A Survey of Recent Developments in Home M2M Networks

Min Chen, *Senior Member, IEEE,* Jiafu Wan, *Member, IEEE,* Sergio González, *Member, IEEE,* Xiaofei Liao, *Member, IEEE,* and Victor C.M. Leung, *Fellow, IEEE*

***Abstract*—Recent years have witnessed the emergence of machine-to-machine (M2M) networks as an efficient means for providing automated communications among distributed devices. Automated M2M communications can offset the overhead costs of conventional operations, thus promoting their wider adoption in fixed and mobile platforms equipped with embedded processors and sensors/actuators. In this paper, we survey M2M technologies for applications such as healthcare, energy management and entertainment. In particular, we examine the typical architectures of home M2M networks and discuss the performance tradeoffs in existing designs. Our investigation covers quality of service, energy efficiency and security issues. Moreover, we review existing home networking projects to better understand the real-world applicability of these systems. This survey contributes to better understanding of the challenges in existing M2M networks and further shed new light on future research directions.**

***Index Terms*—Machine-to-machine, Wireless sensor networks, Wireless body area networks, Home energy management**

I. Introduction

TECHNOLOGICAL advances in recent years have enabled the production and deployment of ubiquitous communication devices that replace traditional human-controlled operations with automated machine-to-machine (M2M) or machine type communications (MTC). This trend has spun significant interest from industry and the research community [1]. The number of M2M-enabled devices (terminals) is increasing exponentially, and forecasted to grow from 50 million in 2008 to well over 200 million in 2014, and up to 50 billion by 2020 [2]. Here, M2M-enabled device means any machine that can capture an event or generate data by itself, and then transmit the information to other devices through a wired or wireless communication network.

In general, the term M2M communications is widely employed to refer to data communications without or with limited human intervention among various terminal devices such as computers, embedded processors, smart sensors/actuators and mobile devices, etc. M2M solutions fulfill very specific requirements that existing technologies are unable to adequately support [3]. The rationale behind M2M communications is based on three observations: 1) a networked machine is more valuable than an isolated one, 2) when multiple machines are interconnected, more autonomous applications can be achieved [4], and 3) smart and ubiquitous services can be enabled by machine-type devices intelligently communicating with other devices at anytime and anywhere [5].

According to ETSI (European Telecommunications Standards Institute), a M2M system includes three domains, i.e., the M2M device domain, network domain, and application domain:

- In the M2M domain, a possibly massive number of wireless devices are integrated to enable automated and diverse services. M2M devices should be equipped with various functions, such as data acquisition, data preprocessing, data storage, distinctive address, wireless transceiver, power supply, etc.
- In the network domain, a large number of heterogeneous access points potentially coexist. Thus, system design supporting the convergence of heterogeneous networks in an optimal way is a challenging issue.
- In the application domain, various monitor, command, control or management services are provided and can be classified into several categories, such as 1) traffic area, including traffic control, traffic navigation, and smart road, etc.; 2) logistic area, including cargo tracking, and machine monitoring, etc.; 3) business area, including electronic payment, and supply chain, etc.; 4) home area, including healthcare, smart grid, home surveillance, and appliances remote control, etc.

While various application services lead to different kinds of M2M networks, a home M2M network is particularly used in a smart home area [6]. Due to its importance in improving people's quality of life in home environments, maturity and market readiness, we will focus on the deployment of home M2M networks, which are typically comprised of a heterogeneous network with a backbone element and multiple home sub-networks. In this paper, the types of home sub-networks are categorized into wireless body area subnetwork (WBA-SN), smart grid sub-network (SG-SN), and home entertainment and convenience sub-network (HEC-SN). Typically, each home sub-network has its own gateway as an entry/exit point that connects multiple machines and the backbone network.

Manuscript received on November 30, 2012; revised June 2, 2013.

M. Chen is with School of Computer Science and Technology, Huazhong University of Science and Technology, China (e-mail: minchen@ieee.org).

J. Wan is with College of Computer Science and Engineering, South China University of Technology, China (e-mail: jiafu_wan@ieee.org). (corresponding author)

S. González is Dept. of Electrical & Computer Engineering, The University of British Columbia, Canada (e-mail: sergiog@ece.ubc.ca).

X. Liao is with School of Computer Science and Technology, Huazhong University of Science and Technology, China (e-mail: xfliao@hust.edu.cn)

V.C.M. Leung is with Dept. of Electrical & Computer Engineering, The University of British Columbia, Canada V6T 1Z4 (e-mail: vleung@ece.ubc.ca).

Digital Object Identifier 10.1109/SURV.2013.110113.00249

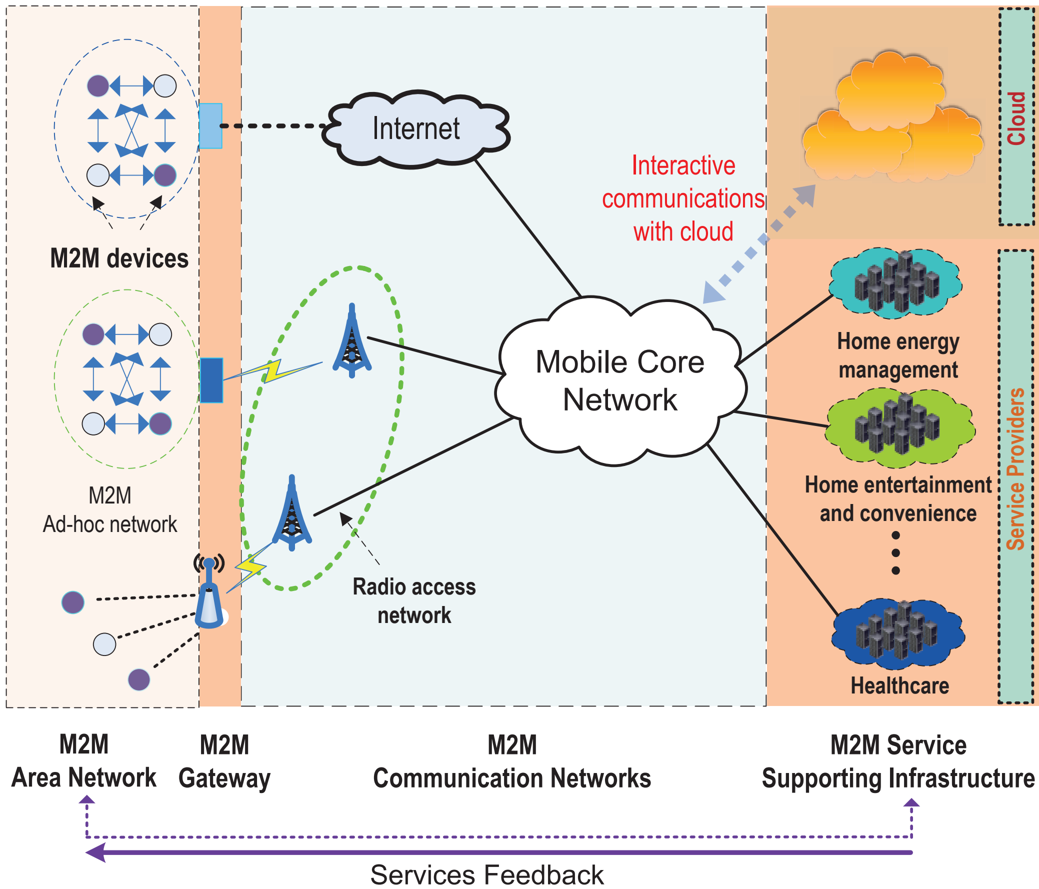

Fig. 1. The proposed home M2M network architecture comprised of five functional components: M2M device, M2M area network, M2M gateway, M2M communications networks, and M2M services supporting infrastructure.

In [7], we presented general architecture for M2M communications, as well as the related standards and applications. Lu *et. al* [8] investigated M2M systems from the perspective of a general purpose wireless sensor network (WSN) connected to a wide area network, and emphasized the importance of energy management, transmission reliability and security. In their work, M2M communications refer to the data transmissions among sensors, which collect and deliver the information through a network to an application. Feng *et. al* [9] provided a survey on energy-efficient wireless communications involving radio and network resource management schemes, such as various cross-layer optimization algorithms, dynamic power saving, and multiple radio access technologies coordination. The work in [10] discusses multiple wireless communication technologies and compared them in terms of power consumption. The previous work reviewed above provides a general introduction to M2M networks, and discuss different aspects of M2M networks, but does not consider M2M networks and applications for smart home environments. There are several M2M surveys that focus on different topics for home M2M networks. Zhang *et. al* [6] presented a hierarchical home networking architecture and introduced two schemes to improve the quality of service (QoS) in home M2M networks. Niyato *et. al* [11] proposed a smart grid architecture for home energy management from the perspective of cluster formation among MTC nodes. Nonetheless, discussions on the relative strengths and weaknesses of each M2M technology, as well as how existing approaches can be integrated to provide a comprehensive solution for improving home M2M networks are lacking in the previous work reviewed above.

Though the current research results in this area are still preliminary and many challenges remain, we categorize open issues and challenges in home M2M networks as follows:

- Interference: An increasingly large number of devices with radio interfaces in home areas, including unlicensed systems operating in the industrial, scientific, and medical (ISM) frequency band, remains of foremost concern. The performance of M2M communications may be seriously degraded or rendered altogether inoperable due to such interference.
- Channel dynamics: Wireless channels in M2M communications are notoriously unreliable due to channel fluctuations and noise, which worsens due to multi-path fading in an indoor environment.
- Resource constraints: Machines implementing wireless interfaces may be resource constrained with respect to computation, storage, bandwidth, and power supply. There is always a trade-off between energy, reliability, and flexibility because of this.
- Device heterogeneity: A home network generally is comprised of a large number of different devices supporting distinct services, which may generate dramatically differ-

ent data streams with diverse QoS requirements.

- Self-organization: Minimal human intervention is a major property of home M2M communications. This requires enhanced system capabilities, including self-organization, self-configuration, self-management, and self-healing.
- QoS support: One typical example that requires QoS support in home M2M communications is a biomedical sensor network. It is extremely important that life-critical medical data be reliably delivered before being dropped due to the limited storage memory of some devices.
- Security: Home M2M communications are typically required to be inexpensive and preferably unattended, which may expose them to a number of potential attacks.

In this survey, we explore the techniques and recent developments in the design of home M2M networks, and review methodologies to improve the QoS of the related M2M systems:

1) We provide a detailed study of home M2M communication and network architectures, as well as their interconnection techniques. The unique features of different radio technologies are also discussed in detail.
2) We present a thorough analysis of QoS improvement methodologies, their characterizations, and opportunities to resolve design problems seen in home M2M networks. Considering the home M2M networks' design challenges, various approaches have been proposed in order to achieve an effectively connected, efficient, and reliable home network. These approaches include energy-efficient medium access control (MAC) protocols, cross-layer joint design, and security mechanisms for home M2M networks.
3) In Fig. 1, we consider that M2M services are closely related to M2M networks. Corresponding to WBA-SN, SG-SN, and HEC-SN, the existing home M2M networking projects are classified into following categories:
    - Healthcare: Health and fitness of a human subject can be remotely monitored by a wireless body area network (WBAN) together with a backbone network and a supporting gateway. We summarize research projects targeting implantable or wearable devices for various patient types, the disabled, aging people, pregnant women and neonates.
    - Home energy management: We review home energy management systems (HEMS) that are employed as a part of a smart grid to autonomously manage and optimize energy consumption of appliances. Other projects (e.g., FIDO Home Energy Watchdog [12]) that have made significant progress in home energy management are also explored.
    - Convenience and entertainment: Home M2M networks are typically deployed to support interconnected media systems, facilitating the enhancement of user's entertainment experience by better usability.

Particularly, we propose four major design issues for home M2M network, i.e., architecture, radio technologies, QoS provisioning, and application & services. Section II to Section V of this survey are organized to address the above four design issues, respectively. Section II introduces cellular & capillary M2M communications in home networks. Section III explains the issues pertaining to commercial radio technologies, and makes a qualitative comparison. In Section IV, a typical home M2M network architecture divided into backbone network and multiple sub-networks is introduced. Then, a five-part structure for home M2M networks is proposed. The methodologies for QoS provisioning in home M2M networks are reviewed in Section V. In Section VI, a taxonomy of home networking projects is given corresponding to the three categories of home M2M area networks. Finally, Section VII concludes this paper and outlines some challenges for future work.

II. Communication Architecture for Home M2M Networks

As standardized in the 3rd Generation Partnership Project (3GPP), the interconnection modes between terminals and a cellular network can be classified into two categories: 1) cellular M2M communications as shown in Fig. 2(a), where each M2M terminal connects directly to a 3G or 4G cellular network; and 2) capillary M2M communications as shown in Fig. 2(b), where terminals in an area (e.g., a high-rise building) are organized in a capillary, typically wireless, network with a mesh- or tree-topology connected via a gateway to the cellular network [13].

Cellular M2M approach aims to leverage the significant benefits of cellular networks in terms of virtually ubiquitous coverage, reliable delivery and delay guarantees, as well as mature security and charging solutions. However, cellular networks are optimized for a large number of mobile devices, though only a small portion of which are active at any given time, and most of the data traffic flows exist in the downlink direction. Thus, connecting M2M networks to cellular networks directly is inefficient because a large number of mostly stationary terminals with low duty cycles would saturate uplink traffic flows [14]. By comparison, the smart devices in capillary M2M communications are organized in a terminal network with only the gateway connected with the cellular network. Consequently, it is easy to see that the capillary M2M is more efficient for large-scale deployment.

A. Cellular M2M Communications

In the context of 3GPP Long Term Evolution (LTE), the architecture for cellular M2M communications consists of several network elements: 1) MTC device, 2) MTC gateway, which allocates bandwidth and coordinates resource usage among MTC devices, and 3) evolved NodeB (eNB), which typically is resource-intensive and provides functions in terms of control plane and user plane. As illustrated in Fig. 2, the different combinations of data transmissions among the three elements lead to four kinds of communications:

- *Gateway-eNB communications*: This type of transmissions uses the licensed spectrum. Bidirectional transmissions take place in this process. Orthogonal and shared resource allocations are needed to avoid or minimize the interference at this stage.
- *Gateway-device communications*: The data rate and the frame structure of different MTC devices usually varies

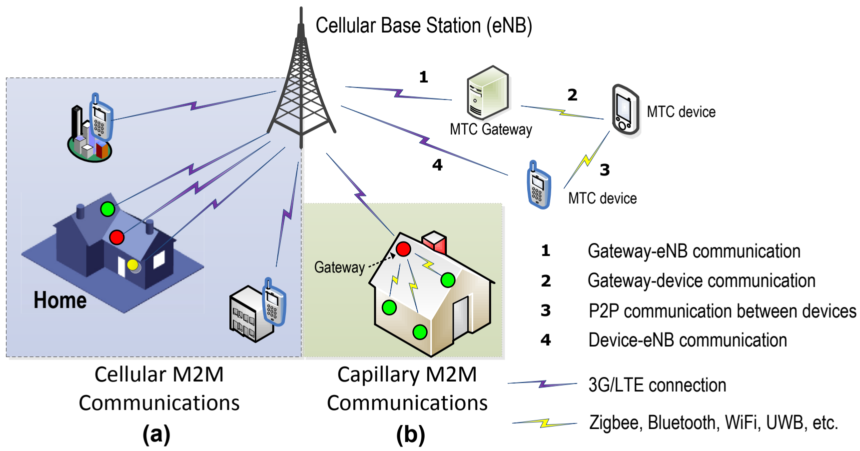

Fig. 2. Communication architecture for home M2M networks.

significantly. The MTC gateway usually provides certain computational capability for processing the data sent from the MTC devices to prevent the eNB from becoming overwhelmed. The MTC gateway can allocate bandwidth and power resources intelligently to MTC devices to make the communications more efficient. Normally, short distance transmission is used between an MTC device and the gateway.

- *P2P communications between devices*: It refers to the direct communications between MTC devices. Various wireless technologies can be applied to P2P communications.
- *Device-eNB communications*: It means that MTC devices directly access the licensed spectrum for communicating with eNB devices. Hence, there exists competition for radio resources and interference between the MTC device and user equipment (UE). Therefore, how to design a communication architecture to avoid congestion and eNB overloading is a challenging issue.

B. Capillary M2M Communications

Though cellular M2M communications exhibit the advantage of larger coverage and lower network deployment cost in the same manner as public cellular and mobile communication services, existing cellular networks are not specially designed for handling aggregate streams generated by capillary M2M devices.

In capillary M2M networks, the data rates of different kinds of devices may vary significantly. Thus, how to forward packets to the next relay node efficiently is a challenging problem. In this section, we identify several solutions to tackle this problem.

1) MAC protocol for terminals with multiple radio interfaces: In [15], a MAC protocol for a multi-channel, multi-interface wireless mesh network using a hybrid channel assignment scheme is proposed. The control separation techniques in the multi-radio multi-channel MAC are surveyed, and a classification of control separation techniques is provided in [16].

Because smart terminals with multiple radio interfaces provide more options for network access, it becomes possible to extend the previous approach by using nodes with multiple interfaces [17]. A node, possibly mobile, can be equipped with an 802.11 interface as well as an 802.15.4 and/or a 802.15.1 one, and use the one with best connectivity (e.g., it is known that 802.15.1 is most resilient to interference due to the use of frequency hopping spread spectrum (FHSS). However, it becomes necessary to develop an M2M MAC overlay scheme with multiple interfaces which will discover nodes in the vicinity and to connect with them using the interface that provides the best performance.

2) Cognitive gateway to accommodate capillary M2M traffic: Capillary M2M networks are meant to avoid some of the difficulties that arise in a large number of M2M terminals by organizing them in a wireless local area network (WLAN) or wireless personal area network (WPAN) with mesh- or tree-based topology. This network is then connected to the cellular network backhaul. A M2M gateway would thus need to be equipped with both WLAN/WPAN and cellular radio interfaces. An M2M gateway will appear to the M2M facilitator as a client that competes with individual M2M terminals, as well as with other M2M gateways. Also the design of a new M2M gateway to accommodate M2M traffic originating from capillary M2M networks is needed. Due to its higher traffic volume, an M2M gateway will need s higher priority in accessing the wireless medium than individual M2M terminals. Therefore, appropriate provisions should be made in the contention-free access mode for the M2M gateway, which will need to aggregate the data coming from the terminals in its WLAN/WPAN, while keeping track of their IDs so as to allow the commands from the M2M server to reach the proper recipients. The M2M gateway will also need to prioritize the data due to the differences in arrival times and the possibility that some data items (e.g., alarms) need to reach the server faster than others (e.g., ordinary metering data).

3) Gateway connecting capillary and cellular M2M communications: Many M2M applications, such as smart grid, require the exchange of data between capillary and cellular M2M networks effectively and efficiently. These heterogeneous networks have a high requirement on the network convergence and interoperability of devices. However, the frame structures and signalling schemes of capillary and cellular

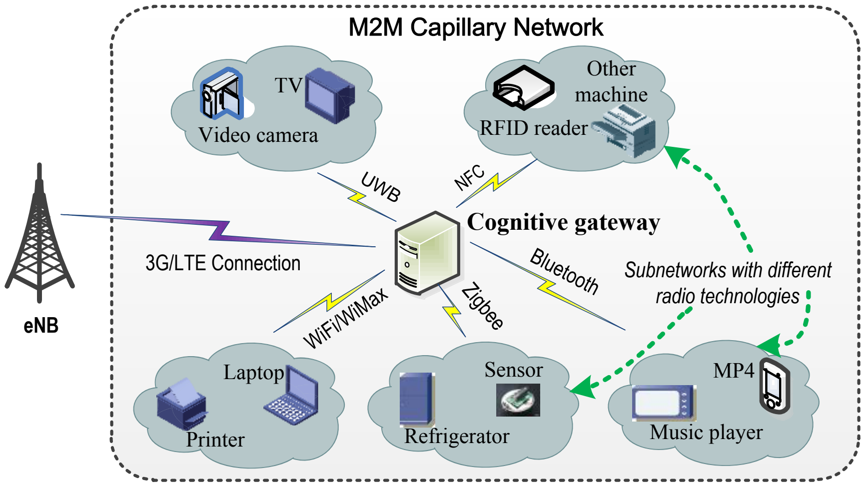

Fig. 3. Gateway connecting capillary and cellular M2M communications.

M2M networks vary considerably, which complicates network design. The cognitive gateway, which can support multiple wireless communication standards, is able to automatically establish communication links among incompatible radios; hence, it is expected to connect capillary and cellular M2M networks seamlessly with flexibility and scalability. Its structure is shown in Fig. 3. This cognitive gateway can provides access control and QoS management, improve the network throughput, extend the convergence, and promote network interoperability. An example for the gateway connecting capillary and cellular M2M communications can be found in [18]. A gateway for the integration of capillary and cellular M2M needs to be carefully designed to ensure the scalability of the system and minimize energy consumption.

4) Sleep management for M2M terminals: Many M2M terminals need sleep management provisions that can be implemented through probabilistic control of the duration of active and inactive (i.e., service and sleep) periods [19]. A node that wishes to power off its radio informs the M2M gateway by a special request packet about its sleeping time pattern. The duration of the sleeping time is a random variable (e.g., with geometric probability distribution), the average of which is calculated by taking into account frame collisions in the M2M gateway domain, and the required information throughput from each metering device that needs to reach the M2M gateway. Each sleeping node wakes up shortly for each beacon and listens to the beacon frame. The M2M gateway advertises the list of MAC addresses of M2M nodes for which it has queued downlink frames (command/configuration) in each beacon frame. If a sleeping node hears its own MAC address, then it wakes up and transmits a data request frame, after which the M2M gateway will transmit a downlink frame.

III. Radio Technologies

In this section, we provide a comparative study of the existing radio technologies for home M2M networks, including Bluetooth, IEEE 802.15.4 and Zigbee, ultra-wideband (UWB), HomeRF, and IEEE 802.15.6, all of which are the leading contenders in recent home network markets, in addition to emerging radio technologies, such as Visible Light Communication (VLC) and 60GHz wireless transmissions. In Table I, a qualitative comparison of short-range wireless technologies is given. Recently, many networking companies have started home networking projects employing these short-range wireless technologies [20].

A. Ultra-low Power and Short Range Radio Technologies

The smart devices in capillary M2M communications generally provide low transmission rates, low or no mobility support, and reduced energy consumption. In this section, Bluetooth and ZigBee are reviewed. Although Bluetooth has good performance in terms of energy consumption, it has long latency problems in the presence of a large number of deployments. On the other hand, ZigBee can ensure low power and long life time, and hence it is typically used in capillary M2M networks.

1) Bluetooth: Designed as a short range wireless communication standard, Bluetooth is widely used for connecting a variety of personal devices supporting data and voice applications. As a WPAN enabler, two or more (up to eight) Bluetooth devices form a short-range network called piconet, where devices are synchronized to a common clock and hopping sequence in the same physical channel. The piconet coordinator is referred as the master, while all other synchronized devices forming a star topology with the master are referred as slaves. Bluetooth devices operate in the license-free 2.4 GHz Industrial, Scientific and Medical (ISM) band, utilizing frequency hopping among 79 channels each 1 MHz wide at a nominal rate of 1,600 hops/sec to reduce interference.

2) IEEE 802.15.4 and Zigbee: IEEE 802.15.4 specifics the PHY and MAC layer standards of Zigbee and supports very low power consumption, making it a cost-effective technology. The Zigbee Alliance has been working on solutions for smart energy, home automation, building automation and industrial automation. There are two operation modes defined for IEEE 802.15.4 multiple-access schemes, i.e., beacon enabled and non-beacon enabled modes. In [21], it is argued that 802.15.4 can suffer from interference with WLAN transmissions. A critical concern with 802.15.4 is that the maximum supported data rate is only 250 kbps which may be insufficient to

TABLE I
THE QUALITATIVE COMPARISON OF SHORT-RANGE WIRELESS TECHNOLOGIES

Standards	Sub-networks	Rate	Energy-constrained	Typical applications	Data type	Typical terminals
Zigbee	Smart grid sub-network	Low	Yes	Sensors, monitoring	Sensors, monitoring	Smart meter
Bluetooth	Home office and entertainment sub-networks	Low	Yes	Music sharing	Voice, low-rate data, music	Smart phone, PDA
UWB	Home office and entertainment sub-networks	High	No	Video, files sharing	Video, high-rate data, files	Camcorders, video projectors
IEEE 802.15.6	Body area sub-network	Low	Yes	Healthcare	Biomedical data	Intelligent sphygmo-manometer
WiFi	Home office and entertainment sub-networks	High	No	Water metering	VoIP, data, video	Smart camera, laptop
Femtocell	Low-power cellular base station	High	No	Cellular phones	VoIP, data, video	Home Node B
HomeRF	Home entertainment and convenience sub-networks	High	No	Voice services	Voice, data	Videophone

support applications that generate heavier data traffic. For these reasons, the IEEE 802.15.6 task group was created in an effort to find solutions to power and data rate limitations for healthcare applications.

B. Broadband Radio Technologies

Compared to low bit-rate and low power radio technologies, broadband radio technologies such as UWB, WiFi, and HomeRF, provide much higher throughput but with the shortcoming of high power consumption.

1) HomeRF: HomeRF uses FHSS in the 2.4 GHz frequency band and can achieve a maximum throughput of 10 Mbit/s. Available HomeRF WLANs support a data rate of 1.6 Mbit/s: a relatively low rate compared to WiFi WLANs. For an example, IEEE 802.11b WLANs have a maximum data rate of 11 Mbit/s, whereas IEEE 802.11n may reach a maximum data rate of 600 Mbit/s. Currently, several working groups are focusing their efforts on advancing wireless networking technology to further improve the IEEE 802.11, 802.16, and Bluetooth technologies.

2) UWB: According to the Federal Communications Commission (FCC), any radio technology having a transmission bandwidth exceeding the lesser of 500 MHz or 20% of the arithmetic center frequency may be considered as UWB. FCC regulations allow license-free use of UWB in the 3.1-10.6 GHz band with relatively low power spectral density emissions. This leads to the suitability of UWB applications in short-range and indoor environments, and in environments sensitive to RF emissions (e.g., in a hospital). Commercial products based on UWB provide extremely high data rates at up to 480 Mbps, enabling short-range wireless multimedia applications, such as wireless monitors, and wireless digital audio and video players.

C. Emerging Radio Technologies

1) IEEE 802.15.6: IEEE 802.15.6 defines three PHY standards, i.e., narrowband (NB), UWB, and human body communications (HBC). The selection of each PHY depends on the different application requirements. The WBAN applications targeted by IEEE 802.15.6 standard are usually divided into medical and non-medical applications.

- Medical applications: They include collecting vital signs of a patient continuously and forwarding it to a remote monitoring station for further analysis. The obtained data can be subsequently analyzed to assess the risk of experiencing a medical emergency (e.g., a myocardial infarction), or to assess the current state of various other diseases (e.g., cancer, asthma, and gastrointestinal or neurological disorders). A WBAN can also be used to help people with disabilities. For example, retina prosthesis chips can be implanted in the human eye to see at an adequate level [23].
- Non-medical applications: Typical examples include notification of forgotten belongings, file transfer, gaming, and social networking applications. In gaming, WBAN sensors can estimate motion patterns of different parts of the body and subsequently correlate it with a game character's motion, e.g., a moving football/soccer player, or for capturing the intensity of a ball in table tennis. Also, using WBAN in social networking schemes would allow people to exchange digital profile or business card only by shaking hands.

In the coming years, WBAN devices will likely have chips implementing the IEEE 802.15.6 standard. In our view, IEEE 802.15.6 technology is better positioned to improve the QoS of WBA-SN links.

2) 60GHz transmission: Recently, the use of 60 GHz spectrum is proposed to tackle problems caused by data-intensive applications. The 60GHz spectrum refers to a continuous block of 7GHz spectrum typically between frequencies of 57∼64 GHz in North America and Korea, and 59∼66 GHz in Europe and Japan. In the USA, this frequency band was set aside by the FCC for use by the general public in 2001 [24]. Similar to the ISM band, the use of this frequency band is license-free for devices satisfying a general set of transmission requirements. The frequency band is located in the millimeter wave section of the electromagnetic spectrum. A major challenge of this band is severe attenuation due to atmospheric conditions [25] and higher loss within building environment. This characteristic makes the 60GHz frequency band not suitable for long range communications, but it could be greatly exploited for short range communications.

3) Visible light communications: In addition to the aforementioned radio technologies, VLC is another emerging technology that can achieve high data rates for short-range communications while minimizing electromagnetic interference. Due to the fast, safe, and isolation from the radio frequency spectrum, VLC may become a promising candidate for the connections between gateways and sub-networks.

IV. Home M2M Networks Architecture

Different from traditional wireless communications, M2M communications focus on data acquisition and data exchange among smart devices to enable multiple applications without human intervention. While some devices can interact with the application directly, others have to be mediated by another device, usually a gateway. The gateway plays an important role in M2M communications by allocating bandwidth, minimizing interference, guaranteeing QoS and aggregating the upstream data flow to prevent the upper layers becoming overwhelmed. ETSI has introduced the term M2M area network in the ETSI TS 102 690 Technical Specification [TS 102 690], which provides PHY and MAC layer connectivity between smart devices. In an M2M area network, M2M devices with limited computation capability can have access to a public network via a router or a gateway. A hierarchical architecture for M2M networks was proposed in [26]. The hierarchical deployment can provide reliable and efficient interaction between multiple communication protocols when there are limitations on cost, size and power. The hierarchical architecture can also be adopted into a smart grid, in which different communication technologies are used at different stages to provide an optimum throughput and energy consumption.

As mentioned before, the past few years have seen increasing research interest in the area of home M2M networks. For instance, in [6], [27], a robust architecture for home M2M network was proposed. Their network architecture can be broken down into three complementary M2M structures: home networking, healthcare, and home energy management. The main features and promising applications in each sub-network are identified. In particular, the home M2M network is essentially a heterogeneous network that has a backbone network and multiple sub-networks. In the backbone network, there is an intelligent home gateway that manages the entire network and connects the home network to the outside world (e.g., Internet). The network-related functionalities are implemented in the home gateway, including access control, multimedia encoding/format conversion, security management, and QoS management. Each sub-network operating in a self-organized manner may be specially designed for an on-demand application, and has a sub-gateway as an endpoint that connects the sub-network to the home gateway and the backbone network. Both home gateway and sub-gateway are logical entities, and their functionalities can be physically implemented in a single device. Following this framework, we also propose a novel and improved home M2M network architecture that incorporates the benefits of inter-cloud computing, as explained in the following sub-sections. The optimal distribution of devices and cloud intelligence can provide another way to solve the problem of seamless connectivity for M2M communications.

In Fig. 1, the new architecture is comprised of five types of functional components, namely M2M devices, M2M area networks, M2M gateways, M2M communication networks, and M2M services supporting infrastructure. In the component of M2M services supporting infrastructure, cloud computing services and data centers are included to enhance the system performance.

A. Home Gateway

Besides supporting well-known wireless network technologies employed in cellular networks (e.g., CDMA, GSM, iDEN and TDMA), heterogeneous home M2M networks also include many types of short-range wireless technologies (e.g., WiFi, UWB and Zigbee). Therefore, implementing a flexible service gateway becomes important in such a heterogeneous network [28]. To autonomously adapt to different radio technologies, the home gateway shall have self-configuration or advanced cognition capabilities.The tasks of the home gateway may be classified in three tiers: network interconnection, network management and application management. In terms of network interconnection, the home gateway connects to the heterogeneous networks in the M2M home network using IP networking. In the IP layer network management, the home gateway needs to seamlessly deal with all network-related aspects, in particular:

- Devices and resource management: commonly realized by adhering to the UPnP and Digital Living Network Alliance (DLNA) standards [29], [30].
- QoS management: This includes admission control, rate control, and other QoS-aware operations.
- Security management: It protects the home M2M network from possible external attacks, by means of trusted access control and networked encryption techniques.

The application management layer is responsible for breaking down the applications into separate M2M communications elements, discerning the network settings, and invoking the M2M transmissions. This includes:

- Context management: For acquiring and merging any contextual information, and adapting the services to diverse contexts. Before an M2M communication is performed, analysis is needed to identify the context of the current communication session (e.g., application type, network status, and device status).
- Event management: It triggers the corresponding signaling scheme in case of routine or emergent events where the home gateway acts as an agent that launches and coordinates the M2M communications session.
- Data format conversion: It translates the media format in the source node into a format amenable for decoding at the destination node when data (e.g., a video file) is shared among heterogeneous devices.

B. Backbone Network

The communication networks between M2M gateways and applications can be further broken down into access, transport, and core networks. Examples for these include, but are not limited to, xDSL, WLAN, satellite, GSM, GPRS, CDMA2000, WiMAX, LTE, and LTE Multi-mode. In the network domain, the efficiency of wired networks (e.g., xDLS, and PLC) and the ubiquity of wireless networks (e.g., 3G cellular, WiMAX, and WiFi) provide cost-effective and reliable channels for transmitting the sensor data packets from the M2M area domain to the service and application domain.

C. Sub-networks

In home M2M architectures, small networks (e.g., WBAN, Zigbee and Bluetooth) linking data collectors of the same type are called sub-networks. Each sub-network can contain an aggregator that in turn connects to the Internet gateways (edge routers). For example, possible aggregators include a cellular phone for WBAN and power meter for the smart grid sub-network [31]. Each sub-network uses a network technology appropriate for the type of information to be collected and distributed. The network technology employed determines the sub-network architecture. Three types of sub-networks (fully distributed, client-server and cooperative) are described as follows:

- Fully distributed network: All nodes (e.g., various computers on a home WiFi network) are connected as peers and may share data amongst themselves. One of the nodes (e.g., a WiFi-enabled wireless router) acts as a super-peer that has the ability to connect through some gateway (e.g., a router's ADSL connection) to the Internet.
- Client-server network: Here, all clients only communicate with the server. An example would be portable media players connecting to a media server. The server then relays appropriate information to other clients (e.g., wireless speakers), and has the ability to connect to the Internet through some gateway (e.g., a home router).
- Cooperative network: Though it is not strictly a sub-network, none of the nodes (e.g., WBAN sensors) communicate directly with each other as is the case on a sub-network, but instead via the gateway.

1) Wireless Body Area Sub-networks: WBA-SNs are healthcare-oriented M2M sub-networks within home networks, which are used to monitor people's health and inform those being monitored, as well as possibly their doctors of any abnormal health conditions that might occur. Data collectors in a WBA-SN are body sensors that monitor various vital signs, such as blood pressure, temperature, heart rate, and cholesterol. Body sensors may be connected to an on-person gateway, such as a smart phone, which also acts as the aggregator for all data collectors. Sensors send data to the smart phone, which processes the data and sends the results over the Internet to health monitoring servers. This M2M paradigm for healthcare allows for the health of an entire population to be monitored in real time. Ambulances can be immediately dispatched to accident scenes and patients can be monitored at their homes just as effectively as in hospitals; e.g., a patient's doctor can also immediately be informed during an emergency. Moreover, healthcare M2M can help track the progression of a virus outbreak by monitoring specific symptoms in the population. Patients that may have been infected during an epidemic outbreak can be notified to seek medical care.

2) Smart Grid Sub-network: Based on the architecture proposed in Fig. 4, the typical smart grid communication architecture for home energy management is shown in Fig. 3 [11]. Power is delivered from the source to end users through two components, i.e., the transmission substation located near the power plant, and a number of distribution substations. The smart grid communication architecture is divided into a number of heterogeneous networks according to the real-life facilities of a city or metropolitan area. Generally speaking, a city may consist of many neighborhoods, each of which has many buildings, and each building may have a number of apartments. Therefore, the communication architecture is derived from this real-life layout of a metropolitan area.

Concretely, the communication architecture for the lower distribution network can be divided into a number of hierarchical networks, including a neighborhood area network (NAN), a building area network or building local area network (BLAN), and a home area network (HAN). In this article, the HAN refers to the SG-SN (e.g., a Zigbee sub-network) that autonomously optimizes and manages energy consumption of any applicable appliance that runs on electricity from the grid. The main features of smart grid communication architecture are outlined as follows:

- Each NAN is comprised of a number of BLANs. On the other hand, a building may contain a number of apartments. In Fig. 4, the apartments are shown to have their respective LANs, each of which is referred to as a HAN.
- Smart meters are the building blocks of an advanced metering infrastructure enabling automated, two-way communications between the device and the utility provider. Smart meters are equipped with two interfaces (power reading and communication gateway interfaces). The smart meters used in NANs, BLANs, and HANs are referred to as gateways for each respective network type. In general, the functionalities of HAN gateways are realized and included in a home gateway.
- In addition, based on the existing standards of smart grid, IP-based communications networking is preferred, which permits virtually effortless interconnections with HAN, BLAN and NAN.

3) Home Entertainment and Convenience Sub-networks: Besides WBA-SN and SG-SN, home M2M networks also include HEC-SN, such as WiFi sub-networks (laptop, printer, and media server), UWB sub-networks (HDTV, and camcorder) and Bluetooth sub-networks (music center, and portable audio player), as shown in Fig. 2. These sub-networks facilitate media distribution by means of the corresponding sub-networks (WiFi, Bluetooth, and UWB), and media consumption (HDTV, smart phones, tablet computers, and desktop computers).

D. Open Issues

1) Gateway connecting Non-IP based component and IP based component: An efficient and secure way of controlling an enormous number of M2M devices remotely is to interconnect M2M devices with IP-based networks. The interoperability among M2M devices can be achieved using multiprotocol gateway, as shown in Fig. 5. The gateways can bridge telecommunication networks, such as Wide Area Network (WAN), LAN and Metropolitan Area Networks (MAN) with local connections efficiently and provide scalable, secure, and energy efficient capabilities. Although there are some conventional schemes to connect Non-IP based components with external IP based networks, they are still insufficient to achieve reliable, robust and short-delay transmissions. The traditional

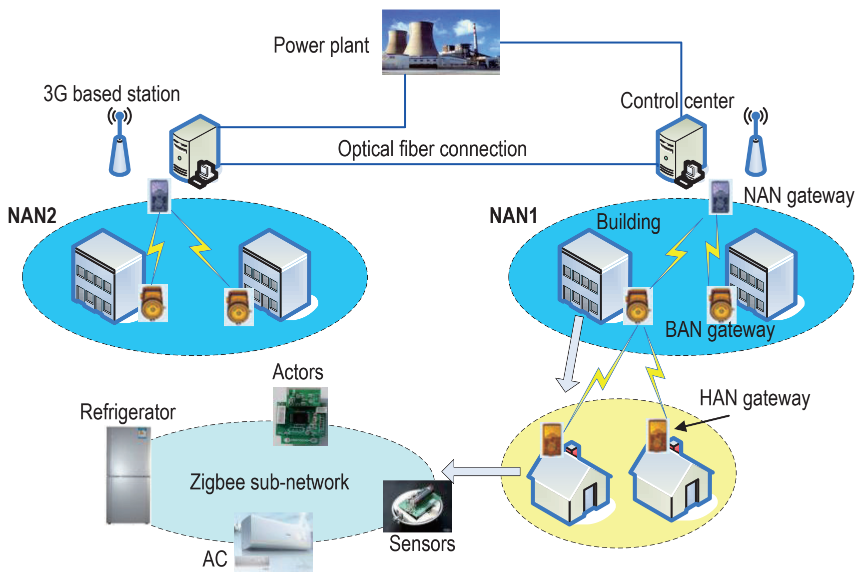

Fig. 4. Architecture of smart grid for home energy management.

proxy-type gateway cannot achieve direct communication, because native protocols are still used in internal networks. Another traditional solution is to assign an IP address to every internal node, but data fragmentation is needed in the gateway due to diverse constraints on packets length, especially when 6LoWPAN standards are used. Beyond the existing schemes, much research is needed on M2M gateway to achieve energy and cost efficient connections between internal nodes and external networks.

2) Optimal design of heterogeneous network: In M2M communications, data need to be exchanged seamlessly among different networks such as WSNs, WPANs and cellular networks. Heterogeneity poses specific challenges that need to be addressed. The convergence of heterogeneous networks calls for data acquisition and exchange among networks efficiently and effectively. At present, Internet is used as the major enabler for the exchange of data. For instance, data collected by wireless sensor nodes cannot be passed to cellular terminals directly, and it has to go through an Internet via the sink of WSNs. This will decrease the system efficiency significantly. In addition, the current network convergence approaches mainly rely on the hierarchical signaling exchange between different networks. Future heterogeneous networks need to converge toward a flat network architecture so that the signaling overhead can be reduced. Another issue is that the access control schemes between different networks are normally different. This difference requires coordination of networks. For instance, the random access control scheme is used in cellular network whereas scheduling is usually used in WSNs. The difference calls for jointly optimized protocol stack design for time coordination among heterogeneous networks.

3) Cloud-assisted Home M2M Networks: With the development of WSNs, as well as low-power embedded systems and cloud computing, WSN-assisted and cloud-assisted M2M technologies are gradually maturing to support typical M2M applications. The home M2M networks can be upgraded by the emerging cloud computing environment. The scalable and elastic cloud-assisted framework shifts the physical location of computation and storage into the network to reduce operational and maintenance costs.

In recent years, cloud computing has provided novel perspectives in cloud-assisted technologies for distinct purposes [32]. A cloud-assisted communication system may include multiple cloud systems operating with different policies to share resources, so that end-to-end QoS to users can be maintained even in the event of large fluctuations in computing load that cannot be handled by a single cloud system [33]. It is known that the previous architectures for home M2M networks have not taken into account the cloud-assisted capability. In our view, it is an important factor for home M2M networks to achieve functionality completeness. Therefore, compared to the previous survey literatures, we propose a cloud-assisted layer for the advancement of the M2M architecture, as shown in Fig. 6.

The information delivered from different domains (e.g., smart grid, and healthcare) is difficult to understand and handle for the computer in the cloud service. With the support of a semantic model, the ontology-based approach can be used to implement information interaction and sharing in cloud-assisted home M2M networks. As shown in Fig. 6, separate cloud systems can interoperate, with an additional root cloud providing different services for healthcare, energy management, convenience and entertainment, etc. The service gateway implements various technologies, protocols, standards and services to diversify communications capabilities and integrate devices. Currently, most service gateways implement well-defined software modes and systems, such as Jini, UPnP and OSGi [34]–[36].

In addition, the communication of heterogeneous objects in home M2M networks is a major problem because different objects provide different information in different formats for different purposes. The semantic web technologies and models may also be used to help solve this problem.The semantic

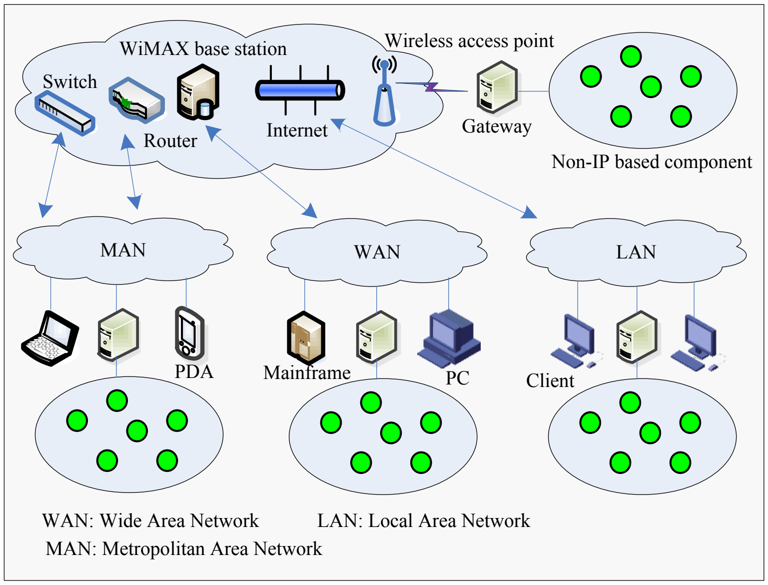

Fig. 5. Gateway connecting Non-IP based component and IP based component.

web technologies can be applied to facilitate communication in home M2M networks.

V. Methodologies for QoS Improvement

The QoS of multiple sub-networks depends heavily on the system architecture and on the type of short-range wireless technologies (e.g., Bluetooth, Zigbee, WiFi, and UWB) being employed.

It is worth noting that most M2M terminals operate on battery power, making energy efficiency a fundamental issue in such systems. In addition, it is reasonable to assume that certain M2M networks are expected to operate unattended over extended periods of time. Also, advanced security mechanisms will be necessary, especially in what relates to device authentication and the ability to disable compromised or misbehaving terminals as quickly as possible upon detection.

In this section, we will review some potential methodologies to improve QoS, including energy-efficient MAC protocols, MAC layer design for terminals with multiple radio interfaces, cross-layer joint design, cognitive gateways to accommodate capillary M2M traffic, and security mechanisms for home M2M networks.

A. Energy-Efficient MAC Protocols

In M2M communications, the limited onboard computing and information/energy storage capabilities of typical smart devices are hampering their ability to support the increasingly sophisticated applications demanded by users. Programs and algorithms' computational complexity influences the rate of battery depletion, and therefore the potential needs to replace many batteries in M2M devices. Consequently, reducing power consumption becomes a major challenge in M2M communications. This section introduces various energy-efficient MAC protocols that would be implemented in M2M system to save energy.

1) Low power MAC protocols for generic-use WSNs: To address the critical issue of extending sensor life-time, several low power MAC protocols have been reviewed for generic-use WSNs [37]. In these protocols, the radio is turned on and off periodically to save energy. S-MAC [38], TRAMA, and T-MAC [39] synchronize their transmission schedules and listening periods to maximize throughput, while reducing energy by turning off radios during much longer sleeping periods. On the other hand, the low-power listening (LPL) approaches, such as WiseMAC [40] and B-MAC [41], use channel polling to check if a node needs to wake up for data transmission/reception, thus reducing the necessity of idle listening. SCP-MAC [42] uses scheduled channel polling to synchronize polling times of all neighbors, and eliminates long preambles in LPL for all transmissions, thereby enabling ultra-low duty cycles.

2) Energy-Efficient MAC for WBANs: In recent years, several MAC protocols have also been proposed specifically for WBANs. In [43], a low-energy protocol dubbed CICADA is presented for wireless, multi-hop, mobile WBANs. CICADA has been developed to support high-traffic BANs where delays should be low; i.e., all sensors send data often instead of buffering them locally. WBAN-MAC [44] is a dedicated ultra-low-power MAC protocol designed for WBANs with star topology. WBAN-MAC is designed to be an adaptive MAC protocol, and is compatible with IEEE 802.15.4, as well as accommodating unique requirements of the body sensors in WBANs. By exploiting feedback information from distributed sensors in the network, WBAN-MAC adjusts protocol parameters dynamically to achieve the best energy conservation on energy-critical sensors. H-MAC [45], a novel TDMA-based MAC protocol designed for body sensor networks, aims to improve energy efficiency by exploiting heartbeat rhythm information to perform time synchronization. Because the heartbeat rhythm is an intrinsic human body feature, biosensors in a WBAN can detect the heartbeat rhythm from their own sensory data by sampling waveform peaks. By using it as

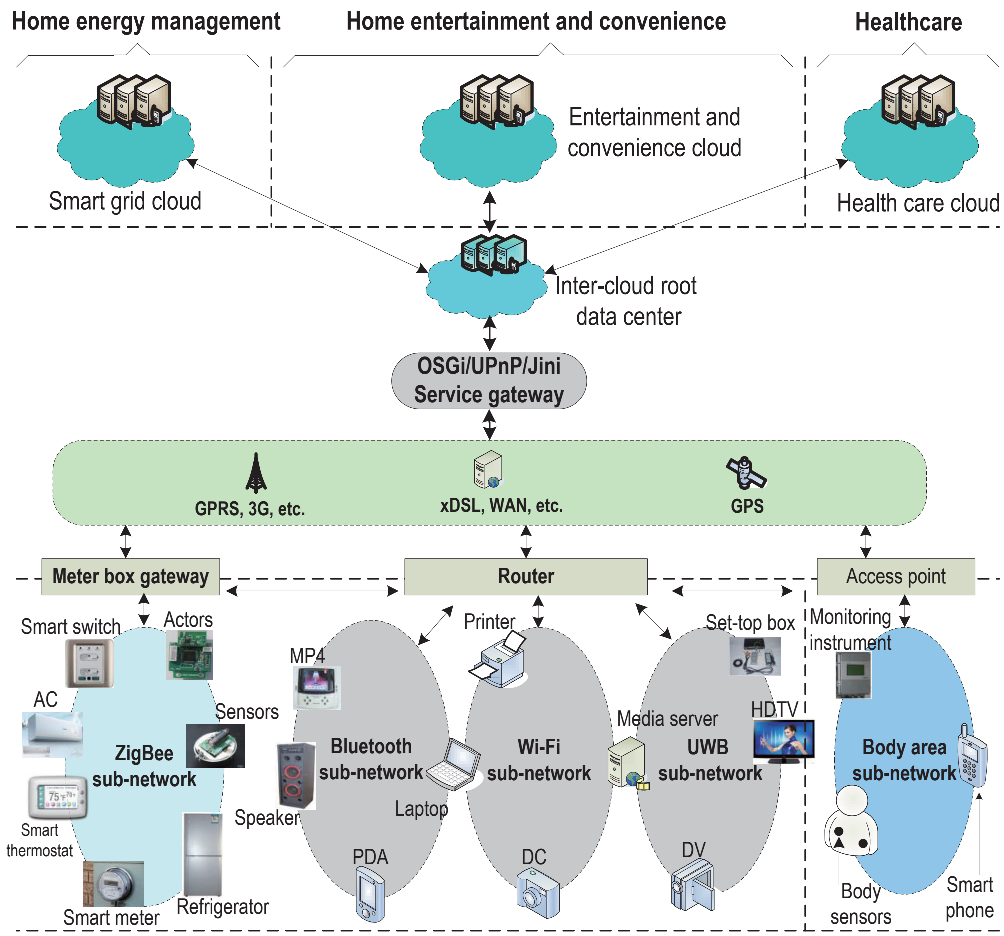

Fig. 6. Architecture of home M2M networks with cloud-assisted capability.

a beacon, biosensors can achieve time synchronization without having to turn on their radios to receive periodic timing information from a central controller, so that synchronization energy cost can be avoided and the network lifetime can be prolonged.

3) MM-QoS: Multi-Level MAC-Layer QoS Design: In [46], a novel multiple level-based QoS design at MAC layer (MM-QoS) was proposed for WBANs. In a typical scenario in a hospital where sensory data from different patients are transmitted over limited bandwidth, the transmission priority should be differentiated to provide situation-aware healthcare services. MM-QoS considers the following three levels of priorities for QoS design: (1) priority of user (PoU), indicates that different users have different priorities. For example, the sensory data of seriously ill patients should have higher priority for faster delivery than those of the patients with chronic disease; (2) priority of data (PoD), means that heterogeneous sensory data collected from various sensor nodes (belonging to one user) should have different priorities. For example, electrocardiogram (ECG) data should be sent prior to temperature data; (3) priority over time (PoT), represents the priority of sensory data collected by the same sensor node may vary over time. For example, the blood sugar data are usually given lower priority; however, if the blood sugar is too high or too low, a high priority should be given.

B. Throughput Enhancement by Addressing Co-channel Interference

QoS performance can degrade significantly upon sharing time and frequency allocations in H2H and M2M communications. The increasing number of M2M devices and the limited amount of shared radio channels call for efficient medium management schemes. A promising solution may lie in cognitive radio technology for reusing the licensed spectrum despite unavoidable interference issues. Multi-path fading, path loss and shadowing phenomena in radio channels further decrease the link reliability. This problem is exacerbated if it is not taken into account during MAC and routing protocol design, which remain a challenge in M2M communications.

Fig. 7 shows a typical example of co-channel interference when 802.15.4 and WiFi coexist. Since WiFi devices transmit at a higher power, 802.15.4/Zigbee networks are forced to use channels with little or no interference, which reduces the number of reasonably available channels to at most four, among which only channel 26 is entirely free from WiFi interference [47]. As a result, the bandwidth is insufficient for M2M traffic in heavily populated business and residential areas. Moreover, if end-to-end reliability is needed, the retransmission rate will increase, resulting in low data rates and vastly increased delays. The communication quality can be

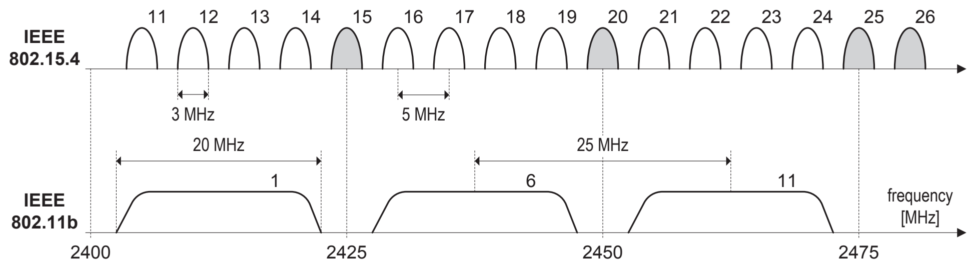

Fig. 7. Spectrum usage in IEEE 802.15.4 and IEEE 802.11b.

further degraded by multipath fading. To alleviate the above problems, spectral holes in ISM band can be exploited as well as time holes, i.e., inactive periods in the WiFi channels. The MAC protocol would require sensor nodes that can advertise free frequency channels and statistics of time holes in busy channels. However, time-hole scheduling is by default less reliable and should be used only in cases when the bandwidth of free channels is not sufficient.

C. Supporting Large-scale Terminal Devices by Group Control

In cellular M2M networks, a massive number of M2M devices with diverse QoS requirements can be supported by an LTE-Advanced station. However, the current frame structure of LTE is designed to support multimedia transmissions with a large amount of data and to achieve a high throughput, which is not well suited for M2M communications involving a small amount of data per flow. Consequently, allocating LTE radio resources for M2M communications may become problematic. Group control has been proposed to solve the massive access and radio resource allocation for MTC devices in LTE-Advanced network without the need to implement sophisticated transmission schemes [48]. However, how to achieve optimal grouping in terms of energy and cost efficiency still needs to be further explored.

D. QoS Enhancement by cross-Layer Joint Design

The cross-layer joint admission and rate control strategy enables QoS resilience of multimedia services as outlined in the following schemes:

- Joint design framework: In [6], a joint rate and admission control (JARC) scheme for QoS provision was proposed for wireless home networks. The key feature of JARC is that it supports QoS simultaneously at both the application and network layers. This QoS management framework has two main components: 1) a rate control entity (RCE) responsible for user-oriented bandwidth configuration, and 2) an admission control entity (ACE) that controls the number of sessions in the network to guarantee the QoS of current multimedia services at the network level.
- Cross-layer routing protocol for capillary M2M: Routing in capillary M2M is conducted from the metering node to M2M gateway towards cellular network or Internet. Since the availability of channels for MAC depends on the current interference and sleeping status of the uplink node, the routing algorithm needs to cooperate with the MAC protocol in order to get information about link availability (time slot/frequency channel). Assuming that links are always available, nodes?sleeping schedules can be customized in order to maintain activity of the network following a spanning tree approach. However under sporadic availability of links in frequency and time, network connectivity cannot be guaranteed, and as a consequence node access delay can have large variations.

E. Security Mechanisms for Home M2M Networks

Advanced security mechanisms will be necessary, especially for terminal authentication, and to detect compromised or misbehaving terminals and isolate them from the network as quickly as possible, in addition to the utmost protection of user privacy. Research in security for M2M communications is still in its infancy.

In this sense, security mainly targets the identification of potential attacks, threats, and vulnerabilities of M2M communications systems. In general, attacks in M2M systems can be classified as either passive or active. A passive attack does not disrupt the operations of an M2M communications system, but it attempts to learn information about M2M communications by eavesdropping. Although difficult to detect, a passive attack causes less damage if well-designed confidentiality mechanisms are adopted. In contrast, an active attack is easy to detect, but the damages can be significant because it attempts to deliberately modify sensory and decision data in the M2M and network domains, or even gain authentication to access the back-end server in the application domain. In addition, active attacks can be further divided into external and internal attacks. An external attack is launched by attackers who are not equipped with key materials in an M2M communications system, while an internal attack is one from compromised M2M nodes that hold the key data. Compared to the external attack, the internal attack may cause more damage to the overall M2M communications system being affected. In [6], two mechanisms adapted to the M2M security domain are introduced, including early detection of a compromised node with bandwidth-efficient cooperative authentication to filter false data.

Most currently accepted security solutions are based on the authentication, authorization and accounting (AAA) architecture [49], which is not directly applicable to M2M application scenarios. The reason for this is that many M2M terminals operate under power constraints, which means that full-fledged security solutions such as X.805 [50] cannot be supported. Instead, low computational complexity algorithms and techniques should be used. We assume that the cellular core networks and the M2M servers, which are owned and operated by the mobile network operators and M2M service providers, respectively, are secure. What remains to be addressed is the security of other components of the overall M2M system: M2M terminals, communications between the terminals and the M2M gateway, and M2M data, including subscriber information.

VI. A Taxonomy of Home Networking Projects

Table 2 summarizes different applications of home M2M networks. As we can see from this table, the existing literature considers only a subset of smart home applications (e.g., home energy management or healthcare). With the convergence of diverse network types and enhancements in smart terminal technologies, novel home M2M network architectures are constantly emerging to support more functions and better QoS. Moreover, cloud computing technology will promote the widespread applications of home M2M networks. We infer that the tendency in this area is to integrate more smart terminals and provide more convenience and entertainment, as well as more intelligent management with or without limited human intervention. Compared to previous work listed in Table 2, we consider more comprehensive applications for supporting convenience and entertainment, energy management, and healthcare needs.

A. Remote Health/Fitness Monitoring

Previous research projects have yielded implantable or wearable devices for patients, the disabled, aging people, pregnant women, and neonates. The following is an overview of the most relevant projects proposed in recent years in the field of healthcare. With the support of mobile cloud computing (MCC), WBA-SN can be significantly enhanced for massive deployment of pervasive healthcare applications, which is a new trend in remote health or fitness monitoring.

Terminals for Home Medical Care: As data sources of the WBA-SN system, body sensors are used for collecting all kinds of vital signals of a user or patient. Based on these body signals, an accurate diagnosis can be obtained to give the patient correct and timely treatments. Here, we briefly introduce some commercially available sensor devices for WBA-SN.

- *Accelerometer/Gyroscope*: Wearable devices that employ an accelerometer may be used to recognize and monitor body posture. The accelerometer-based posture monitoring sensors are strategically placed around the human body to measure vibrations, as well as acceleration due to the Earth's gravity. A gyroscope sensor can be used together with accelerometers to enhance the functionality of inertial motion sensors.
- *Wireless pulse oximeter sensor*: This device measures the oxygen saturation using a non-invasive probe attached a person's finger, earlobe, or toe.
- *Electromyogram (EMG) sensor*: The EMG sensor serves as a WBA-SN input to measure electrical signals produced by muscles during contractions or at rest.
- *Electroencephalogram (EEG) sensor*: It measures the electrical activity within the brain by attaching small electrodes to the human's scalp at multiple locations. With the aid of home M2M networks, EEG data of (potential) patients can be transmitted to off-site doctors for diagnosis and further processing.
- *Environmental sensors and other sensors*: Monitoring environmental parameters is also essential for patient's healthcare, enabling comfortable home environment in terms of temperature, humidity, CO_2, etc [51].
  In addition, many other sensors, such as security system sensors, occupancy and motion sensors, power and electrical sensors, and infrared sensors, can be placed in home M2M networks in order to facilitate all kinds of convenience and remote monitoring services.

Projects in Home Healthcare: In this subsection, we introduce three representative projects in home healthcare as follows:

- Code Blue [52]: In this project, body sensors are individually connected to Zigbee-enabled radio transmitters, which communicate with access points (APs) directly. However, this approach stipulates that multiple APs be attached to a wall. Without centralized control, this WBA-SN communication scheme forms a mesh structure where patients' sensor devices publish all relevant information. Due to the ad-hoc architecture and the self-organizing capability of the system, connecting various wireless devices becomes straightforward. It also has a flexible security model, in addition to the ability to prioritize the critical messages.
- AID-N [53]: This scheme targets application aimed at dealing with mass casualty incidents. Though AID-N utilizes a similar mesh structure for its WBA-SN communication as in CodeBlue, its application scenario is different. Instead of deploying APs on the wall, wireless repeaters are located along a predefined emergency route. When APs flash green lights, patients and medical staff can recognize the correct emergency route. Due to its application as a medical emergency response system, a GPS module is included in a personal server (PS) to provide an outdoor location service.
- CareNet [54]: This project develops an integrated wireless environment used for remote healthcare systems. It offers features such as high reliability and performance, scalability, security and integration with web-based portal systems. High reliability is achieved using a two-tiered architecture. The portal allows caregivers to efficiently access the sensor network data through a unified medical record system.

Cloud-Enabled WBA-SN for Home Healthcare: The efficient management of the large number of monitored data collected from various WBA-SN is an important issue for its large scale adoption in pervasive healthcare services. MCC provides a flexible stack of massive computing, storage and software services in a scalable and virtualized manner at low cost. The integration of WBA-SN and MCC can facilitate the development of cost-effective, scalable and data driven pervasive healthcare systems. In [55], a cloud-enabled WBA-

TABLE II
HOME M2M NETWORKS SUPPORTING DIFFERENT APPLICATIONS

Applications	Typical references	Sub-networks	Standards
Home energy management	[10] [11]	SG-SN (e.g., Zigbee)	Zigbee, etc.
Healthcare	[51]	WBA-SN (e.g., Zigbee)	IEEE 802.15.6, Zigbee, etc.
Convenience and entertainment	[52]	HEC-SN (e.g., IEEE 802.15.11)	WiFi, UWB, etc.
All of the above	[2] [6] [26]	Zigbee sub-network, WiFi sub-network, Bluetooth sub-network, etc.	Zigbee, WiFi, UWB, Bluetooth, etc.

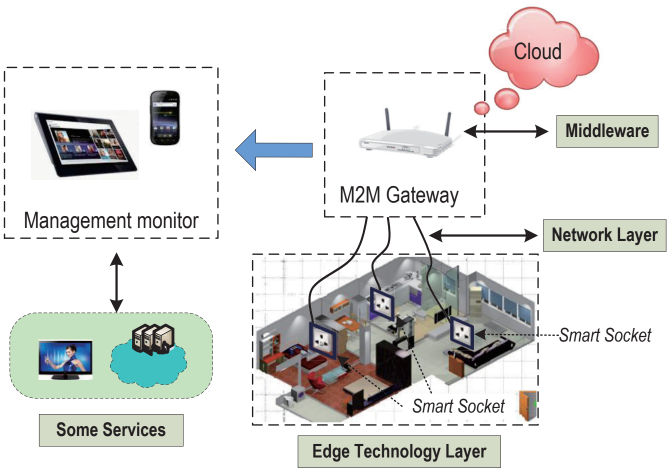

Fig. 8. Architecture of home energy management system.

SN architecture and its applications are proposed. This literature focuses on the methodologies for transmitting vital sign data to the cloud by using energy-efficient routing, cloud resource allocation, semantic interactions, and data security mechanisms. However, the integration of WBA-SN and MCC will introduce many issues and challenges such as medical data mining.

B. Home Energy Management System

Smart grids enable the next-generation electrical power grid with the capability of adaptive and optimal power generation, distribution, and consumption. HEMS is a part of a smart grid on the consumption side to collect data from home appliances using smart meters. The representative examples for HEMS are as follows:

Wiser HEMS [56]: Wiser HEMS is a comprehensive energy management solution for utilities and consumers that allows homeowners to reduce or shift energy use during peak time to improve grid efficiency. The system helps provide visibility into household energy consumption and costs, and allows consumers to actively manage and reduce energy use to improve the efficiency of their home. The system also helps utilities to increase grid efficiency, reduce peak usage costs and maximize power reliability, resulting in improved service to consumers and a reduced need for expensive infrastructure upgrades. The overall view of system is shown in Fig. 8.

FIDO Home Energy Watchdog [57]: This system oversees energy use and recommends how consumers can reduce their electricity bills. Homeowners get the current pricing information from the utility provider through a software interface and identify where and when they are using the most electricity to enable cost-saving changes proactively. The personalized system enables short messaging service or email access and provides a high-level of privacy to record personal energy usage patterns without the need to share it with utility providers or third parties.

C. Home Networks Supporting Convenience and Entertainment

The following are some of examples that support convenience and entertainment applications in smart home.

Illuminator [58]: Recently, UCLA NESL & the UCLA Hypermedia Studio have proposed the Illuminator project, a preliminary sensor network-based intelligent light control system for entertainment and media production, which focuses on closing the loop between light sensing and lighting control. The entire Illuminator system can be divided into three subsystems: Sensor network, Illuminator core, and DMX (DMX refers to the entertainment industry standard control signal for lights, 8-bit dimmer levels multiplexed on an RS485 serial link.) controller and dimmer.

To satisfy the high-performance light sensing requirements of entertainment and media production applications, the system uses the Illuminator scheme, which is a multi-modal and high-fidelity light sensor module well-suited to wireless sensor networks. Illuminator can handle various high-level constraints and generate an optimal light actuation profile to support entertainment and media production applications.

WiMoCA [59]: The Wireless Sensor Node for a Motion Capture System with Accelerometers (WiMoCA) project at several Italian universities deals with the design and implementation of a distributed gesture recognition system. The system has a star topology with all sensing nodes sending data to a non-sensing coordinator node using a TDMA-like approach, where the coordinator in turn relays the data to an external processing unit using Bluetooth. The sensing modules, each made up of a tri-axial accelerometer, can be put on multiple parts of the body for motion detection. The radio modules of all nodes work in the 868 MHz European license-exempt band with up to 100 kb/s data rate. A Java-based graphical user interface at the processing unit side interprets the data stream for posture recognition.

Dyson [60]: Dyson is a new software architecture for building customizable WLANs that defines a set of application programming interfaces (APIs) and allows clients and APs to send pertinent information (e.g., radio channel condition) to a central controller. Currently, Dyson's prototype runs on a 28-node testbed distributed across one floor of a typical academic building. It examines various aspects of the architecture in detail and demonstrates the ease of implementing a wide range of policies. This project can optimize associations, handle VoIP clients, reserve airtime for specific users, and achieve handoffs for mobile clients.

VII. Conclusion and Outlook

In this article, we have summarized advancements by several major international projects for home M2M networks, and discussed the state-of-the-art research on recent developments of home M2M networks. The architecture of home M2M networks, short-range wireless technologies, as well as methodologies for improving the QoS of home M2M networks have been introduced. M2M communications can involve a wide diversity of M2M devices, resulting in many problems as well as research issues. Optimization of M2M communications with respect to energy consumption, total cost and reliability is an active research area. In order to enable seamless, robust, efficient and reliable M2M communications and hence realize the high expectations for M2M communications, many research problems need to be thoroughly analyzed and solved. In the following we highlight some key research challenges.

- M2M communications will change many aspects in the conventional business processes by putting a greater amount of data in the hands of more people. Therefore, better system integration schemes are required to integrate M2M elements as well as operations into such a complex system.
- Heterogeneous M2M networks, especially mesh networks are complex and expensive to design for high reliability and security. Improved design methodologies are needed.
- Security remains a very important concern because the existing M2M applications tend to rely on legacy security schemes.
- Design of MTC devices for capillary M2M communications is challenging, as each node typically consists of a sensor, a radio transciever, a microcontroller and an energy supply. In addition, the node should possess some intrinsic features, such as: low-cost, low-complexity, low-size, and low-energy. Each node must have the ability to maintain long-running operation by faultlessly solving the problem of energy supply.
- Though external interfacing has a major impact on wireless link reliability, it is often neglected in protocol design. Also, MAC and routing protocols are often channel-agnostic, on top of the random fluctuations of wireless channels.

Acknowledgment

This work was supported by China National Natural Science Foundation (No. 61322210, 61272408, 61262013), and the Ministry of Science and Technology (MOST), China, the International Science and Technology Collaboration Program (Project No.: S2014GAT014), the Hubei Provincial Key Project (No. 2013CFA051), the High-level Talent Project for Universities, Guangdong Province, China (No. 431, YueCai-Jiao 2011), and the Natural Science Foundation of Guangdong Province, China (No. S2011010001155).

References

[1] K. Zheng, F. Hu, W. Wang, W. Xiang, and M. Dohler, “Radio resource allocation in LTE-advanced cellular networks with M2M communications”, *IEEE Commun. Mag.*, vol. 50, no. 7, pp. 184–192, Jul 2012.
[2] The Global Wireless MTC Market – 2nd Edition, Gothenburg, Sweden: Berg Insight, Dec. 2009.
[3] Service requirements for machine-type communications (MTC); stage 1, release 11. *Technical Report TR 22.368 V11.0.1*, 3GPP, Sophia Antipolis, France, Feb. 2011.
[4] J. Wan, M. Chen, F. Xia, D. Li, and K. Zhou, “From machine-to-machine communications towards cyber-physical systems”, *Computer Science and Information Systems*, vol. 10, no. 3, pp. 1105–1128, Jun 2013.
[5] M. Chen, V. Leung, R. Hjelsvold, X. Huang, “Smart and interactive ubiquitous multimedia services,” *Computer Communications*, vol. 35, no. 15, pp.1769–1771, Sep. 2012.
[6] Y. Zhang, R. Yu, S. L. Xie, W. Q. Yao, Y. Xiao, and M. Guizani, “Home M2M networks: architectures, standards, and QoS improvement, ” *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 44–52, April, 2011.
[7] M. Chen, J. Wan, and F. Li, “Machine-to-machine communications: architectures, standards, and applications,” *KSII Transactions on Internet and Information Systems*, vol. 6, no. 2, pp. 480–497, Feb. 2012
[8] R. Lu, X. Li, X. Liang, X. Shen, and X. Lin. “GRS: The green, reliability, and security of emerging machine to machine communications,” *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 28–35, Apr. 2011.
[9] D. Feng, C. Jiang, G. Lim, L. J. Cimini, Jr., G. Feng, and G. Y. Li, “A survey of energy-efficient wireless communications,” IEEE Commun. Surveys & Tutorials, vol. pp, no. 99, pp. 1–12, Feb. 2012.
[10] Z. M. Fadlullah, M M. Fouda, N. Kato, A. Takeuchi, N. Iwasaki, and Y. Nozaki, “Toward intelligent machine-to-machine communications in smart grid,” *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 60–65, Apr. 2011.
[11] D. Niyato, L. Xiao, and P. Wang, “Machine-to-Machine communications for home energy management system in smart grid,” *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 53–59, Apr. 2011.
[12] “Products for home energy monitoring and solar optimization.” [Online]. Available at: http://ecodoginc.com/ecodog/product.htm.
[13] N. Accettura, M. Palattella, Micha Dohler, L. Grieco, and G. Boggia, “Standardized power-efficient & internet-enabled communication stack for capillary M2M networks,” IEEE Wireless Commun. Netw. Conf. Workshops (WCNCW), pp. 226–231, 2012.
[14] A. Lioumpas and A. Alexiou, “Uplink scheduling for Machine-to-Machine communications in LTE-based cellular systems,” *IEEE GLOBECOM* Workshops, pp. 353–357, Dec. 2011.
[15] C. Li, A. Jeng, and R. Jan, “A MAC protocol for multi-channel multi-interface wireless mesh network using hybrid channel assignment scheme,” *J. Information Science and Engineering*, vol. 23, no. 4, pp. 1041–1055, 2007.
[16] J. Wang, M. Abolhasan, F. Safaei, and D. Franklin, “A survey on control separation techniques in multi-radio multi-channel MAC protocols,” in *Proc. of Intl. Symp. on Commun. and Information Technologies*, Wollongong, Australia, pp. 854–859, 2007.
[17] J. Castillo “The survival of communications in ad hoc and M2M networks: Study of the applications of hybrid intelligent nodes that process simultaneous signals IEEE802.11h/Bluetooth in comparison with IEEE 802.11h/802.15.3,” in *Proc. of the World Congress on Engineering and Computer Science* San Francisco, USA, Oct 2009.
[18] G. Wu, S. Talwar, K. Johnsson, N. Himayat, and K. D. Johnson, “M2M: From mobile to embedded internet,” *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 36–42, Apr. 2011.
[19] J. Misic, S. Shafi, and V. B Misic,“Maintaining reliability through activity management in 802.15.4 sensor clusters,” *IEEE Trans. Veh. Technol.*, vol. 55, no. 3, pp. 779–788, May 2006.
[20] Cisco, “http://www.cisco.com/web/consumer/glossary/homenetworking.html.”
[21] “WLAN Interference to IEEE802.15.4.” [Online]. Available at: http:z-wavealliance.org.
[22] A. Barth, S. Wilson, M. Hanson, H. Powell, D. Unluer, and J. Lach “Body-coupled communication for body sensor networks,” in *Proc. 3rd Int. Conf. on Body Area Networks (BodyNets)* Tempe, Arizona, 2008.
[23] T. Tokuda, K. Hiyama, S. Sawamura, K. Sasagawa, “CMOS-based multichip networked flexible retinal stimulator designed for image-based retinal prosthesis,” *IEEE Trans. Electron Devices*, vol. 56, no. 11, pp. 2577–2585, Nov. 2009.
[24] R. Daniels, R. Heath, “60 GHz wireless communications: emerging requirements and design recommendations,” *IEEE Veh. Technol. Mag.*, vol. 2, no. 3, pp.41–50, Sept. 2007.

[25] R. Daniels, J. Murdock, T. Rappaport, R. Heath, "60 GHz Wireless: Up Close and Personal," *IEEE Microwave*, vol. 11, no. 7, pp.44–50, Dec. 2010.

[26] M. J. Booysen, J. S. Gilmore, S. Zeadally and G. J. van Rooyen, "Machine-to-machine (M2M) communications in vehicular networks," *KSII Transactions on Internet and Information Systems*, vol. 6, no. 2, pp. 480–497, Feb. 2012.

[27] J. Wan, H. Yan, Q. Liu, K. Zhou, R. Lu, and D. Li, "Enabling cyber-physical systems with machine-to-machine technologies," *Int. J. of Ad Hoc and Ubiquitous Computing*, vol. 13, no. 3/4, pp. 187–196, 2013.

[28] K. Yang, J. Zhang and H. Chen, "A flexible QoS-aware service gateway for heterogeneous wireless networks," *IEEE Network*, vol. 21, no. 2, pp. 612, Mar./Apr. 2007.

[29] "Universal plug and Pplay, understanding universal plug and play: A white paper." [Online]. Available: http://upnp.org/resources/whitepapers.asp.

[30] "DLNA, DLNA overview and vision white paper." [Online]. Available: http://www.dlna.org/en/industry/about/dlna_white_ paper_2006.pdf.

[31] G. Lu, D. Seed, M. Starsinic, C Wang, and P. Russell, "Enabling Smart Grid with ETSI M2M standards," *IEEE Wireless Commun. Netw. Conf. Workshops (WCNCW)*, pp. 226–231, 2012.

[32] X. Wang, M. Chen, T. Kwon, L. Yang, and V. Leung, "AMES-cloud: a framework of adaptive mobile video streaming and efficient social video sharing in the clouds," *IEEE Trans. Multimedia*, vol. 15, no. 4, pp. 811–820, Jun 2013.

[33] M. Chen, "AMVSC: a framework of adaptive mobile video streaming in the cloud," *IEEE Globecom 2012*, Anaheim, California, USA, Dec. 3-7, 2012.

[34] W. K. Edwards, Core Jini. Prentice Hall: Upper Saddle River, NJ, USA, 1999.

[35] H. Song, D. Kim, K. Lee, and J. Sung, "UPnP-based sensor network management architecture," in *Proc. Int. Conf. on Mobile Computing and Ubiquitous Networking*, Osaka, Japan, Apr. 2005.

[36] C. Lee, D. Nordstedt, and S. Helal, "Enabling smart spaces with OSGi," *IEEE Pervas. Comput.,*vol.2, no. 3, pp. 89–94, 2003.

[37] P. Huang, L. Xiao, S. Soltani, M. Mutka, and N. Xi, "The evolution of MAC protocols in wireless sensor networks: A survey," *IEEE Commun. Surveys & Tutorials*, vol. 15, no. 1, pp. 101–120, 2012.

[38] W. Ye, J. Heidemann, and D. Estrin, "Medium access control with coordinated, adaptive sleeping for wireless sensor networks," *IEEE/ACM Trans. Netw.*, vol. 12, no. 3, pp. 493–506, Jun. 2004.

[39] T. Dam and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," in *Proc. 1st ACM SenSys Conf.*, Los Angeles, USA, 2003, pp 171–180.

[40] A. Hoiydi, J. Decotignie, C. Enz C, and E. Roux, "WiseMAC: an ultra low power MAC protocol for the wisenet wireless sensor networks," in *Proc. 1st ACM SenSys Conf.*, Los Angeles, USA, 2003.

[41] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," in*Proc. 2nd ACM SenSys Conf.*,. Baltimore, USA, 2004, pp 95–107.

[42] W. Ye and J. Heidemann, "SCP-MAC: reaching ultra-low duty cycles (poster)," in*Proc. IEEE SECON'05*, Santa Clara, USA, 2005.

[43] B. Latr, B. Braem, I. Moerman, C. Blondia, E. Reusens, W. Joseph, P. Demeester, "A low-delay protocol for multihop wireless body area networks," in *Proc. of Mobiquitous*, Philadelphia, PA, 2007.

[44] H. Li and J. Tan, "Heartbeat driven medium access control for body sensor networks," in *Proc. ACM SIG-MOBILE Int. Workshop on Systems and Network-ing Support for Healthcare and Assisted Living Environments*, San Juan, Puerto Rico, 2007.

[45] J. Ortiz and D. Culler, "Exploring diversity: evaluating the cost of frequency diversity in communication and routing", *ACM SenSys*, Raleigh, NC, Nov. 2008.

[46] M. Chen, "MM-QoS for BAN: multi-level MAC-layer QoS design in body area networks," *IEEE Globecom 2013*, Atlanta, Georgia, USA, Dec. 9-13, 2013.

[47] H. Li and J. Tan, "An ultra-low-power medium access control protocol for body sensor network," in *Proc. IEEE-EMBS*, Reading, UK, 2005.

[48] S. Lien, and K. Chen, "Massive access management for QoS guarantees in 3GPP machine-to-machine communications," *IEEE Commun. Lett.*, vol. 15, pp. 311-313, 2011.

[49] C. de Laat, G. Gross, and L. Gommans. Generic AAA architecture. Internet Engineering Task Force Network Working Group, Request for Comment (RFC) 2903, 2000.

[50] Recommendation X.805 Security architecture for systems providing endtoend communications.ITU-T Lead Study Group on Telecommunication Security, Oct. 2003.

[51] M. Chen, S. Gonzalez, A. Vasilakos, H. Cao, and V. Leung, "Body area networks: A survey," *ACM/Springer Mobile Networks and Applications*, vol. 16, no. 2, pp. 171–193, Apr 2011.

[52] N. Jun and V. Rajaravivarma, "Multimedia file sharing in multimedia home or office business networks," in *Proc. 35th Southeastern Symp. on System Theory*, New Britain, USA, pp. 237–241, 2003.

[53] C. Harnett, "Nanotechnology in environmental sensors," IEEE *Instrumentation & Measurement Magazine*, vol. 13, no. 2, pp. 8–12, 2010.

[54] V. Shnayder, B Chen, K. Lorincz, T Fulford-Jones, and M. Welsh, "Sensor networks for medical care," *Harvard University Technical Report TR-08-05*

[55] T. Gao, T. Massey, L. Selavo, D. Crawford, B. Chen, K. Lorincz, V. Shnayder, L. Hauenstein, F. Dabiri, J. Jeng, A. Chanmugam, D. White, , M. Sarrafzadeh, and M. Welsh, "The advanced health and disaster aid network: a light-weight wireless med-ical system for triage," *IEEE Trans. Biomed. Circuits Syst.,* vol. 1, no. 3, pp. 203–216, Sept. 2007.

[56] S. Jiang, Y. Cao, S. Lyengar, P. Kuryloski, R. Jafari, Y. Xue, R. Bajcsy, and S. Wicker, "CareNet: an integrated wireless sensor networking environment for remote healthcare," in *Proc. Int. Conf. on Body Area Networks* Tempe, Arizona, 2008.

[57] J. Wan, S. Ullah, C. Lai, M. Zhou, X. Wang, and C. Zou, "Cloud-enabled wireless body area networks for pervasive healthcare," *IEEE Network*, vol. 27, no. 5, pp. 56–61, Sep 2013.

[58] Wiser EMS, "http://www.schneider-electric.us/go/wiser."

[59] Ecodog, "http://ecodoginc.com/."

[60] Illuminator, "http://nesl.ee.ucla.edu/project/show/48."

[61] E. Farella, A. Pieracci, A. Acquaviva, "Design and implementation of WiMoCA node for a body area," in *Proc. Int. Conf. on Systems Commun.*, Bologna, Italy, pp. 342–347, 2005.

[62] R. Murty, J. Padhye, A. Wolman, and M. Welsh, "Dyson: An architecture for extensible wireless LANs," in *Proc. 2010 USENIX*, pp. 15–15, 2010.

Min Chen is a professor in School of Computer Science and Technology at Huazhong University of Science and Technology. He was an assistant professor in School of Computer Science and Engineering at Seoul National University (SNU) from Sep. 2009 to Feb. 2012. He worked as a Post-Doctoral Fellow in Department of Electrical and Computer Engineering at University of British Columbia (UBC) for three years. Before joining UBC, he was a Post-Doctoral Fellow at SNU for one and half years. He has more than 170 paper publications. He received Best Paper Award from IEEE ICC 2012, and Best Paper Runner-up Award from QShine 2008. He is a Guest Editor for IEEE Network, IEEE Wireless Communications, etc. He is Symposium Co-Chair for IEEE ICC 2012 and IEEE ICC 2013. He is General Co-Chair for IEEE CIT 2012. He is a TPC member for IEEE INFOCOM 2014. He is Keynote Speaker for CyberC 2012 and Mobiquitous 2012. He is an IEEE Senior Member since 2009.

Jiafu Wan is an associate research fellow at South China University of Technology, China. Dr. Wan has authored/co-authored one book and more than 50 scientific papers. He is managing editor for International Journal of Arts and Technology (IJART). His research interests include cyber-physical systems (CPS), internet of things, machine-to-machine (M2M) communications, mobile cloud computing, and wireless body area networks (WBANs). He is a CCF senior member, and a member of IEEE, IEEE Communications Society, IEEE Control Systems Society, and ACM.

Sergio González received the B.E. degree in electronics (special mention) from the Instituto Tecnológico de Sonora, Ciudad Obregón, Sonora, Mexico, in 1995, and the M.A.Sc. and Ph.D. degrees in electrical and computer engineering from the University of British Columbia (UBC), Vancouver, BC, Canada, in 2002 and 2008, respectively. From 2008 to 2011, he was a Postdoctoral Fellow in the Department of Electrical and Computer Engineering, UBC, where his research interests were in the areas of wireless sensor networks, body area networks, and ad hoc networks.

Xiaofei Liao received his Ph.D. degree in Computer Science from Huazhong University of Science and Technology (HUST), China, in 2005. He is now a professor in the school of Computer Science and Technology at HUST. He has served as a reviewer for many conferences and journal. His research interests are in the areas of virtualization technology, system software. He is a member of the IEEE and the IEEE Computer Society.

Victor C.M. Leung is a Professor of Electrical and Computer Engineering and holder of the TELUS Mobility Research Chair at the University of British Columbia (UBC). He has contributed some 600 technical papers, 25 book chapters and 5 book titles in the areas of wireless networks and mobile systems. He was a Distinguished Lecturer of the IEEE Communications Society. He has been serving on the editorial boards of the IEEE Transactions on Computers, IEEE Wireless Communications Letters and several other journals, and has contributed to the organizing and technical program committees of numerous conferences. Dr. Leung was a winner of the 2012 UBC Killam Research Prize, and the IEEE Vancouver Section Centennial Award.