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Sensors and Sensor Networks with Applications on Cyber-Physical Systems

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1.1 Introduction

1.1.1 Sensor Definition and the Use of Sensors

Sensors are devices that measure physical quantities of the environment around them and convert these quantities into electrical/optical/sound-wave/mechanical signals, which can be read or viewed by an observer or by an instrument. The physical quantity can be a movement of a human body or movement of an object or environmental temperature or wind velocity or gun shots. The signal can be in the form of electrical or mechanical or sound. In general, various sensor devices are typically used by wireless sensor networks (WSNs) and Mobile ad hoc networks (MANETs) that construct a cyber-physical system (CPS) for monitoring the physical quantities specified by a user. This section defines sensor networks and their uses in CPSs.

1.1.2 Sensor Network Definition and the Use of Sensor Networks

Sensor networks are wired or wireless networks of sensors, which can collect and disseminate environmental data. WSNs have applications on modern and emerging CPSs, such as in health care, environmental and structural monitoring in smart cities, smart battlefields, cyber space tracking, borderlines, platform location determination, platform self-navigation, and gathering sensing information remotely in both hostile and friendly locations. Sensor networks employ the types of sensor described in Section 1.2.1 in their general-purpose design approach that provides services to many aforementioned applications. The networks are designed and engineered according to specific plans with sensing devices and networks operating in a specified environment. Traditionally, the networks usually consist of a number of sensor nodes that are wired or wirelessly connected to a central processing station.

1.1.3 Traditional Sensor Networks vs. WSNs

Traditional sensor networks are generally designed to provide services for specific applications, for example, plant monitoring, home monitoring, and traffic monitoring. The networks are designed and engineered according to specific plans with sensing devices and networks operating in well-controlled environments. The networks usually consist of a small number of sensor nodes that are wired to a central processing station. The primary design concerns for traditional sensor networks are network performance and latencies; usually power and cost are not primary concerns. Unlike the traditional sensor networks, WSNs usually consist of a dense number of sensor nodes. Each sensor node is capable of only a limited amount of processing. But when coordinated with the information from a large number of other sensor nodes, they have the ability to measure a given physical environment in great detail. Thus, WSN employed by CPSs can be considered as a large collection of sensor nodes, which are working together in a coordinated manner to perform some specific action, such as movement monitoring in a remote area.

Presently, the researchers on sensor networking focus more on wireless, distributed, mobile sensing nodes for CPS applications when the exact location of a particular phenomenon is not known, thus distributed and mobile sensing allows for closer placement to the phenomenon than a single sensor would permit. By placing multiple sensor nodes around the phenomenon, the observer can overcome environmental obstacles like obstructions, line of sight constraints, etc. For wireless sensing applications on CPSs, the environment to be monitored usually does not have an existing infrastructure for either power or communications.

1.2 Sensors Employed by CPS

1.2.1 Types of Sensors

In general, sensors used by CPSs can be classified into 14 sensing types: (1) acoustic, sound, and vibration; (2) automotive and transportation; (3) chemical; (4) electric, magnetic, and radio; (5) environment, weather, moisture, and humidity; (6) flow and fluid velocity; (7) ionizing radiation and subatomic particles; (8) navigation instruments; (9) position, angle, displacement, distance, speed, and acceleration; (10) optical, light, and imaging; (11) pressure; (12) force, density, and level; (13) thermal, heat, and temperature; and (14) proximity and presence. Some examples describing these sensing types are given in the following for illustration purpose.

Acoustic, sound, and vibration sensors include microphone, geophone, seismometer, and accelerator. Automotive and transportation sensors are speedometer, map sensor, water sensor, parking sensor, and video sensor. Chemical sensors consist of sensing carbon, gas, hydrogen, oxygen, and smoke. Electric, magnetic, and radio sensors are magnetometer, metal detector, and telescope. Environment, weather, moisture, and humidity sensors are leaf sensor, rain/snow gauge, and pyranometer. Flow and fluid velocity sensors are air flow meter, flow sensor, and water meter. Ionizing radiation and subatomic particles sensors include cloud chamber, neutron detection, and particle detector. Navigation instruments sensors are air speed indicator, depth gauge, gyroscope, and turn coordinate. Position, angle, displacement, distance, speed, and acceleration sensors are accelerometer, position sensor, tilt sensor, and ultrasonic sensor. Optical, light, and imaging sensors consist of colorimeter, electro-optical sensor, infrared sensor, and photodiode. Pressure sensor includes barometer, boost gauge, pressure gauge, and tactile sensor. Force, density, and

level sensors are force gauge, level sensor, load cell, and hydrometer. Thermal, heat, and temperature sensors are heat sensor, radiometer, thermometer, and thermistor. Proximity and presence sensors include motion detector, occupancy sensor, and touch switch.

1.2.2 Sensor Performance

Sensor performance can be characterized by the (1) range of values, from minimum to maximum value, that it can measure, (2) the measurement resolution, which is the smallest discernable change in the measured value, (3) sensor linearity or maximum deviation from a "straight-line" response, (4) sensor sensitivity or a measure of the change at the sensor output for a given change of sensor input, and (5) sensor accuracy or sensor precision or a measure of the difference between measured and actual values. A sensor network designer selects the sensors based on their performances to meet a specific requirement in designing a sensor network.

1.2.3 Smart Sensors

Smart sensors are currently employed by many contemporary CPSs. There are several definitions for smart sensors that basically describe a sensor that is capable of processing, manipulation, and computation of the sensor-derived data [1–4]. To perform "processing–manipulation–computation," the smart sensor requires interfacing circuit, logic functions, two-way communication device, and decision-making device. Ref. [4] describe three-key components of the smart sensor in action/reaction loop including Observe, Analyze-Make Decision, and Act. According to [4], the "Act" is connected to the "Observe" component by a "Process" that is provided as a Human-In-The-Loop (HITL) or an automated process. The smart sensor defined in this chapter is illustrated in Figure 1.1. It follows the OODA (Observe, Orient, Decide, and Act) loop developed by a military strategist and USAF Col. John Boyd [5,6]. As shown in Figure 1.1, the smart sensor is defined as the one that acts based on the "sensor goal" and "sensor control process." "Sensor goal" controls the "Orient" and "Decide" components through the "Analysis & Synthesis" process. The "Act" and Observe" components are controlled by the "Decide" component and "sensor control process, respectively."

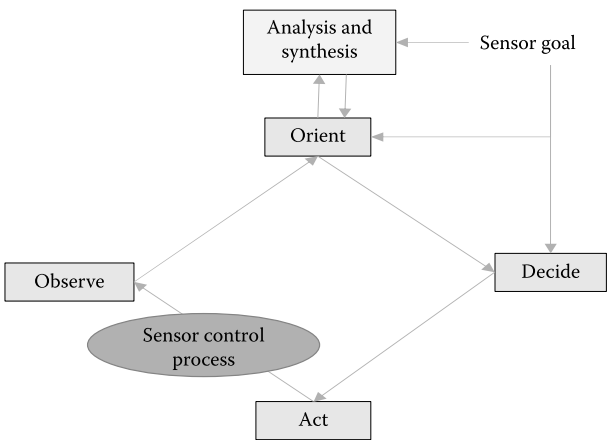

FIGURE 1.1
Definition of smart sensor using OODA loop for modern CPSs.

A smart sensor that employs the process shown in Figure 1.1 should include at least three baseline hardware/software components, including Sensor Networking Processor (SNP), Sensor Interface Module (SIM), and Sensor Control Processor (SCP). Basic SNP functions include two-way communication, message routing, message encoding and decoding, discover and control, and data correction interpretation. Basic SIM functions are storage, Analog Signal Conditioner (ASC), Analog-to-Digital Converter (ADC), trigger, command processor, data transfer, and two-way communication. SCP functions consist of sensor resource management and associated sensing control requirements to meet the sensor goal. Examples of smart sensors are accelerometers, optical angle encoders, optical arrays, infrared detector array, integrated multi-sensor, structural monitoring, and geological mapping. Applications of smart sensors include but are not limited to smart homes, smart cities, intelligent building, predictive maintenance, health care, industrial automation, energy saving, and defense.

1.2.4 Sensor Products

Presently, there are many types of sensor products available in the market. Examples of existing state-of-the-art sensor products are produced by Omoron Industrial Automation [7], Keyence Inductive Proximity Sensors [8], Pressure Profile Systems (PPS) [9], Harry G Security [10], Fujifilm Optical Devices for interferometer [11], Baumer Sensor Products for presence detection/distant measurement/angle measurement/process instrumentation/identification image processing [12], System Sensor for life and safety [13], SICK Sensor Intelligence for industrial sensors [14], Analog Devices for MEMS Accelerators/Gyroscopes/Internal Measurement Units (IMU)/Inertial sensors/Temperature sensors [15], Samsung for CMOS Image sensors [16], ST Life Augmented for MEMS Accelerometers/Gyroscopes/Digital Compasses/Pressure sensors/Humidity sensors and microphones/smart sensors/sensor hubs/temperature sensors/touch sensors [17], Linear Technology for wireless sensor networking [18], Honeywell Aerospace for magneto-resistive sensors [19], and GE Measurement & Control for MEMS Pressure sensors [20].

1.3 Sensor Networks and Associated Technologies for CPS Applications

Sensor networks can be classified into two categories, namely, wired sensor networks and WSNs. This section focuses on the WSNs that are used by modern and emerging CPSs described in Section 1.6. For the sake of completeness, this section also discusses the traditional centralized sensor networking approach using wired sensors. Typical sensor networks are used for monitoring and tracking objects, animals, humans, vehicles, structures, factory, etc.

1.3.1 WSNs—A Traditional Centralized Sensor Networking Approach

Traditional Centralized Sensor Network (TCSN) is a general-purpose design using centralized network management approach, which intends to serve many applications. The TCSNs are designed and built according to detailed plans with primary design concerns focused on sensor network performance and latencies that aligned with a required operational plan in a controlled environment. Control environment allows for easy access to sensor repair and maintenance with component failure and maintenance are addressed through sensor maintenance and repair plans. An example of TCSN is a sensor network

for a plastic bottle manufacturing product line, where sensors are used to monitor temperature, pressure, and counting the bottles for making the bottles and packaging the bottles, respectively.

As opposed to TCSN, WSN is usually used for CPS applications, which is a single-purpose design using distributed network management to serve a specific application where power is the key design constraint for all sensor nodes and network components. WSN deployment for a CPS is often ad hoc without planning, and it usually operates in an environment with harsh conditions with very difficult physical access to sensor nodes. Unlike TCSN, WSN component failure is addressed through the design of the network. The focus of this chapter is on WSN with applications to CPSs, and the subsequent sections will describe the current state-of-the-art WSNs.

1.3.2 Distributed WSNs

Emerging CPSs employ MANET and distributed WSNs for collecting sensing data to gain knowledge on the activities of interest to users. This section discusses MANET and distributed WSNs that are currently used by emergent CPSs, including intelligent health-care cyber system, intelligent rescue cyber system, intelligent transportation cyber systems, and intelligent social networking cyber system.

1.3.2.1 Mobile Sensing Network

MEMS, NEMS, MANET technology, and advanced sensor products allow for the deployment of Mobile Sensing Network (MSN) with a collection of small, low cost, low power wireless sensor nodes that can move on their own and interact with the physical environment. These wireless sensor nodes are capable of sensing, local processing, wireless communication networking, and dynamic routing [21,22]. Ref. [22] has provided a good comparison among MSN, MANET, and CPS. A summary of the comparison is given in Table 1.1. A Wireless Network as Sensor Network described in Section 1.3.3 can be considered as a special case of MSN, since the wireless radio nodes are mobile.

1.3.2.2 Compressive Wireless Sensing Network

Recently, Compressive Wireless Sensing Network (CWSN) has been developed based on Compressive Sensing (CS) technology, which is a novel sampling technique to reduce the minimum samples required to reconstruct a signal by exploiting its compressibility property [23,24]. CS technology allows for less communication bandwidth, sensor processing, and power requirements imposed on the CWSN design and deployment. Hence, the key features of CWSN are: (1) processing and communications—they are combined into one distributed operation, (2) without or very little in-network processing and communications, and (3) consistent field estimation is possible even if little or no prior knowledge about the sensed data, while the total power required for the CWSN grows at most sub-linearly with the number of nodes in the network [25]. For a centralized CWSN, when there is no knowledge about the sensed data, Ref. [25] shows that there exists a power-distortion-latency, D, trade-off of the form:

$$D \approx \frac{1}{P_{tot}^{2\alpha/(2\alpha+1)}} \approx \frac{1}{L^{2\alpha/(2\alpha+1)}} \tag{1.1}$$

TABLE 1.1

Comparison of MANET, MSN, and CPS

Feature	Mobile Ad hoc Network (MANET)	Mobile Sensing Network (MSN)	Cyber-Physical System (CPS)
Network formation	Random and can support node mobility	Field-specific and allows less mobility	Crosses several fields. Connecting these fields usually relies on the Internet
Communication pattern	Supports arbitrary communication patterns, such as unicast, multicast, and broadcast	Support collective communications, for example, converge cast and query-and-response transactions. Requirements on routing capability are different from MANET	Very often required intra-WSN communications and cross-domain communications
Power management	Emphasizes on energy saving	Energy saving is critical, since sensors are usually deployed in unattended areas. Deeper sleeping modes and redundancy are required	Activation of sensors is usually mission oriented
Network coverage	Requires to meet some connectivity requirements	Requires to meet both connectivity and some coverage criteria	Same requirements for a WSN, but different levels of connectivity and coverage for different WSNs
Node mobility	Usually arbitrary	Requires both controllable and uncontrollable mobility	Requires both controllable and uncontrollable mobility
Knowledge mining	Emphasizes only on networking issues	Focuses more on collecting and managing sensing data	Emphasizes more on how to discover new knowledge across multiple sensing domains and to utilize intelligence properly
Quality of services	Quality of data transmissions is important	Quality of sensing data is important	Emphasizes on higher-level QoS, such as availability of networking and sensing data, security and confidentiality of sensing data, quality of knowledge/intelligence, etc.

Source: Wu, F.J. et al., *Pervasive Mobile Comput. J.*, 2011.

where

α is a non-zero and positive coefficient, that is, $\alpha > 0$, and it is used to quantify the structural regularity of the centralized CWSN sensor network, which needs not to be known to the network

P_{tot} is the total power consumption by CWSN

L is the network latency. Note that when the approximation error exponent in Equation 1.1 for piecewise constant functions represented in a wavelet basis is: $2\alpha = 1$, then Equation 1.1 becomes

$$D \approx \frac{1}{P_{tot}^{1/2}} \approx \frac{1}{L^{1/2}} \tag{1.2}$$

When there is sufficient prior knowledge about the sensed data, the distortion D is given by:

$$D \approx \frac{1}{P_{tot}^{2\alpha}} \approx \frac{1}{L^{2\alpha}} \tag{1.3}$$

The distortion D can be used in the selection of optimum CS technique to achieve a desired network latency of a centralized CWSN.

1.3.2.3 IP-Based Sensor Network

IP-based sensor network (IP-BSN) allows the networks in a CPS to cross several sensor fields and connect these fields by Internet. The emergence of the IETF 6LoWPAN* (RFC 4944) standard for IP communication over low-power radio has made the design and implementation of IP-BSN a reality [26–31]. Figure 1.2 illustrates an example of IP-BSN. This network uses IETF 6LoWPAN adaptation layer that carries IPv6 addresses in a compact form using small IEEE 802.15.4 short addresses [30]. This network supports a variety of IP links while understanding the links, characteristics through the use of abstraction layer. A packet frame format using IEEE 802.15.4 standard is described in Figure 1.3 [31].

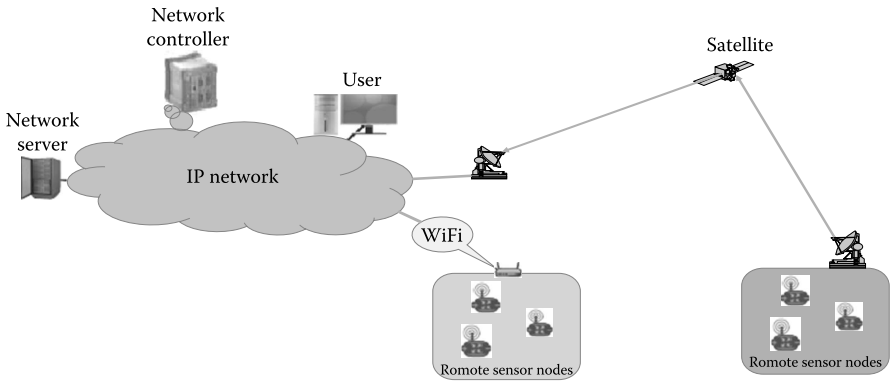

FIGURE 1.2
Example of an IP-based sensor network (IP-BSN).

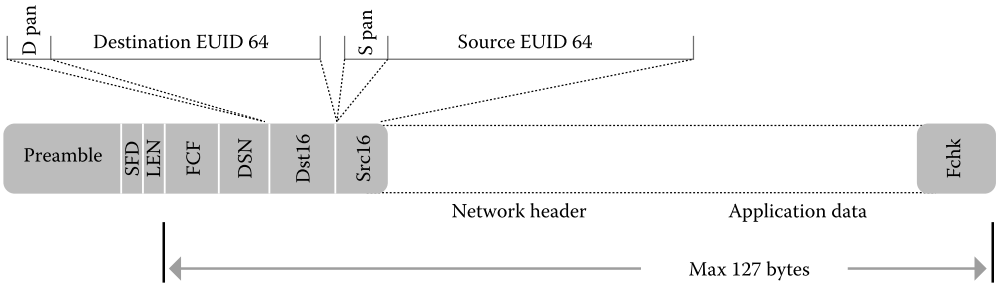

FIGURE 1.3
IEEE 802.15.4 standard packet frame format. (From Arch Rock Corporation, IP-based wireless sensor networking: Secure, reliable, low-power IP connectivity for IEEE 802.15.4 networks, Website: http://www.cs.berkeley.edu/~jwhui/6lowpan/Arch_Rock_Whitepaper_IP_WSNs.pdf.)

* IPv6 over low power personal area networks.

1.3.2.4 Dynamic Spectrum Access (DSA) Sensing Networks

DSA Sensing Network (DSA-SN) consists of a set of wireless sensor nodes that are placed in a specified location for monitoring the RF (Radio Frequency) environment of interest. The purpose of DSA-SN is to perform spectrum sensing and detect unused spectrum for sharing the spectrum without harmful interference among users. A survey of the spectrum sensing techniques is provided in Table 1.2 [31]. The use of DSA-SN allows a CPS to achieve the same network coverage as typical WSNs but at different levels of connectivity and coverage for different WSNs.

The IP-BSN with a CS-based technique can be used in the design and implementation of a DSA-SN. DSA-SN is usually employed by a Cognitive Radio (CR) wireless network for frequency and bandwidth scheduling among coexisting network users [32–36].

1.3.2.5 Cognitive Radios (CR) Sensing Networks

CR Sensing Network (CRSN) adopts the CR capability in sensor networks [31,41]. Thus, a WSN comprises a number of sensor nodes equipped with CR that are likely to benefit from the potential advantages of the DSA features, such as (1) opportunistic channel usage for bursty traffic, (2) DSA, (3) using adaptability to reduce power consumption, (4) overlaid deployment of multiple concurrent WSN, and (5) access to multiple channels to conform to different spectrum regulations [31]. In general, CRSN can be defined as "a distributed network of wireless cognitive radio sensor nodes, which sense an event signal and collaboratively communicate their readings dynamically over available spectrum bands in a multi-hop manner ultimately to satisfy the application-specific requirements." CRSN applications can be classified into four categories [31]:

1. *Indoor Sensing*: Tele-medicine [34], home monitoring, emergency networks, and factory automation.
2. *Multimedia Sensing*: Video, still image, audio.
3. *Multi-class Heterogeneous Sensing*: Information is gathered through several WSNs and fused to feed a single decision support [42].
4. *Real-time Surveillance Sensing*: Military surveillance for target detection and tracking.

TABLE 1.2

Survey of Spectrum Sensing Techniques

Spectrum Sensing Method	Cons	Pros
Matched filter [37]	Requires a priori info on Primary User (PU) transmissions, and extra hardware on nodes for synchronization with PU	Best in Gaussian noise. Needs shorter sensing duration (less power consumption)
Energy detection [38]	Requires longer sensing duration (high power consumption). Accuracy highly depends on noise level variations	Requires the least amount of computational power on nodes
Feature detection [39]	Requires a priori knowledge about PU transmissions. Requires high computational capability on nodes	Most resilient to variation in noise levels
Interference temperature [40]	Requires knowledge of location PU and imposes polynomial calculations based on these locations	Recommended by FCC. Guarantees a predetermined interference to PU is not exceeded

Source: Akan, O.B. et al., Cognitive radio sensor networks, Website: http://nwcl.ku.edu.tr/paper/J20.pdf.

TABLE 1.3

A Survey of MAC Approach for CRSN

MAC Design Approach	Disadvantages in CRSN	Reasons to Adopt CRSN	Open Research Issues
On-demand negotiation [43]	Contention due to single channel for all negotiations	On-demand reservation is suitable for bursty traffic	Coordination of multiple control channels required for heavy traffic
Home channel [44]	Multiple transceiver requirement	Does not require negotiation for each packet (helps power conservation)	Mechanisms to make this scheme work with single transceiver needed
Time division-based negotiation [45]	Requires network-wide synchronization for negotiation intervals	Simple and very few rules imposed on nodes	Need for network-wide synchronization must be eliminated

Source: Azad, A.K.M. and Kamruzzaman, J., A framework for collaborative multi class heterogeneous wireless sensor networks, in *Proceedings of the IEEE ICC 2008*, May 2008, pp. 4396–4401.

CRSN requires complex Dynamic Spectrum Management (DSM) framework to regulate the spectrum access for the deployed wireless sensor nodes. The framework includes three key components, namely, Spectrum Sensing Component (SSC) (see Table 1.2), Spectrum Decision Component (SDC), and Spectrum Hand-off Component (SHC). A communication framework is required to support the DSM. The communication framework consists of Physical Layer (PL), Data Link Layer (DL2), Network Layer (NL), Transport Layer (TL), and Application Layer (AL). For CRSN, the design of Medium Access Control (MAC) within the DL2 to support wireless sensor nodes with access to medium in a fair and efficient manner is essential for minimum network latency. Table 1.3 summarizes MAC design approach for CRSN. A detailed description of these layers can be found in [42].

Emerging CPSs employ CRSN to allow for intra-WSN communications and cross-domain communications with emphasis on higher-level QoS, such as availability of networking and sensing data.

1.3.3 Wireless Networks as Sensor Networks

Extracting information from the variation in the strength of received signal from a wireless network can turn a wireless network into a sensor network. This type of sensor network is also referred to as Wireless Network as Sensor Network (WNaSN). The Received Signal Strength Indicator (RSSI) provided by a wireless network can be used for localization by position determination, motion detection, and velocity estimation of the wireless radio nodes in the network or position and motion of bodies external to the network [46–51]. The RSSI-based WNaSN can be divided into active and passive localization. Active localization is the practice of locating a person or asset that is carrying an RF device, such as Personal Communications Service (PCS) device or RF tag. Passive localization does not require the person or asset to carry any electronic device, sensor, or tag. The WNaSN employs passive localization, which is referred to as Device-Free Localization (DFL) or RF Tomography (RFT) [52]. For a narrowband receiver, the RSSI in dB (decibel) of a wireless radio node can be expressed mathematically as:

$$\text{RSSI (dB)} = P_T + 20\log_{10}\left|\sum_{i=1}^{N} s_i(t)\right| \tag{1.4}$$

TABLE 1.4

Typical Range of RSSI

RSSI Range (dB)	Signal Quality
Better than –40	Exceptional
–40 to –55	Very good
–55 to –70	Good
–70 to –80	Marginal
–80 and beyond	Intermittent to no operation

Source: Veris White Paper, Veris Aerospond Wireless Sensors: Received Signal Strength Indicator (RSSI), http://www.veris.com/docs/whitePaper/vwp18_RSSI_RevA.pdf.

where

$S_i(t)$ is the complex amplitude gain of the received component ith

N is the number of multipath components received at the wireless radio node

P_T is the transmitted power in dB

A typical range of RSSI expressed in dB is given in Table 1.4 [53].

1.3.4 Smart Sensor Networks

As discussed in Section 1.2.3, a smart sensor employs a process shown in Figure 1.1 with three basic components: SNP, SIM, and SCP. Thus, a Smart Sensor Network (SSN) consists of a network of smart sensors that are connected through a wireless network, and the network is designed to meet a specific application, such as smart home or smart city or intelligent building, etc. [54–57]. A typical system architecture for an SSN is presented in Figure 1.4. The wireless sensor networking nodes presented in this figure are assumed to use low power devices that meet IEEE 802.15.4 standard, which defines various layers for interconnecting these sensor nodes. The Operating System (OS) employed by SSN is the TinyOS operating system, which is a small core, multitasking. TinyOS was developed by the University of California [58] and used the NesC language [59]. The remote management and visualization system includes but is not limited to 4G Android or/and Personal Computer (PC) or/and Ipad with the smart sensor process described in Figure 1.1 incorporated into the system. SSN has been used by emerging CPS, such as intelligent health-care cyber system and intelligent transportation cyber system presented in Section 1.6.

1.3.5 Ubiquitous Sensor Networks for Internet of Things (IoT)

As defined in [60], the term "Ubiquitous Sensor Network" or USN is a network of intelligent sensors that are available "anywhere, anytime, by anyone and anything." USN is also referred to as "invisible," "pervasive" or "ubiquitous" computing or to describe "Internet of Things" or IoT. The network consists of three key elements including sensors, tags, and communication/processing capacity. By 2020, Gartner predicts that IoT would be made up of 26 billion "units" [61]. USN for IoT has been applied for CPS applications such as battle damage assessment described in the following and smart cities presented in Section 1.6.

Recently, Ref. [62] has defined IoT as the Networks of Sensors (NoSs) that are used by people through "Process," "Data," and "Things." Ref. [62] has also defined the "Process" as an approach to deliver the right information to the right person, and "Things" as the physical devices and object connected to the Internet and each other for intelligence decision making. In addition, Ref. [62] has envisioned an IoT "Connectivity" platform, including

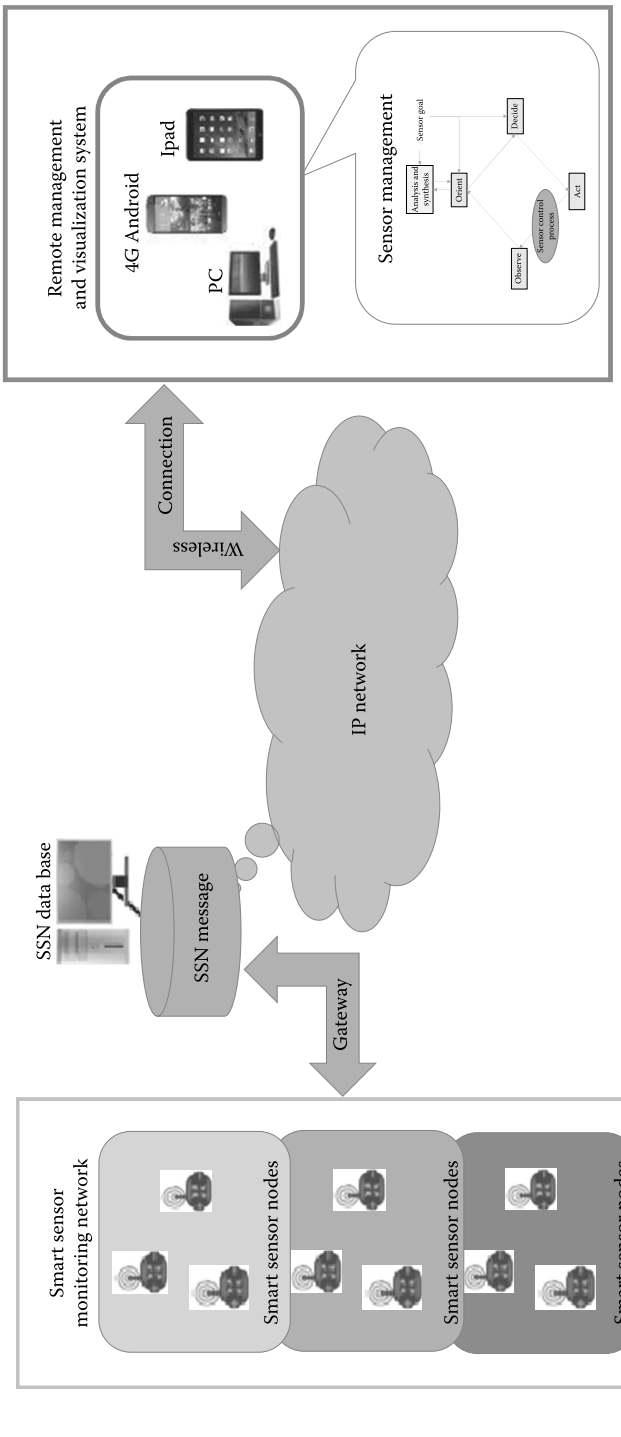

FIGURE 1.4
Typical SSN system architecture.

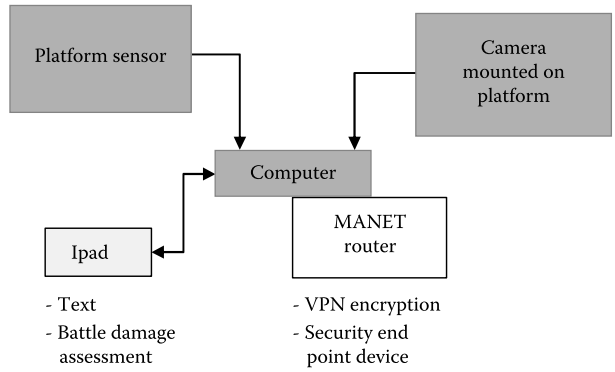

FIGURE 1.5
Example of cisco mobile ready net.

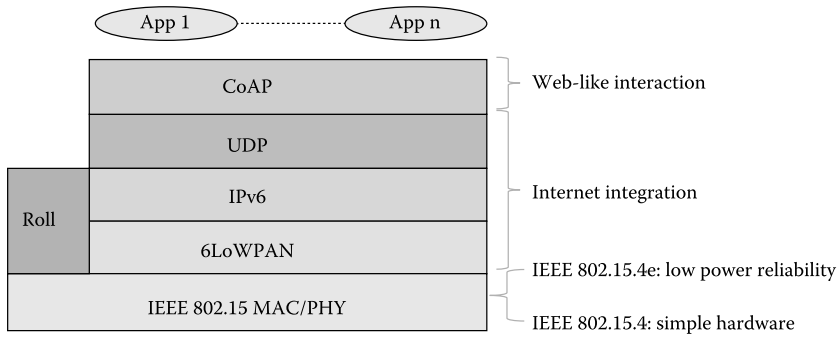

FIGURE 1.6
Recommended standard IoT protocol stack. (Revised from Liu, H., IoT, sensor networks, in *Workshop Proceedings on Future Research Needs and Advanced Technologies*, The Catholic University of America, Washington, DC, May 2, 2014.)

(1) operational technologies, (2) networks, "Fog" computing, storage, (3) data analysis, and (4) control system. The "Connectivity" includes data center and networks. "Fog" computing is defined as a computing layer to make simple determination of what information is needed for the mission. Figure 1.5 shows an IoT example of Cisco Mobile Ready Net developed for a mobile platform consisting of a platform sensor with an Ipad, a computer, and a MANET router for a battle damage assessment application. This Cisco Mobile Ready Net can also be used for a surveillance application.

As IoT technology evolves, standard organizations, such as IEEE, IETF, ETSI, etc., are working to make IoT protocols more robust, scalable, and efficient. The current enhancement task focuses on improving IETF Constrained Application Protocol (CoAP) and Routing Over Low Power and Lossy Networks protocol (ROLL) [63]. The CoAP and ROLL layers are currently incorporated in a standard protocol stack for IoT and it is illustrated in Figure 1.6.

1.3.6 Underwater Sensor Network

Underwater Sensor Network (UnSN) is also referred to as Underwater Acoustic Sensor Network (UW-ASN), which consists of a number of fixed sensor nodes and mobile sensor nodes deployed underwater. The data links use to connect these fixed and mobile sensor nodes

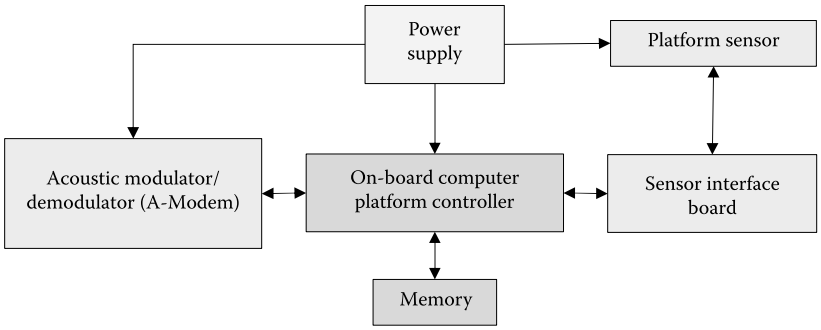

FIGURE 1.7
A typical underwater sensor system architecture.

employ acoustic wireless communications [64–67]. A typical underwater sensor system architecture using acoustic wireless communications is shown in Figure 1.7. The platform sensor can be placed in a fixed or mobile platform with an on-board computer that serves as the platform sensor controller providing sensor and communication resources management. The controller provides self-configuration of the network of underwater sensor nodes and adapts to harsh ocean environment. The Acoustic Modulator/Demodulator (A-Modem) connects the sensor nodes using underwater sensor network protocols. The four protocols employed by the existing A-Modem are flooding-based, multipath-based, cluster-based, and miscellaneous-based routing protocols [64]. The power supply is a limited battery, which cannot be replaced or recharged. The issue of energy conservation for UW-ASN is currently evolving to more power efficient underwater communication and networking techniques.

Applications of UW-ASN include scientific, Industrial, Military, and homeland security applications [65].

1.4 Architecture of WSNs for CPS Applications

A WSNs design for CPS applications can be very complex depending on their goal or mission. WSNs are broadly divided into infrastructured and infrastructureless WSNs [68]. The infrastructured WSN consists of a set of wireless nodes with a network backbone, and the infrastructureless WSN consists of distributed, independent, dynamic topology, low-power, and task-oriented wireless nodes. As shown in Figure 1.8, a basic network backbone includes a task manager for local management, a task manager for remote management, a router, a transit network gateway acting as a proxy for the sensor network on the Internet, a data storage, and an Internet satellite network. In either case, the architecture design should be scalable and flexible allowing for extending additional sensor nodes and preserving network stability.

The WSN architecture design goal for CPS applications is to maximize the network density, $D_N(d)$, within the WSN operating region R. If d is defined as the radio transmission range between the sensor nodes, and N is the number of wireless sensor nodes to be placed in the region R, the $D_N(d)$ is given by:

$$D_N(d) \approx \frac{(N \cdot d^2)}{R} \tag{1.5}$$