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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 quan- **tity** 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 wire- less** 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 **dis-** seminate 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 applica- tions. 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.

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**1.1.3 Traditional Sensor Networks** vs. **WSNs**

**Traditional** sensor **networks are** generally designed to **provide** services **for** specific appli- **cations**, **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 envi- ronment in great **detail. Thus**, WSN employed **by** CPSs can be considered as a large col- lection **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 phenom- enon than a single sensor **would** permit. **By** placing multiple sensor nodes around the phe- nomenon, 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, den- **sity**, 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** magnetom- eter, metal detector**,** and telescope. Environment, weather, **moisture,** and humidity sen- **sors 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 par- ticles 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 con- sist **of** colorimeter**, electro-**optical sensor**, infrared** sensor**,** and photodiode. **Pressure** sensor includes barometer, boost gauge, **pressure** gauge, and tactile sensor**.** Force, **density,** and

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**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**" compo- nents are controlled by the "Decide" component and "sensor control process, respectively."

**Analysis and synthesis**

**Sensor goal**

Orient

**Observe**

**Sensor control**

**process**

**Act**

**FIGURE 1.1**

**Definition of** smart **sensor using** OODA loop **for** modern CPSs.

**Decide**

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**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, dis- cover 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 man- agement 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 build- ing, 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 **instrumen- tation**/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 tradi- tional 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 cen- **tralized** 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 **opera-** tional 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

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for a plastic **bottle** manufacturing product line**,** where sensors **are** used to monitor **tem- perature**, 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 **deploy-** ment 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 **dis- tributed** 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 **deploy-** ment 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 envi- ronment. 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** con- sidered **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 prop- **erty** [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)** consis- tent 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≈

1

1

2

p2a/(**2a+1**) *[*2a**/(2a+1)**

**tot**

(1.1)

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**TABLE 1.1**

Comparison **of** MANET, MSN, and CPS

**Feature**

**Network**

**formation**

**Communication**

**pattern**

**Power**

**Mobile Ad hoc**

**Network (MANET)**

**Random** and **can**

support node **mobility** Supports **arbitrary communication** patterns**,** such **as unicast, multicast**, and **broadcast**

management

Emphasizes on energy **saving**

**Network**

**coverage**

**Requires to meet**

some **connectivity** requirements

**Usually arbitrary**

Emphasizes only on networking issues

**Node mobility**

**Knowledge**

mining

**Quality of**

**Quality of data**

services

**transmissions is** important

**Mobile Sensing** Network **(MSN**)

**Field**-specific and **allows less**

**mobility**

Support collective

**communications, for** example**,** converge cast and **query-and**-response transactions. Requirements on **routing capability are** different **from MANET**

**Energy** saving **is critical,** since

sensors **are usually deployed in unattended areas**. Deeper **sleeping modes** and redundancy **are** required

**Requires to meet** both

connectivity and some **coverage criteria**

Requires **both controllable**

and uncontrollable **mobility** Focuses **more** on collecting

and managing sensing **data**

**Quality of sensing data** is

important

**Cyber-Physical System (CPS)**

**Crosses several fields.** Connecting these **fields usually** relies on the **Internet**

Very often required intra-WSN **communications** and cross- **domain communications**

**Activation of** sensors is **usually**

**mission oriented**

**Same requirements for** a WSN,

**but different levels of** connectivity and **coverage for different** WSNs Requires **both controllable** and

uncontrollable **mobility** Emphasizes more **on** how to

discover **new** knowledge across **multiple** sensing **domains** and to **utilize** intelligence **properly** 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

a is a non-zero and positive coefficient, **that** is**, a > 0, and it is** used to **quantify** the **struc-** tural **regularity** of the centralized CWSN sensor network**,** which needs not to be known **to** the **network**

Ptot 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**: 2α = 1**, then Equation 1.1 becomes

**1**

1 D≈

P1/**2 1/2**

**tot**

**(1.2**)

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

1

1

D≈

*p2a*

***[2α***

**tot**

(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** 6L0WPAN\* **(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 com- pact 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].

Network **controller**

User

**Network**

**server**

**IP network**

**FIGURE 1.2**

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

**pan**

**FCF**

DSN

**Destination EUID 64**

Dst16

Src16

**S pan**

**Preamble**

**WiFi**

**Satellite**

**Romote** sensor **nodes**

Romote **sensor nodes**

**Source EUID 64**

**Network header**

**Application data**

**Max 127 bytes**

**Fchk**

**FIGURE 1.3**

IEEE **802.15.4 standard** packet **frame format. (From** Arch **Rock Corporation, IP-based** wireless sensor **network-** ing: **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.

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***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 spec- trum 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 col- laboratively 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**

**Matched filter** [**37**]

Energy **detection [38]**

**Feature detection [39]**

Interference

temperature **[40**]

**Cons**

**Requires a priori** info on Primary **User**

**(PU**) transmissions, and extra **hardware** on nodes for synchronization with PU Requires longer sensing **duration** (high **power** consumption**)**. Accuracy **highly** depends on noise **level** variations Requires a **priori** knowledge **about** PU

transmissions. **Requires high** computational capability on nodes Requires knowledge **of** location PU and imposes **polynomial calculations** based on **these locations**

**Pros**

Best **in** Gaussian noise. **Needs** shorter

sensing duration (less **power** consumption)

**Requires** the **least amount of**

computational power on **nodes**

Most **resilient to variation** in **noise levels**

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.

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**TABLE 1.3**

A **Survey of** MAC Approach for CRSN

**MAC Design Approach**

On**-demand**

negotiation **[43]**

Home channel **[44**]

**Time** division**-based**

**negotiation [45]**

Disadvantages **in CRSN** Contention **due** to **single**

channel **for all** negotiations **Multiple** transceiver

requirement

Requires network**-wide**

synchronization for **negotiation intervals**

Reasons **to Adopt CRSN**

**On**-demand reservation **is suitable** for bursty **traffic**

Does not require

negotiation for each **packet (helps power** conservation**)** Simple and **very few** rules

imposed on nodes

**Open Research** Issues **Coordination** of multiple

control channels required for heavy **traffic** Mechanisms **to make this**

scheme **work with single** transceiver **needed**

**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 net- working 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 posi- tion 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:

N

RSSI (dB**)** = *P2* +20 log 10 s;***(t*)**

**i=**1

**(1.4**)

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**TABLE 1.4**

Typical Range **of** RSSI

**RSSI Range (dB)**

**Better than -40**

**-40 to -55**

-55 to **-70**

**-70 to -80**

**-80** and **beyond**

**Signal Quality**

Exceptional

**Very good**

**Good**

**Marginal**

**Intermittent** to no operation

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where

*Source*: **Veris** White **Paper**, **Veris** Aerospond **Wireless** Sensors**:** Received Signal Strength Indicator (RSSI**),** http://www.veris.com/docs/ **whitePaper/vwp18\_RSSI\_RevA.pdf**.

*S1****(t)* is** the complex **amplitude** gain of the received component ith *N* is the number of multipath components received at the wireless radio node *Pr* 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 manage- ment 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 incorpo- rated 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 intelli- gent 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 phys- ical 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

**Smart** sensor monitoring **network**

**Smart sensor nodes**

Smart **sensor nodes**

**Smart sensor** nodes

**FIGURE 1.4**

Typical SSN system **architecture**.

SSN **data base**

SSN **message**

**Gateway**

**IP network**

**Wireless**

**Remote management and visualization system**

**4G Android**

Connection

**PC**

Ipad

**Sensor management**

Analysis and

**synthesis**

Sensor **goal**

**Orient**

Observe

**Sensor control**

**process**

Act

**Deckle**

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**Platform** sensor

Ipad

- **Text**

- **Battle damage**

**assessment**

Computer

**MANET**

**router**

- **VPN encryption**

- Security **end**

**point device**

**FIGURE 1.5**

**Example of** cisco **mobile** ready **net**.

**Roll**

**App** 1

**Camera** mounted **on platform**

**App n**

**CoAP**

**Web-like interaction**

UDP

IPv6

**6LoWPAN**

**IEEE** 802.15 MAC**/PHY**

**Internet integration**

IEEE 802.15.4e**: low power reliability**

**IEEE 802.15.4: simple hardware**

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**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"** comput- ing 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 devel- oped 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 enhance- ment **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

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**Acoustic modulator/ demodulator (A-Modem**)

**Power supply**

**Platform sensor**

**On-board computer platform controller**

**Sensor interface board**

**Memory**

**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 manage- ment. 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 **infra-** structured WSN consists **of a** set **of wireless** nodes with a network backbone, and the **infra-** structureless 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** tran- sit 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(****d),*** within the WSN operating region *R.* If ***d*** is defined as the radio transmis- sion range between the sensor **nodes,** and N is **the number** of wireless sensor nodes to be placed in the **region *R***, the *Dy(****d)*** is given **by:**

*DN* ***(d)***≈

(*N.d2*) **R**

(1.5)