Low Power Wide Area Machine-to-Machine Networks: Key Techniques and Prototype

While M2M communications have been developed for many years, major challenges still remain with their efficient implementation from the perspective of low energy consumption and wide coverage. To address these challenges, low power wide area (LPWA) technology is investigated as one of the potential candidate solutions.

Xiong Xiong, Kan Zheng, Rongtao Xu, Wei Xiang, and Periklis Chatzimisios

Abstract

As one of the fastest growing technologies, machine-to-machine (M2M) communications are expected to provide ubiquitous connectivity. M2M devices can be used for a wide range of emerging applications that have various communications requirements. While M2M communications have been developed for many years, major challenges still remain with their efficient implementation from the perspective of low energy consumption and wide coverage. To address these challenges, low power wide area (LPWA) technology is investigated as one of the potential candidate solutions. In this article, we first introduce some typical LPWA M2M application scenarios. Given their requirements, we highlight key techniques and standards that are explicitly designed for LPWA M2M communications. Finally, we present an LPWA prototype system to evaluate its performance and demonstrate its potential in bridging a technological gap for future Internet-of-Things (IoT) applications.

Communications Standards

Introduction

Machine-to-machine (M2M) communications enable direct connectivity among devices, which can be organized as a network in order to exchange information and perform actions without human intervention. It is an integral part of the Internet-of-Things (IoT), which can benefit end users from its countless range of applications [1].

There are some notable requirements and properties of M2M networks, such as low costs, low energy consumption, wide coverage, tolerable low latency, relatively low data throughput, etc. Among them, low energy consumption and wide coverage are the most desired features since M2M devices can be deployed at locations without main power and operate only on battery power. Moreover, numerous M2M devices are widely distributed in a wide variety of locations, some of which are difficult to reach either because they are remote or because they are underground or located deep inside buildings.

However, these requirements and properties cannot be well supported by existing wireless network technologies that are designed for human users, such as cellular mobile networks [2]. As a result, various systems have been specifically designed for M2M communications, such as Zigbee/IEEE 802.15.4 in wireless sensor networks (WSNs), Bluetooth, radio frequency identification (RFID), etc [3]. However, almost all these techniques are short-range connectivity solutions, which have difficulty meeting some of the requirements of M2M applications. In addition, another promising system based on IEEE 802.11ah, also known as Low-Power Wi-Fi, is now being developed to meet specific requirements of M2M networks, e.g., transmission range up to 1 kilometer in outdoor scenarios, low data rates, and low energy consumption [4]. It is still not suited for remote and underground areas.

Due to the limitation of the above short-range communications systems, low power wide area (LPWA) technology has been specifically designed with the objectives of low energy consumption and wide coverage. In particular, ultra-narrowband (UNB) and direct sequence spread spectrum (DSSS) modulation schemes have been proposed for the physical layer of LPWA M2M systems thanks to their excellent coverage performance. Meanwhile, in order to enable low energy consumption, the star topology and the random access method can be employed in the MAC layer. A key feature of these LPWA techniques is that they provide a trade-off between the data rate, battery life, and deployment costs. Such a trade-off is acceptable for most M2M applications, which do not require high data rates and low latency [5]. This is a significant difference between LPWA M2M systems and traditional wireless communication systems. Thus, LPWA M2M networks are expected to play a crucial role in the IoT. Meanwhile, standardization efforts for LPWA M2M networks are underway. In this paper, we first present an overview of typical LPWA M2M application scenarios. Then some key techniques that are currently under consideration for LPWA M2M systems are studied in detail. Several preliminary standards are compared with an emphasis on highlighting their key differences.

To the best of our knowledge, there still remain many open problems with the implementation of LPWA M2M networks, which are the main focus of this paper. Open source software-defined radio (SDR) platforms are appealing and efficient for fast prototyping LPWA M2M designs, where most modules are programmed by software and easily upgradable [7]. We implement an LPWA M2M prototype based upon the specifications of IEEE 802.15.4k by using an open source SDR based GNU radio real-time signal processing framework. To demonstrate the advantages of LPWA M2M networks, field experiments are conducted to evaluate the performance of our prototype in several deployment scenarios.

Xiong Xiong and Kan Zheng are with Beijing University of Posts & Telecommunications.

Rongtao Xu is with Beijing Jiaotong University.

Wei Xiang is with the University of Southern Queensland.

Periklis Chatzimisios is with Alexander Technological Educational Institute of Thessaloniki (ATEITHE).

Application Scenarios

LPWA M2M networks are suitable for deployment in a broad range of application scenarios, which can be classified into the five categories (see Fig. 1): infrastructure monitoring, transportation, asset tracking, security, and healthcare.

Infrastructure Monitoring: Under this scenario, an LPWA M2M device equipped with sensors (i.e. smart meters) plays a significant role in measuring and reporting usage, functionality, and environmental data to an LPWA M2M network. The resources under monitoring (such as water, electricity, oil, or gas) are crucial for our modern society, so ensuring an adequate supply of such resources is currently a major focus for countries around the world.

Transportation: Transportation related applications enable monitoring of critical transportation conditions, e.g. road conditions, traffic congestion, public transport, and so on. LPWA M2M networks can offer the opportunity to establish a direct interaction between vehicles and information systems/centers. The vehicle's status information can help service providers develop new applications, and help relevant government agencies improve the efficiency of managing traffic and public transportation in city premises.

Asset Tracking: LPWA M2M networks offer a low-cost and reliable solution to asset tracking by owners, who do not have to actively manage their assets. Asset tracking is widely used in the manufacturing industry to achieve real-time visibility throughout the supply and distribution chains, monitor inventory levels and condition, and manage the overall processes and workflows, while improving product quality and reducing the costs of waste and disruption.

Security: Security services are imperative for end users to minimize their personal losses and to predict risks in advance. When security systems are breached, LPWA M2M networks can facilitate secure communications for emergency services by allowing them to transmit critical emergency information to building owners or national security agencies.

Healthcare: With the growing demand for disease treatment, the healthcare industry now faces many challenges, including a vast cost burden. LPWA M2M networks can provide a solution that decentralizes medical costs and hospital care. This trend toward user-centric healthcare and individually tailored medicine may drive the market for M2M healthcare applications in the foreseeable future.

As mentioned above, all these applications require wide coverage and extremely low energy consumption, which can be provided by LPWA M2M networks. The performance requirements of different applications are summarized in Table 1.

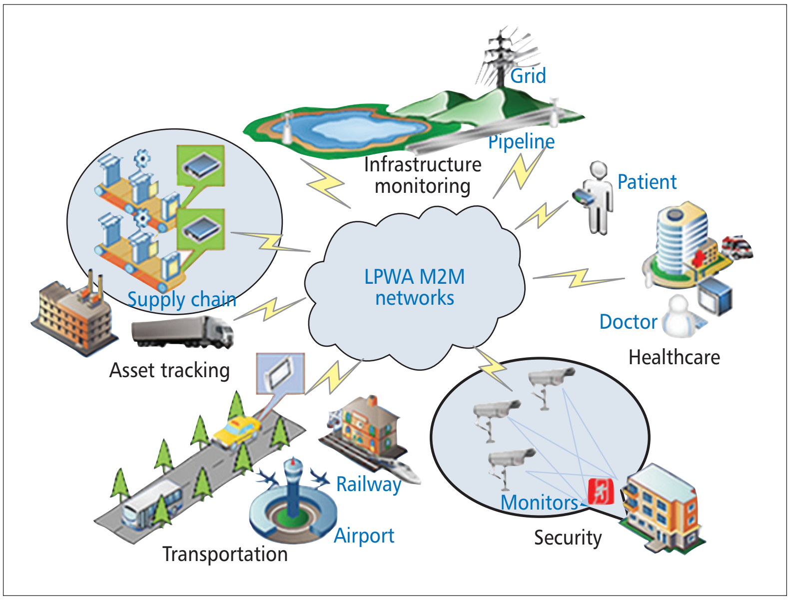


Figure 1. Illustration of five typical LPWA M2M application scenarios.

Key Techniques and Early Standards in LPWA M2M Networks

One of the most important requirements of an LPWA system is to provide ubiquitous communications. This implies that the architecture similar to a cellular network may be a possible solution. However, network components must be substantially simplified in comparison to cellular networks for easy deployment and maintenance [8]. Moreover, outdoor, indoor, and underground areas need to be covered by LPWA systems. In order to meet these performance demands of LPWA M2M networks, new advanced techniques have been proposed in both the physical (PHY) and medium access control (MAC) layers of LPWA M2M networks.

PHY Techniques

The PHY layer design of LPWA M2M networks is instrumental in enabling wide coverage. A key requirement is to design a transceiver with an ultra-low receiver sensitivity threshold in dBm. As such, two candidate techniques, i.e. UNB modulation or DSSS, have become attractive solutions lately.

UNB Modulation: UNB modulation was initially proposed as a promising technique to improve spectral efficiency. However, the UNB technique is used for long distance communications in LPWA M2M networks. The typical procedure of UNB modulation consists of two significant stages, i.e. the abrupt phase shift modulation and UNB filtering stages. An input signal is first modulated and then passed through a UNB filter. Two key issues arise in designing a UNB system: the signal waveform of the modulator and the UNB filter.

For abrupt phase shift modulation, the phase of a carrier is abruptly switched to represent a digital one or zero. There are various abrupt phase shift modulation schemes that can be chosen for UNB, e.g. very maximum sideband keying (VMSK), pulse position phase shift keying (3PSK), and pulse position phase reversal keying (3PRK), also known as missing cycle modulation (MCM) [11]. Thanks to the abrupt phase shift property, the power spectral density (PSD) of the modulated signal waveform consists of a higher discrete component and a lower continuous component. All the information required for detection exists only in a single sideband of the discrete component without

Application category	Typical user case	Coverage	Power consumption	Data traffic	Periodicity	Mobility	Real-time requirement	Security/reliability requirement
Infrastructure monitoring	Water/Electric/Gas meter	Urban areas	Low	Medium	Tens of minutes	No	Medium	Low
	Agriculture/soil & oil/gas pipeline monitoring	Open fields	Low	Low	Event driven	No	Low	Medium
Transportation	Traffic congestion monitoring	Urban areas	Low	High	Tens of minutes	High	Medium	Low
	Public transport management	Urban areas	Low	Medium	Event driven	High	Medium	Medium
Asset tracking	Supply chain monitoring	Urban areas/in-building	Low	Low	Event driven	Medium	Low	Low
	Vehicle tracking	Urban areas/open fields	Low	High	Several minutes	High	Medium	Low
Security	Access control & building security systems	In-building	Low	Low	Event driven	No	High	High
	Natural disasters preparedness	Urban areas/open fields	Low	Low	Event driven	No	High	Medium
Healthcare	Health status monitoring	Urban areas/in-building	Low	Medium	Tens of minutes	Medium	Low	Low
	Medical alert	Urban areas/in-building	Low	Low	Event driven	Medium	High	Low

Table 1. Requirements of LPWA M2M applications.

measurable bandspread, which is a single frequency containing phase reversal modulation. Then a UNB filter with a zero or negative group delay is able to filter all the other sidebands and harmonics so as to keep the only single sideband. Conventional filters with a group delay disrupt the abrupt phase shift information in the modulated signal. Thanks to the UNB filter, the output UNB signal contains a single frequency requiring a transmission bandwidth of only 1 Hz (in theory) or several Hz in practice. As a result, the noise power is greatly reduced. Thus, the receiver sensitivity threshold in dBm of the UNB receiver can be extremely low.

To date there is no open acceptable method to implement the UNB band filter and baseband UNB modulation. At the RF level, the filters are very complex and must be hand tuned. It is impossible to configurate a zero group delay narrow band filter using finite impulse response (FIR) or infinite impulse response (IIR) filters [11]. This limitation poses a big challenge for commercial UNB products.

DSSS: The DSSS technique has been widely used in commercial wireless communications systems, e.g. the third generation (3G) mobile communications networks. In the DSSS system, the large process gain allows a DSSS receiver to successfully detect signals with a very low carrier-to-interference ratio, which is essential for implementing the LPWA M2M network. Such a feature can be exploited thoroughly by employing a very long spreading sequence, e.g. the receiver sensitivity threshold may decrease by 3 dB when the length of the spreading sequence doubles.

Unlike conventional DSSS systems, the spreading sequences employed in LPWA M2M networks always utilize a much larger SF to make the receiver sensitivity threshold low enough to extend the communications range. However, employing long spreading sequences brings about its own challenges. For example, with an increase in the length of the spreading sequence, the computational complexity of the DSSS transceiver increases exponentially. Therefore, more efficient digital signal processing algorithms become necessary in the hardware design. Nevertheless, DSSS is still one of the most promising techniques for the LPWA system.

MAC Techniques

An efficient MAC layer design plays a vital role in improving the energy efficiency of LPWA M2M networks [12, 13]. It is also responsible for overcoming the challenge of potential massive accesses in LPWA M2M networks. To achieve these goals, the topology and channel access techniques have to be carefully considered.

Star Topology: In wireless networks, topology directly impacts the performance of the network including scalability, energy efficiency, reliability, data latency, overhead, etc. There are several topologies widely adopted in traditional WSNs, such as the mesh, cluster, tree, and chain topologies [14]. These topologies share a common feature, where an end device (ED) doubles as a router to form multi-hop links in order to extend the communications coverage.

However, the features of LPWA M2M networks are greatly different from those of WSNs.

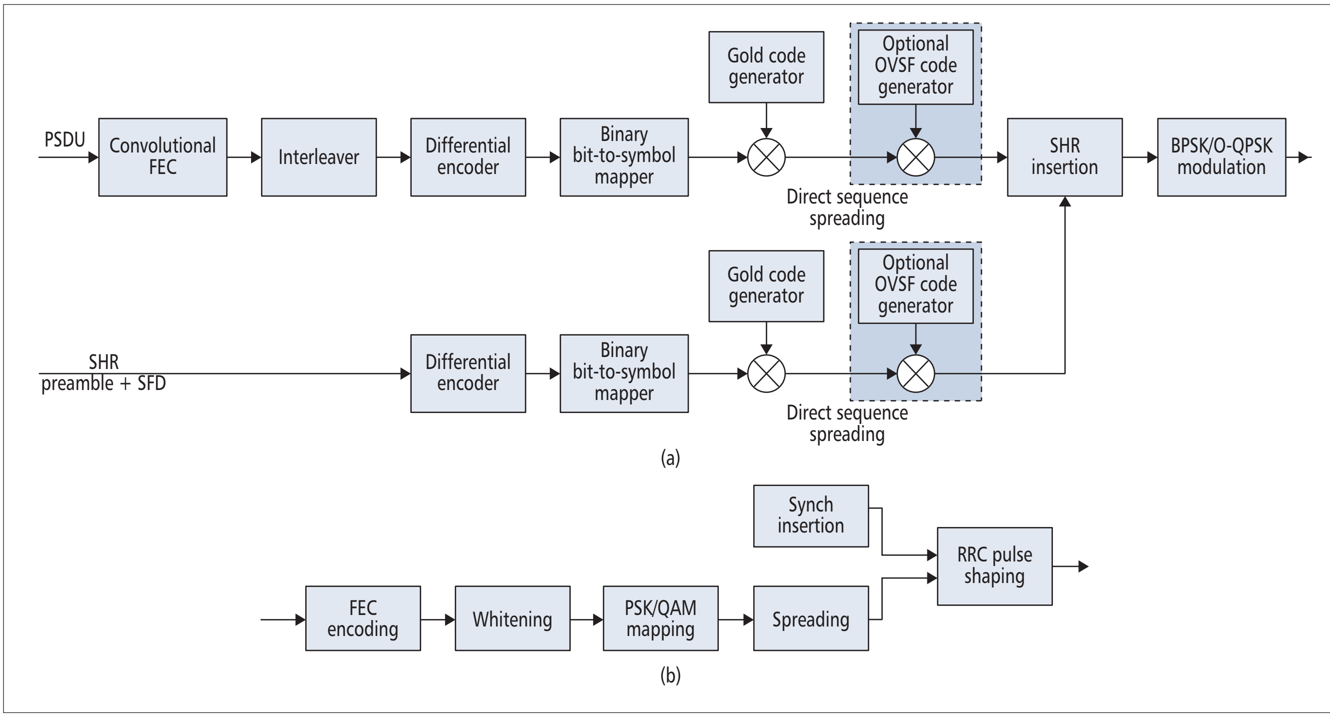


Figure 2. LPWA transmitter block diagram: a) IEEE 802.15.4k [6]; b) Weightless [10].

Since the physical layer techniques of the LPWA system are capable of providing coverage wide enough, the main concerns for the LPWA system when selecting a proper topology are the low costs and energy consumption. Compared to the aforementioned topologies, the star topology with only a single hop is considered to be the best choice for LPWA M2M networks. In this topology, each ED distributed in the coverage area communicates directly with a centralized access point (AP). There are various advantages of using such a simple topology. In particular, direct communications between an endpoint and the AP help minimize transmission latency. There are also no unnecessary packets for routing and multi-hop communications in the star topology, which help the EDs to reduce and balance their energy consumption. Besides, the star topology is easy for deployment. In terms of reliability and robustness, the star topology is not as good as the mesh and cluster topologies, but better than its tree and chain counterparts.

Channel Access: Channel access is probably the most crucial issue for LPWA M2M networks, since a large number of devices need to be simultaneously served in a large coverage area. There are two main categories of channel access methods for sharing access to the wireless medium: reservation-based access and contention-based access.

Specifically, reservation-based methods require the channelization of radio resources in different dimensions, which offer various advantages (e.g. reduced collisions and guaranteed delivery delays, etc). However, reservation-based access methods are unable to accommodate a vast number of devices in LPWA M2M networks due to limited channel resources.

Compared to reservation-based access methods, contention-based access methods, also dubbed random access methods, are more appealing for LPWA systems. In a contention-based approach, devices compete for access to the shared medium as required, which is a relatively simple and flexible process. With this on-demand characteristic, reservation-based access methods may have to handle massive and unpredictable access activities. Besides, synchronization is no longer needed, which helps reduce energy consumption due to synchronization signaling, and enables the devices to sleep so as to save energy. However, contention-based access methods have to deal with other sources of energy waste, e.g. idle listening, overhearing, collisions, overhead, etc.

Several well-known solutions have been proposed for the above issues. A well-known protocol is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), which employs the carrier sensing mechanism to reduce channel collisions. However, CSMA-based protocols cannot work well all the time in LPWA M2M networks. In some extreme cases, the signals transmitted from other EDs may not be detected by a target ED because of the large path loss caused by a long distance between the EDs. As a result, the carrier sensing mechanism is neither practical nor valid under this scenario. Another challenge is the massive connectivity requests that the LPWA M2M network has to handle, which renders CSMA-based protocols inefficient due to simultaneous massive requests for channel access.

Compared with CSMA-based protocols, Aloha-based protocols offer better performance when coupled with a properly designed PHY technique in LPWA M2M networks. For instance, adopting the DSSS technique in the PHY layer provides the LPWA M2M network with the capability of detecting and identifying multiple EDs arriving simultaneously. When

Our prototype network is deployed with the star topology. The AP can be configured as a multiple-baseband receiver with various physical parameters, e.g. different spreading factors, different seeds of the Gold code, and so on. The AP can collect all packets from EDs with different PHY configurations within its serving area.

	Attribute	IEEE 802.15.4k (DSSS)	Weightless
PHY	Operation frequency band	470 ~ 510 MHz; 779 ~ 787 MHz; 863 ~ 870 MHz; 902 ~ 928 MHz; 915 ~ 928 MHz; 917.1 ~ 923.5 MHz; 920 ~ 928 MHz; 921 ~ 928 MHz and 2.4 ~ 2.4835 GHz in different counties	470 ~ 790 MHz in Europe; 470 ~ 698 MHz in U.S.
	Channel bandwidth	100 kHz; 200 kHz; 400 kHz; 600 kHz; 800 kHz and 1 MHz	8 MHz in Europe; 6 MHz in U.S.
	Effective isotropic radiated power (EIRP)	Minimum: –3 dBm; Maximum: limited by local regulatory bodies	4 ~ 32 dBm
	FEC	Convolutional encoding: rate 1/2, constraint length 7	Convolutional encoding: rate 3/4 or 1/2, constraint length 7
	Interleaving	Pruned bit reversal interleaving algorithm	Matrix interleaving with 8 columns
	Spreading sequence	Gold code: SF 16 ~ 32768	Gold code and Kasami code: SF 15 ~ 1023
	Modulation	BPSK; OQPSK	16-QAM; pi/4-QPSK; pi/2-BPSK; pi/4-DQPSK; pi/2-DBPSK
	Frequency hopping	No	Yes
	Minimum receiver sensitivity threshold	–148 dBm	Downlink: –128 dBm; Uplink: –140 dBm
	Typical coverage	Up to 20 km in LoS and 5 km in NLoS	Up to 10 km
	Data rate	0.00153 ~ 125 kb/s	Downlink: 0.0025 ~ 16.0 Mb/s; Uplink: 0.00025 ~ 0.5 Mb/s
	Sync sequence length	Preamble: 0/2/4 octets; SFD: 0/1 octets	8 ~ 2048 Symbol (No need to multiply by spreading sequence any more)
MAC	Packet length	16/24/32 octets	0 ~ 255 octets
	Topology structure	Star	Star, with multi-hop relay capability
	Channel access method	CSMA/CA; CSMA/CA with PCA; Aloha with PCA	TDMA/FDMA
	Traffic priority	Yes	Yes

Table 2. Comparison between IEEE 802.15.4k and Weightless systems.

multiple EDs transmit packets with the Aloha mode, the receiver can detect and decode each packet successfully with the specified spreading sequences, even if the transmission periods of the EDs overlap completely. Therefore, the potential massive access issue in the LPWA M2M network may be properly dealt with. Moreover, the unnecessary overhead of the carrier sensing mechanism, such as the request to send (RTS) and clear to send (CTS) control messages, is eliminated in Aloha-based protocols, helping meet the energy efficiency requirement of LPWA M2M networks.

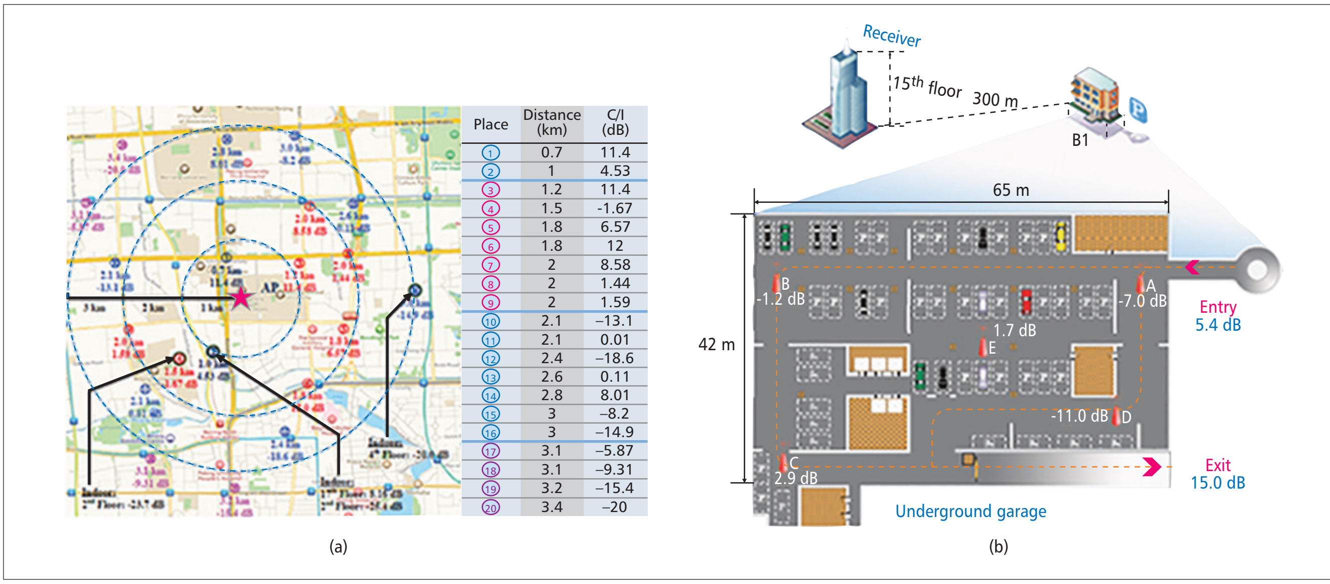
Also, interference cancellation techniques can be used by the receiver to improve the efficiency of channel access. This brings another new perspective of MAC protocol design for massive access in LPWA M2M networks.

Early Standards

Several early standards for M2M communications have been developed by different standardization organizations, such as the ETSI technical committee (TC), 3GPP, IETF, and so on. Among them, IEEE 802.15.4k and Weightless have been proposed for LPWA applications.

IEEE 802.15.4k aims at low energy critical infrastructure monitoring (LECIM) networks, to facilitate point-to-multi-point communications for monitoring and managing critical infrastructure applications [6]. In the standard, two PHY modes are specified to support LECIM applications, i.e. DSSS and frequency shift keying (FSK). The transmitter block diagram of DSSS PHY is illustrated in Fig. 2a.

The Weightless draft standard is developed



Place	Distance (km)	C/I (dB)
1	0.7	11.4
2	1	4.53
3	1.2	11.4
4	1.5	-1.67
5	1.8	6.57
6	1.8	12
7	2	8.58
8	2	1.44
9	2	1.59
10	2.1	–13.1
11	2.1	0.01
12	2.4	–18.6
13	2.6	0.11
14	2.8	8.01
15	3	–8.2
16	3	–14.9
17	3.1	–5.87
18	3.1	–9.31
19	3.2	–15.4
20	3.4	–20

Figure 3. Coverage performance of the developed LPWA prototype: a) outdoor/indoor; b) underground.

by the Weightless special interest group (SIG) [9]. The Weightless specifications define not only the PHY and MAC layers, but also an upper layer, dubbed the server layer. A basic transmitter block diagram of PHY is depicted in Fig. 2b.

The IEEE 802.15.4k and Weightless standards have different attributes and also share some common features. To elaborate, a detailed comparison between IEEE 802.15.4k and Weightless is summarized in Table 2.

Prototype System and Results

Prototype System based on SDR

In order to evaluate the performance of the LPWA M2M network, we have developed an IEEE 801.15.4k prototype based on SDR, which consists of GNU radio and universal software radio peripheral (USRP) [15].

The AP consists of an industrial personal computer (IPC) for baseband signal processing, and an Ettus USRP B210 as the RF transmitter and receiver. Powered by IPC via USB3.0, the USRP B210 can operate on different carrier frequency ranging from 70 MHz to 6 GHz covering all the operating frequency bands of LPWA devices. The IPC is assembled with a high-performance multi-core CPU, and runs the programs for both transmitter and receiver signal processing of 802.15.4k DSSS PHY.

At the receiver, non-coherent detection is used for symbol demodulation to eliminate the effect of the frequency and phase offsets. Then a parallel preamble detection scheme is designed to find the beginning of a packet. We apply a fast Fourier transform (FFT)-based algorithm to implement the correlation process for preamble detection. To decode traffic data, a dynamic timing adjustment algorithm is proposed to obtain the optimal sampling time. The FFT transform and the Viterbi algorithm for convolutional decoding are derived from the IT++ library.[1]

In our developed prototype, Gaussian frequency shift keying (GFSK) is chosen as the modulation scheme, which is different from the design in IEEE 802.15.4k, because GFSK can overcome the effect of the frequency or phase offset. Although performance degradation is unavoidable due to non-coherent demodulation, the DSSS PHY is able to tolerate an acceptable frequency offset at very low SNRs.

Our prototype network is deployed with the star topology. The AP can be configured as a multiple-baseband receiver with various physical parameters, e.g. different spreading factors, different seeds of the Gold code, and so on. The AP can collect all packets from EDs with different PHY configurations within its serving area.

Experiment Results and Discussions

Our experiments are carried out in an urban environment. The wipe antenna of the AP is installed on the roof of a 15-floor building in the campus. Then the received RF signal is fed into the USRP B210 located in our laboratory with a 10-meter cable connected to the antenna. Preamble detection is performed at the chip level in parallel in order to capture all possible frame heads. Also, the cyclic redundancy check (CRC) bits of the decoded payload data are checked to ensure data integrity so that false preamble detection can be disregarded. In our field tests, the carrier-to-interference (C/I) value is approximated as the ratio of the normalized peak output value of the preamble detector to the received signal power, which can be used as a metric measuring communications reliability in the LPWA M2M network. Moreover, it is worth mentioning that received packets can be decoded without errors in most cases where C/I is greater than –30 dB.

Some common parameters of our field tests are stated as follows. Both the AP and EDs operate at 433 MHz with a symbol rate 200 k symbols per second. In all packets sent by the EDs, the physical protocol data unit (PPDU) that consists of a four-octet preamble, and a 16-octet physical service data unit (PSDU) is spread by the Gold code with a SF of 32,768.

[1] http://itpp.sourceforge.net/devel/tutorial.html

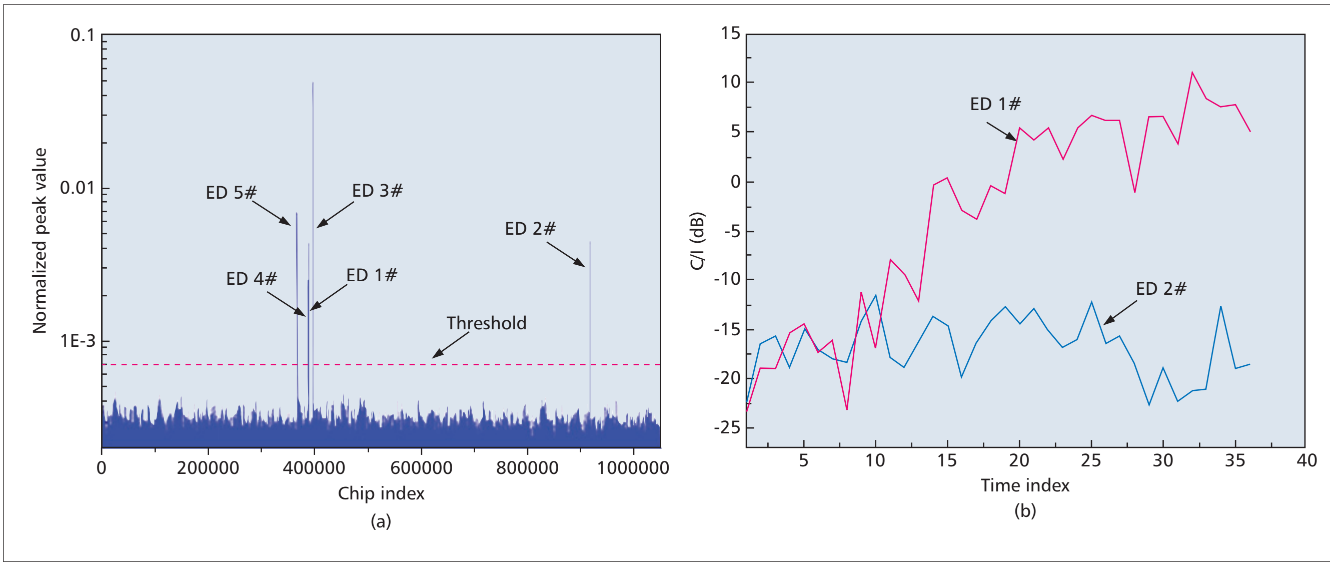


Figure 4. Multi-user performance of the developed LPWA prototype: a) MU-case 1 for preamble detection; b) MU-case 2 for the near-far effect.

Coverage Performances: For the first time, coverage in various application environments is evaluated in our experiments, in which the transmit power of the ED is fixed to 15 dBm. Apart from the outdoor environment, tests are also performed in both the indoor and underground environments.

Outdoor/Indoor: Figure 3a shows the experiment results for the outdoor/indoor scenarios, where 20 spots are chosen to conduct the field tests. In each spot, the upper number stands for the distance from the AP, while the lower number indicates the average C/I. In all the cases, there is no LoS between the transmitter and receiver.

Since the radio propagation characteristics in urban areas are too complicated to predict, the received C/I in the testing spots is not always larger with a smaller communications distance. For instance, spot 15 is further than spot 10, but the former has a higher C/I. However, in all the spots in the outdoor scenarios, the packets sent by the EDs can be successfully decoded at the AP. Moreover, the measured C/I value at the farthest spot with 3.4 km distance is still larger than –30 dB, i.e. the C/I threshold to ensure correct decoding of the received packets. It is believed that wide coverage can be provided by our LPWA prototype, which will be validated in our next steps. Furthermore, due to the low receiver sensitivity threshold in dBm of the LECIM device, the EDs close to the AP can decrease their transmit power to reduce energy consumption.

When the EDs are installed inside buildings for monitoring or industry metering, building penetration is more likely to be a major performance constraint. Therefore, the indoor environments in buildings located in 2, 4, and 16 in Fig. 3a are selected to perform the indoor tests. In the building with 23 floors located in spot 2, we place the testing ED on different floors and collect the measured C/I, i.e. 8.16 dB on the 17th floor and –25.4 dB on the 2nd floor, respectively. It can be found that the height of the ED location significantly affects performance. That is, the C/I increases with the height of the position. Although the distances of buildings 2, 4, and 16 are different, i.e. 1.0 km, 1.5 km, and 3.0 km, respectively, the received packets are all decoded successfully at the AP, which demonstrates the effectiveness of our prototype in indoor environments.

Underground: To further evaluate the coverage performance of LPWA M2M networks, we carry out several field tests in an underground environment. Figure 3b gives the measurement results in an underground car park, which is located at a distance of 300 meters from the AP. EDs are installed in five typical places at the basement level for measurement purposes. The wireless signal can traverse through the exit or entry of the car park to reach the AP. The C/I value is shown for each place in Fig. 3b. The results indicate that LPWA M2M networks are also able to ensure reasonable underground coverage.

Multi-User Performance: Due to the large SFs in DSSS, signals from other devices are likely to be undetectable because they may fall below the effective noise floor. As a result, sensing the wireless channel is neither practical nor useful, and thus the MAC protocol works under the Aloha mode. Due to thousands of EDs in the LPWA M2M network, the packets from the EDs randomly arrive at the AP asynchronously. Collisions seldom occur even if packets arrive at the AP synchronously within one chip difference in time.

The multi-user (MU) performance of LPWA M2M networks is evaluated through two field tests, i.e. *MU-Case 1* for preamble detection and *MU-Case 2* for the near-far effect test. In *MU-Case 1*, five EDs are deployed on the second floor of the same building as shown in Fig. 3b, located 300 meters from the AP. Due to the limited number of EDs, the transmission timing of each ED is adjusted manually to ensure that the packets from all the EDs are able to arrive at the AP nearly simultaneously. Thus, this is similar to the highly concurrent traffic in an LPWA M2M network with a large number of EDs. Fig. 4a shows that the preamble of each packet sent from each ED is properly detected in the first half of the FFT window. Although the packets from ED 1 and ED 4 arrive at the receiver almost at the same time, their preambles are completely detectable and distinguishable.

The near-far effect of DSSS may degrade detection performance. However, this impairment has little impact on the LPWA M2M network because of the high spreading factors. The C/I values in *MU Case 2* are plotted in Fig. 4b. The transmit power of ED 1 is fixed, while the transmit power of ED 2 increases step by step. The dynamical fluctuation of the two curves is due to channel fading and variation. It can be observed that the transmit power of ED 2 has little effect on the C/I of ED 1.

Conclusions

LPWA M2M networks can meet the requirements of a broad range of IoT applications. Due to the ubiquitous coverage and low power consumption of the LPWA M2M network, endpoint devices are able to remain connected for an extended period of time. We first discussed and analyzed several application scenarios of LPWA M2M networks as well as the key techniques and early standards. Then field experiments were carried out with our developed SDR prototype to evaluate the field trial performances in urban environments. The large coverage performances are shown, e.g. more than 3 km in the outdoor environment and approximately 1 km in the indoor environment. Furthermore, the multiuser performance results are also presented to validate the MAC design. Our results clearly have demonstrated the feasibility and effectiveness of our developed prototype, as well as the advantages of LPWA M2M networks.

Acknowledgment

This work was supported by the National High-Tech R&D Program under grant 2015AA01A705, the China Natural Science Funding under grant 61271183, the National Key Technology R&D Program of China under grant 2015ZX03002009-004, and the Fundamental Research Funds for the Central Universities under grant 2014ZD03-02.

References

[1] K. Zheng *et al.*, "Radio Resource Allocation in LTE-Advanced Cellular Networks with M2M Communications," *IEEE Commun. Mag.*, vol. 50, no. 7, July 2012, pp. 184–92.

[2] L. Lei *et al.*, "Performance Analysis of Device-to-Device Communications with Dynamic Interference Using Stochastic Petri Nets," *IEEE Trans. Wireless Commun.*, vol. 12, no. 12, Dec. 2013, pp. 6121–41.

[3] Z. M. Fadlullah *et al.*, "Toward Intelligent Machine-to-Machine Communications in Smart Grid," *IEEE Commun. Mag.*, vol. 49, no. 4, Apr. 2011, pp. 60–65.

[4] T. Adame *et al.*, "IEEE 802.11AH: The WiFi Approach for M2M Communications," *IEEE Wireless Commun.*, vol. 21, no. 6, Dec. 2014, pp. 144–52.

[5] J. Morrish, "Low Power Wide Area Wireless Network Technologies for M2M: A Technical Comparison of On-Ramp, Sigfox and Weightless," *Machina Research*, June 2013.

[6] "IEEE Standard for Local and Metropolitan Area Networks Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 5: Physical Layer Specifications for Low Energy, Critical Infrastructure Monitoring Networks," *IEEE Std 802.15.4k-2013*, Aug. 2013.

[7] T. Ulversoy, "Software Defined Radio: Challenges and Opportunities," *IEEE Commun. Surveys & Tutorials*, vol. 12, no. 4, 4th Quarter 2010, pp. 531–50.

[8] S. Bayat *et al.*, "Distributed Data Aggregation in Machine-to-Machine Communication Networks Based on Coalitional Game," *IEEE Wireless Communications and Networking Conf. (WCNC)*, Istanbul, Turkey, Apr. 2014, pp. 2026–31.

[9] W. Webb, *Dynamic White Space Spectrum Access*, Webb Search Limited, Oct. 2013.

[10] *Weightless System Specification (version 0.8)*, Weightless SIG, July 2012.

[11] H. R. Walker, *Ultra Narrow Band Modulation Textbook*, Dec. 2014, http://www/vmsk.org/.

[12] K. Zheng *et al.*, "Challenges of Massive Access in Highly Dense LTE-Advanced Networks with Machine-to-Machine Communications," *IEEE Wireless Commun.*, vol. 21, no. 3, Jun. 2014, pp. 12–18.

[13] A. Bachir *et al.*, "MAC Essentials for Wireless Sensor Networks," *IEEE Commun. Surveys & Tutorials*, vol. 12, no. 2, 2nd Quarter 2010, pp. 222–48.

[14] Q. Mamun, "A Qualitative Comparison of Different Logical Topologies for Wireless Sensor Networks," *Sensors*, vol. 12, no. 11, Nov. 2012, pp. 14998–13.

[15] X. Xiong *et al.*, "Implementation and Performance Evaluation of LECIM for 5G M2M Applications with SDR," *IEEE Globecom Wks.ps (GC Wksps.)*, Austin, USA, Dec. 2014, pp. 612–17.

Biographies

Xiong Xiong received his B.S. degree from Beijing University of Posts&Telecommunications (BUPT), China, in 2013. Since then he has been working toward a Ph.D. degree at BUPT. His research interests include M2M networks and software defined radio.

Kan Zheng [SM'09] is currently a full professor at Beijing University of Posts & Telecommunications (BUPT), China. He received the B.S., M.S., and Ph.D. degrees from BUPT, China, in 1996, 2000, and 2005, respectively. He has extensive experience in the research and standardization of the new emerging technologies. He is the author of more than 200 journal articles and conference papers in the field of wireless networks, M2M networks, VANET, and so on. He holds editorial board positions for several journals. He has organized several special issues in famous journals including *IEEE Communications Surveys & Tutorials*, *IEEE Communication Magazine*, and *IEEE System Journal*.

Rongtao Xu received his bachelor degree in radio technology from Xian Jiaotong Universy in 1997, the master degree in communication and information system from Beijing University of Posts and Telecommunications in 2000, and the Ph.D. in electronic and information engineering from Hong Kong Polytechnic University in 2007. From 2000 to 2003 he worked at Siemens Ltd. China as a system engineer. In 2007 he joined Beijing Jiaotong University, where he is currently an associate professor with the State Key Laboratory of Rail Traffic Control and Safety. His research areas include wideband mobile communications, railway communications, and wireless sensor network.

Wei Xiang [SM'10] received the B.Eng. and M.Eng. degrees, both in electronic engineering, from the University of Electronic Science and Technology of China, Chengdu, China, in 1997 and 2000, respectively, and the Ph.D. degree in telecommunications engineering from the University of South Australia, Adelaide, Australia, in 2004. Since January 2004 he has been with the School of Mechanical and Electrical Engineering, University of Southern Queensland, Toowoomba, Australia, where he is currently an associate professor. He has been awarded a number of prestigious fellowship titles, including the Queensland International Fellow (2010–2011) by the Queensland Government of Australia, the Endeavour Research Fellow (2012–2013) by the Commonwealth Government of Australia, the Smart Futures Fellow (2012–2015) by the Queensland Government of Australia, and the JSPS Invitational Fellow (2014–2015) by the Japan Society for the Promotion of Science (JSPS). He received the Best Paper Award at the 2011 IEEE WCNC, and the USQ Excellence in Research Award in 2013. He is an editor of *IEEE Communications Letters*. His research interests are in the broad area of communications and information theory, particularly coding and signal processing for multimedia communications systems.

Periklis Chatzimisios serves as an associate professor at the Computing Systems, Security and Networks (CSSN) Research Lab of the Department of Informatics at the Alexander TEI of Thessaloniki (ATEITHE), Greece. Recently he was a visiting academic/researcher at the University of Toronto (Canada) and Massachusetts Institute of Technology (USA). Dr. Chatzimisios is involved in several standardization activities serving as a member of the Standards Development Board for the IEEE Communication Society (ComSoc) (2010 to today), and recently as an active member of the IEEE Research Groups on IoT Communications & Networking Infrastructure and on Software Defined & Virtualized Wireless Access. He is also very active in IEEE activities such as serving as the vice chair of the Emerging Technical Subcommittee on Big Data (TSCBD) and the secretary of the IEEE Technical Committee on Cognitive Networks (TCCN) (2012-2014). He has served as organizing/TPC committee member for more than 150 conferences and as a founder/organizer/co-chair for many workshops that are co-allocated with major IEEE conferences. He also holds editorial board positions for several IEEE and non-IEEE journals, and he is the director (co-director from 2012 to 2014) for the E-letter of the IEEE Technical Committee on Multimedia Communications (MMTC). He is the author/editor of eight books and more than 100 peer-reviewed papers and book chapters on the topics of performance evaluation and standardization activities of mobile/wireless communications, quality of service/quality of experience and vehicular networking. His published research work has received more than 1500 citations by other researchers. He received his Ph.D. from Bournemouth University (UK) (2005) and his B.Sc. from Alexander TEI of Thessaloniki (Greece) (2000).

LPWA M2M networks can meet the requirements of a broad range of IoT applications. Due to the ubiquitous coverage and low power consumption of the LPWA M2M network, endpoint devices are able to remain connected for an extended period of time.