This chapter summarizes the main results in the six publications of this thesis and organizes them into four categories based on the three key components for energy optimization aforementioned.

3.1 Smart Trigger

The main reason for developing the smart trigger is to integrate threshold filtering into the hardware by leveraging passive transducers. This component not only saves significant energy, but also enables long-term, continuous environmental monitoring without any sleep. This trigger is a pure analogue module and thus can only provide coarse-grained condition checking. On the other hand, it removes a lot of operations in digital circuits, such as CPU clock, memory access, A/D conversion and so on. Consequently, the smart trigger can react fast to external excitations at ultra-low power. By combining with digital modules on the sensor node, we can define ceiling and floor conditions to activate precise measurement when the environmental condition satisfies the application requirement.

In general, there are two triggers in S-WSN applications. One is the timer trigger for regular monitoring and the other is the event trigger for critical state warning and subsequent reaction. Our design focuses on the second case and separates environmental condition detection and precise measurement of the object state. The important assumption behind this principle is that the critical moment of a monitoring status comes after the detection of an predefined condition or event with a certain delay. This is true in practice because objects have specific endurance and the monitoring process should reveal a trend of either growth or decline. For example, the damage detection and evaluation in SHM applications have a narrow focus on the concerned status and external events, such as excessive mate-

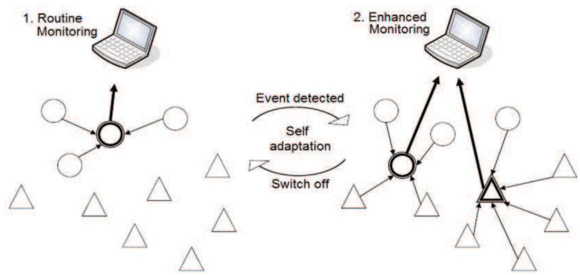

Figure 3.1. Self-adaptation of cognitive clustering, circles are duty-cycled nodes and triangles are environment-triggered nodes

rial deterioration, overload and impact. The measurement process should be adaptive to the trend and highlight the status or event which poses a threat to safety. The smart trigger provides a solution as Figure 3.1 illustrates. The hybrid monitoring process can switch between routine mode and enhanced mode automatically with both the timer trigger and event trigger. Publication I describes the cognitive clustering process in detail.

Later, we developed a prototype of the smart trigger, validated our design in a lab test and evaluated the advantages of the environment triggering policy in a generic model in comparison with duty cycle scheduling. Figure 3.2 gives a snapshot of our implementation, which is elaborated in Publication II. When comparing with the duty cycle scheduling, we concluded that given (i) the event duration(γ), (ii) minimum detection probability $(1-\rho)$ and maximum detection latency (μ), (iii) duty cycled-node active time (τ_A), (iv) the total running time of any type of sensor nodes (T), that the performance of the smart triggered-node is better than the duty cycled-node when the following inequality holds:

$$\frac{\gamma}{T-\gamma} \leq \max\left\{\frac{\tau_A \cdot (1-\rho)}{\rho \cdot \tau_A + \gamma}, \frac{\tau_A}{\mu}\right\} \tag{3.1}$$

To sum up our contributions, I list the three findings as follows:

1. The environmental context of the monitoring application can be built into the hardware to improve the energy efficiency of the sensor node and optimize network topology dynamically.

2. The analogue circuit is a good supplement to the digital circuit in terms of energy-efficient threshold filtering of the external condition.

3. The environment triggering policy outperforms the duty cycle schedul-

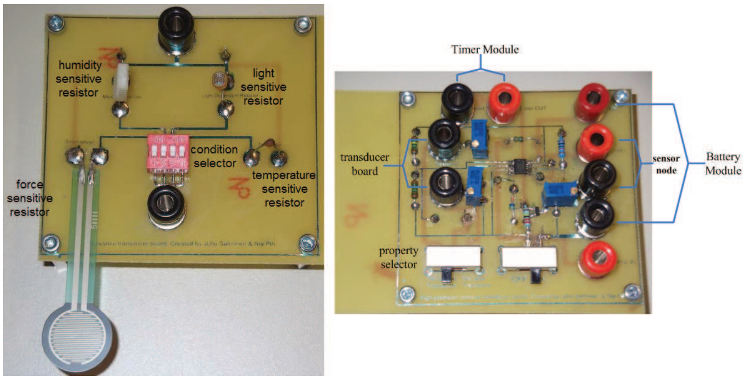

Figure 3.2. Passive transducer board and switching module of the smart trigger

ing in long-term, time-critical S-WSN applications. A hybrid solution would incorporate the advantages of both sides for better adaptability.

3.2 Clustering and Data Aggregation

There are many clustering protocols [66, 11, 18, 28] for WSN which aim at certain applications with different focuses and assumptions. Our clustering algorithm *Mires*++ addresses two concerns: reliability and energy-awareness. Meanwhile, we considered two important requirements in our protocol development: decoupling from lower layers and imposing less signaling overhead. Figure 3.3 depicts our system state machine in the recovery process of the CH failure and the role transitions of a sensor node in the cluster. The energy-based CH election and backup CH (BCH) substitution circulate data aggregation tasks among cluster participants and balance the energy consumption of the whole cluster. Connectivity with CH lost and battery lower than threshold are two triggers to start the CH delegation protocol for failure recovery or load balancing. One thing worth emphasizing is that our clustering algorithm relies solely on remaining energy for CH and BCH selection and uses radio connectivity for CM registration. There are two reasons for this policy. Firstly, from our numerous experiments, we notice that radio connectivity is not a stable indicator in many cases. The signal strength and connectivity can be affected by many factors, such as moving objects, obstacles or changes of surrounding environment, and the height of sensor nodes. Sometimes, the signal strength may not be even symmetric on both ends, which means

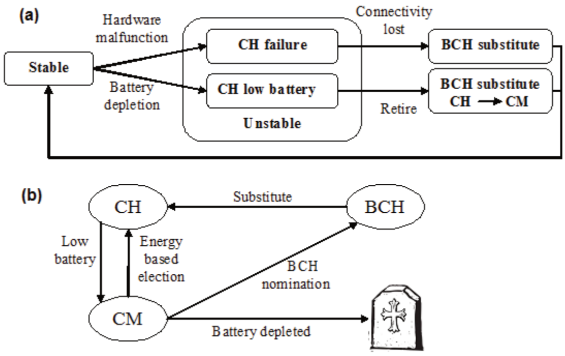

Figure 3.3. Self-adaptive clustering recovery process (a) and the role transitions between the Node, CM, CH and Backup CH (b)

different nodes see different values of the same connection. Therefore, we let CMs decide which CH they would like to join based on the quality of the connection. Secondly, over a long run, it is simpler to use only energy to organize tasks on a distributed network for high reliability and more stable network structure in stationary WSN.

In order to quantify the benefit of energy efficiency with our clustering algorithm, we conducted simulations on two different deployment schemes for three different cluster sizes on three network scales over two hundreds of duty cycles. The results shown in the figure 3.4 illustrate significant energy saving for middle size and large scale WSN, especially for a long span network like the bridge topology. For generality, our simulation does not include any smart data aggregation techniques. Otherwise, we could expect more energy saving by further suppressing redundant transmissions and trivial measurements at the CHs. Our clustering algorithm is elaborated and evaluated in Publication IV.

Based on our clustering algorithm, we proposed a cluster-based data aggregation architecture to raise energy efficiency one step further. From our extensive survey on S-WSN applications, we identified two trends in S-WSN practices. One trend is that more sensors (e.g, accelerometer, tiltmeter, temperature sensor, light sensor) are directly attached or wirelessly connected with sensor nodes to provide multidimensional measurements for more accurate observation and a better understanding of the causality between multiple factors. The other trend is that less data and more knowledge becomes increasingly demanded to mitigate overwhelming data flood. The first trend implies a marriage of data acquisition and semantic analysis to enable situation awareness at real-time. The second

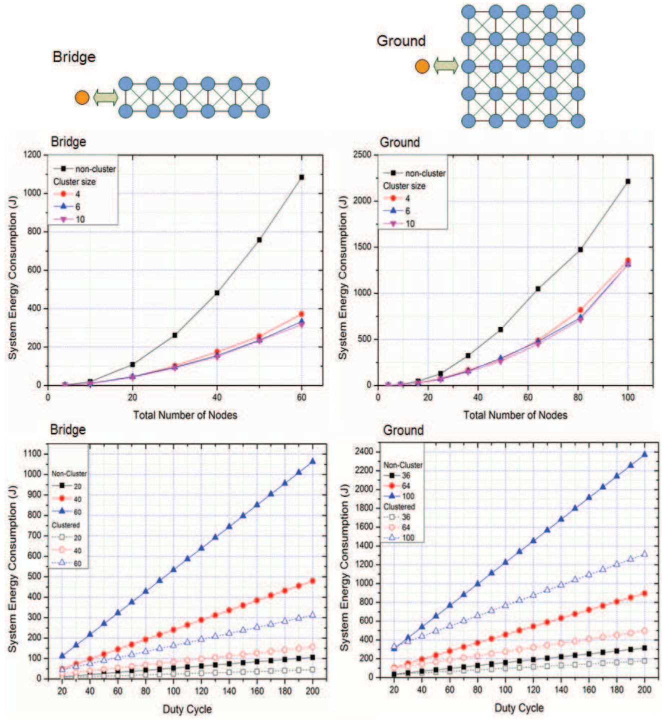

Figure 3.4. Improved energy efficiency of clustered topology with two deployment schemes over network scale and duty cycle

trend indicates that spatio-temporal statistical data processing is necessary to highlight changes and extract patterns. Cluster topology provides a good platform to perform in-network data aggregation level by level.

Figure 3.5 illustrates the principle of our cluster-based data aggregation architecture to extract useful information from raw data in three steps. From bottom up, we developed multiple filtering and summary techniques to refine measurement conditions, remove outliers and correlate multiple measurements of different types or locations. Figure 3.6 lists five general filters used in our program. These filters can be used for either data cleansing on every single node or measurements correlation at the CHs. Intermediary processing results can be iteratively processed by the same techniques between clusters until the results finally reach the sink node at the top. From the system perspective, this incremental aggregation policy improves energy efficiency and information throughput. Moreover, it allows application developers to fine-tune distributed data processing. Our experiment confirms these two advantages in Publication V.

However, there are two trade-offs to balance the benefits and associated costs of in-network data processing. One trade-off is the E2E latency of

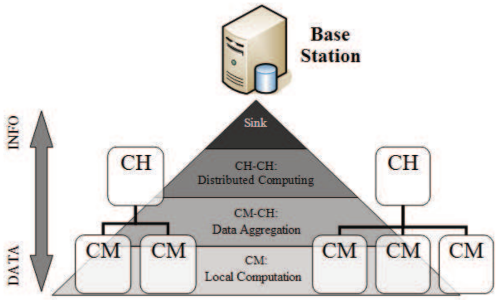

Figure 3.5. Cluster-based data aggregation architecture

data delivery and energy optimization. Computing at the CHs takes a certain time which depends on the total number of incoming messages and the complexity of the processing algorithm. This accumulative delay is added to the long-haul multi-hop transmission and should be considered in the synchronization protocol for proper scheduling adjustment. Usually, rule-based filtering processes do not add much latency. In contrast, signal processing, information fusion and collaborative inference [44] may increase E2E latency noticeably, which is a particular concern in safety-critical S-WSN applications.

The other trade-off is information throughput and data accuracy. We may lose some information during the process of data aggregation. This will affect the precision of modeling and analysis in the back-end. One negative consequence is the rising risk of generating false alarms. How much data loss can be tolerated is largely dependent on the S-WSN application and the back-end analysis algorithms. No matter what algorithm is used in S-WSN applications, a common fact is that the collected dataset from the WSN is error-prone and delay-bounded. Due to the variable radio properties, the larger the WSN, the bigger variation may happen. Therefore, the quality of system performance should be measured in the worst case and rated with the lowest benchmark values to provide a certain guarantee in real deployment.

To sum up our contributions, I list the five findings as follows:

1. Cluster topology combined with distributed data aggregation increases network reliability and energy efficiency for S-WSN applications.

2. Cluster size and the complexity of data aggregation at the CH should be considered together to avoid overloading and excessive delay.

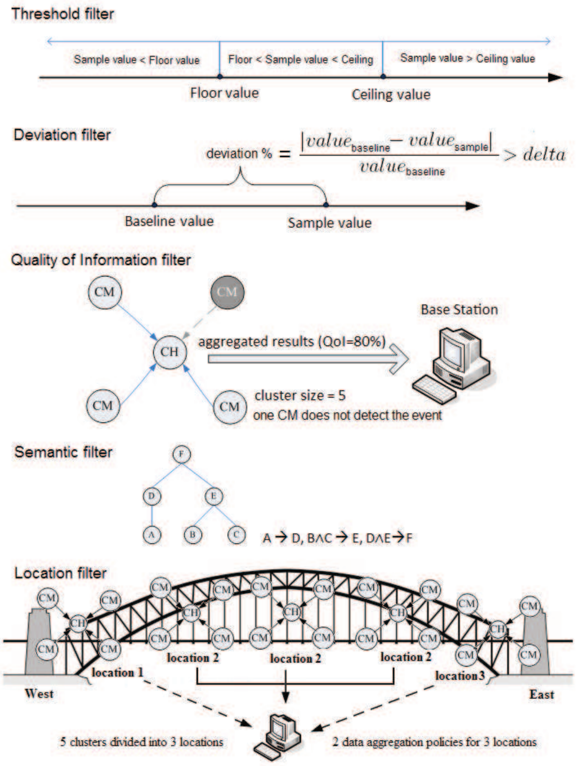

Figure 3.6. Threshold, deviation, QoI, semantic and location filters

3. The cluster size can be controlled by transmission power and hop distance. The adaptive power control is more effective in high density deployment, and maximum hop distance is more useful in low density deployment.

4. An efficient modular design for matchmaking measurement types and associated data aggregation is to create a registration table and encode all measurements and aggregation processes into one or two bytes for bitwise operations, i.e., $< type, operation >$.

5. Sensor nodes' positions should be considered in data aggregation to avoid mysterious data missing, such as the standing wave at node position for vibration measurement.

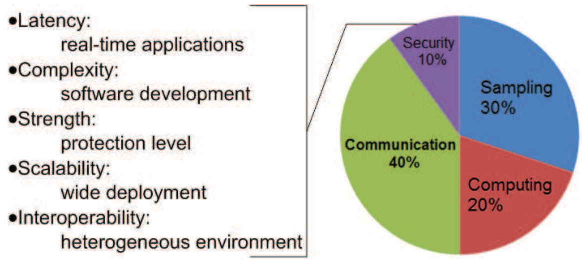

Figure 3.7. Security requirements and battery allocation in a typical S-WSN SHM application

3.3 Lightweight Security Establishment

Twelve years ago, the researchers identified three principal security issues, i.e., confidentiality, integrity and availability (CIA) in constrained ad-hoc wireless networks [58]. Today, as information and communication technology (ICT) advances, these security issues are passed down from powerful personal electronics to a constrained WSN. Consequently, the resurrecting duckling security policy finds a new niche in S-WSN applications. The imprinting process to establish a secure connection with a shared secret at the system startup phase is necessary in S-WSN applications. Among many imprinting solutions, HIP DEX provides a highly efficient security handshake protocol dedicated to WSN.

Although security is paramount in S-WSN applications, surprisingly little resources can be allocated to its implementation. Figure 3.7 shows the energy share of four major tasks on a typical wireless sensor node in our SHM system. Security barely takes 10% of the total battery. This unfair resource allocation is due to the fact that the other three tasks produce the real value of a WSN system. In contrast, security does not generate any value, but only provides an assurance just in case of attacks. Furthermore, security is a very difficult task with five different considerations. Therefore, in the trade-off between system complexity and/or network lifespan and security, more resources are allocated to the regular tasks.

In searching for an appropriate security protocol for S-WSN applications, we selected HIP DEX and proposed a few improvements based on our performance analysis in Publication III. Our evaluation mainly focuses on energy consumption and the computing latency of four security primitives (puzzle, ECDH, AES and CMAC) defined in the protocol. Security strength is analyzed in five general processes in WSN applications in consideration of six attack models. Our experimentation on SunSPOT [1] showed the high energy efficiency and low computing latency of HIP DEX. The major contributions to the performance advantages are an efficient ECC security component, a smaller memory footprint of CMAC computation and short protocol messages. However, HIP DEX also has several shortcomings. Lack of a digital signing process implies that some external whitelisting procedure should be added to the protocol to enhance identity protection, especially for safety-critical and/or privacy sensitive WSN applications. Another controversial component is the puzzle mechanism, which adds significant overhead to the security association with an ambiguous benefit in practice. Finally, we tested three different key lengths for the ECDH handshake based on the NIST recommendation for key management [12]. As we expected, a longer key consumes more energy and introduces higher computing latency. Hence, hardware acceleration on ECC may bring considerable performance benefit [46].

To sum up our contributions, I list the four findings as follows:

1. HIP DEX is an efficient security protocol for S-WSN applications with certain whitelist configurations. It is likely to be standardized by IETF.

2. ECC and CMAC are optimized for constrained sensor nodes. They are likely to be integrated in hardware acceleration on security chips.

3. Lightweight security association should be refreshed every certain number of duty cycles to prevent malicious packet sniffing.

4. Whitelisting and blacklisting should be used in S-WSN applications to enhance identity protection and mitigate packet DoS attack.

3.4 Unified Information Dissemination

One essential building block in communication is a common language and protocol to carry and exchange information. A standard communication protocol is not only an enabler of information dissemination, but also an amplifier of system performance and capability. The more devices speak a common protocol, the smoother data flows from one device to another, and the faster information circulates through connected computer systems and users. Therefore, we selected XMPP, a unified data representation and exchanging protocol, to integrate S-WSN applications to the WoT.

In contrast to the current Internet which is built around human society, IoT will cover the whole nature from artificial structures and environmental phenomena to various animals and plants in the ecosphere. Particularly, the huge scale and diversity of S-WSN applications decide that a flexible and scalable service for information dissemination is critical to network and data management. IMPS is so far the most efficient method to deliver short messages in real-time for a large number of users. This service has great potential to merge numerous S-WSN applications within the framework of WoT with existing web services. However, two prerequisites must be met to support wide employment of XMPP-based IMPS. They are extensions for sensor nodes representation and task configuration, and an application program interface (API) for developers.

Figure 3.8 presents the overall architecture to integrate WSN into the WoT via XMPP networks. We create a small XMPP client called *sensor bot* to collect data from sensor nodes and send customized messages to remote XMPP entities. A data analyzer is built into the sensor bot for data logging, event producing and feedback study. All other XMPP entities remain intact without any change. Information flows smoothly from the physical world to the Web through two basic services: data query and event notification. User feedback rating is used to evaluate the popularity of multiple measurements for prioritized scheduling. By reusing the standard web interfaces and XML parsers, our solution simplifies S-WSN application development and service creation.

The features of our XMPP sensor bot rely on the rules and patterns that are defined in the API. The program component *rulebook* specifies application logics for data processing in an XML file which defines filtering conditions and publishing events for each type of sensor. Another program component *message parser* reads incoming data queries, tasks configuration commands and feedback ratings. To support flexible interactions with users, we define a few patterns using regular expressions to differentiate diverse requests. If an incoming message does not comply with any of the expression patterns, a list of allowable patterns will be replied automatically to the requester. Since both program components employ XML format, it is very flexible and scalable to distribute and extend application logics with plain text files across different S-WSN systems of the

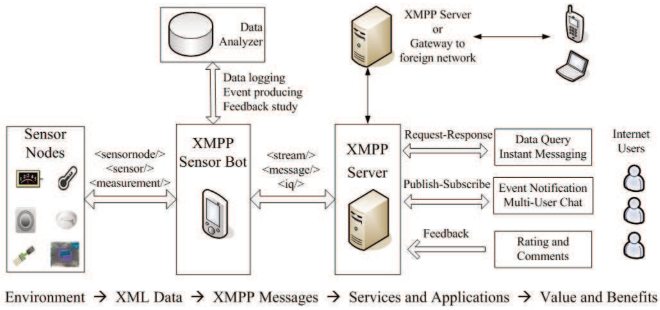

Figure 3.8. WSN-enabled XMPP Architecture

same kind.

We developed two generic XMPP extensions for sensor node representation and task configuration. To represent a sensor node in a concise profile, we designed a new XML stanza <sensornode/> with two child elements: <sensor/> for capability discovery and <measurement/> for information distribution. The second extension uses 'get/set' methods in XMPP <iq/> stanza to fetch configurable parameters on a sensor node and to update parameter values respectively. In order to overcome verbose XML format and heavy TCP connection, we use abbreviated initials to compress redundant XML tags and attributes, and a single MAC packet to carry a whole XML stanza with multiple measurements. Publication VI gives a few examples and demonstrates our protocol design in a real application.

To sum up our contributions, I list the three findings as follows:

1. XMPP is a suitable communication protocol for S-WSN applications with certain extensions. The great benefit is derived from three prominent advantages: flexibility, scalability and interoperability.

2. IMPS is an optimal service platform for S-WSN applications to distribute large number of short observations to many users in real-time.

3. It is more efficient to piggyback the application protocol directly on the MAC layer without a TCP/IP stack on the sensor nodes. This vertical integration offers a huge benefit for application development on highly constrained sensor nodes.

Layers	Techniques	Contributions	Achievements
Information Dissemination	XMPP, IMPS	XMPP extensions XMPP sensor bot	seamless integration to the WoT
Data Aggregation	filters, summaries feature extraction	cluster-based distributed computing	condense information remove outliers
Efficient Clustering	topology control middleware	Mires++ clustering algorithm	enhance reliability load balancing
Lightweight Security	HIP DEX, ECC CMAC, AES	whitelist and blacklist overhead measurement	security investigation protocol evaluation
Environmental Triggering	analog circuit smart materials	smart trigger cognitive clustering	built-in event detection self-adaptive monitoring

Table 3.1. Summary of the contributions based on the layered model of energy optimization for S-WSN applications

3.5 Summary of the contributions

According to our layered model of energy optimization for S-WSN applications 1.1, we organize our contributions in the following table 3.1 for a clear picture. The column **Techniques** lists existing techniques and protocols that have been adopted and investigated in our research work. Corresponding to prior progress, we developed new protocol extensions, a clustering algorithm and a distributed computing architecture, a hardware prototype and a cognitive clustering mechanism in the column **Contributions**. As a result of our contributions, we have accomplished multifaceted optimization of energy efficiency for Stationary WSN Applications through several steps in the column **Achievements**. Recall the first two research questions in 1.1, this table clarifies what we have achieved and how we have developed existing work for larger scale and easier integration. The third research question is answered in our publications regarding their different subject.

Considering future work, there are a few open questions on fine-tuning our solutions. Depending on the specific S-WSN application, configurable parameters in our clustering algorithm (e.g., cluster size, cluster radius in hop distance, timeout settings), event threshold configurations on smart trigger, and the content of rulebook and message matcher in XMPP sensor bot have to be tested extensively to achieve the optimal performance. Therefore, a good understanding of the application requirements and our solution details is essential. After all, a good tool can only function well on the right hand.

4. Conclusions

Energy efficiency is an important issue for all battery-powered devices and networking systems. Particularly in S-WSN applications, this issue becomes a decisive factor in directing practical deployment and usage. The scarcity of resources on sensor nodes, the harsh environment in the physical world and the long-term uptime running regular tasks push application development to the limits. It is worth emphasizing that any solo technique is not a complete solution to this multidimensional problem in WSN development. Distributed software and network architecture require careful study of application-specific features. As a result, extreme optimization with multifaceted considerations have to be practiced from protocol design to program structure.

In this thesis, our research investigated four key subjects for energy optimization in S-WSN applications. We strove to provide generic and modular solutions so that more application developers could adopt them. In our hardware design of the smart trigger, we used passive transducers to switch on/off the sensor node automatically based on the surrounding condition. The ultra-low power consumption enables persistent monitoring without sleep at all. By mixing the environment trigger policy and duty-cycled scheduling, we propose cognitive clustering to visualize environmental changes through network topology at run-time. Next, we developed a reliable clustering algorithm and incorporated a flexible data aggregation architecture on the top of the cluster network. This vertical integration provided a good balance to distribute data processing with little signaling overhead for network management.

Later, we conducted a performance evaluation of an efficient security protocol for WSN. Our experimental work gave some insights into its cost on the real sensor node in terms of energy consumption and computing latency. We also suggested a few improvements to reinforce identity protection. Finally, our research climbed up to the application layer and proposed to integrate WSN into the WoT by using XMPP. We developed an XMPP sensor bot to ease application development on WSN and extended XMPP specifications for node representation and task configuration. Our implementation work demonstrates the feasibility of our solution in the prototype on a mobile phone. By leveraging existing XMPP infrastructure and IMPS, we bridge the gap between the physical world and numerous Internet users in cyberspace. The seamless interface serves as a windows to broaden our perception and vision.

Based on my five years research work and hands-on experience in WSN development, I want to provide four useful lessons to sum up this thesis:

1. WSN is a complex system which requires multidisciplinary cooperation to provide holistic optimization. Simply put, electrical engineering and computer science are must-have to set up the platform. A certain knowledge in mechanical engineering and material science helps to select correct actuators and sensors for the given application. Some study in automation and control is necessary for sensor calibration and appropriate process configuration.

2. It is extremely difficult and time-consuming to debug a WSN. To eliminate human errors and accelerate program development, it is critical to automate testing for basic stand-alone features and protocol transactions.

3. WSN deals with the hard core of the physical world, such as radio propagation and environmental effects. There are a lot of hidden factors and interactions in between. They are quite often ignored in theoretical study due to the oversimplified models and unrealistic assumptions. It is better to try things out in practice. A failed implementation is more valuable than plausible ideas on the paper.

4. In S-WSN applications, there may be several alternatives to solve the same problem. Pick up the cheaper solutions and explore the potential of onboard components. A good example is that SIM card can provide significant storage space to expand the internal memory of a sensor node equipped with a GSM modem.

Nowadays, green ICT and environmental protection are gaining global attention. As one effective method, intelligent data acquisition is becoming an industrial standard in S-WSN applications. It does not only improve energy efficiency for long-term operations, but also increases information throughput for situation awareness. Eventually, these WSN systems should enhance human understanding of the nature and benefit the organization and management of our society. Hopefully, some of the results in this thesis can help to shape a brighter future.

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Errata

Publication II

In the section IV, it states "The total uptime of the WSN monitoring application is T." This sentence should be corrected to "The average inter-arrival time between events is T."

Publication II

In the section IV, our mathematic modelling simplies event detection by assuming an event can be detected instantly by a DC-node. Although this assumption may not be realistic, it is still valid to obtain an approximation value as long as this assumption does not bring any bias effect to the compared method, namely duty cycling. Actually, in our case, the simple assumption of instant event detection gives a certain advantage to the comparative DC-nodes in terms of latency and energy consumption.

Publication III

In the section IV, it states "ECDH handshake costs most energy and time on both sides." This sentence should be corrected to "ECDH handshake costs much energy and time on both sides."

Publication III

In the section IV, there are two figures slightly different in the Table I and Table II, i.e., 135.60 vs 135.61 and 143.12 vs 136.46. The cause of this variance comes from several factors, such as measurement accuracy and harware jitters.

Publication IV

In the equation (2), the numerator and denominator in the fraction on the right hand side of the right equation should be switched.

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