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Wireless Sensor Systems for Extreme Environments

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Taking a new step, uttering a new word, is what people fear most
Fyodor Dostoyevsky

1.1 Introduction

The last 40 years of economic and political unrest has wrought a series of drastic changes throughout the world. Many technological trends have come to a halt as new developments have taken over, surprising the experts. Amongst the successful ones are smart sensing, flourishing as a result of promises of a higher quality of life and worries about the deterioration of the climate.

Although there have been many projects throughout the world and many successful civil and industrial applications, we are still awaiting to see a real paradigm shift. As increasing resources have expanded and increased research activity, too many research reports have somehow failed to demonstrate the eye-catching industrial applications required to justify the resources being expended. To this end, we have to judge on a global scale the performance of sensors in the last 20 years; we have looked at earlier surveys [1] and analysed the economic effectiveness of the projects described. One of the main conclusions is that too many young researchers try to make their work publishable rather than practical and useful for real applications that to help improve the quality of life. As well as the few useful research activities – such as energy conservation, optimized performance, cross layering, efficient sampling, and data management – we see many trivial patterns of common networking manipulation: routing, scheduling, node replacement, mobility, and coverage under oversimplified working conditions, where simple computer simulations can generate huge volumes of inaccurate data; they are simply creating a new black hole for consuming computer resources.

Following our series of conferences on wireless technologies for space and extreme environments (WiSEE) and the associated sensor workshops we have decided that we need to direct research towards the environments that need sensors most: space and other harsh, industrial or unconventional environments.

Wireless Sensor Systems for Extreme Environments: Space, Underwater, Underground, and Industrial.
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Following Edison's problem-solving attitude when demonstrating the use of electricity to create the light to brighten our nights, we need to encourage our youth to have strong belief and true dedication. They need to enjoy creativity and achieving their objectives so that they can engineer a better quality of life. They should be solving problems, breaking the old boundaries, opening new windows of opportunity and creating new paradigms. Applying new technologies, such as wireless and ever-improving smart sensors and actuators, gives us many possibilities for creating new and much smarter technological systems and services.

To be successfully deployed, a new technology must meet four basic measures: trust, objectivity, security, and sustainability. Here, objectivity is the demand for a product or service, which in our case means overcoming unconventional working conditions, to that the working product or a system enables new services, whether in the vacuum of space, in the oceans, underground or in places with very high, very low, and highly variable temperature, humidity, winds and pressure.

The rest of this chapter is devoted to two main summary sections. Section 1.2 describes our earlier work on wireless sensor systems (WSSs) for space and other extreme environments, while Section 1.3 provides an extended summary of the remaining twenty-one chapters of the book.

1.2 Wireless Sensor Systems for Space and other Extreme Environments

This section summarises our earlier review of our work on WSSs for space and extreme environments [1]. This was based on our WSS workshop at WiSEE 2013. Our main message is this section is to analyse how to break away from conventional wireless sensor networks (WSNs) by adopting an agile heterogeneous unconventional wireless sensing (UWS) deployment system.

1.2.1 Definitions

A comparative analysis is better than a simple definition of the terms, which often can vary upon application scenarios and its working environment.

Wireless sensor networks (WSNs) are normally complex networks of large numbers of interconnected sensor nodes and clusters. A wireless sensor system (WSS), however, is a smaller-scale system of data-oriented interconnected sensing devices for extracting well-defined sensing information. The sensor nodes in WSSs are expected to be less constrained and more flexible, and therefore more adaptive and autonomous. In WSSs, use of terms such as wireless sensor and actuator networks, wireless smart intelligent sensing, wirelessly connected distributed smart sensing, and unmanaged aerial vehicle sensor networks makes sense. However, wireless underground sensor networks, underwater wireless sensor networks, wireless body-sensor mesh networks and industrial wireless sensor networks are normally more complex, and are therefore more applicable to WSNs by definition.

As heterogeneous sensing services require UWS solutions, one way to compare WSSs and WSNs is to look objectively at the purpose for which they are designed. WSS-based solutions for self-managed heterogeneous sensing services are more dynamic and practical if kept small. This is due to our basic service principles:

- conventional WSNs, normally deployed for homogenous sensing services using generic smart sensors
- unconventional WSSs, designed for dynamic, heterogeneous, UWS services using specific sensors.

UWS solutions therefore require to be kept simple and they therefore suit smaller and less complex WSSs.

1.2.2 Networking in Space and Extreme Environments

In many WSNs, the simplicity of the data collection can allow deployment of sensors on multi-service networks, in which densely distributed sensors and actuators are used for a wide range of applications. In space and extreme environments (SEEs) smart networking is needed to make this process more efficient, and so it can benefit from the low-cost, low-power operation of networks. For example, a multi-timescale adaptation routing protocol can use multi-timescale estimation to minimize variation of packet transmission times by calculating the mean and variance. Another example is the deployment of distributed radar sensor networks (RSNs), grouped together in an intelligent cluster network in an ad hoc fashion. These can then provide spatial resilience for target detection and tracking. Such RSNs may be used for tactical combat systems deployed on airborne, surface, and subsurface unmanned vehicles in order to protect critical infrastructure.

1.2.3 Node Synchronization in SEEs

Management aspects of WSNs for time synchronization and cooperative collaboration of the nodes is important in SEEs. Techniques such as the sliding clock synchronization protocol is used for time synchronization under extreme temperatures. The key aspect of this protocol is a central node that periodically sends time synchronization signals. Then, the node measures the time between two consecutive signals as well as the locally measured time, from which it can determine and rectify any possible errors.

Another good example is creation of an ultra-reliable WSN that will never stop monitoring, even in extreme conditions, and does not require maintenance. Such a system can detect a failing sensor node through a dynamic routing protocol, enabling other nodes to take over the function being carried out by the dead node.

1.2.4 Spectrum Sharing in SEEs

In space, the demand for spectrum is huge, particularly where the safety of personnel and the reliability of control systems are heavily dependent on wireless sensors such as:

- structural health
- impact detection and location
- leak detection and localization.

Robust and reliable dynamic spectrum-sharing schemes are needed. In order to make use of spectrum-sharing in space, we need to make modify systems used in terrestrial networks, in which, for example, errors in spectrum sensing are unavoidable but which often lack incentives for primary users to allow network access to secondary users.

1.2.5 Energy Aspects in SEE

Medium access control (MAC) plays a crucial role in providing energy-efficient and low-delay communications for WSNs. Sensing systems designed for operation in space or underwater face additional challenges, notably long and potentially variable propagation delays, which severely inhibit the throughput capability and delay performance of conventional MAC schemes. Outages due to energy shortages and adverse propagation conditions also pose significant problems. We now examine similar challenges associated with reliable and efficient multiple access in SEEs, focusing on underwater sensing systems.

The use of energy-harvesting technology has important implications for medium access, since uncertainty surrounding the future availability of energy makes it difficult to arrange reliable duty-cycles, schedules or back-off times in the traditional way. The challenges associated with long propagation delays are well understood for satellite systems. Demand assignment multiple access is commonly employed as a means of achieving high channel utilization, since capacity can be allocated to nodes in response to time-varying requirements.

1.3 Chapter Abstracts

The chapters for this book come from two sources:

- expansions of previously published journal or conference papers, where the authors' work has already been peer reviewed
- original reviews to expand the scope of the book, at the choice of senior and experienced academic or industrial experts.

1.3.1 Abstract of Chapter 2

This chapter, entitled 'Feedback Control Challenges with Wireless Networks in Extreme Environments', presents a new perspective on feedback control systems that operate in a wireless fashion. Motivated by the high cost of installing a wired control system in aerospace vehicles and even automobiles and the added weight and fuel requirements that comes with it, this chapter aims at redesigning control systems by eliminating wires from sensors to the controller and eventually to actuators. Replacing wires with wireless links in a control system may be modeled in different ways. This chapter describes a delay and noise model with parameters coming from the wireless system. The performance of the control system is then studied with added delay and noise in the loop to address the feasibility of wireless control.

A case study is presented in which a launch vehicle is instrumented with several accelerometer sensors to model the vibration modes. This information will be useful for fine-tuning the trajectory of a rocket as its structure bends at high speeds. The system dynamics and controller are modeled using first- and second-order differential equations with a parameter used to determine rise time, settling time, and overshoot of the closed-loop response of the system.

A fixed delay is then added to the system and presented in rational form using the Pade approximation. The effect of the delay on the stability of a first-order system is then studied. This result is further extended to multi-sensor inputs with different delays. The effect of the delay on the transient response of a second-order system is studied too.

External disturbances affecting a wireless link are modeled using an additive white Gaussian noise model, which will slightly alter the parameters of the system's differential equation. Rise time and overshoot changes versus noise are plotted and analysed.

Although there is still a long way to go before such systems are implemented in critical applications, this chapter lays the groundwork for modeling, analysing and studying such systems and presents a framework for designing a wireless controller for sensor and actuator networks in SEEs.

1.3.2 Abstract of Chapter 3

This chapter, entitled 'Optimizing Lifetime and Power Consumption for Sensing Applications in Extreme Environments', considers power optimization in a general sensor network; that is, without specifying any particular application. An optimization problem is defined with a view to extending the network's lifetime by using the minimum power possible. The proposed problem is shown to be convex, therefore having a global solution that can be obtained by applying traditional numerical methods and convex optimization theory.

An upper and lower bound on network lifetime is derived as a guideline for designing power-constrained WSNs. A lower-complexity method to find near-optimal solutions is also presented. Several practical scenarios are also described and numerical results are presented to verify the proposed method.

A specific section in this chapter is dedicated to power optimization in applications in SEEs, which is the main focus of this book. It is noted that since sensors nodes may fail for various reasons (including battery depletion), the number of sensors in a network may change over time, hence power allocation should also be changed to follow the optimal solution for the most recent status of the network. The proposed power allocation approach performs better than uniform power allocation; in other words, using the same battery in each sensor node in sensor networks with limited and non-renewable energy sources.

The application scenarios considered in this chapter include passive multiple radar sensing, where an unknown target signal is detected or classified. Carrying out this task using a network of low-cost sensors is much more reliable and cost-effective than using a single complex radar system.

Another scenario is a solution for construction of oceanographic maps. This application uses sinking sensors to create a 3D map of the ocean bed. Using the optimal power-allocation strategies presented in this chapter eliminates the need for using large batteries and can reduce the overall cost of the network.

In summary, this chapter finds the power-allocation scheme that can best extend the network lifetime without violating signal-quality requirements.

1.3.3 Abstract of Chapter 4

This chapter, entitled 'On Improving Connectivity-based Localization in WSNs', addresses the issues of uncommon sensor-node localization methods. These are methods that are used where more common methods, such as GPS, are unavailable (most extreme environments do not have the luxury of GPS), too expensive or complicated.

A review of recent advances in localization for both single- and multi-hop networks is presented, emphasizing connectivity-based localization built upon information gathered from neighboring nodes.

For single-hop networks, centroid and improved-centroid algorithms are presented. The improved method discriminates against hearable anchor nodes among all other nodes and assigns them different weights. For multi-hop networks, the distance vector (DV) hop algorithm is presented. This method is based on the average hop distance and the calculation of a correction factor. The theoretical underpinning of the Hop-count-based localization is discussed, using probability theory and maximum-likelihood estimation. The chapter goes on to present several ways to improve the accuracy of connectivity-based localization: by adjusting the correction factor based on the expected hop progress, an approach that is then extended to exploit neighborhood information. The problem of hop distance ambiguity is noted and a neighbor-partitioning algorithm is proposed to overcome this issue. Numerical results show that this method gives more accurate localization than the original DV hop method as the number of nodes is increased.

Reading this chapter sheds light on the different definitions of the shortest path – shortest hop, shortest regulated neighborhood distance (RND) and shortest distance – and how these can affect localization strategy. The effect of packet reception rate, which captures both physical and network layer status, is also studied for different localization methods. This chapter also distinguishes between isotropic and anisotropic networks and demonstrates that many improved algorithms may emerge from shortest-path or straight-line calculations due to the nature of the network being anisotropic.

In summary, this chapter provides a comprehensive overview of connectivity-based localization (also called the range-free method) in WSNs. The simplicity and low cost of implementation of these methods suits them to many different applications. In SEEs, the lack of GPS requires use of these methods anyway. Therefore, the solutions in this chapter are potentially beneficial for many SEE applications.

1.3.4 Abstract of Chapter 5

This chapter, entitled 'Rare Events Sensing and Event-powered Wireless Sensor Networks', focuses on rare events with low probability but high impact, such as structural failure of a bridge or engine failure of an aircraft.

Detection probability and detection delay are defined as the main parameters of interest in WSNs for detecting rare events. An interesting idea to address the challenge of prolonging network lifetime and increasing the probability of detection while reducing detection delays is energy harvesting.

This chapter starts with investigation of a fully distributed sensor network with energy harvesting and duty cycling to conserve energy. The discussion continues with study of rare events that can produce enough energy to be harvested and used to power sensor networks. Examples such as earthquakes or explosions are among the many rare events that can produce enough vibration energy to trigger a sensor network to switch on and then harvest the energy.

Wireless sensor-node design is examined in two sections: on microcontroller and power-management circuitry. The concept of cluster-centric WSNs for monitoring rare events is presented next. Monitoring civil infrastructure often requires a large amount of data, which may be beyond the current limits of MAC protocols. The network processing and data-aggregation methods presented in this chapter can alleviate this issue, thus expanding the reach of WSNs to SEEs.

The system model presented in this chapter includes a personal area network (PAN) coordinator, which remains idle until an event occurs. When listening to data coming from different clusters, high priority is given to uncorrelated data from different clusters to ensure fairness. A performance analysis in terms of packet arrival times for the IEEE 802.15.4 standard is presented later in the chapter to show how cluster-centric MAC performs in comparison with traditional methods. Average and total time-to-transmit are also studied in the performance analysis section.

In summary, this chapter provides new insights into how to design a WSN for rare-event detection that is both efficient and reliable.

1.3.5 Abstract of Chapter 6

This chapter, entitled 'Batteryless Sensors for Space', describes the challenges of battery operation or replacement and maintenance in SEEs, and the difficulties that this imposes on use of WSNs. Although most examples are from space, the concepts can be generalized to other challenging environments. The benefits of using wireless technology – reduced vehicle weight and cost – are presented in detail.

A cost–benefit analysis of wired and wireless networks is presented. Two different categories of sensors, namely passive and active, are studied and relevant design considerations are presented. Other than the obvious benefits of wireless over wired systems, such as cost and weight, other challenges such as supporting structures, fixtures, cabling, cost of routing and electromagnetic interference and compatibility are noted.

A reliability analysis of wireless systems from data-collection and transmission-channel perspectives is presented. It is noted that combined-source channel-coding methods that take correlation among data streams into account may give high accuracy and reliability even when the individual sensor data may not be reliable. This result is based on well-known CEO problem, which can be extended to correlated sensor data when multiple sensors are in proximity to the same source.

The different categories of active and passive sensors, and the maintenance- and battery-free nature of passive reflective RF sensors are discussed next. The basic operation principles of these kinds of sensor are presented and the challenges in terms of sensor materials, code design and interference are noted. Several methods of interference cancellation at the source and at the receiver side are studied.

In summary, this chapter presents the benefits and design challenges of battery-free wireless sensors for SEEs. Implementation technologies covering the material and physical layer all the way to coding and higher layers such as networking and interference issues are all presented in a coherent manner. The references in this chapter range from traditional academic papers to industry and space agency reports, giving a realistic impression of the current state of the art in this field.

1.3.6 Abstract of Chapter 7

This chapter, entitled 'Contact Plan Design for Predictable Disruption-tolerant Space Sensor Networks', focuses on the design, planning and implementation of disruption-tolerant networks in space. The concept of end-to-end connectivity in the context of the highly dynamic space environment is defined. Network disruption that causes delays but not data losses is at the core of this chapter.

Methodologies to design contact plans for disruption-tolerant WSNs in a systematic way are presented next. The performance of three contract plan design methodologies (FCP, RACP and TACP) are compared.

Communications-system parameters, such as transmission power, modulation and bit error rate (BER0 are used together with orbital dynamics parameters such as position, range and antenna orientation to determine the future contacts. Other constraints include time-zone limitations and concurrent resources. Several examples, such as satellite-to-Earth and intra-satellite communications, are provided for further clarity.

The contact plan design is based on input parameters such as the number of nodes, topology states, the initialization time, interval duration, buffer capacity and traffic. A case study is presented to analyse the contact plan design and includes an experiment, 3 hours and 22 minutes in duration, with four flights over the north pole. Resulting traffic flow for all four half orbits is presented. The TACP, RACP and FCP methodologies are compared for various network loads.

The chapter continues with a discussion of safeguard margins and topology granularity of TACP, followed by the contact plan computation and the distribution and implementation considerations.

In summary, this chapter presents the benefits of using WSNs in space to enhance the performance of Earth observation missions. Since conventional Internet-based protocols fail in the space, disruption-tolerant networks are offered as a reliable alternative and the problems and challenges associated with their design and performance analysis are presented. The main goal in these systems is to ensure reliable sensor data delivery, even if some portion of the data may experience more delays than others.

1.3.7 Abstract of Chapter 8

This chapter, entitled 'Infrared Wireless Sensor Network Development for the Ariane Launcher', describes WSN development for launch vehicles. This poses a unique set of constraints and requires careful attention to reliability. One of these constraints is the strict limit on electromagnetic emission of the sensor nodes. The focus of this chapter is on infrared WSN links inside the upper stage of the rocket and finding ways to minimize packet loss.

Experimental results on the infrared transmitter–receiver link at 1–2 m without line of sight are presented. The design consideration at the device level in terms of bit-error-rate changes versus diode resistance at different illumination levels and angles is presented. Dual use of multi-layer insulation as reflector for infrared communications at low data rates is studied.

This chapter also covers ASIC development strategies for low-power infrared operations. Deciding on the optimal modulation, synthesizing and testing the receiver in a FPGA, and designing the ASIC and testing it on the sensor are discussed. Signalling methods, such as Uni-polar and Manchester codes, are compared in terms of their power spectral efficiency. The ASIC design details include an analysis for both leakage and dynamic power. A radiation-hardened ASIC with similar characteristics was ultimately used on the launch vehicle.

Time synchronization in a reliable sensor network is also examined. The objective is to achieve time synchronization with minimal hardware on the sensor nodes and with as small a load as possible. The stochastic nature of wireless communication, which yields less deterministic delay than wired communication, is noted. Techniques using visible light communication are used to synchronize all sensors. Some of the sensors used in this system are air pressure, temperature, infrared and visible light and humidity sensors.

The chapter presents a complete sensor-node system from the design to the implementation and test phases for space launch vehicles.

1.3.8 Abstract of Chapter 9

This chapter, entitled 'Multichannel Wireless Sensor Networks for Structural Health Monitoring of Aircraft and Launchers', discusses an adaptive multi-channel approach to structural health monitoring that is collision-free and addresses challenges such as latency, throughput and robustness.

Although many other books may address different aspects of structural health monitoring, this chapter considers the very complex structure of an aircraft with its many interconnected sections. Automated monitoring of such a complex system requires many different types of sensor, all connected to a central processing unit using wired or wireless systems. This chapter focuses on wireless systems, which are desirable because of their lower weight and cost. Wireless may even be the only solution, if the component under monitoring is not easily accessible or on a rotating blade, where wires cannot be used.

WSN requirements for aircraft in an industrial setting are considered. Only non-critical sensors and off-the-shelf technologies are used, to make for shorter development times. Static and dynamic sensors with various sampling rates and network sizes are considered.

After a brief overview of the existing research and development activities in this area, the challenges facing multi-channel use and data-gathering applications are presented. The solution presented in this chapter is a unified approach, which addresses both IEEE 802.15.4 requirements and the limitations imposed by use in aircraft. Issues such as signal propagation inside the aircraft cabin, mesh multi-channel wireless networks, node discovery and synchronization, channel selection and network connectivity are among the many challenges that are discussed in this chapter.

When it comes to medium access control, contention-free, contention-based and hybrid protocols are studied. Dynamic multi-hop routing and energy efficiency are discussed next. Collisions, overheating, control-packet overhead, idle listening and interference issues are discussed as part of the energy-efficiency topic. Energy-saving methods, such as data reduction, overhead reduction, energy-efficient routing, duty cycling and topology control are discussed in detail.

Finally, the robustness of adaptive WSNs to changes in environment, topology or traffic are discussed, and centralized and distributed methods are compared.

1.3.9 Abstract of Chapter 10

This chapter, entitled 'Wireless Piezoelectric Sensor Systems for Damage Detection and Localization', starts with applications of Lamb waves and their detection using piezoelectric lead zirconate titanate (PZT) sensors, and a brief overview of prior work in this area. The majority of has been based on wired systems, but this chapter presents the advantages of using wireless systems for damage detection and the challenges that need to be addressed. Transforming current WSNs to support high sampling rates is one such challenges, and is due to the high-frequency content of Lamb waves. Techniques adopted from the compressive sensing literature are presented as a possible workaround solution. This may seem to solve the problem, but embedding a compressive sensing algorithm in a sensor node is another challenge that comes with this solution, and is discussed in this chapter in detail.

An introduction to Lamb-wave-based damage detection is presented in the chapter, before WSNs aspects are addressed in more depth. Active piezoelectric-based sensing is discussed next, and issues such as frequency tuning, windowing and data processing are presented in depth.

The next part of this chapter moves to networking aspects and presents a topology with multiple regions, each with its own wireless node, relaying PZT sensor data to the base station for processing.

The detailed architecture of the sensor nodes, including analogue-to-digital converters, digital signal-processing cores, ARM processors and wireless radio communications, are presented. Distributed data processing for the proposed method is described next. This discussion covers data synchronization issues and consideration of the required buffers and direct memory access.

The chapter concludes with some remarks on synchronization and the scalability and reliability of this method. It is noted that damage detection using structural-borne ultrasonics is a recently revisited and hot topic of research. This chapter presents a concise but comprehensive overview of this area of research that can be used by academics to develop further theories and by professional engineers to implement new systems with more capabilities and higher efficiency.

1.3.10 Abstract of Chapter 11

This chapter, entitled 'Navigation and Remote Sensing using Near-space Satellite Platforms', deals with navigation in near-space (20–100 km altitude). This is a special area of the atmosphere, which is unsuitable for aircraft and satellites. With recent developments in microelectronics and propulsion systems, however, it has gained some attention mainly due to the lower cost of implementing near-space platforms compared to aeroplanes or satellites.

Some advantages of near-space are the ability to control the platform and keep it stationary over the region of interest or to move it on demand to other areas. Two examples of NASA-designed platforms for near-space use are HELIOS and Pathfinder, which are solar powered. Since near-space platforms are much closer to Earth and potential observation-area wireless sensors can detect much weaker signals, which are not otherwise detectable by low-Earth orbit satellites. It is also important to note the line-of-sight advantage of communications using these platforms.

In addition to detailed discussions of the NASA-developed platforms, this chapter also provides a information on ESA-developed projects such as HeliNet, CAPANINA, UAVNET, CAPECON, and USICO.

Other applications of near-space platforms, such as radar and navigation sensors, are also discussed. Specifically, storage aspect ratio imaging is highlighted as one of the potential areas that can benefit from these closer-to-Earth imaging platforms.

An integrated framework that combines near-space platforms with satellites and aircraft into one coherent network with sensor systems at different levels is depicted, illustrating the potential benefits and the coordination challenges. The design considerations for satellite-to-Earth augmentation using near-space platforms and optimal placement and coverage analysis are also presented in this chapter. The limitations and vulnerabilities, as well as legal and implementation issues, are also discussed.

In summary, this chapter presents an alternative platform for wireless sensor networking, which enables new applications but can also enhance the performance of existing applications. The design challenges in such environments will be interesting for professional engineers who are interested in designing such systems.

1.3.11 Abstract of Chapter 12

This chapter is entitled ‘Underwater Acoustic Sensing: An Introduction’, and introduces readers to underwater networked sensors, their limitations, and potential applications. The authors argue that the underwater environment is far more hostile than it normally sounds, making it a true extreme environment. This is mainly due to its very poor communication channels under existing technologies. Whilst exploring a wide range of transmission possibilities they look at options such as free-space optics, magnetic induction, radio with upper and lower frequencies, and acoustics in the form of audio, sonar and ultrasonic waves. The analysis and modelling of acoustic waves for their characteristics and multi-path solutions highlight important features of underwater acoustic transmission and its associated networking.

They expand this analysis with an in-depth consideration of acoustics, as the most popular technology, used for centuries in marine applications, along with its well-known problems including:

- long distance requirements
- heavy signal loss
- node losses
- poor localization due to a lack of GPS (taken for granted in terrestrial sensor networks)
- poor accessibility
- problems of biological fouling
- high cost of experimentation
- high cost of maintenance.

The authors survey some recent developments to highlight the advances made. They describe small mobile platform technologies, such as smart and autonomous vehicles for monitoring and exploration: remotely operated underwater vehicles, autonomous underwater explorers, unmanned underwater vehicles, underwater drones, and underwater gliders. They also look at the possibility of larger complex platforms that might be the basis of a smart underwater environment, with multifunctional complexes as pilot deployment centers for the demonstration of new multi-technological developments.

1.3.12 Abstract of Chapter 13

This chapter, entitled ‘Underwater Anchor Localization using Surface-reflected Beams’, addresses the localizing of underwater objects near the surface of the water using a new mathematical model. This is applicable to most immersing vehicles and well over 90% of the sensing and underwater traffic today. Then, the author extends the model to make use of bottom-reflected acoustic beams, an approach applicable to shallow waters and some special cases of object localization in deep water. A lab-based prototype has been set up to validate some parts of the model in a scaled 3D underwater environment.

The localization model uses line-of-sight and surface-reflected non-line-of-sight links for locating a node that has been lost or drifted away from the network-controlled system, using reference points shown to be very effective in accuracy and speed of the process. One of the main features of the method is estimation of the angle of arrival (AOA) at the lost node; this has made a significant contribution and involves combining the surface-reflected non-line-of-sight signal arrays using directional acoustic transducers. The simulation results demonstrate the method's localization performance and the advantages of the proposed scheme when more reference nodes are available; the localization error is halved. Further observations bring the benefits of combining both the line-of-sight and non-line-of-sight signals. This is significant when the water's surface is rough, and most of the effective signal power of the acoustic channel comes from indirect rather than direct paths.

1.3.13 Abstract of Chapter 14

This chapter, entitled 'Coordinate Determination of Submerged Sensors with a Single Beacon using the Cayley–Menger Determinant', introduces a new dynamic method for locating sensor-enabled nodes, objects and vehicles with higher precision.

In this measurement system, a closed-form solution is used to determine the coordinates and associated specifications using beacon nodes at the surface; these can give continuous updates, with the coordinates claimed to be achieved instantly, without a need for any complex infrastructure or use of reference points. The method uses the Cayley–Menger determinant and linearized trilateration. An interesting feature is associated with using the Cayley–Menger determinant: the six edges of the planar quadrilateral are not independent and need to satisfy certain equality constraints. This constraint then can be exploited to reduce the impact of distance measurement errors, and this insight can be extended to give TDOA and AOA localization measurements.

The Cayley–Menger determinant gives the volume of a tetrahedron created by one beacon at the surface and three sensors at the bottom of the water column to determine the coordinates of each of the sensors with respect to one of them, where the determinant is nonlinear. Then, applying the degree-of-freedom property to expand the determinant, a linearized system is solved once the coordinates of the sensor are found with respect to known distances, trilateration and linear transformation of the reference point. This is used to determine the coordinates of the sensors with respect to the beacon node.

At first, the coordinates of the submerged sensors are determined assuming the sensors are stationary; voluntary or involuntary mobility of the sensors is incorporated into the mathematical model at a later stage.

1.3.14 Abstract of Chapter 15

This chapter, entitled 'Underwater and Submerged Wireless Sensor Systems Security Issues and Solutions', addresses the security aspects of underwater wireless sensor systems (UWSSs), which for most applications – scientific exploration, commercial, surveillance and defence – is essential. It looks at the specific characteristics of the underwater sensing environment and sets out the need for a new and more suitable network architecture that can overcome the most critical drawbacks of UWSSs, including the unavailability of commonly used features of open-air and terrestrial facilities, such as GPS localization and the maintenance of security requirements.

Security considerations of underwater projects are related to issues such as adversary nodes eavesdropping on traffic and also can interrupting and modifying messages, creating more critical vulnerabilities for data confidentiality, integrity, and authentication processes.

Because of the impracticality of asymmetric encryption mechanisms, the authors have looked for *symmetric* encryption mechanisms suitable for UWSSs, and have therefore tried to find a suitable key-management technique too. Aspects considered include:

- Connectivity security requirements and issues for the new key-distribution approach, considering nomadic and meandering current mobility models.
- Denial of service attacks: jamming by reducing duty cycles, power exhaustion by limiting retransmission, multiple identities using location verification techniques and sinkhole attacks by adopting more secure routing protocols.
- Secure localization approaches, which are mostly under development.
- Secure cross layer techniques for more efficient communications; these are to be designed and adopted as they mature.
- Secure time synchronization in scheduling and TDMA protocols normally caused by long propagation-delay transmission and highly mobile nodes.

1.3.15 Abstract of Chapter 16

This chapter, entitled 'Achievable Throughput of Magnetic-induction-based Sensor Networks for the Underground Communications', addresses one of the most difficult communication environments. Underground communication for sensing and actuating is truly challenging due to the unique channel variability and complexity involved. Wireless underground sensor networks (WUSNs) are required for industrial applications ranging from soil monitoring, earthquake prediction, inspection of mines, oil reservoirs, tunnels, structural and construction health monitoring, and agriculture. They can also be used for many other common purposes, such as underground object identification and localization.

Communication in such environments represents a bottleneck for WUSNs. Due to the heavy path loss, traditional electromagnetic radio wave propagation techniques can be used only over very short distances and degrade extensively with increase in soil moisture. The authors therefore consider alternative communication technologies and, due to its popularity in short-depth applications, they suggest magnetic induction (MI) as a possible solution. MI has already been used for near-field communication and wireless power transfer. The MI-WUSN has been tried in various ways, including MI waveguides with passive relaying, in which multiple magnetic relays implemented as resonant coils are combined in a waveguide structure for making connections between the active nodes of the networks. The practical round figure of a 3-m relay system with no passive relays is an interesting solution for many underground industrial applications.

Following their underground transmission model for MI-WUSNs the chapter explores some details of modelling and maximization, including network specifications, throughput maximization, direct transmission throughput and waveguide style throughput, and compares the methods used for various applications.

1.3.16 Abstract of Chapter 17

This chapter, entitled 'Agricultural Applications of Underground Wireless Sensor Systems', is a technical review addressing underground WSSs for agriculture. There is a technological challenge between the established terrestrial wireless sensor network (TWSN) technology and the new and immature technology of WUSN. Comparing underground technologies with TWSNs is unrealistic. Combination of WUSN and TWSN technology can provide breakthroughs. Bringing these new solutions to dry lands and mountains where the soil is extremely rich but where water efficiency is vital may become more important than just a contribution to the global economy.

The authors have made significant efforts to unearth the recent history of sensor technology development from decades of scattered research and less-known developments and real projects in remote areas. At a time where pressure from global businesses and expanding towns threatens the future of traditional farming, and while Internet trading and self-sufficiency could save many small villages from disappearance, there could be a big market for combined TWSNs and WUSNs: mass production of the parts and systems by larger industries, and SMEs providing a whole range of services and systems including parts, devices, sensors, expertise and advice, training, and sharing or hiring out new and advanced agricultural tools, machineries, and systems.

1.3.17 Abstract of Chapter 18

At the dawn of the Internet of Things (IoT) and WSNs this chapter, 'Structural Health Monitoring with WSNs', shows us how smart sensors bring new safety measures to our monuments, buildings, tunnels and bridges, reducing casualties and saving the structures.

A statistical literature review shows that whilst research into the IoT and WSNs has begun to fall, interest in structural health monitoring (SHM) is still on the rise, demonstrating its resistance to the hype. The authors examine SHM technologies and associated breakthroughs including compressed sensing and energy consumption. Then, under the title of 'WSN-enabled SHM applications', they look into:

- integrating the IoT and SHM
- commercially available acoustic emission sensors
- RFID-assisted SHM.

The network topology and associated network overlay part of the chapter introduces the new idea of multifunctional overlaying network management.

Then the authors consider the power requirements and energy consumption of WSNs, trying to ensure the maximum lifetime achieved. Choices include use of the correct processors. For a global architecture, rapid development of IoT-SHM systems will enable mass production of the parts at extremely low prices, following global Internet and sensor interworking standards.

SHM is unusual; although it sounds as though it should be an industrial application of WSNs, because of its use in, for example, internal measurement of walls, buildings, bridges, tunnels, and in embedded, and movement-enabled monitoring, we therefore group it with underground and confined applications of the WSSs.

1.3.18 Abstract of Chapter 19

This chapter, entitled 'Error Manifestation in Industrial WSN Communications and Guidelines for Countermeasures', addresses the problem of insufficient reliability in classic industrial wireless sensor networks (IWSNs). The authors suggest that this is due to the existing de facto standards' inability to cope with the physical and electromagnetic properties of industrial environments.

As the compromising factors in industrial WSN communications, they list physical factors as follows: sensor placement, reflective surfaces, open-space layout and moving objects. They also consider electromagnetic interference and signal distortion.

To meet the high reliability requirements of wireless sensor applications in the harsh propagation conditions of industrial environments, they propose a resilient lightweight solution based upon the nature of errors, follow their footprints on the bit-, symbol- and DSSS chip-level of IWSN signals, trying to distinguish the differences made by WLAN interference to those caused by multipath fading and attenuation. Because signal waveforms and physical layer properties are defined by WSN communication standards, the solutions for higher reliability are to be found in the design space of the data link layer and its medium access control sublayer.

1.3.19 Abstract of Chapter 20

This chapter is entitled 'Medium Access Approach to Wireless Technologies for Reliable Communication in Aircraft', addresses wireless communication systems and their impact on sensor and actuator networks and the safety aspects of controlling the aircraft. After a preliminary investigation and discussion of practical wiring problems and outlining passenger concerns about aeroplane safety, the authors set out a procedure to meet the required objectives. To do this they introduce their fault-tree analysis, as the framework of a reliability assessment. Then they introduce their performance metrics and analyse feasible wireless technologies. The chosen candidate wireless system is evaluated against the performance metrics in the reliability framework.

The reliability model is illustrated through an example of a passenger heat sensor application, building upon the errors from four main contributing components of power, sensor, control, and communication systems. Then they expand these elements to the hardware, application message delivery, and security components, which are all converted into an accumulative set of packet-level failures.

The reliability assessment model takes the requirements from aircraft safety standards and merges them down to the level of packet transmission probability failures. Then there is a lengthy analysis and comparison of six associated standards:

- Wireless Interface for Sensors and Actuators
- ECMA-368
- IEEE 802.11e
- IEEE 802.15.4 (IoT)

- IEEE 802.15.4 (WirelessHART)
- 3GPP LTE

for a typical aircraft application. There is benchmarking of the unmodified capabilities, and plots and tables to be used by designers for engineering the best possible solution for a wireless enabled sensor based aircraft communication system.

The authors claim their method is practical and note that is makes use of commercial off-the-shelf hardware and that their work gives communication engineers better insights into designing more reliable MAC systems.

1.3.20 Abstract of Chapter 21

This chapter, entitled 'Application of Wireless Sensor Systems for Monitoring of Offshore Windfarms', addresses the way WSSs can be used in offshore windfarms. Wind is everywhere and abundant. In coastal areas, the intensity of wind energy is higher and present everywhere, and wind turbines can go onshore or offshore. Onshore wind turbines are easier to maintain, monitor and control than offshore wind turbines. Offshore turbines do not occupy valuable land, but suffer from corrosion because of the salt water and humid air.

The authors discuss the various applications of WSNs in windfarm monitoring systems. A unique energy-efficient application-specific routing protocol called the network lifetime enhancing tri-level clustering and routing protocol (NETCRP) is discussed. A fault detection method is also discussed. Suitable enhancements can be incorporated to further decrease the energy consumption and hence increase network lifetime. Examples include the introduction of sleep periods. Moreover, the effects of

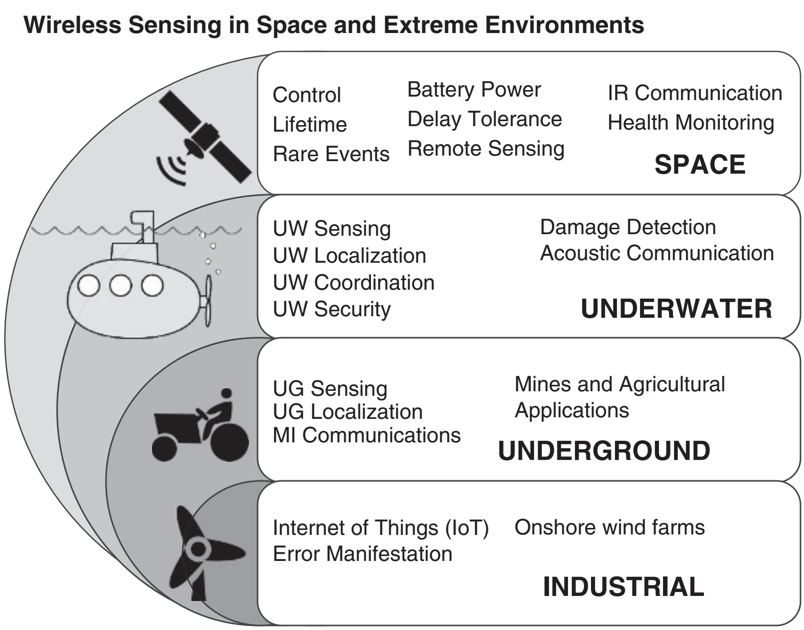

Figure 1.1 An illustration of the four harsh, and most difficult areas for using the WSS and its new applications.

increasing and decreasing the number of quantization levels are studied, and equations for the optimal number are established.

The above Chapter summaries demonstrate a unique blend of R&D and Implementation activities in the field of Wireless Sensor Systems from today's academic research and industrial deployments. Penetrating and breaking the existing limiting barriers in the very challenging environments, under four topical applications of Space, Underwater, Underground, and Industrial, with considerable potentials to enhance our lives and prosper our future industries, as shown in Figure 1.1.

Reference

1 Rashvand, H., Abedi, A., Alcaraz-Calero, J., Mitchell, P. D., and Mukhopadhyay, S. (2014). Wireless sensor systems for extreme environments: a review. *IEEE Sensors Journal*, **14**(11), 3955–3970.