Wireless Sensor Networks

Ian F. Akyildiz

Georgia Institute of Technology, USA

Mehmet Can Vuran

University of Nebraska-Lincoln, USA

WILEY

A John Wiley and Sons, Ltd, Publication

Wireless Sensor Networks

IAN F. AKYILDIZ SERIES IN COMMUNICATIONS AND NETWORKING

The *Ian F. Akyildiz Series in Communications and Networking* offers a comprehensive range of graduate-level text books for use on the major graduate programmes in communications engineering and networking throughout Europe, the USA and Asia. The series provides technically detailed books covering cutting-edge research and new developments in wireless and mobile communications, and networking. Each book in the series contains supporting material for teaching/learning purposes (such as exercises, problems and solutions, objectives and summaries etc), and is accompanied by a website offering further information such as slides, teaching manuals and further reading.

Titles in the series:

Akyildiz and Wang: *Wireless Mesh Networks*, 978-0470-03256-5, January 2009
Akyildiz and Vuran: *Wireless Sensor Networks*, 978-0470-03601-3, August 2010
Akyildiz, Lee and Chowdhury: *Cognitive Radio Networks*, 978-0470-68852-6 (forthcoming, 2011)
Ekici: *Mobile Ad Hoc Networks*, 978-0470-68193-0 (forthcoming, 2011)

Wireless Sensor Networks

Ian F. Akyildiz

Georgia Institute of Technology, USA

Mehmet Can Vuran

University of Nebraska-Lincoln, USA

WILEY

A John Wiley and Sons, Ltd, Publication

This edition first published 2010

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

Akyildiz, Ian Fuat.
Wireless sensor networks / Ian F. Akyildiz, Mehmet Can Vuran.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-03601-3 (cloth)
1. Wireless sensor networks. I. Vuran, Mehmet Can. II. Title.
TK7872.D48A38 2010 681’.2–dc22
2010008113

A catalogue record for this book is available from the British Library.

ISBN 978-0-470-03601-3 (H/B)

Set in 9/11pt Times by Sunrise Setting Ltd, Torquay, UK.
Printed and bound in Singapore by Markono Print Media Pte Ltd, Singapore.

To my wife Maria and
children Celine, Rengin
and Corinne for their continous
love and support...

IFA

Hemşerim'e...
To the loving memory of my
Dad, Mehmet Vuran...

MCV

Contents

About the Series Editor

Ian F. Akyildiz is the Ken Byers Distinguished Chair Professor with the School of Electrical and Computer Engineering, Georgia Institute of Technology; Director of Broadband Wireless Networking Laboratory and Chair of the Telecommunications Group. Since June 2008 he has been an Honorary Professor with the School of Electrical Engineering at the Universitat Politècnica de Catalunya, Barcelona, Spain. He is the Editor-in-Chief of *Computer Networks Journal* (Elsevier), is the founding Editor-in-Chief of the *Ad Hoc Networks Journal* (Elsevier) in 2003 and is the founding Editor-in-Chief of the *Physical Communication (PHYCOM) Journal* (Elsevier) in 2008. He is a past editor for *IEEE/ACM Transactions on Networking* (1996–2001), the *Kluwer Journal of Cluster Computing* (1997–2001), the *ACM-Springer Journal for Multimedia Systems* (1995–2002), *IEEE Transactions on Computers* (1992–1996) as well as the *ACM-Springer Journal of Wireless Networks (ACM WINET)* (1995–2005).

Dr Akyildiz was the Technical Program Chair and General Chair of several IEEE and ACM conferences including ACM MobiCom'96, IEEE INFOCOM'98, IEEE ICC'03, ACM MobiCom'02 and ACM SenSys'03, and he serves on the advisory boards of several research centers, journals, conferences and publication companies. He is an IEEE Fellow (1996) and an ACM Fellow (1997), and served as a National Lecturer for ACM from 1989 until 1998. He received the ACM Outstanding Distinguished Lecturer Award for 1994, and has served as an IEEE Distinguished Lecturer for IEEE COMSOC since 2008. Dr Akyildiz has received numerous IEEE and ACM awards including the 1997 IEEE Leonard G. Abraham Prize award (IEEE Communications Society), the 2002 IEEE Harry M. Goode Memorial award (IEEE Computer Society), the 2003 Best Tutorial Paper Award (IEEE Communications Society), the 2003 ACM SIGMOBILE Outstanding Contribution Award, the 2004 Georgia Tech Faculty Research Author Award and the 2005 Distinguished Faculty Achievement Award.

Dr Akyildiz is the author of two advanced textbooks entitled *Wireless Mesh Networks* and *Wireless Sensor Networks*, published by John Wiley & Sons in 2010.

His current research interests are in Cognitive Radio Networks, Wireless Sensor Networks, Wireless Mesh Networks and Nano-networks.

Preface

Wireless sensor networks (WSNs) have attracted a wide range of disciplines where close interactions with the physical world are essential. The distributed sensing capabilities and the ease of deployment provided by a wireless communication paradigm make WSNs an important component of our daily lives. By providing distributed, real-time information from the physical world, WSNs extend the reach of current cyber infrastructures to the physical world.

WSNs consist of tiny sensor nodes, which act as both data generators and network relays. Each node consists of sensor(s), a microprocessor, and a transceiver. Through the wide range of sensors available for tight integration, capturing data from a physical phenomenon becomes standard. Through on-board microprocessors, sensor nodes can be programmed to accomplish complex tasks rather than transmit only what they observe. The transceiver provides wireless connectivity to communicate the observed phenomena of interest. Sensor nodes are generally stationary and are powered by limited capacity batteries. Therefore, although the locations of the nodes do not change, the network topology dynamically changes due to the power management activities of the sensor nodes. To save energy, nodes aggressively switch their transceivers off and essentially become disconnected from the network. In this dynamic environment, it is a major challenge to provide connectivity of the network while minimizing the energy consumption. The energy-efficient operation of WSNs, however, provides significantly long lifetimes that surpass any system that relies on batteries.

In March 2002, our survey paper "Wireless sensor networks: A survey" appeared in the Elsevier journal *Computer Networks*, with a much shorter and concise version appearing in *IEEE Communications Magazine* in August 2002. Over the years, both of these papers were among the top 10 downloaded papers from Elsevier and IEEE Communication Society (ComSoc) journals with over 8000 citations in total.[1] Since then, the research on the unique challenges of WSNs has accelerated significantly. In the last decade, promising results have been obtained through these research activities, which have enabled the development and manufacture of sophisticated products. This, as a result, eventually created a brand-new market powered by the WSN phenomenon. Throughout these years, the deployment of WSNs has become a reality. Consequently, the research community has gained significant experience through these deployments. Furthermore, many researchers are currently engaged in developing solutions that address the unique challenges of the present WSNs and envision new WSNs such as wireless underwater and underground sensor networks. We have contributed to this research over the years through numerous articles and four additional survey/roadmap papers on wireless sensor actor networks, underwater acoustic networks, wireless underground sensor networks, and wireless multimedia sensor networks which were published in different years within the last decade.

In summer 2003, we started to work on our second survey paper on WSNs to revisit the state-of-the-art solutions since the *dawn* of this phenomenon. The large volume of work and the interest in both academia and industry have motivated us to significantly enhance this survey to create this book, which is targeted at teaching graduate students, stimulating them for new research ideas, as well as providing academic and industry professionals with a thorough overview and in-depth understanding of the state-of-the-art in wireless sensor networking and how they can develop new ideas to advance this technology as well as support emerging applications and services. The book provides a comprehensive coverage of

[1] According to Google Scholar as of October 2009.

the present research on WSNs as well as their applications and their improvements in numerous fields. This book covers several major research results including the authors' own contributions as well as all standardization committee decisions in a cohesive and unified form. Due to the sheer amount of work that has been published over the last decade, obviously it is not possible to cover every single solution and any lack thereof is unintentional.

The contents of the book mainly follow the TCP/IP stack starting from the physical layer and covering each protocol layer in detail. Moreover, cross-layer solutions as well as services such as synchronization, localization, and topology control are discussed in detail. Special cases of WSNs are also introduced. Functionalities and existing protocols and algorithms are covered in depth. The aim is to teach the readers what already exists and how these networks can further be improved and advanced by pointing out *grand research challenges* in the final chapter of the book.

Chapter 1 is a comprehensive introduction to WSNs, including sensor platforms and network architectures. Chapter 2 summarizes the existing applications of WSNs ranging from military solutions to home applications. Chapter 3 provides a comprehensive coverage of the characteristics, critical design factors, and constraints of WSNs. Chapter 4 studies the physical layer of WSNs, including physical layer technologies, wireless communication characteristics, and existing standards at the WSN physical layer. Chapter 5 presents various medium access control (MAC) protocols for WSNs, with a special focus on the basic carrier sense multiple access with collision avoidance (CSMA/CA) techniques used extensively at this layer, as well as distinct solutions ranging from CSMA/CA variants, time division multiple access (TDMA)-based MAC, and their hybrid counterparts. Chapter 6 focuses on error control techniques in WSNs as well as their impact on energy-efficient communication. Along with Chapter 5, these two chapters provide a comprehensive evaluation of the link layer in WSNs. Chapter 7 is dedicated to routing protocols for WSNs. The extensive number of solutions at this layer are studied in four main classes: data-centric, hierarchical, geographical, and quality of service (QoS)-based routing protocols. Chapter 8 firstly introduces the challenges of transport layer solutions and then describes the protocols. Chapter 9 introduces the cross-layer interactions between each layer and their impacts on communication performance. Moreover, cross-layer communication approaches are explained in detail. Chapter 10 discusses time synchronization challenges and several approaches that have been designed to address these challenges. Chapter 11 presents the challenges for localization and studies them in three classes: ranging techniques, range-based localization protocols, and range-free localization protocols. Chapter 12 is organized to capture the topology management solutions in WSNs. More specifically, deployment, power control, activity, scheduling, and clustering solutions are explained. Chapter 13 introduces the concept of wireless sensor–actor networks (WSANs) and their characteristics. In particular, the coordination issues between sensors and actors as well as between different actors are highlighted along with suitable solutions. Moreover, the communication issues in WSANs are discussed. Chapter 14 presents wireless multimedia sensor networks (WMSNs) along with their challenges and various architectures. In addition, the existing multimedia sensor network platforms are introduced, and the protocols are described in the various layers following the general structure of the book. Chapter 15 is dedicated to underwater wireless sensor networks (UWSNs) with a major focus on the impacts of the underwater environment. The basics of underwater acoustic propagation are studied and the corresponding solutions at each layer of the protocol stack are summarized. Chapter 16 introduces wireless underground sensor networks (WUSNs) and various applications for these networks. In particular, WUSNs in soil and WUSNs in mines and tunnels are described. The channel properties in both these cases are studied. Furthermore, the existing challenges in the communication layers are described. Finally, Chapter 17 discusses the grand challenges that still exist for the proliferation of WSNs.

It is a major task and challenge to produce a textbook. Although usually the authors carry the major burden, there are several other key people involved in publishing the book. Our foremost thanks go to Birgit Gruber from John Wiley & Sons who initiated the entire idea of producing this book. Tiina Ruonamaa, Sarah Tilley, and Anna Smart at John Wiley & Sons have been incredibly helpful, persistent, and patient. Their assistance, ideas, dedication, and support for the creation of this book will always be greatly appreciated. We also thank several individuals who indirectly or directly contributed to our book. In particular, our sincere thanks go to Özgur B. Akan, Tommaso Melodia, Dario Pompili, Weilian Su, Eylem Ekici, Cagri Gungor, Kaushik R. Chowdhury, Xin Dong, and Agnelo R. Silva for their help.

I (MCV) would like to specifically thank the numerous professors who have inspired me throughout my education in both Bilkent University, Ankara, Turkey and Georgia Institute of Technology, Atlanta, GA. I would like to thank my colleagues and friends at the University of Nebraska–Lincoln and the Department of Computer Science and Engineering for the environment they created during the development of this book. I am especially thankful to my PhD advisor, Professor Ian F. Akyildiz, who introduced me to the challenges of WSNs. I wholeheartedly thank him for his strong guidance, friendship, and trust during my PhD as well as my career thereafter. I would also like to express my deep appreciation to my wife, Demet, for her love, exceptional support, constructive critiques, and her sacrifices that made the creation of this book possible. I am thankful to my mom, Ayla, for the love, support, and encouragement that only a mother can provide. Finally, this book is dedicated to the loving memory of my dad, Mehmet Vuran (or *Hemşerim* as we used to call each other). He was the greatest driving force for the realization of this book as well as many other accomplishments in my life.

I (IFA) would like to specifically thank my wife and children for their support throughout all these years. Without their continuous love, understanding, and tolerance, none of these could have been achieved. Also my past and present PhD students, who became part of my family over the last 25 years, deserve the highest and sincerest thanks for being in my life and letting me enjoy the research to the fullest with them. The feeling of seeing how they developed in their careers over the years is indescribable and one of the best satisfactions in my life. Their research results contributed a great deal to the contents of this book as well.

Ian F. Akyildiz and Mehmet Can Vuran

1

Introduction

With the recent advances in *micro electro-mechanical systems* (MEMS) technology, wireless communications, and digital electronics, the design and development of low-cost, low-power, multifunctional sensor nodes that are small in size and communicate untethered in short distances have become feasible. The ever-increasing capabilities of these tiny sensor nodes, which include sensing, data processing, and communicating, enable the realization of wireless sensor networks (WSNs) based on the collaborative effort of a large number of sensor nodes.

WSNs have a wide range of applications. In accordance with our vision [18], WSNs are slowly becoming an integral part of our lives. Recently, considerable amounts of research efforts have enabled the actual implementation and deployment of sensor networks tailored to the unique requirements of certain sensing and monitoring applications.

In order to realize the existing and potential applications for WSNs, sophisticated and extremely efficient communication protocols are required. WSNs are composed of a large number of sensor nodes, which are densely deployed either inside a physical phenomenon or very close to it. In order to enable reliable and efficient observation and to initiate the right actions, physical features of the phenomenon should be reliably detected/estimated from the collective information provided by the sensor nodes [18]. Moreover, instead of sending the raw data to the nodes responsible for the fusion, sensor nodes use their processing capabilities to locally carry out simple computations and transmit only the required and partially processed data. Hence, these properties of WSNs present unique challenges for the development of communication protocols.

The intrinsic properties of individual sensor nodes pose additional challenges to the communication protocols in terms of energy consumption. As will be explained in the later chapters, WSN applications and communication protocols are mainly tailored to provide high energy efficiency. Sensor nodes carry limited power sources. Therefore, while traditional networks are designed to improve performance metrics such as throughput and delay, WSN protocols focus primarily on power conservation. The deployment of WSNs is another factor that is considered in developing WSN protocols. The position of the sensor nodes need not be engineered or predetermined. This allows random deployment in inaccessible terrains or disaster relief operations. On the other hand, this random deployment requires the development of self-organizing protocols for the communication protocol stack. In addition to the placement of nodes, the density in the network is also exploited in WSN protocols. Due to the short transmission ranges, large numbers of sensor nodes are densely deployed and neighboring nodes may be very close to each other. Hence, multi-hop communication is exploited in communications between nodes since it leads to less power consumption than the traditional single hop communication. Furthermore, the dense deployment coupled with the physical properties of the sensed phenomenon introduce correlation in spatial and temporal domains. As a result, the spatio-temporal correlation-based protocols emerged for improved efficiency in networking wireless sensors.

Wireless Sensor Networks Ian F. Akyildiz and Mehmet Can Vuran

In this book, we present a detailed explanation of existing products, developed protocols, and research on algorithms designed thus far for WSNs. Our aim is to provide a contemporary look at the current state of the art in WSNs and discuss the still-open research issues in this field.

1.1 Sensor Mote Platforms

WSNs are composed of individual embedded systems that are capable of (1) interacting with their environment through various sensors, (2) processing information locally, and (3) communicating this information wirelessly with their neighbors. A sensor node typically consists of three components and can be either an individual board or embedded into a single system:

- **Wireless modules** or **motes** are the key components of the sensor network as they possess the communication capabilities and the programmable memory where the application code resides. A mote usually consists of a microcontroller, transceiver, power source, memory unit, and may contain a few sensors. A wide variety of platforms have been developed in recent years including Mica2 [3], Cricket [2], MicaZ [3], Iris [3], Telos [3], SunSPOT [9], and Imote2 [3].
- **A sensor board** is mounted on the mote and is embedded with multiple types of sensors. The sensor board may also include a prototyping area, which is used to connect additional custom-made sensors. Available sensor boards include the MTS300/400 and MDA100/300 [3] that are used in the Mica family of motes. Alternatively, the sensors can be integrated into the wireless module such as in the Telos or the SunSPOT platform.
- **A programming board**, also known as the gateway board, provides multiple interfaces including Ethernet, WiFi, USB, or serial ports for connecting different motes to an enterprise or industrial network or locally to a PC/laptop. These boards are used either to program the motes or gather data from them. Some examples of programming boards include the MIB510, MIB520, and MIB600 [3]. Particular platforms need to be connected to a programming board to load the application into the programmable memory. They could also be programmed over the radio.

While the particular sensor types vary significantly depending on the application, a limited number of wireless modules have been developed to aid research in WSNs. Table 1.1 captures the major characteristics of popular platforms that were designed over the past few years in terms of their processor speed, programmable and storage memory size, operating frequency, and transmission rate. The timeline for these platforms is also shown in Figure 1.1. As can be observed, the capabilities of these platforms vary significantly. However, in general, the existing platforms can be classified into two based on both their capabilities and the usage. Next, we overview these existing platforms as *low-end* and *high-end* platforms. Moreover, several standardization efforts that have been undertaken for the proliferation of application development will be explained in Section 1.1.3. Finally, the software packages that have been used within these devices are described.

1.1.1 Low-End Platforms

The low-end platforms are characterized by their limited capabilities in terms of processing, memory, and communication. These platforms are usually envisioned to be deployed in large numbers in a WSN to accomplish sensing tasks as well as providing a connectivity infrastructure. The following platforms have been mostly used in developing communication protocols recently:

Mica family: The Mica family of nodes consist of Mica, Mica2, MicaZ, and IRIS nodes and are produced by Crossbow [3]. Each node is equipped with 8-bit Atmel AVR microcontrollers with a speed of 4–16 MHz and 128–256 kB of programmable flash. While the microcontrollers are similar, the Mica family of nodes have been equipped with a wide range of transceivers. The Mica node includes a 916 or 433 MHz transceiver at 40 kbps, while the Mica2 platform is equipped with a 433/868/916 MHz

Table 1.1 Mote hardware.

Mote type	CPU speed (MHz)	Prog. mem. (kB)	RAM (kB)	Radio freq. (MHz)	Tx. rate (kbps)
Berkeley [3]					
WeC	8	8	0.5	916	10
rene	8	8	0.5	916	10
rene2	8	16	1	916	10
dot	8	16	1	916	10
mica	6	128	4	868	10/40
mica2	16	128	4	433/868/916	38.4 kbaud
micaz	16	128	4	2.4 GHz	250
Cricket [3]	16	128	4	433	38.4 kbaud
EyesIFX [17]	8	60	2	868	115
TelosB/Tmote [3]	16	48	10	2.4 GHz	250
SHIMMER [16]	8	48	10	BT/2.4 GHz[a]	250
Sun SPOT [9]	16–60	2 MB	256	2.4 GHz	250
BTnode [1]	8	128	64	BT/433–915[a]	Varies
IRIS [3]	16	128	8	2.4 GHz	250
V-Link [15]	N/A	N/A	N/A	2.4 GHz	250
TEHU-1121 [7]	N/A	N/A	N/A	0.9/2.4 GHz	N/A
NI WSN-3202 [6]	N/A	N/A	N/A	2.4 GHz	250
Imote [3]	12	512	64	2.4 GHz (BT)	100
Imote2 [3]	13–416	32 MB	256	2.4 GHz	250
Stargate [3]	400	32 MB	64 MB SD	2.4 GHz	Varies[b]
Netbridge NB-100 [3]	266	8 MB	32 MB	Varies[b]	Varies[b]

[a] BTnode and SHIMMER motes are equipped with two transceivers: Bluetooth and a low-power radio.
[b] The transmission rate of the Stargate board and the Netbridge depends on the communication device connected to it (MicaZ node, WLAN card, etc.).

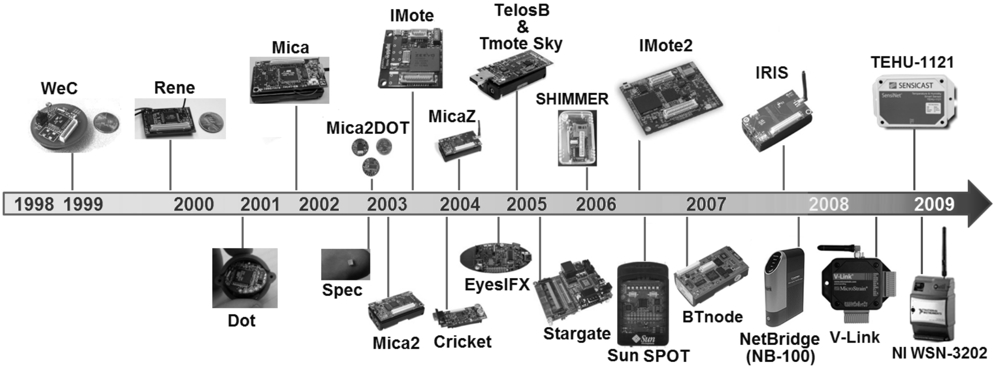

Figure 1.1 Timeline for the sensor mote platforms.

transceiver at 40 kbps. On the other hand, the MicaZ and IRIS nodes are equipped with IEEE 802.15.4 compliant transceivers, which operate at 2.4 GHz with 250 kbps data rate. Each platform has limited memory in terms of RAM (4–8 kB) and data memory (512 kB). Moreover, each version is equipped with a 51-pin connector that is used to connect additional sensor boards and programming boards to the mote.

Telos/Tmote: An architecture similar to the MicaZ platform has been adopted for the Telos motes from Crossbow and Tmote Sky motes from Sentilla (formerly Moteiv). While the transceiver is kept intact, Telos/Tmote motes have larger RAM since an 8 MHz TI MSP430 microcontroller with 10 kB RAM is used. Furthermore, Telos/Tmote platforms are integrated with several sensors including light, IR, humidity, and temperature as well as a USB connector, which eliminates the need for additional sensor or programming boards. Moreover, 6- and 10-pin connectors are included for additional sensors.

EYES: The EYES platform has been designed as a result of a 3-year European project and is similar to the Telos/Tmote architectures. A 16-bit microcontroller with 60 kB of program memory and 2 kB data memory is used in EYES [24]. Moreover, the following sensors are embedded with the mote: compass, accelerometer, and temperature, light, and pressure sensors. The EYES platform includes the TR1001 transceiver, which supports transmission rates up to 115.2 kbps with a power consumption of 14.4 mW, 16.0 mW, and 15.0 μW during receive, transmit, and sleep modes, respectively. The platform also includes an RS232 serial interface for programming.

In addition to these platforms, several low-end platforms have been developed with similar capabilities as listed in Table 1.1 and shown in Figure 1.1. An important trend to note is the appearance of proprietary platforms from the industry such as V-Link, TEHU, and the National Instruments motes in recent years (2008–2009).

The low-end platforms are used for sensing tasks in WSNs and they provide a connectivity infrastructure through multi-hop networking. These nodes are generally equipped with low-power microcontrollers and transceivers to decrease the cost and energy consumption. As a result, they are used in large numbers in the deployment of WSNs. It can be observed that wireless sensor platforms generally employ the *Industrial, Scientific, and Medical* (ISM) bands, which offer license-free communication in most countries. More specifically, most recent platforms include the CC2420 transceiver, which operates in the 2.4 GHz band and is compatible with the IEEE 802.15.4 standard. This standardization provides heterogeneous deployments of WSNs, where various platforms are used in a network. Most of the communication protocols discussed in this book are developed using these platforms.

1.1.2 High-End Platforms

In addition to sensing, local processing, and multi-hop communication, WSNs require additional functionalities that cannot be efficiently carried out by the low-end platforms. High-level tasks such as network management require higher processing power and memory compared to the capabilities of these platforms. Moreover, the integration of WSNs with existing networking infrastructure requires multiple communication techniques to be integrated through *gateway* modules. Furthermore, in networks where processing or storage hubs are integrated with sensor nodes, higher capacity nodes are required. To address these requirements, high-end platforms have been developed for WSNs.

Stargate: The Stargate board [8] is a high-performance processing platform designed for sensing, signal processing, control, and sensor network management. Stargate is based on Intel's PXA-255 Xscale 400 MHz RISC processor, which is the same processor found in many handheld computers including the Compaq IPAQ and the Dell Axim. Stargate has 32 MB of flash memory, 64 MB of SDRAM, and an on-board connector for Crossbow's Mica family motes as well as PCMCIA Bluetooth or IEEE 802.11 cards. Hence, it can work as a wireless gateway and computational hub for in-network processing algorithms.

When connected with a webcam or other capturing device, it can function as a medium-resolution multimedia sensor, although its energy consumption is still high [22].

Stargate NetBridge was developed as a successor to Stargate and is based on the Intel IXP420 XScale processor running at 266 MHz. It features one wired Ethernet and two USB 2.0 ports and is equipped with 8 MB of program flash, 32 MB of RAM, and a 2 GB USB 2.0 system disk, where the Linux operating system is run. Using the USB ports, a sensor node can be connected for gateway functionalities.

Imote and Imote2: Intel has developed two prototypal generations of wireless sensors, known as Imote and Imote2 for high-performance sensing and gateway applications [3]. Imote is built around an integrated wireless microcontroller consisting of an 8-bit 12 MHz ARM7 processor, a Bluetooth radio, 64 kB RAM, and 32 kB flash memory, as well as several I/O options. The software architecture is based on an ARM port of TinyOS.

The second generation of Intel motes, Imote2, is built around a new low-power 32-bit PXA271 XScale processor at 320/416/520 MHz, which enables DSP operations for storage or compression, and an IEEE 802.15.4 ChipCon CC2420 radio. It has large on-board RAM and flash memories (32 MB), additional support for alternate radios, and a variety of high-speed I/O to connect digital sensors or cameras. Its size is also very limited, 48×33 mm, and it can run the Linux operating system and Java applications.

1.1.3 Standardization Efforts

The heterogeneity in the available sensor platforms results in compatibility issues for the realization of envisioned applications. Hence, standardization of certain aspects of communication is necessary. To this end, the IEEE 802.15.4 [14] standards body was formed for the specification of low-data-rate wireless transceiver technology with long battery life and very low complexity. Three different bands were chosen for communication, i.e., 2.4 GHz (global), 915 MHz (the Americas), and 868 MHz (Europe). While the PHY layer uses binary phase shift keying (BPSK) in the 868/915 MHz bands and offset quadrature phase shift keying (O-QPSK) in the 2.4 GHz band, the MAC (Medium Access Control) layer provides communication for star, mesh, and cluster tree-based topologies with controllers. The transmission range of the nodes is assumed to be 10–100 m with data rates of 20 to 250 kbps [14]. Most of the recent platforms developed for WSN research comply with the IEEE 802.15.4 standard. Actually, the IEEE 802.15.4 standard, explained in Chapter 4, acquired a broad audience and became the *de facto* standard for PHY and MAC layers in low-power communication. This allows the integration of platforms with different capabilities into the same network.

On top of the IEEE 802.15.4 standard, several standard bodies have been formed to proliferate the development of low-power networks in various areas. It is widely recognized that standards such as Bluetooth and WLAN are not well suited for low-power sensor applications. On the other hand, standardization attempts such as ZigBee, WirelessHART, WINA, and SP100.11a, which specifically address the typical needs of wireless control and monitoring applications, are expected to enable rapid improvement of WSNs in the industry. In addition, standardization efforts such as 6LoWPAN are focused on providing compatibility between WSNs and existing networks such as the Internet.

Next, three major standardization efforts will be described in detail: namely, ZigBee [13], WirelessHART [12], and 6LoWPAN [4]. In addition, other standardization efforts will be summarized.

ZigBee

The ZigBee [13] standard has been developed by the ZigBee Alliance, which is an international, non-profit industrial consortium of leading semiconductor manufacturers and technology providers. The ZigBee standard was created to address the market need for cost-effective, standard-based wireless networking solutions that support low data rates, low power consumption, security, and reliability

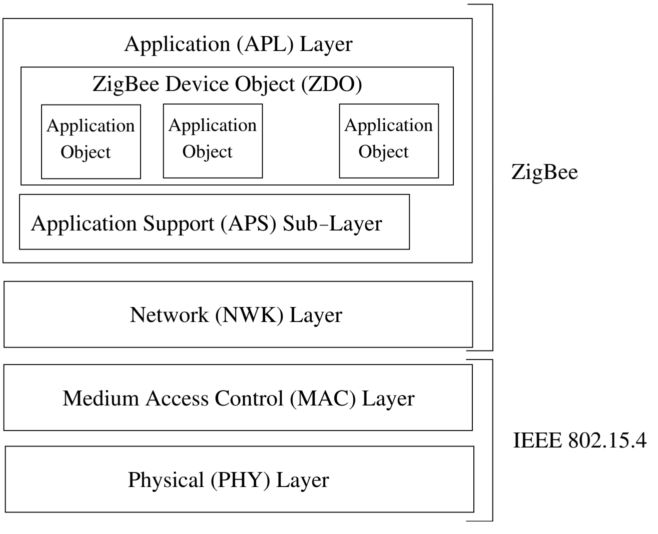

Figure 1.2 IEEE 802.15.4 and the ZigBee protocol stack [13].

through wireless personal area networks (WPANs). Five main application areas are targeted: home automation, smart energy, building automation, telecommunication services, and personal health care.

The ZigBee standard is defined specifically in conjunction with the IEEE 802.15.4 standard. Therefore, both are usually confused. However, as shown in Figure 1.2, each standard defines specific layers of the protocol stack. The PHY and MAC layers are defined by the IEEE 802.15.4 standard while the ZigBee standard defines the network layer (NWK) and the application framework. Application objects are defined by the user. To accommodate a large variety of applications, three types of traffic are defined, Firstly, *periodic data traffic* is required for monitoring applications, where sensors provide continuous information regarding a physical phenomenon The data exchange is controlled through the network controller or a router. Secondly, *Intermittent data traffic* applies to most event-based applications and is triggered through either the application or an external factor. This type of traffic is handled through each router node. To save energy, the devices may operate in disconnected mode, whereas they operate in sleep mode most of the time. Whenever information needs to be transmitted, the transceiver is turned on and the device associates itself with the network. Finally, *repetitive low-latency data traffic* is defined for certain communications such as a mouse click that needs to be completed within a certain time. This type of traffic is accommodated through the polling-based frame structure defined by the IEEE 802.15.4 standard.

The ZigBee network (NWK) layer provides management functionalities for the network operation. The procedures for establishing a new network and the devices to gain or relinquish membership of the network are defined. Furthermore, depending on the network operation, the communication stack of each device can be configured. Since ZigBee devices can be a part of different networks during their lifetime, the standard also defines a flexible addressing mechanism. Accordingly, the network coordinator assigns an address to the devices as they join the network. As a result, the unique ID of each device is not used for communication but a shorter address is assigned to improve the efficiency during communication. In a tree architecture, the address of a device also identifies its parent, which is used for routing purposes. The NWK layer also provides synchronization between devices and network controllers. Finally, multi-hop routes are generated by the NWK layer according to defined protocols.