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.).

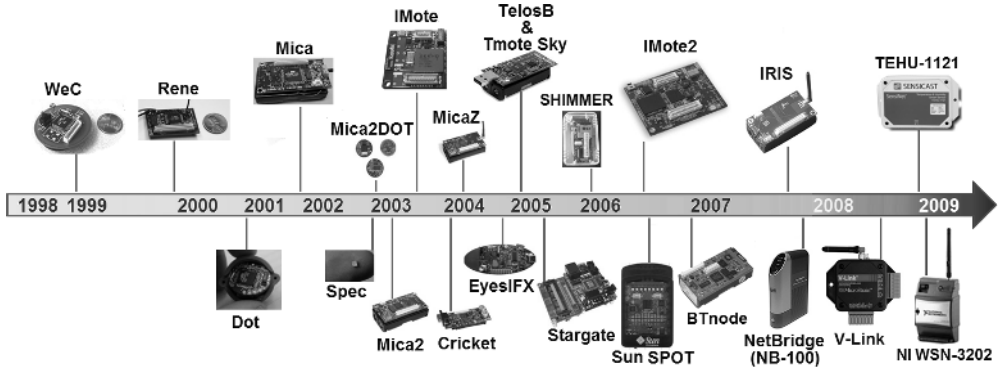

Figure 1.1 Timeline for the sensor mote platforms.

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

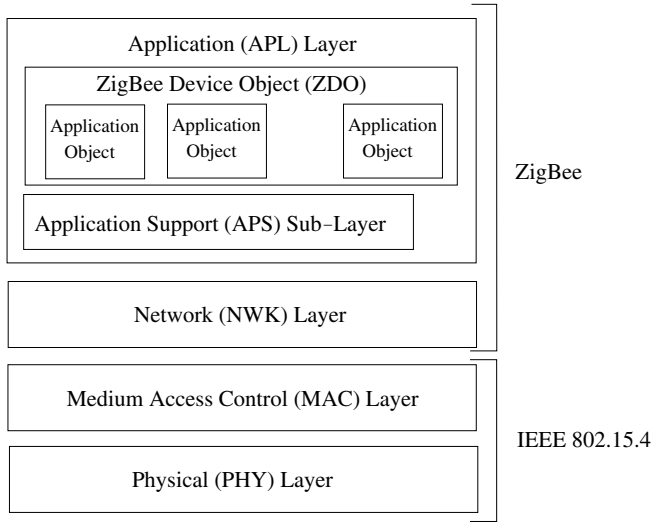

Figure 1.2 IEEE 802.15.4 and the ZigBee protocol stack [13].

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.

As shown in Figure 1.2, the ZigBee standard also defines certain components in the application layer. This layer consists of the APS sub-layer, the ZigBee device object (ZDO), and the manufacturer-defined application objects [13]. The applications are implemented through these manufacturer-defined application objects and implementation is based on requirements defined by the standard. The ZDO defines functions provided by the device for network operation. More specifically, the role of devices such as a network coordinator or a router is defined through the ZDO. Moreover, whenever a device needs to be associated with the network, the binding requests are handled through the ZDO. Finally, the APS sub-layer provides discovery capability to devices so that the neighbors of a device and the functionalities provided by these neighbors can be stored. This information is also used to match the binding requests of the neighbors with specific functions.

WirelessHART

WirelessHART [12] has been developed as a wireless extension to the industry standard Highway Addressable Remote Transducer (HART) protocol. HART is the most used communication protocol in the automation and industrial applications that require real-time support with a device count around 20 million [12]. It is based on superimposing a digital FSK-modulated signal on top of the 4–20 mA analog current loop between different components. HART provides a master/slave communication scheme, where up to two masters are accommodated in the network. Accordingly, devices connected to the system can be controlled through a permanent system and handheld devices for monitoring and control purposes.

The WirelessHART standard has been released as a part of the HART 7 specification as the first open wireless communication standard specifically designed for process measurement and control applications [12]. WirelessHART relies on the IEEE 802.15.4 PHY layer standard for the 2.4 GHz band. Moreover, a TDMA-based MAC protocol is defined to provide several messaging modes: one-way publishing of process and control values, spontaneous notification by exception, ad hoc request and response, and auto-segmented block transfers of large data sets.

The network architecture of the WirelessHART standard is shown in Figure 1.3. Accordingly, five types of components are defined: *WirelessHART field devices* (WFDs) are the sensor and control elements that are connected to process or plant equipment. *Gateways* provide interfaces with wireless portions of the network and the wired infrastructure. As a result, host application and the controller can interact with the WFDs. The *network manager* maintains operation of the network by scheduling communication slots for devices, determining routing tables, and monitoring the health of the network. In addition to the three main components, the *WirelessHART adapters* provide backward compatibility by integrating existing HART field devices with the wireless network. Finally, *handhelds* are equipped with on-board transceivers to provide on-site access to the wireless network and interface with the WFDs.

Based on these components, a full protocol stack has been defined by the WirelessHART standard. As explained above, at the PHY layer, the IEEE 802.15.4 standard is employed and a TDMA-based MAC protocol is used at the data link layer. In addition, the network topology is designed as a mesh network and each device can act as a source or a router in the network. This network topology is very similar to what is generally accepted for WSNs.

At the network layer, table-based routing is used so that multiple redundant paths are established during network formation and these paths are continuously verified. Accordingly, even if a communication path between a WFD and a gateway is corrupted, alternate paths are used to provide network reliability greater than 3σ (99.7300204%). In addition to established paths, source routing techniques are used to establish ad hoc communication paths. Moreover, the network layer supports dynamic bandwidth management by assigning allocated bandwidth to certain devices. This is also supported by the underlying TDMA structure by assigning appropriate numbers of slots to these devices. The bandwidth is allocated on a demand basis and can be configured when a device joins the network.

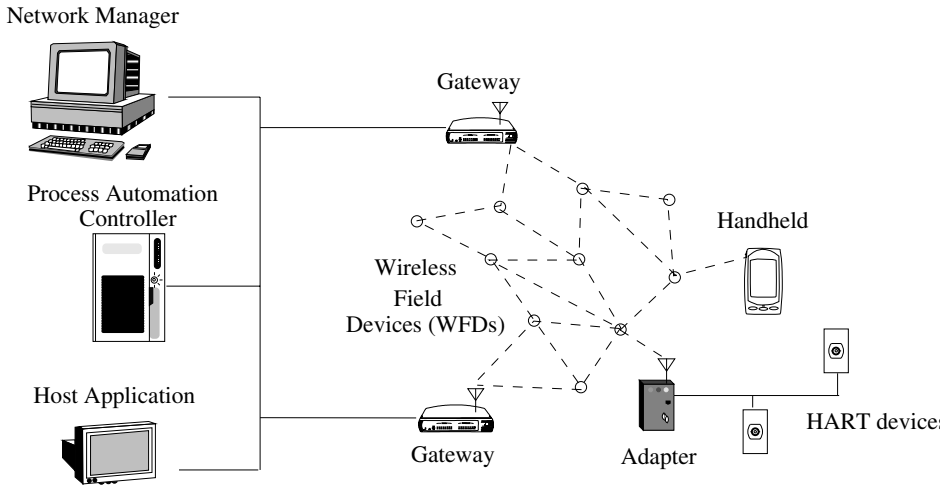

Figure 1.3 WirelessHART architecture and components [12].

The transport layer of the WirelessHART standard provides reliability on the end-to-end path and supports TCP-like reliable block transfers of large data sets. End-to-end monitoring and control of the network are also provided. Accordingly, WFDs continuously broadcast statistics related to their communication success and neighbors, which is monitored by the network manager to establish redundant routes and improve energy efficiency.

Finally, the application layer supports the standard HART application layer, where existing solutions can be implemented seamlessly.

6LoWPAN

The existing standards enable application-specific solutions to be developed for WSNs. Accordingly, stand-alone networks of sensors can be implemented for specific applications. However, these networks cannot be easily integrated with the Internet since the protocols based on IEEE 802.15.4 are not compliant with the IP. Therefore, sensors cannot easily communicate with web-based devices, servers, or browsers. Instead, gateways are required to collect the information from the WSN and communicate with the Internet. This creates single-point-of-failure problems at the gateways and stresses the neighbors of the gateway.

To integrate WSNs with the Internet, the Internet Engineering Task Force (IETF) is developing the IPv6 over Low-power Wireless Personal Area Network (6LoWPAN) standard [4]. This standard defines the implementation of the IPv6 stack on top of IEEE 802.15.4 to let any device be accessible from and with the Internet.

The basic challenge in integrating IPv6 and WSNs is the addressing structure of IPv6, which defines a header and address information field of 40 bytes. However, IEEE 802.15.4 allows up to 127 bytes for the *whole* packet including header and payload information. Accordingly, straightforward integration of both standards is not efficient. Instead, 6LoWPAN adds an adaptation layer that lets the radio stack and IPv6 communications operate together. A *stacked header* structure has been proposed for the 6LoWPAN standard [23], where, instead of a single monolithic header, four types of headers are utilized according to the type of packet being sent. In addition, stateless compression techniques are used to decrease the size of the header from 40 bytes to around 4 bytes, which is suitable for WSNs.

The four header types are as follows:

- **Dispatch header (1 byte):** This header type defines the type of header following it. The first 2 bits are set to 01 for the dispatch header and the remaining 6 bits define the type of header following it (uncompressed IPv6 header or a header compression header).
- **Mesh header (4 bytes):** This header is identified by 10 in the first 2 bits and is used in mesh topologies for routing purposes. The first 2 bits are followed by additional 2 bits that indicate whether the source and destination addresses are 16-bit short or 64-bit long addresses. A 4-bit hop left field is used to indicate the number of hops left. Originally, 15 hops are supported but an extra byte can be used to support 255 hops. Finally, the remaining fields indicate the source and the destination addresses of the packet. This information can be used by the routing protocols to find the next hop.
- **Fragmentation header (4–5 bytes):** IPv6 can support payloads up to 1280 bytes whereas this is 102 bytes for IEEE 802.15.4. This is solved by fragmenting larger payloads into several packets and the fragmentation header is used to fragment and reassemble these packets. The first fragment includes a header of 4 bytes, which is indicated by 11 in the first 2 bits and by 000 in the next 3 bits. This is followed by the datagram size and datagram tag fields. The following fragment header uses 11100 in the first 5 bits followed by the datagram size, tag, and the datagram offset.
- **Header compression header (1 byte):** Finally, the 40-byte IPv6 header is compressed into 2 bytes including the header compression header. This compression exploits the fact that IEEE 802.15.4 packet headers already include the MAC addresses of the source and destination pairs. These MAC addresses can be mapped to the lowest 64 bits of an IPv6 address. As a result, the source and destination addresses are completely eliminated from the IPv6 header. Similar techniques are used to eliminate the unnecessary fields for each communication and allow these fields to be inserted when the packet reaches a gateway to the Internet.

Header compression is not the only challenge for WSN–Internet integration. The ongoing efforts in the development of the 6LoWPAN standard aim to address some of these challenges including routing and transport control to provide seamless interoperation of WSNs and the Internet.

Other Standardization Efforts

In addition to the above efforts, several additional platforms have been engaged with defining standards for WSN applications. The ISA SP100.11a standard [5] also centers around the process and factory automation and is being developed by the Systems and Automation Society (ISA). Moreover, the Wireless Industrial Networking Alliance (WINA) [11] was formed in 2003 to stimulate the development and promote the adoption of wireless networking technologies and practices to help increase industrial efficiency. As a first step, this ad hoc group of suppliers and end-users is working to define end-user needs and priorities for industrial wireless systems. The 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.

WSN applications have gained significant momentum during the past decade with the acceleration in research in this field. Although existing applications provide a wide variety of possibilities where the WSN phenomenon can be exploited, there exists many areas waiting for WSN empowerment. Moreover, further enhancements in WSN protocols will open up new areas of applications. Nevertheless, commercialization of these potential applications is still a major challenge.

1.1.4 Software

In addition to hardware platforms and standards, several software platforms have also been developed specifically for WSNs. Among these, the most accepted platform is the TinyOS [10], which is an

open-source operating system designed for wireless embedded sensor networks. TinyOS incorporates a component-based architecture, which minimizes the code size and provides a flexible platform for implementing new communication protocols. Its component library includes network protocols, distributed services, sensor drivers, and data acquisition tools, which can be further modified or improved based on the specific application requirements. TinyOS is based on an event-driven execution model that enables fine-grained power management strategies.

Most of the existing software code for communication protocols today is written for the TinyOS platform. Coupled with TinyOS, a TinyOS mote simulator, TOSSIM, has been introduced to simplify the development of sensor network protocols and applications [21]. TOSSIM provides a scalable simulation environment and compiles directly from the TinyOS code. It simulates the TinyOS network stack at the bit level, allowing experimentation with low-level protocols in addition to top-level application systems. It also provides a graphical user interface tool, TinyViz, in order to visualize and interact with running simulations.

In addition to TinyOS, several software platforms and operating systems have been introduced recently. LiteOS [19] is a multi-threading operating system that provides Unix-like abstractions. Compared to TinyOS, LiteOS provides multi-threaded operation, dynamic memory management, and command-line shell support. The shell support, LiteShell, provides a command-line interface at the user side, i.e., the PC, to provide interaction with the sensor node to be programmed.

Contiki [20] is an open-source, multitasking operating system developed for use on a variety of platforms including microcontrollers such as the TI MSP430 and the Atmel AVR, which are used in the Telos, Tmote, and Mica families. Contiki has been built around an event-driven kernel but it is possible to employ preemptive multithreading for certain programs as well as dynamic loading and replacement of individual programs and services. As a result, compared to TinyOS, which is statically linked at compile-time, Contiki allows programs and drivers to be replaced during run-time and without relinking. Moreover, TCP/IP support is also provided through the μIP stack.

The recent SunSPOT platform [9] does not use an operating system but runs a Java virtual machine (VM), Squawk, on the bare metal, which is a fully capable Java ME implementation. The VM executes directly out of flash memory.

While several operating systems with additional capabilities have become available, TinyOS is still being widely used in WSN research. One of the main reasons for this popularity is the vast code space built throughout the development of WSN solutions. Clearly, it is hard to port existing applications and communication protocols to these new operating systems. This calls for platforms that support interoperability for existing code space so that additional flexibility and capabilities are provided to both the research community and industry.

1.2 WSN Architecture and Protocol Stack

The sensor nodes are usually scattered in a *sensor field* as shown in Figure 1.4. Each of these scattered sensor nodes has the capability to collect data and route data back to the *sink/gateway* and the end-users. Data are routed back to the end-user by a multi-hop infrastructureless architecture through the sink as shown in Figure 1.4. The sink may communicate with the *task manager/end-user* via the Internet or satellite or any type of wireless network (like WiFi, mesh networks, cellular systems, WiMAX, etc.), or without any of these networks where the sink can be directly connected to the end-users. Note that there may be multiple sinks/gateways and multiple end-users in the architecture shown in Figure 1.4.

In WSNs, the sensor nodes have the dual functionality of being both data originators and data routers. Hence, communication is performed for two reasons:

- **Source function:** Source nodes with event information perform communication functionalities in order to transmit their packets to the sink.
- **Router function:** Sensor nodes also participate in forwarding the packets received from other nodes to the next destination in the multi-hop path to the sink.

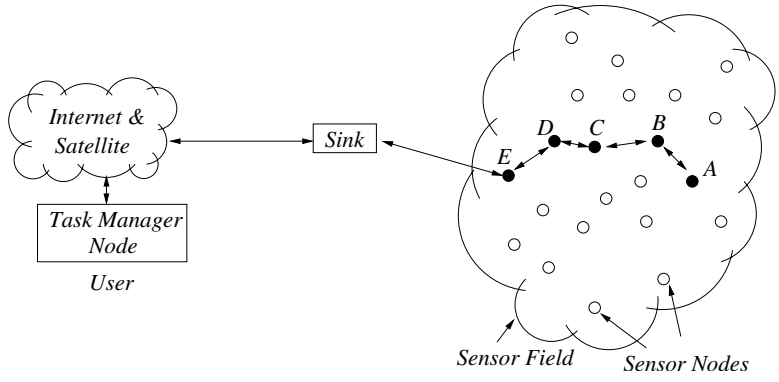

Figure 1.4 Sensor nodes scattered in a sensor field.

The protocol stack used by the sink and all sensor nodes is given in Figure 1.5. This protocol stack combines power and routing awareness, integrates data with networking protocols, communicates power efficiently through the wireless medium, and promotes cooperative efforts of sensor nodes. The protocol stack consists of the *physical layer*, *data link layer*, *network layer*, *transport layer*, *application layer*, as well as *synchronization plane*, *localization plane*, *topology management plane*, *power management plane*, *mobility management plane*, and *task management plane*. The physical layer addresses the needs of simple but robust modulation, transmission, and receiving techniques. Since the environment is noisy and sensor nodes can be mobile, the link layer is responsible for ensuring reliable communication through error control techniques and manage channel access through the MAC to minimize collision with neighbors' broadcasts. Depending on the sensing tasks, different types of application software can be built and used on the application layer. The network layer takes care of routing the data supplied by the transport layer. The transport layer helps to maintain the flow of data if the sensor network application requires it. In addition, the power, mobility, and task management planes monitor the power, movement, and task distribution among the sensor nodes. These planes help the sensor nodes coordinate the sensing task and lower the overall power consumption.

The power management plane manages how a sensor node uses its power. For example, the sensor node may turn off its receiver after receiving a message from one of its neighbors. This is to avoid getting duplicated messages. Also, when the power level of the sensor node is low, the sensor node broadcasts to its neighbors that it is low in power and cannot participate in routing messages. The remaining power is reserved for sensing. The mobility management plane detects and registers the movement of sensor nodes, so a route back to the user is always maintained, and the sensor nodes can keep track of their neighbors. By knowing these neighbor sensor nodes, the sensor nodes can balance their power and task usage. The task management plane balances and schedules the sensing tasks given to a specific region. Not all sensor nodes in that region are required to perform the sensing task at the same time. As a result, some sensor nodes perform the task more than others, depending on their power level. These management planes are needed so that sensor nodes can work together in a power-efficient way, route data in a mobile sensor network, and share resources between sensor nodes. Without them, each sensor node will just work individually. From the standpoint of the whole sensor network, it is more efficient if sensor nodes can collaborate with each other, so the lifetime of the sensor networks can be prolonged.

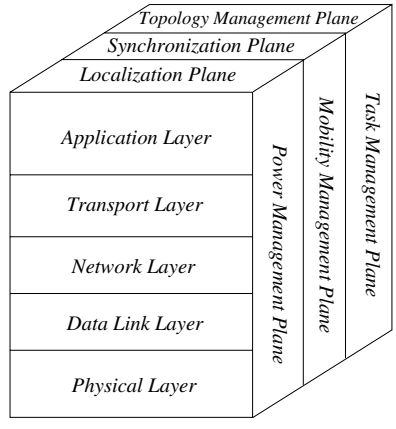

Figure 1.5 The sensor network protocol stack.

1.2.1 Physical Layer

The physical layer is responsible for frequency selection, carrier frequency generation, signal detection, modulation, and data encryption. Frequency generation and signal detection have more to do with the underlying hardware and transceiver design and hence are beyond the scope of our book. More specifically, we focus on signal propagation effects, power efficiency, and modulation schemes for sensor networks.

1.2.2 Data Link Layer

The data link layer is responsible for the multiplexing of data streams, data frame detection, and medium access and error control. It ensures reliable point-to-point and point-to-multipoint connections in a communication network. More specifically, we discuss the medium access and error control strategies for sensor networks.

MAC

The MAC protocol in a wireless multi-hop self-organizing sensor network must achieve two goals. The first goal is creation of the network infrastructure. Since thousands of sensor nodes can be densely scattered in a sensor field, the MAC scheme must establish communication links for data transfer. This forms the basic infrastructure needed for hop-by-hop wireless communication and provides the self-organizing capability. The second objective is to fairly and efficiently share communication resources between sensor nodes. These resources include time, energy, and frequency. Several MAC protocols have been developed for WSNs to address these requirements over the last decade.

Regardless of the medium access scheme, energy efficiency is of utmost importance. A MAC protocol must certainly support the operation of power saving modes for the sensor node. The most obvious means of power conservation is to turn the transceiver off when it is not required. Though this power saving method seemingly provides significant energy gains, it may hamper the connectivity of the network. Once a transceiver is turned off, the sensor node cannot receive any packets from its neighbors, essentially becoming disconnected from the network. Moreover, turning a radio on and off has an overhead in terms of energy consumption due to the startup and shutdown procedures required for both

hardware and software. In fact, if the radio is blindly turned off during each idling slot, over a period of time the sensor may end up expending more energy than if the radio had been left on. As a result, operation in a power saving mode is energy efficient only if the time spent in that mode is greater than a certain threshold. There can be a number of such useful modes of operation for the wireless sensor node, depending on the number of states of the microprocessor, memory, A/D converter, and the transceiver. Each of these modes can be characterized by its power consumption and the latency overhead, which is the transition power to and from that mode.

Error Control

Another important function of the data link layer is the error control of transmission data. Two important modes of error control in communication networks are forward error correction (FEC) and automatic repeat request (ARQ), and hybrid ARQ. The usefulness of ARQ in sensor network applications is limited by the additional retransmission cost and overhead. On the other hand, decoding complexity is greater in FEC, as error correction capabilities need to be built in. Consequently, simple error control codes with low-complexity encoding and decoding might present the best solutions for sensor networks. In the design of such a scheme, it is important to have a good knowledge of the channel characteristics and implementation techniques.

1.2.3 Network Layer

Sensor nodes are scattered densely in a field either close to or inside the phenomenon as shown in Figure 1.4. The information collected relating to the phenomenon should be transmitted to the sink, which may be located far from the sensor field. However, the limited communication range of the sensor nodes prevents direct communication between each sensor node and the sink node. This requires efficient multi-hop wireless routing protocols between the sensor nodes and the sink node using intermediate sensor nodes as relays. The existing routing techniques, which have been developed for wireless ad hoc networks, do not usually fit the requirements of the sensor networks. The networking layer of sensor networks is usually designed according to the following principles:

- Power efficiency is always an important consideration.
- Sensor networks are mostly data-centric.
- In addition to routing, relay nodes can aggregate the data from multiple neighbors through local processing.
- Due to the large number of nodes in a WSN, unique IDs for each node may not be provided and the nodes may need to be addressed based on their data or location.

An important issue for routing in WSNs is that routing may be based on data-centric queries. Based on the information requested by the user, the routing protocol should address different nodes that would provide the requested information. More specifically, the users are more interested in querying an attribute of the phenomenon rather than querying an individual node. For instance, “the areas where the temperature is over 70 °F (21 °C)” is a more common query than “the temperature read by node #47.”

One other important function of the network layer is to provide internetworking with external networks such as other sensor networks, command and control systems, and the Internet. In one scenario, the sink nodes can be used as a gateway to other networks, while another scenario is to create a backbone by connecting sink nodes together and making this backbone access other networks via a gateway.

1.2.4 Transport Layer

The transport layer is especially needed when the network is planned to be accessed through the Internet or other external networks. TCP, with its current transmission window mechanisms, does not address

the unique challenges posed by the WSN environment. Unlike protocols such as TCP, the end-to-end communication schemes in sensor networks are not based on global addressing. These schemes must consider that addressing based on data or location is used to indicate the destinations of the data packets. Factors such as power consumption and scalability, and characteristics like data-centric routing, mean sensor networks need different handling in the transport layer. Thus, these requirements stress the need for new types of transport layer protocols.

The development of transport layer protocols is a challenging task because the sensor nodes are influenced by hardware constraints such as limited power and memory. As a result, each sensor node cannot store large amounts of data like a server in the Internet, and acknowledgments are too costly for sensor networks. Therefore, new schemes that split the end-to-end communication probably at the sinks may be needed where UDP-type protocols are used in the sensor network.

For communication inside a WSN, transport layer protocols are required for two main functionalities: reliability and congestion control. Limited resources and high energy costs prevent end-to-end reliability mechanisms from being employed in WSNs. Instead, localized reliability mechanisms are necessary. Moreover, congestion that may occur because of the high traffic during events should be mitigated by the transport layer protocols. Since sensor nodes are limited in terms of processing, storage, and energy consumption, transport layer protocols aim to exploit the collaborative capabilities of these sensor nodes and shift the intelligence to the sink rather than the sensor nodes.

1.2.5 Application Layer

The application layer includes the main application as well as several management functionalities. In addition to the application code that is specific for each application, query processing and network management functionalities also reside at this layer.

The layered architecture stack has been initially adopted in the development of WSNs due to its success with the Internet. However, the large-scale implementations of WSN applications reveal that the wireless channel has significant impact on the higher layer protocols. Moreover, resource constraints and the application-specific nature of the WSN paradigm leads to *cross-layer* solutions that tightly integrate the layered protocol stack. By removing the boundaries between layers as well as the associated interfaces, increased efficiency in code space and operating overhead can be achieved.

In addition to the communication functionalities in the layered stack, WSNs have also been equipped with several functionalities that aid the operation of the proposed solutions. In a WSN, each sensor device is equipped with its own local clock for internal operations. Each event that is related to operation of the sensor device including sensing, processing, and communication is associated with timing information controlled through the local clock. Since users are interested in the collaborative information from multiple sensors, timing information associated with the data at each sensor device needs to be consistent. Moreover, the WSN should be able to correctly order the events sensed by distributed sensors to accurately model the physical environment. These timing requirements have led to the development of *time synchronization* protocols in WSNs.

The close interaction with physical phenomena requires location information to be associated in addition to time. WSNs are closely associated with physical phenomena in their surroundings. The gathered information needs to be associated with the location of the sensor nodes to provide an accurate view of the observed sensor field. Moreover, WSNs may be used for tracking certain objects for monitoring applications, which also requires location information to be incorporated into the tracking algorithms. Further, location-based services and communication protocols require position information. Hence, *localization* protocols have been incorporated into the communication stack.

Finally, several *topology management* solutions are required to maintain the connectivity and coverage of the WSN. The topology management algorithms provide efficient methods for network deployment that result in longer lifetime and efficient information coverage. Moreover, topology control protocols help determine the transmit power levels as well as the activity durations of sensor nodes to minimize

energy consumption while still ensuring network connectivity. Finally, clustering protocols are used to organize the network into clusters to improve scalability and improve network lifetime.

The integration of each of the components for efficient operation depends on the applications running on the WSN. This application-dependent nature of the WSNs defines several unique properties compared to traditional networking solutions. Although the initial research and deployment of WSNs have focused on data transfer in wireless settings, several novel application areas of WSNs have also emerged. These include *wireless sensor and actor networks*, which consist of actuators in addition to sensors that convert sensed information into actions to act on the environment, and *wireless multimedia sensor networks*, which support multimedia traffic in terms of visual and audio information in addition to scalar data. Furthermore, recently the WSN phenomenon has been adopted in constrained environments such as underwater and underground settings to create *wireless underwater sensor networks* and *wireless underground sensor networks*. These new fields of study pose additional challenges that have not been considered by the vast number of solutions developed for *traditional* WSNs.

The flexibility, fault tolerance, high sensing fidelity, low cost, and rapid deployment characteristics of sensor networks create many new and exciting application areas for remote sensing. In the future, this wide range of application areas will make sensor networks an integral part of our lives. However, realization of sensor networks needs to satisfy the constraints introduced by factors such as fault tolerance, scalability, cost, hardware, topology change, environment, and power consumption. Since these constraints are highly stringent and specific for sensor networks, new wireless ad hoc networking techniques are required. Many researchers are currently engaged in developing the technologies needed for different layers of the sensor network protocol stack. Commercial viability of WSNs has also been shown in several fields. Along with the current developments, we encourage more insight into the problems and more development of solutions to the open research issues as described in this book.

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