INTERNATIONAL JOURNAL OF INTELLIGENT CONTROL AND SYSTEMS
VOL.15,NO.4,DECEMBER 2010,49-58

Recent Advances in Wireless Sensor Networks for Health Monitoring

Jin Soo CHOI and MengChu ZHOU

Abstract- **Current technological advances in sensors, power efficient integrated circuits, and wireless transferring have allowed the development of miniature, lightweight, low-cost, and smart physiological sensor nodes. These sensor nodes have capacity of sensing, controlling, processing, and communication one or more vital signs. Furthermore, they can be used in wireless personal area networks (WPANs) or wireless body sensor networks (WBSNs) for health monitoring. Many studies were performed and/or are under way in order to develop flexible, reliable, secure, real-time, and power-efficient WBSNs suitable for healthcare applications. This paper reviews the applications of wireless sensor networks in the healthcare area and discusses the related issues and challenges. It reviews some applications of WSNs developed or currently being developed for health monitoring.**

***Index Terms*— Wireless physiological monitoring systems (WPMS), Wireless sensor networks (WSNs), Body sensor networks (BSN), Health monitoring, ZigBee, Bluetooth, UWB, Wi-Fi**

1. INTRODUCTION

Wireless sensor networks (WSNs) have gained many different applications in such areas as health monitoring, industrial automation, military operations, building automation, agriculture, environmental monitoring, and multimedia [Akyildiz, *et al.*, 2008; Khemapech, *et al.*, 2005; Estrin, 2002; Willig, *et al.*, 2005]. In particular, their application to healthcare areas received much attention recently. The design and development of wearable biomedical sensor systems for health monitoring has drawn particular attention from both academia and industry.

This paper presents the current state in research and development of wireless sensor networks and related sensors for health monitoring. It analyzes the current research prototypes and commercial products.

Section 2 presents the overview of wireless physiological monitoring systems (WPMS). Section 3 overviews their applications in health monitoring systems. Section 4 discusses limitations and challenging issues in wearable health monitoring systems for real life applications. Sections 5 and 6 review and compare the most common wireless technologies for healthcare application. Section 7 discusses the existing research prototypes and commercial systems. Finally, Section 8 concludes the paper.

2. OVERVIEW OF WIRELESS SENSOR NETWORKS

A WSN is defined as a network of devices, called as nodes, which sense given objects or entities and communicate the sensed data through wireless links. The data is transmitted via a single hop or multi-hops, to a base station or PDA/cell phone, which can be connected to other networks, e.g., Internet.

A wireless sensor node consists of one or more sensors for sensing physical variables, main processing unit (a microcontroller or low power consuming processor), analog-to-digital converter (ADC), flash memory, and RF transceiver. It often has limited power source.

Figure 1 presents basic components of a typical wireless sensor node. Most WSN nodes use an 8051 microcontroller as their main processing unit because of its low cost and low power consumption as well as their limited size, e.g., in [Barth, *et al.*, 2009; Chen and Wang, 2008; Choi, *et al.*, 2007; Choi and Song, 2008; Zhang, *et al.*, 2009].

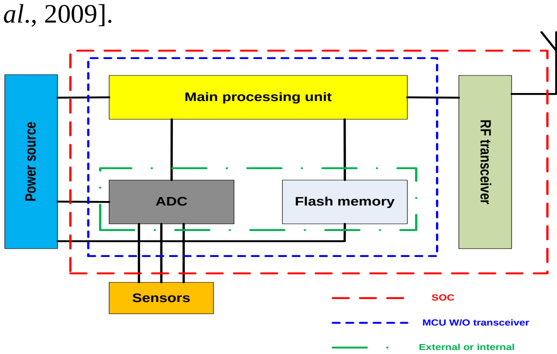

Fig. 1 Basic components of a typical wireless sensor node.

Some systems use the SOC (system on chip) such as CC2430 that includes the ADC, flash memory, and RF transceiver [Chai and Yang, 2008]. Because of the small size of SOC, one can develop a small and low power sensor node. But its limitations are the low quality of ADC and small memory size. Some sensor nodes are developed by using a microcontroller unit (MCU), such as MSP430F1611 and Atmel with external RF transceiver [Jovanov, *et al.*, 2005]. Other developers [Mangharam, *et al.*, 2006] use MCU with external ADC or external extra flash memory to achieve higher quality of service.

3. WIRELESS SENSOR NETWORKS IN HEALTH MONITORING

A wireless physiological data monitoring system uses a radio channel to send real time vital sign data from wearable biomedical sensor devices to a coordinator. Patients can wear wireless devices that sense physiological conditions and send the sensed data to their doctors in real time. Wireless health monitoring systems have several advantages compare to wired healthcare equipment.

Manuscript received March 18, 2010; revised October 31, 2010.
J. S. CHOI and M. C. ZHOU are with Electrical and Computer Engineering Department, Discrete Event Systems Laboratory, New Jersey Institute of Technology, 323 MLK Blvd., Newark, NJ 07102, USA (e-mail: jsc3@njit.edu and zhou@njit.edu).

First, patients no longer waste waiting time to meet their doctor. Moreover, the use of wireless healthcare systems outside the hospital helps to save the healthcare cost for care providers. Also, it allows many patients to work while they are still under their doctor's care.

Second, such systems can alert any medical emergency if specific vital signs change drastically, e.g., heart rate is beyond the norm.

A heart attack is the death of heart muscle from the sudden blockage of a coronary artery by a blood clot. If blood flow is not restored to the heart muscle within 20 to 40 minutes, irreversible death of the heart muscle begins to occur. Approximately one million Americans suffer a heart attack each year. 40 % of them die as a result of their heart attack [http://www.medicinenet.com]. Because heart attack suddenly happens to old people or patients, continuous real time heart rate monitoring can certainly save lives.

Currently, most heart beat monitors, e.g. ECG, are available at certain locations, e.g., hospitals and doctor's offices. They require several wired electrodes on the skin of a patient. Medical professionals often use stethoscopes to check the heart beat sound of a patient. Unfortunately, these have critical limitation in heart beat monitoring. As mentioned before, it is highly desired to monitor heart beat continuously for unexpected heart attack. However, it is almost impossible with the existing medical equipment.

Therefore, wireless health monitoring systems carry many advantages compared to the current wired healthcare equipment.

Figure 2 shows a typical wireless sensor network for healthcare application. In this network, the data collected by the sensor nodes are transmitted using an RF channel to the base station, coordinator or PDA/cell phone, which is connected to other networks via wired or wireless connection. The whole network is controlled and monitored by a server in real time. Depending on an application, various transmission techniques are used for wireless communication such as Wi-Fi, Bluetooth, ZigBee, UWB, and cellular networks.

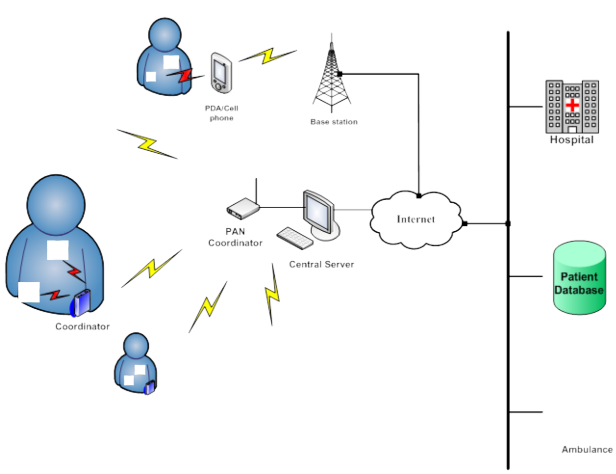

Fig. 2. A typical wireless sensor network infrastructure for healthcare applications.

4. TECHNOLOGIES FOR WPMS

This section reviews three wireless standard technologies, i.e., IEEE 802.15.4 (ZigBee), IEEE 802.15.1 (Bluetooth), and IEEE 802.15.3a (UWB) for WPAN, and one IEEE 802.11 a/b/g (Wi-Fi) as WLAN is briefly reviewed for their applications in wireless health monitoring systems.

WPMS engage small, low power-consuming devices for collecting medical data. Their nodes sense and collect data and then communicate to a coordinator or a remote monitoring device, i.e., PDA, cell phone, or PAN coordinator directly using wireless data transfer technology. The PAN coordinator has large-size memory and fast processors to analyze and present given data.

The physical radio layer defines the operating frequency, modulation scheme, network data rate, and hardware interface between nodes and between a node and the central server. Depending on different medical object, such as continuous or periodic monitoring, size of a physiological data packet, transmission range, network speed, and network size, several wireless technologies can be adopted as discussed next.

4.1 ZigBee

IEEE 802.15.4 and ZigBee are standard-based protocols that provide the network infrastructure required for wireless sensor network applications. 802.15.4 itself defines the physical and MAC layers, whereas ZigBee defines the network and application layers. They can be used to develop low data rate, low complexity, low power consumption, and low cost WSNs.

The physical layer (PHY) supports three radio bands, 2.4GHz ISM band (global) with 16 channels, 915MHz ISM band (Americas) with 10 channels, and 868MHz band (Europe) with a single channel. The data rates are 250Kbps at 2.4GHz, 40Kbps at 915MHz, and 20Kbps at 868MHz. The MAC layer controls access to the radio channel using the Carrier Sense Multiple Access with Collision Avoidance mechanism.

The IEEE 802.15.4 PHY uses direct sequence spread spectrum coding to reduce packet loss due to noise and interference. Also, it supports two PHY layer modulation options. The 868/915 MHz PHY adopts binary phase shift keying modulation, whereas the 2.4 GHz PHY uses offset quadrature phase shift keying.

ZigBee defines three types of devices: coordinator (MAC Full Function Device-FFD), Router (MAC FFD), and end device (MAC Reduced Function Device-RFD). An FFD can serve as a network coordinator or regular device. It can communicate with any other devices. An RFD is intended for applications that are simple, such as a light switch or simple sensor device. It can communicate only with FFD. ZigBee Coordinator is a base station node that automatically initiates the composition of the network and controls the overall network process. It needs the large memory and high processing power. A ZigBee Router is also an FFD that links groups together and supports multihoping for packet transmission. It can connect with other routers and end-devices. ZigBee end devices can only communicate with an FFD. It has limited functionality.

Theoretically, ZigBee can support up to 65,536 nodes. For security, it uses 128-bit Advanced Encryption Standard (AES) encryption and authentication. The transmission range is from 10 to 75m, depending on the different application's power output and environmental features. Approximately, ZigBee devices are expected to have a battery life ranging from several months to years.

4.2 Bluetooth

Bluetooth, also known as IEEE 802.15.1, is a low cost, low power wireless radio frequency standard for short distance. The Bluetooth protocol stack is somewhat complicated in comparison with other IEEE networking stacks. It defines many components above the PHY and MAC layers. Some are optional, thereby complicating its overall protocol [Hackmann, 2006].

Bluetooth operates in the unlicensed 2.4 GHz ISM band, occupying 79 channels. The PHY layer uses frequency hopping spread spectrum coding to reduce interference and fading. The maximum data rate is up to 3Mbps in the enhanced data rate mode. However, the actual data payload is usually reduced due to the each type of unit address and other header information to provide compatibility with other Bluetooth sensor nodes.

Bluetooth's basic connectivity technology is the piconet based on the star network topology. It consists of one master device that communicates directly with up to seven active slave network devices. In a given piconet, all devices are synchronized using the clock and frequency hopping pattern of the master, and slave devices communicate only with their master in the one-to-one way. Bluetooth has three power saving modes. At the hold mode, devices just process reserved slots for synchronous links. After that they enter the sleep status. At the sniff mode, a device is in the sleep mode for most of the time. It wakes up periodically in a given time for communication. At the parked mode, the device just holds the parked slave broadcast (PSB) link and turn off any other links to the master device. If the latter would like to wake up parked devices, it sends beacons to them over the PSB link [Hackmann, 2006]. A slave device at the active mode can reduce the power consumption by entering the above power saving modes.

4.3 UWB

UWB (IEEE 802.15.3a) is a wireless radio technology for short-range, high bandwidth communication at very low energy levels by using a larger portion of the radio spectrum. UWB is a latent competitor to the IEEE 802.11 standards. One of its most outstanding properties is its huge bandwidth. Wireless USB currently delivers a bandwidth of up to 480 Mbps at 3 meters and 110Mbps at 10 meters. It can support multimedia applications such as audio and video transmission in home networks. It can also be used as a wireless cable replacement of high speed serial bus such as USB 2.0 and IEEE 1394 [Lee, *et al*., 2007]. However, IEEE 802.11 is more intended for data networking such as WLAN and to replace Ethernet cables. Currently, Bluetooth is popular for small WPAN-covering area applications, such as wireless mouse, and cell phone set. But UWB supports much higher bandwidth than the Bluetooth. It uses very low-powered, short-pulse radio signals to transfer data over a wide spectrum of frequencies.

4.4 Wi-Fi

Wi-Fi (*wireless fidelity*) is the general term for any type of IEEE 802.11 network. Examples of 802.11 networks are the 802.11a (up to 54 Mbps), 802.11b (up to 11 Mbps), and 802.11g (up to 54 Mbps). These networks are used as WLANs. Three 802.11 standards differ in their offered bandwidth, coverage, security support and, therefore, applications. 802.11a is better suited for multimedia voice, video and large-image applications in densely populated user environments. However, it provides relatively shorter range than 802.11b, which consequently requires fewer access points for coverage of large areas. The 802.11g standard is compatible with and may replace 802.11b, partly due to its higher bandwidth and improved security.

5. TECHNOLOGY COMPARISON

Table 1 provides a summary of the most popular wireless technologies for wireless health monitoring systems. From a general perspective, the main difference among the wireless technologies comes from the fact that they are optimized for different target applications.

Bluetooth is designed for voice application and aims to replace short distance cabling. It is good for hands free audio or multimedia file transfer with cell phone, PDA, and any other devices. This kinds of application require just tens of meters network range with a few (1~2) Mbps network speeds.

ZigBee intends to meet the needs of sensors and control devices for short message applications. Typically, ZigBee is designed for small data packet transmission with a lightweight and simple protocol stack in network devices. Because of their small data transmission and multi network devices, ZigBee does not need high network speed. Currently, it provides only 250 Kbps data rate.

UWB provides high network speeds together with robust communication using a broad spectrum of frequencies. It best suits for very short range networks, e.g., a few meters. Its speed is up to 480 Mbps.

Wi-Fi is very popular as WLAN. It is developed to replace wired Ethernet cable used in a home or office. They provide maximum data rate up to 54 Mbps in an around 50 meter range.

Clearly Bluetooth and ZigBee are suitable for low data rate applications with limited power source such as battery-operated sensor nodes or mobile devices. Low power consumption helps prolong a node's life time and reduce its size.

Table. 1 COMPARISON OF BLUETOOTH, UWB, ZIGBEE, AND WI-FI PROTOCOLS

Standard	Bluetooth	UWB	ZigBee	Wi-Fi
IEEE spec.	802.15.1	802.15.3a	802.15.4	802.1 1a/b/g
Frequency band	2.4 GHz & 2.5 GHz (Ver. 1.2)	3.1-10.6 GHz	868/915 MHz, 2.4 GHz	2.4 GHz (b/g) & 5 GHz(a)
Max signal rate	1 Mbps (Ver. 1.0) 3 Mbps (Ver. 1.2) 12 Mbps (Ver. 2.0)	50-100 Mbps (480 Mbps within short range expected	250 Kbps	54 Mbps (802.11a) 11 Mbps (802.11b) 54 Mbps (802.11g)
Max data payload (bytes)	339 (DH5)	2044	102	2312
Max overhead (bytes)	158/8	42	31	58
Nominal range	10m	20m (effective 10 m)	10 - 100 m (effective 20 m)	100 m (effective 50 m)
Nominal TX power	0 - 10 dBm	-41.3 dBm/MHz	(-25) - 0 dBm	15 - 20 dBm
Number of RF channels	79	(1-15)	1/10; 16	14 (2.4 GHz)
Channel bandwidth	1 MHz	500 MHz - 7.5 GHz	0.3/0.6 MHz; 2 MHz	22 MHz
Modulation type	GFSK	BPSK, QPSK	BPSK (+ ASK), O-QPSK	BPSK, QPSK COFDM, CCK, M-QAM
Spreading	FHSS	DS-UWB, MB-OFDM	DSSS	OFDM or DSSS with CCK
Coexistence mechanism	Adaptive freq. hopping	Adaptive freq. hopping	Dynamic freq. selection	Dynamic freq.selection, transmit power control (802.1 1 h)
Basic cell	Piconet	Piconet	Star	BSS
Extension of the basic cell	Scatternet	Peer-to-peer	Cluster tree, Mesh (ZigBee)	ESS
Max number of cell nodes	8	8	> 65000	2007
Encryption	EQ stream cipher	AES block cipher (CTR, counter mode)	AES block cipher (CTR, counter mode)	RC4 stream cipher (WEP), AES block cipher
Authentication	Shared secret	CBC-MAC (CCM)	CBC-MAC (ext. of CCM)	WPA2 (802.11i)
Data protection	16-bit CRC	32-bit CRC	16-bit CRC	32-bit CRC
Main applications	· Voice applications, · Replacement of short distance cable	· Multimedia app. · Healthcare app.	· Sensors/control · Remote control · Large scale automation	· Office/home networks · WLAN · Replace Ethernet cables
Pros	· Easy synchronization of mobile devices · Frequency hopping tolerant to harsh	· High bandwidth · Broad spectrum of bandwidth	· Static network · Low duty cycle · Low power · Network size extension	· Dominating WLAN tech.

On the other hand, UWB and Wi-Fi would be better selection for high data rate applications such as audio/video multimedia appliance. ZigBee is widely developed as a low rate WPAN, and its similar technology is Bluetooth. But they have some contrast: characteristics, because of their originally different optimized designs. ZigBee is focused on control and automation, while Bluetooth on the replacement of wired cables among laptops, PDA's, cell phone, and so on.

As for power consumption, a ZigBee node can operate at low power for a time period ranging from several months to 2 years from two AA batteries. But a Bluetooth node running on the same batteries would last just one week. ZigBee networks can support a larger number of devices and a longer range between devices than Bluetooth ones. ZigBee can support the configuration of static and dynamic star networks, a peer to peer network, and mesh network that can provide up to 65000 nodes in a network. Bluetooth allows only eights nodes in a master-slave piconet figure, i.e., it supports star networks only.

6. CURRENT WPMS IN HEALTHCARE APPLICATIONS

In this section we discuss some specific applications that have been developed for the health monitoring purpose.

In MobiCare [Rajiv, 2006], a WPMS as a MobiCare client and health care servers employ short-range Bluetooth between BSN and a BSN manager, and GPRS/UMTS cellular networks between the BSN manager and health care providers. Bluetooth is applied in this system, allowing data rate up to 1Mbps. However, it consumes high power and has limited network size (up to 7 slave nodes). Thus, it does not suit for LR-WPAN (Low Rate WPAN) as required in many healthcare applications.

Firefly is a sensor network-based rescue device used in coal mine as developed at Carnegie Mellon University [Mangharam, *et al*., 2006]. Voice streaming over WSN is implemented in this system. A TDMA based network scheduling is investigated to meet audio timing requirements. The developed hardware has a dual radio architecture for data communication and hardware based global time synchronization. This system is designed for the rescue in coal mine and has a small network size. It uses the codec chip and SD card for additional memory for sound transmission. It has high power consumption, high cost of a sensor node, and bulky size.

The CodeBlue [Malan, *et al*., 2004] project from Harvard University explores WSN for a range of medical applications. It employs WSN in emergency medical care, hospitals and disaster area as an emergency message delivery system. With MICA motes, CodeBlue uses pulse oximetry and electrocardiogram (ECG) sensors to monitor and record blood oxygen and cardiac information from a large number of patients.

Lee *et al*. [2006] introduce a vital sign monitoring system with life emergency event detection using WSN. Vital signs such as ECG and body temperature of patients are transmitted wirelessly to the base station connected to sever or PDA.

Dagtas *et al*. [2007] present a framework for a wireless health monitoring system within a smart home environment using ZigBee. They design some basic processing platform that allows the heart rate and fatal failure detection. They are currently building a prototype of the proposed system using in-home ECG probes and ZigBee radio modules.

In a wireless physiological sensor system, Jovanov *et al*. [2005] intend to develop wireless sensor technology for ambulatory and implantable human psycho-physiological applications. They have developed the devices for monitoring the heart, prosthetic joints for a long period of time and other organs.

Juyng and Lee [2008] describe a device access control mechanism. They propose the reliable data transmission of a physiological health data in a ZigBee based health monitoring system. They develop a wrist, chest belt, shoulder, and necklace type physiological signal devices. They use a CC2430 microcontroller as the central unit and two PDMS (Polydimethylsil-oxane) electrodes for ECG, a ribbon type temperature sensor, and SpO2 sensor for sensing the physiological signals. Their wrist type physiological signal device's (W-PSD) size is of 60×65×15 mm and total system weight is 160g including one Lithium-polymer battery. A reliable data transmission mechanism is also provided by using a retransmission. They recognize the power problem for a network device. It needs small battery as its power source. It can work for 6 hours without replacement or recharging. It is small, light weight, and easy to bring, but its life time from small battery should be improved.

Chien and Tai [2006] propose a prototype portable system to measure phonocardiography (PCG), ECG, and body temperature. They insert a capacitor-type microphone into the stethoscope's tube for PCG and develop a 3-wired lead ECG. Bluetooth transceiver and receiver modules are used with a microcontroller and PDA for wireless link between a sensing module and PDA. This system has some weak points as a health monitoring system. First, users should initiate the PDA whenever they want to measure health conditions. Thus this system is not operated automatically or in an event driven or schedulable way. Second, this system has many sizable external circuits, wired leads for ECG, and memory unit. It is not suitable as a wearable device and thus difficult to carry, because of its heavy weight and bulky size. Third, because of their complicated and many external devices, power consumption is high. Hence, it is limited in terms of wireless health monitoring.

In [Oliver and Msngas, 2006], Microsoft announces the HealthGear, a wearable real time health monitoring system. It consists of several physiological sensors for monitoring and analyzing the blood oxygen level (SpO_2), heart rate, and plethysmographic signal.

Gyselinckx, *et al*., [2007] develop a cardiac monitoring system, Human++, for ambulatory multi-parameter health monitoring such as ECG, EEG, and EMG. This system consists of three sensor nodes in body area networks and a base station. They sample the bio-signal at 1024 Hz with a 12-bit ADC in an MSP430F149 microcontroller. The base station collects the data from each sensor node and transfers to PC or PDA through a USB interface. This system is designed to run autonomously for 3 months on two AA batteries. This system is improved in [Brown, *et al*., 2009]. A small, lightweight and low power WPMS platform is developed for ambulatory and continuous monitoring for autonomic responses in real life applications. The Human++ UniNode uses an MSP 430 MCU, Nordic nRF24L01 2.4 GHz radio, 50 Ohm antenna, and a 165 mAh lithium-ion battery. The size of a node including battery is 20×29×9 mm^3. Their network topology is a star network using a static TDMA protocol. Their wearable medical sensors are developed chest-belt and wrist-band. The ECG and respiration sensors (20×22×4 mm^3) is connected to one Human++ UniNode and integrated into a chest belt, while the skin conductance and skin temperature sensors (20×25×5 mm^3) is connected to a second Human++ UniNode and integrated into a wrist band. The chest node consumes 2.6 mA in full active operation, while the wrist node consumes 4 mA, resulting in a roughly battery lifetime of 63 hours and 41 hours, respectively.

Fensli, *et al*., [2005] present a wearable ECG device for continuous monitoring. The hand-held device, which is a common PDA, collects the amplified ECG signal from a wearable device. The sensor senses ECG signals with 500 Hz sampling frequency, and this signal is digitized with 10 bit resolution. After digitizing the signal, it continuously transmits to a hand-held device by using a modulated RF link at 869.700 MHz. This system has focused its application on the emergency situation.

Monton *et al*. [2008] present WPMS-based patient monitoring. This BSN follows a star network technology, and is composed of two types of modules. A small device (34×48mm), called sensor communication module (SCM) is connected to one or several sensors for sensing the health signals. SCMs transmit signals to a central processing unit (73×110×25mm), called personal data processing unit (PDPU) via ZigBee. PDPU is designed to connect to local external systems through: 1) UWB to connect individual devices such as PCs or PDA, 2) Wi-Fi to connect with LAN, or 3) GPRS for WAN.

The development of a belt type wearable wireless body area network is described [Wang, *et al*., 2009]. A photoplethysmograph (PPG) sensor, and a respiratory inductive plethysmograph (RIP) sensor for pulse rate and oxygen saturation measurements are used for dynamic respiration monitoring. A WPMS node includes an MSP430F149 microcontroller as its main control unit, nRF905 as RF transceiver (915MHz), and 64 Megabit AT25DF641 as external memory. They follow a simple communication protocol. Its overall process is very simple, i.e., one sensor to one base station at a time.

Milankovic *et al*. [2006] propose a single-hop WSN topology. Each sensor for health monitoring is directly connected to an individual PDA, which provides the connectivity to a central server. They mainly focus on the synchronization and energy efficiency issues on the single-hop communication network between devices and PDA.

A wireless mobile healthcare application is developed to operate together with IEEE 802.15.4 enabled devices and adopted the CDMA cellular network for hospital and home environments [Yan and Chung, 2007].

Table 2 summarizes the major systems, their advantages, and limitations.

7. Challenge issues for WPMS

A number of parameters should be considered when developing a miniature wireless sensor device for real life health monitoring system.

7. 1 Reliability

Reliability in a wireless health monitoring system is the most critical issue. Wireless health monitoring system has to transmit accurate measured data in a timely manner to a medical doctor or other people for monitoring and analyzing the data from patients.

The reliability issue can be considered into three main stages: 1) reliable data measurement, 2) reliable data communications, and 3) reliable data analysis [Hyun, *et al*., 2008]. Stages 1 and 3 are mainly about hardware and software for sensing and analyzing the data without errors. Stage 2 needs more consideration than the other stages because it is about communication between sensor node and coordinator or central monitoring server.

For reliable communication, Varshney [2007] proposes combined wireless networks that include WSN, ad-hoc wireless networks, cellular networks, WLAN, and satellite networks. Juyng and Lee [2008] make a reliable data transmission by using a retransmission protocol. A sensor device sends the data with ACK (Acknowledgement) request. If the sensor node doesn’t received an ACK from mobile device or coordinator within *AckWaitDuration*, the sensor node transmit the same data frame again until receive the ACK from mobile device. This repeat process is limited by predefined *MaxFrameRetries* [IEEE Std. 802.15.4-2003].

7. 2 Power

The power issue is researched for all kinds of WSN applications. Since most WSN devices are battery-operated, one of the major challenges for their design is to optimize their power usage. Some WSN applications such as passive RFID [Finkenzeller, 2003], do not require battery. Instead they use power from their reader, i.e., backscattering. However, they have limited communication range and very small data size. Other applications adopt energy harvest systems for WSNs such as solar cell [Hande, et al., 2007], vibration using piezoelectric devices [Roundy and Wright, 2004], temperature difference [Stark, 2006], and shoes insert [Paradiso and Starner, 2005]. But these energy harvest systems have some problems for real WSN applications, e.g., their power earning depends on their environment and they tend to be over-sized.

Van Dam and Langendoen [2003], Zheng, *et al*. [2005], Ramakrishnan, *et al*. [2004] and Miller and Vaidya [2005] present energy efficient protocols for WPMS by designing energy-efficient MAC protocols.

Omeni *et al*. [2007] propose to control standby or sleep mode periods of sensor nodes to reduce energy consumption. They propose MAC protocol operations based on three main communication processes. A link establishment process is to associate a process to a network. A wakeup service process is to wake up a slave and master after an assigned sleep time interval. An alarm process operates only when a slave node urgently wants to send data to the master. These processes can be initiated by the master node only.

7. 3 Portability

Integration of sensing components into a wireless sensor node should be conducted in a functional, robust, small, light weight, and low cost way. For this reason, most WPANs use a small chip system, i.e., SOC, which includes a microcontroller and RF transceiver or single MCU with an external transceiver. Currently, there are some biomedical systems that suit the requirements of easy-to-wear or attach on the body for monitoring physiological signals [Barth, et al., 2009; Jung. et al., 2008]. Thus they exhibit good portability.

Table 2. SOME CURRENT WIRELESS PHYSIOLOGICAL MONITORING SYSTEMS

Ref.	Para-meters	Hardware Data rate Distance	Wireless option	Network topology	Reliab ility	Power/ Lifetime	Porta-bility	Inter-ference	QoS	Net-work Size
Rajiv' 06	Pulse ECG Temp.	P4032 board R5 MIPS RM5231	Bluetooth GPRS UMTS network	7 slaves 1 PDA cellular network	Un-known	Fair	Prototy pe	Unkno wn	Non-real time, selective data TX	Small
Man-ghara m'06	Voice	CC2420/Voice codec chip SD card	TDMA	Star	Fair	Poor	Poor Bulky	Poor	Continuo us /real time	Tiny
Malan' 04	Pulse Oximeter ECG	Berkeley MICA mote PDA	433/ 916MHz	Ad-Hoc	Fair	Fair 2AA: 6 d Sleep: 20y	Fair 5.7×3.2 ×2.2cm	Fair	Un-known	Big
Dagtas '07	ECG	M16C MCU (802.15.4)	802.15.4/ ZigBee	Star/Peer to Peer	Un-known	Unknown	Un-known	Unkno wn	Un-known	Small
Jung' 08	ECG SpO2	CC2430	ZigBee	Star/Peer to Peer	Good	Poor Li-p: 6 hr.	Good 60×65× 15mm 160g	Fair	Good	Med.
Chien' 06	ECG , PCG, Temp.	Bluetooth /PDA/Ext. memory	Bluetooth	7 slaves 1 PDA	Poor	Poor	Poor (bulky)	Fair	Poor (Single data TX)	Small
Oliver '06	ECG SpO2	DSP/Bluetooth /Cell phone	Bluetooth	7 slaves 1 PDA	Fair	Poor 2 AAA: 12 hours	Poor	Unkno wn	Real time	Small
Gyse-linckx' 07	ECG EEG EMG	MSP430/ nRF2401	2.4 GHz, TDMA	Star BSN to PDA	Fair	Fair 2 AA: 3 mon.	Fair	Fair	Un-known	Med
Brown '09	ECG EEG EMG	MSP430/ nRF2401	2.4 GHz static TDMA	Star	Fair	Fair UniNode	Good 20×29× 9 mm	Fair	Continu-ous/real time	Small
Fensli' 05	ECG	ECG sensor	879/700 MHz GPRS GMS	One sensor to hand-held dev.	Fair	Unknown	Poor	Unkno wn	Real time	Tiny
Mon-ton'08	ECG EMG EEG	MSP430F427, CC2420, FRAM Central unit-AT91RM9200, GPRS modem	ZigBee UWB Wi-Fi GPRS	Star (BAN)	Good	Fair Li-ion battery	Good 73×110 ×25 mm	Expecte d with Zigbee and WiFi	Un-known	Small
Wang' 09	PPG RIP	MSP430F149 Ext. memory 3D Accelerometer	915MHz	Star	Fair	Active: 7.8mW Sleep: 860μW	Good	Un-known	Un-known	Small
Milen-kovic' 06	ECG EMG EEG	MSP430 with CC2420 ADXL202	ZigBee	Star BAN w/ PDA	Good	Two AA batteries	Fair	Un-known	Real time	Med
Yan'07	ECG	MSP430F1611 CC2420 4×4×0.2cm	802.15.4 CDMA WLAN	Star CDMA	Good	Active: 330μA Standby: 1.1 μA	Fair 4×4×0. 2 cm	802.15. 4 with WLAN	Real time	Small
Juyng' 08	PPG, ECG, Temp.	CC2430 BIP-5000 (mobile)	ZigBee/ CDMA	Star CDMA	Good	Unknown	Good	802.15. 4 with WLAN	Delayed real time	Small

7. 4 Network interference

In general, a wireless link is more sensitive to interference than a wired connection link. In WSN environments, generally two or more different communication techniques are used together in a same network. Usually, WPANs and WLANs coexist using the same Industrial, Science and Medical (ISM) band. Therefore, they can lead to a network interference problem. Network interference or data collision problems cause intermittent network connectivity, packet loss and ultimately result in lower network throughput and increased energy expenditures [Razvan and Andreas, 2007].

The interference and coexistence problems between Bluetooth and WLAN have been presented in [Jo and Jayant, 2003; Sakal and Simunic, 2003; Howitt, 2001; Feng, *et al*., 2002]. Also, interference problems between IEEE 802.15.4/ZigBee and WLAN are described in [Razvan and Andreas, 2007; Kim, *et al*., 2005; Kang, *et al*., 2007; Yang and Yu, 2009; Hauer, *et al*., 2009]. BER (Bit Error Rate), PER (Packet Error Rate), RSSI (Radio Signal Strength Indicator), or SINR (Signal Interference Noise Ratio) for interference avoidance are measured and analyzed.

7.5 Real time and continuous monitoring

Some physiological data, such as heart beat sound, lung sound, ECG, and RIP, should be monitored continuously and in real time. Also, a biomedical sensor is imagined to operate for days sometimes weeks without a user's intervention. A good example is a heartbeat monitoring system for patients who has heart disease. Since the heart rate is reported periodically, a heartbeat sensing device should be always on and transmit continuously with low transmit delay and latency for real time monitoring. If a sensing device could transmit periodic data discontinuously or transmit continuous data with much delay time, it is hard for doctors to monitor and prepare a patient's heart attack. Therefore, real time and continuous monitoring is critical in handling an emergent patient.

8. LIMITATIONS AND CHALLENGES IN WPMS

Table 2 presents several current researches or prototypes of their medical applications and issues mentioned in Section 7. From it, most applications use MCU as a control unit for low power consumption, and size of the device. Also, all devices receive the power from batteries such as AAA, AA, and Li-ion. Size and weight of devices are mainly determined by those of the batteries. Otherwise, a battery's capacity is directly proportional to its size. Malan, *et al*. [2004], Oliver and Msngas [2006], Gyselinckx, *et al*. [2007], and Milenkovic, *et al*. [2006] use 2 AA or 2 AAA battery and [Juyng and Lee, 2008] and [Monton, *et al*., 2008] use the Li-ion or Li-P battery. A small Li-P battery's life time [Juyng and Lee, 2008] is about 6 hours, while AA or AAA battery's life time is several days or even 3 months in a full active mode [Gyselinckx, *et al*., 2007]. Therefore, battery types need be carefully selected for portability and power consumption of different healthcare applications.

Some applications implement several wireless infrastructures for health monitoring systems. Rajiv [2006], Chien and Tai [2006], and Oliver and Msngas [2006] apply Bluetooth to WPMS with PDA, Cell phone, or WLAN. Milenkovic, et al. [2006], Yan and Chung [2007], and Juyng and Lee [2008] apply ZigBee to BAN with PDA, or WLAN for extended network size. When several wireless infrastructures are deployed in the same network area, interference and data collision can occur in their overlapped channels. Different network topology, such as star, peer-to-peer, and mesh, should be considered for different health data applications.

Table 2 summarizes the platforms for physiological data sensing and monitoring with several wireless options. Each project meets some above-mentioned issues, such as reliability, power, portability, network interference, and QOS, for real life. But they did not satisfy all of them. For example, some applications ([Jung, et al., 2008], and [Milenkovic, et al., 2006]) have good reliability, portability, and QOS, but their power consumption is not suitable for real life application. Also, applications ([Mangharam, et al., 2006], [Chien and Tai, 2006], [Oliver, et al., 2006]) have good performance, but their devices are too big and heavy to carry or attach on the body in real life applications. FireFly project [Mangharam et al., 2006] can send the continuous voice data in real time, but they have poor power consumption, bulky size device and small network size.

As such, each application on a health monitoring system has to consider or improve their weak points for real-life using.

9. CONCLUSION

This paper reviews the current research of sensor based systems for biomedical health monitoring. Current health monitoring still has many challenges and issues that must be addressed such as reliability, portability, low power consumption, and real time communication.

Most reviewed systems focused on single hop topologies, and have very limited real time monitoring capability. Also, some systems are hard to attach or carry because of their size and weight.

Even if they can monitor the health conditions, they cannot be readily available for real life application. They use the different wireless technologies for their different health parameters, situation, and areas. For example, some small data such as body temperature and patient ID are communicated by IEEE 802.15.4/ZigBee, even if this standard has low data rate. Also, these kinds of data are not much affected by time synchronization in real time. But some physiological data such as ECG, EEG, and EMG, need continuous and real time transmission. Also, they require high data rate for reliable transmission. Therefore, selecting a proper wireless option for each different healthcare monitoring system is very important.

References

[1] Akyildiz I. F., Su W, Sankarasubra-maniam Yand Cayirci E, “Wireless Sensor Networks: a Survey”, *Computer Networks*, vol. 38, pp. 393-422, 2002.

[2] Barth, A.T., Hanson, M.A., Powell Jr., H.C., and Lach, J., " TEMPO 3.1: A body area sensor network platform for continuous movement assessment", in *Proc. of th 6th International Workshop on Wearable and Implantable Body Sensor Networks*, Article number 5226915, pp. 71-76 , Berkeley, CA, 2009.

[3] Brown, L, Grundlhner B, Penders J, and Gyselinckx B, “Body Area Network for Monitoring Autonomic Nervous System Responses”, in *Proc. of 2009 3rd International Conference on Pervasive Computing Technologies for Healthcare - Pervasive Health 2009*, Article number 5173603, April 2009.

[4] Chai, J, and Yang H, “The research of the community healthcare network based on ZigBee technology”, in *Proc. of the 7th Asian-Pacific Conference on Medical and Biological Engineering*, vol.19, pp. 567-570, Beijing, China, April 2008.

[5] Chen, Y., and Wang X., "Design of Distributed Intelligent physiological parameter Monitor System Based on Wireless Communication Technology", in *Proc. of International Seminar on Future BioMedical Information Engineering*, pp. 403-406, 2008.

[6] Chien, R., and Tai C., "A New Wireless-Type Physiological Signal Measuring System Using a PDA and the Bluetooth Technology", in *Proc. of IEEE International Conference on Industrial Technology*, pp.119–120, 2006.

[7] Choi, S., Cha H., and Cho S., " A Soc-based Sensor Node: Evaluation of RETOS-enabled CC2430", in *Proc. of the 4th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*, SECON 2007, Article number 4292825, pp. 132-141, San Diego, CA, 2007.

[8] Choi, K., and Song J., "A Miniaturized Mote for Wireless Sensor Networks", in *Proc. of International Conference on Advanced Communication Technology*, ICACT ,Vol 1, Article number 4493814, pp. 514-516, 2008.

[9] Dagtas, S., Pekhteryev G., and Sahinoglu Z., “Multi-stage Real Time Health Monitoring via ZigBee in Smart Homes”, in *Proc. of the 21st International Conference on Advanced Information Networking and Applications*, pp. 782-786, 2007.

[10] Estrin, D., “Embedded Networked Sensing Research: Emerging System Challenges,” in *NSF Workshop on Distributed Communications and Signal Processing for Sensor Networks*, Illinois, USA, 2002

[11] Feng, W., Arumugam N., and Krishna G. H., “Impact of interference on a Bluetooth network in the 2.4 GHz ISM band,” in *Proc. of the 8th International Conference on Communication Systems*, Vol. 2, pp. 820 - 823, Nov. 2002.

[12] Fensli, R., Gunnarson E, and Gundersen T, “A wearable ECG-recording system for continuous arrhythmia monitoring in a wireless tele-homecare situation”, in *Proc. of the 18th IEEE Symposium on Computer-Based Medical Systems*, pp. 407-412, 2005.

[13] Finkenzeller, K., *RFID Handbook*: *Fundamentals and Applications in Contactless Smart Cards and Identification*, 2nd Edition, Wiley, 2003.

[14] Gyselinckx, B, Penders J, and Vullers R, “Potential and challenges of body area networks for cardiac monitoring”, *J. Electrocardiology*, vol. 40, pp. S165–S168, Nov, 2007.

[15] Heart Attack http://www.medicinenet.com

[16] Hande A., Polk T., Walker W., and Bhatia D., “Indoor solar energy harvesting for sensor network router nodes”, *Microprocessor and Microsystems*, Volume 31, No. 6, pp. 420-432, 1 Sept. 2007.

[17] Howitt, I., "WLAN and WPAN coexistence in UL band", *IEEE Transactions on Vehicular Technology*, Vol. 50, No. 4, pp. 1114 - 1124, July 2001.

[18] Hauer, J., Handziski V., and Wolisz A., “Experimental Study of the Impact of WLAN Interference on IEEE 802.15.4 Body Area Networks”, in *Proc. of the 6th European Conference on Wireless Sensor Networks*, Cork, Ireland, pp, 17-32, February 2009.

[19] Hackmann, G., “802.15 Personal Area Networks”, Department of Computer Science and Engineering, Washington University, 2006.

[20] http://www.cse.wustl.edu/~jain/cse574-06/wpans.htm

[21] Hyun, L. et al., “Issues in data fusion for healthcare monitoring”, in *Proc. of the 1st international conference on pervasive Technologies Related to Assistive Environments*, Vol. 282, Article No. 3, Athens, Greece 2008.

[22] IEEE Std. 802.15.4-2003, IEEE Standard for Information Technology – Telecommunications and Information Exchange Between Systems –Local and Metropolitan Area Networks – Specific Requirements – Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs), 2003.

[23] Jovanov E, Milenkovic A, Otto C, Groen P. D., Johnson B, Warren S, and Taibi G, “A WBAN System for Ambulatory Monitoring of Physical Activity and Health Status: Applications and Challenges,” in *Proc. of the 27th Annual IEEE International Conference on EMBS*, pp. 3810 - 3813, 2005.

[24] Jo J.-H., and Jayant N, "Performance Evaluation of Multiple IEEE 802.11b WLAN Stations in the Presence of Bluetooth Radio Interference," *IEEE Journal on Communications*, vol. 2, pp. 1163-1168, May 2003.

[25] Jung J., Ha K., and Lee J., Kim Y. and Kim D."Wireless body area network in a ubiquitous healthcare system for physiological signal monitoring and health consulting", *International Journal of Signal Processing and Pattern Recognition*, Vol.1, pp. 47-54, 2008.

[26] Juyng J, and Lee J, “ZigBee Device Access Control and Reliable Data Transmission in ZigBee Based Health Monitoring System”, 10th International Conference on Advanced Communication Technology, Vol. 1, pp.795 – 797, 17-20 Feb. 2008.

[27] Khemapech I, Duncan I, and Miller A, “A Survey of Wireless Sensor Networks Technology,” in *Proc. of the 6th Annual PostGraduate Symposium on the Convergence of Telecommunications, Networking & Broadcasting*, pp. 26-31, June 2005.

[28] Kim S. M., Chong J. W., Jung C. Y., Jeon T. H., Park J. H., Kang Y. J., Jeong S. H., Kim M. J., and Sung D. K., "Experiments on Interference and Coexistence between Zigbee and WLAN Devices Operating in the 2.4 GHz ISM Band", *NGPC 2005*, pp. 15 - 19, Nov 2005.

[29] Kang M. et al., “Adaptive Interference-Aware Multi-Channel Clustering Algorithm in a ZigBee Network in the Presence of WLAN Interference,” in *Proc. of the International Symposium on Wireless Pervasive Computing*, San Juan, Puerto Rico, pp. 5-7, 2007.

[30] Lee, J. S., Su Y. W., and Shen C. "A comparative study of wireless protocols: bluetooth, uwb, zigbee, and wi-fi", in *Proc. of the 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON)*, pp. 46-51, Nov. 2007.

[31] Lee, D.-S., Lee Y.-D., Chung W.-Y. ,and Myllyla R., "Vital Sign Monitoring System with Life Emergency Event Detection using Wireless Sensor Network," in *Proc. of the 5th IEEE Conference on Sensors*, Daegu, South Korea, pp. 518-521, 2006.

[32] Mangharam, R., Rowe A., Rajkumar R., and Suzki R., “Voice over sensor networks”, In *RTSS ’06: Proc. of the 27th IEEE International Real-Time Systems Symposium*, pp. 291-302, Dec 2006.

[33] Miller, M.J., and Vaidya N.H., “A MAC protocol to reduce sensor network energy consumption using a wakeup radio”, *IEEE Transactions on Mobile Computing*, 4(3), pp. 228 – 242, May-June 2005.

[34] Musaloiu, R. and A. Terzis, "Minimizing the effect of WiFi interference in 802.15.4 wireless sensor networks", *International Journal of Sensor Networks*, Vol. 3, No. 1, pp. 43-54, December 2007.

[35] Malan, D., Fulford-Jones T.R.F., Welsh M S., Moulton, "CodeBlue: an ad hoc sensor network infrastructure for emergency medical care", in *Proc. of the MobiSys 2004 Workshop on Applications of Mobile Embedded Systems (WAMES 2004)*, pp. 12-14, 2004.

[36] Monton, E., Hernandez J. F., Blasco J. M., Herve T., Micallef J., Grech I, Brincat A, and Traver V, “Body area network for wireless patient monitoring,” *Telemed. E-Health Commun. Syst.*, vol. 2, no. 2,

pp. 215–222, Feb. 2008.
[37] Milenkovic, A., Otto C, and Jovanov E, "Wireless sensor networks for personal health monitoring: Issues and an implementation," *Computer Communications*, vol. 29, pp. 2521-2533, 2006.
[38] Omeni, O., Eljamaly O, and Burdett A, "Energy Efficient Medium Access Protocol for Wireless Medical Body Area Sensor Networks", in *Proc. IEEE-EMBS Symposium on Medical Devices and Biosensors*, pp. 29-32, Cambridge, UK, Aug 2007.
[39] Oliver, N., and Flores Msngas F, "HealthGear: A real-time wearable system for monitoring and analyzing physiological signals" *International Workshop on Wearable and Implantable Body Sensor Networks, BSN 2006*, pp. 61-64, Cambridge, MA, 3-5 April 2006
[40] Paradiso, J. A., and Starner T, "Energy scavenging for mobile and wireless electronics" *IEEE Pervasive Computing*, Volume 4, No. 1, pp. 18-27, 2005.
[41] Roundy, S., and Wright P.K., "A Piezoelectric Vibration Based Generator for Wireless Electronics," *Smart Materials and Structures*, 13, pp. 1131–1142, 2004.
[42] Ramakrishnan, S., Huang H., Balakrishnan M., and Mullen J., "Impact of sleep in wireless sensor MAC protocol", in *Proc. of IEEE Vehicular Technology Conference*, pp. 4621-4624, 2004.
[43] Rajiv C, "Mobicare: A Programmable Service Architecture for Mobile Medical Care", in *Proc. of 4th Annual IEEE International Conference on Pervasive Computing and Communications Workshops, PerCom Workshops 2006*, pp. 532-536, March 2006.
[44] Stark I, "Invited Talk: Thermal Energy Harvesting with Thermo Life", in *Proc. of the International Workshop on Wearable and Implantable Body Sensor Networks*, BSN 2006, pp. 19-22, 2006.
[45] Sakal I, and Simunic D, "Simulation of interference between Bluetooth and 802.11b systems", in *Proc. of IEEE International Symposium on Electromagnetic Compatibility*, Vol. 2, pp. 1321 - 1324, May 2003.
[46] Tijs van Dam, and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks", in *Proc. of the 1st International Conference on Embedded Networked Sensor Systems*, pp. 171 - 180, 2003.
[47] Varshney, U, "Pervasive healthcare and wireless health monitoring", *Mobile Networks and Application*, 12(2-3), pp. 113-127, 2007.
[48] Willig, A., Matheus K., and Wolisz A., "Wireless technology in industrial networks", *Proc. of the IEEE*, 93(6), pp. 1130-1151, 2005.
[49] Wang B., et all., "A Body Sensor Networks Development Platform for Pervasive Healthcare", in *Proc. of the 3rd International Conference on Bioinformatics and Biomedical Engineering*, pp.1 - 4, 11-13 June 2009.
[50] Yang, G., and Yu Y., " ZigBee networks performance under WLAN 802.11b/g interference", in *Proc. of the 4th International Conference on Wireless Pervasive Computing*, pp. 337-340, 2009.
[51] Yan, C.-L., and Chung, W.-Y., "IEEE 802.15.4 Wireless Mobile Application for Healthcare system", International Confer-ence on Convergence Information Technology, ICCIT 2007, Article number 4420456, pp.1433-1438, 2007.
[52] Zhang, J., Li, W., Xia, Z., Wang, G., and Wan, Z., " The Implementation of Communication for CC2430-Based wireless Sensor Network Nodes", in *Proc. of the 5th International Conference on Wireless Communications, Networking and Mobile Computing, WiCom '09*, pp. 1-4, 2009.
[53] Zheng, T., Radhakrishnan, S., Sarangan, V., "PMAC: an adaptive energy-efficient MAC protocol for wireless sensor networks", in *Proc. of the 19th IEEE International Parallel and Distributed Processing Symposium (IPDPS'05)* - Workshop 12, pp. 8, 2005.

Jin Soo Choi was born in Taejon, South Korea, in January 1976. He received a Master in engineering degree, electrical and computer engineering, from New Jersey Institute of Technology in 2003. From 2005 to 2009, he worked at New Jersey Microsystems. Inc., NJ, USA, as an RFID design engineer. Currently, he is a Ph.D. candidate in the department of Electrical and Computer Engineering, New Jersey Institute of Technology, New Jersey, USA. His current research interests include wireless sensor networks, wireless body area network for healthcare, statistical signal processing, and RFID.

MengChu Zhou received his B.S. degree in Electrical Engineering from Nanjing University of Science and Technology, Nanjing, China in 1983, M.S. degree in Automatic Control from Beijing Institute of Technology, Beijing, China in 1986, and Ph. D. degree in Computer and Systems Engineering from Rensselaer Polytechnic Institute, Troy, NY in 1990. He joined New Jersey Institute of Technology (NJIT), Newark, NJ in 1990, and is currently a Professor of Electrical and Computer Engineering and the Director of Discrete-Event Systems Laboratory. He also serves as the Director of the MS in Computer Engineering Program and Area Coordinator of Intelligent Systems at NJIT. His research interests are in intelligent automation, lifecycle engineering and sustainability evaluation, Petri nets, wireless *ad hoc* and sensor networks, system security, semiconductor manufacturing, and energy systems. He has over 360 publications including 10 books, 150+ journal papers, and 17 book-chapters. He is currently Editor of *IEEE Transactions on Automation Science and Engineering*, and Associate Editor of *IEEE Transactions on Systems, Man and Cybernetics: Part A* and *IEEE Transactions on Industrial Informatics*. Dr. Zhou has led or participated in 40 research and education projects with total budget over $10M, funded by National Science Foundation, Department of Defense, New Jersey Science and Technology Commission, and industry. He was the recipient of NSF's Research Initiation Award, CIM University-LEAD Award by Society of Manufacturing Engineers, Perlis Research Award by NJIT, Humboldt Research Award for US Senior Scientists, Leadership Award and Academic Achievement Award by Chinese Association for Science and Technology-USA, and Distinguished Lecturership of IEEE SMC Society. He was the founding chair of Discrete Event Systems Technical Committee and founding Co-Chair of Enterprise Information Systems Technical Committee of IEEE SMC Society, and Chair (founding) of Semiconductor Manufacturing Automation Technical Committee of IEEE Robotics and Automation Society. He is a life member of Chinese Association for Science and Technology-USA and served as its President in 1999. He is Fellow of IEEE.