A Survey of Enabling Technologies of Low Power and Long Range Machine-to-Machine Communications

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***Abstract*—Low power and long range machine-to-machine (M2M) communication techniques are expected to provide ubiquitous connections for the wireless devices. In this paper, three major low power and long range M2M solutions are surveyed. The first type of solutions is referred to as the low power wide area (LPWA) network. The design of the LPWA techniques features low cost, low data rate, long communication range, and low power consumption. The second type of solutions is the IEEE 802.11ah which features higher data rates using a wider bandwidth than the LPWA-based solutions. The third type of solutions is operated under the cellular network infrastructure. Based on the analysis of the pros and cons of the enabling technologies of the surveyed M2M solutions, as well as the corresponding deployment strategies, the gaps in knowledge are identified. The paper also presents a summary of the research directions for improving the performance of the surveyed low power and long range M2M communication technologies.**

***Index Terms*—M2M, LPWA, IEEE 802.11ah, LTE-M, NB-IoT.**

I. Introduction

MACHINE-TO-MACHINE (M2M) communication is defined as: "communication occurs among machines (some objects or devices) with computing/communication capabilities without human intervention" [1]. To a great extent, the machines in M2M networks will be battery powered, with energy consumption of communication dominating that of computing. In order to prolong the battery lifetime, this necessitates that machines (devices) consume low transmit (Tx) energy, in other words, use low Tx power, which serves as a key requirement of M2M communication. On the other hand, the communication range also needs to be considered in M2M communication networks. According to [2], typical M2M network applications include: e-Health, smart environment (both indoor and outdoor), intelligent transportation, security and public safety, and various futuristic applications [2]. For example, in the e-Health system, on-body/in-body wireless health monitoring sensors may need to transmit data to the doctor or health service provider's office that can be miles away. Moreover, for the M2M-enabled intelligent transportation systems application, the mobility of vehicles requires wide area network (WAN) connection. Therefore, long communication range is another key requirement for a wide variety of practical M2M communication applications. Combining the low Tx power and long range requirements, the M2M communications treated in this paper are referred to as low power and long range M2M communications.

A study of traffic patterns is important when designing the enabling technologies of low power and long range M2M communication network. This is because M2M communication traffic patterns tend to be significantly different than that of the human-to-human (H2H) communication [3]. The major characteristics of the traffic patterns in M2M communication networks are summarized as follows:

- Uplink (UL) traffic dominated [2];
- Bursty traffic due to the event-driven wireless sensor networks (WSN) [4];
- Varying traffic loads [5];
- Varying quality of service (QoS) characteristics (e.g., traffic of wireless devices having different delay and throughput requirements) [6].

In typical M2M networks, the UL traffic originates from the wireless devices, destines to the access point (AP, or the sink node, or the base station) and is heavier than the downlink (DL) traffic. This is caused by the fact that the current M2M communication applications are mostly used for data gathering. Thus, in this paper, the focus is on the solutions for handling the UL traffic dominated characteristic. Besides the UL traffic direction feature, the bursty nature of M2M communication data traffic should also be considered. Combining the influence of massive access caused by the large number of machines with bursty traffic introduces high collision rate to the network. The traffic loads are determined by the data rate and channel utilization characteristics, as well as the number of active devices. For the high data rate cases, wider bandwidth and higher modulation and coding scheme (MCS) can be used with a tradeoff of higher energy consumption due to the higher noise level. Meanwhile, the limited channel resources makes the wide bandwidth communication unfavorable when the number of simultaneous transmissions is high, which can be considered as a scalability issue. Furthermore, the M2M network applications have different QoS requirements. For example, the delay requirement of a fire alarm system is more

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stringent than that of an air conditioning control device in a home automation network.

Generally, the design of the enabling technologies for a wide variety of low power and long range M2M communication networks is challenging. There are three major reasons. First, the number of devices that are connected and maintained by one AP is usually large in an M2M communication network. It is highly likely that the large number of devices share limited network resources such as spectrum and time slot. If the network is designed for the highly congested industrial, scientific and medical (ISM) radio band, the coexistence problem needs to be studied. Meanwhile, for the licensed radio band deployment scenarios, the operating cost of using the spectrum also influences the design. Second, the energy consumption of M2M communication network devices is usually constrained. Wireless devices must operate on their own batteries for years instead of days. This constraint poses design challenges on both the physical (PHY) layer and media access control (MAC) layer protocols. Therefore, while on the one hand low Tx power and high receiver sensitivity are expected, on the other hand, the channel access mechanism must be energy aware, minimizing the energy consumption. Third, it is likely that one network supports M2M communication devices with ability to generate and process different traffic patterns. Under this scenario, the MAC scheme of the network must be adaptive to the different traffic types to achieve energy efficiency while maintaining their QoS requirements.

In this paper, three types of low power and long range M2M communication enabling technologies are reviewed: (i) LPWA network, (ii) Sub-1 GHz wireless local area network (i.e., Sub-1 GHz WLAN, IEEE 802.11ah [7]), and (iii) cellular-based M2M communication network. To achieve energy efficiency, LPWA solutions apply the ultra-narrowband (UNB) transmission that demodulates the signal with low receive power (-142 dBm) [8], and the network devices operate at extremely low duty cycle (e.g., only transmit several bytes per day [9]). The cellular-based M2M solutions also apply the concept of narrow bandwidth for energy efficiency [10]. Besides energy efficiency, scalability is also important for low power and long range M2M communication solutions. For the LPWA solutions, spread spectrum can be used to demodulate multiple signals simultaneously. The IEEE 802.11ah features a grouping based mechanism to reduce the possibility of collision in massive access situations. As for the cellular-based solutions, dedicated random access (RA) channel is used to support large number of active user devices.

The motivation for discussing the three types of M2M network solutions is twofold. First, the three M2M network solutions are the representative technologies in the field of low power and long range M2M communication. Second, the three solutions complement each other through interconnectivity to enhance the reachability of wireless devices to the Internet. As an illustration, Fig. 1 shows a possible interconnection scheme of the surveyed technologies. Notice from Fig. 1 that the wireless nodes in the cellular-based M2M network connect to the Internet through the evolved NodeB (eNodeB) which operates in the licensed frequency band. For LPWA networks, most

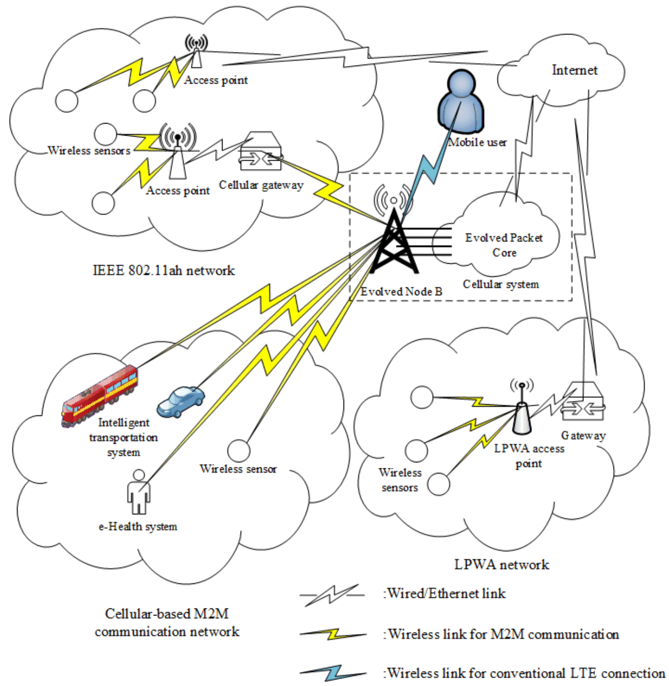

Fig. 1. Interconnection of the surveyed low power and long range M2M communication networks.

of the existing solutions, e.g., LoRaWAN (Long Range Wide Area Network) [11] only define the PHY and MAC mechanisms and the higher layer protocols are not directly supported. Hence, Internet access by such LPWA networks is via a gateway, as shown in Fig. 1. If a M2M network is expected to have native TCP/IP (Transmission Control Protocol/Internet Protocol) support, it is beneficial to use the cellular-based solutions. Meanwhile, due to the high deployment of the cellular infrastructure in an urban area, cellular-based network solution is more suitable for M2M applications requiring high reliability. Those applications include the intelligent transportation system (such as the connected car/train), and the e-Health system. The eNodeB in Fig. 1 is also responsible for the conventional Long-term Evolution (LTE) connection, such that the mobile users can use the services provided by the M2M communication networks (i.e., the IEEE 802.11ah, the cellular-based, and the LPWA networks). For the IEEE 802.11ah network, Internet connection can be realized either through the Ethernet link, or through the cellular gateway. Generally, Internet access is the major reason of having interconnections among the different networks.

Several works have been reported in the literature, surveying the current state-of-the-art technologies for M2M communications. In [11], the LPWA standards and proprietary LPWA technologies, as well as the challenges and open research directions of LPWA in general are discussed. However, the details on the PHY and MAC layers of the surveyed solutions, the deployment strategies of the surveyed technologies, and the potential methods to enhance the performance of the surveyed technologies, were omitted. In [12], the PHY and MAC layers of only the IEEE 802.11ah are introduced in the context of smart city application. The cellular-based M2M solutions are surveyed in [2], [4], [13], and [14]. Unlike the aforementioned survey works, this paper presents in a holistic manner the PHY and MAC layer technologies of all the three types of the low power and long range M2M communication solutions.

The major contributions of this paper are multi-fold which are listed below:

- Holistic review of LPWA, Sub-1 GHz WLAN, and cellular-based M2M solutions, the representative technologies in the field of low power and long range M2M communication.
- In-depth assessment of the pros and cons of the three surveyed technologies.
- Presentation of the network deployment strategies of the three technologies.
- Identification of the gaps in knowledge and the open challenges of the three technologies.
- Proposal of future research directions to bridge the gaps in knowledge and to tackle the open challenges.

The remainder of this paper is organized as follows. The LPWA solutions, including both the open and proprietary solutions, are discussed in Section II. The PHY and MAC layer technologies of the IEEE 802.11ah are provided in Section III. A review of the cellular-based M2M solutions is the topic of Section IV. In Section V, the network deployment strategies of the surveyed low power and long range M2M communication solutions are presented. The gaps in knowledge and the open challenges of designing the low power and long range M2M communication enabling technologies form the topic of Section VI. The future research directions are presented in Section VII. Finally, Section VIII concludes the paper.

II. Low Data Rate LPWA Solutions

The majority of current low power M2M communication technologies are designed for short range communication. For example, the Bluetooth (IEEE 802.15.1) [15] is targeting short range communication, and the Zigbee/IEEE 802.15.4 [16] is proposed for local area wireless sensor networks (WSNs). In some application scenarios, such as infrastructure monitoring, smart transportation, asset tracking, security and healthcare [17], energy efficient long range communication technologies are required. The LPWA is proposed to bridge the gap between the current low power M2M network solutions and the long communication range requirement. In this section, a survey of the mainstream LPWA PHY and MAC technologies is conducted.

A. LECIM Based Prototype LPWA Network

In [17], a low energy critical infrastructure monitoring (LECIM), known as IEEE 802.15.4k based prototype LPWA network, is designed. The LECIM works in the 433 MHz and is developed to allow one AP to connect with thousand endpoints located at long distances (up to 20 km) [18]. Since the most popular choices of the LPWA PHY in the literature are UNB and spread spectrum mechanisms, the choice of PHY layer technique of the prototype LPWA solution needs to be justified. The UNB PHY and the direct sequence spread spectrum (DSSS) PHY are compared in [17]. According to the comparison, the UNB modulation contains two stages: first, the phase of the carrier is "abruptly changed" to represent the digit one and zero. Second, a UNB filter with zero or negative group delay is used to keep only the single sideband. Thanks to the UNB filter, the output of the signal has only 1 Hz bandwidth in theory, thus the noise power level is low [17]. However, it is pointed out in [17] that there is no practical method to implement the UNB band filter, which renders the UNB impractical.

Unlike the UNB PHY, the DSSS approach shows its prominence as a practical LPWA PHY solution. The reasons lie in the large processing gain which allows the receiver to deal with very low carrier-to-interference ratio, such that the Tx power can be reduced [17]. In spite of the relatively higher computational complexity, the prototype system in [17] chooses the DSSS as its PHY protocol. The UNB is not applied because of the aforementioned filter issue. Details of the DSSS PHY design of the prototype LPWA network are based on the LECIM DSSS mechanism defined in [16].

Instead of using the binary phase-shift keying (BPSK) or offset-quadrature phase shift keying (O-QPSK) originally designed for LECIM, the Gaussian frequency-shift keying (GFSK) is chosen. According to [17], GFSK can overcome the "effect of the frequency and phase offset", while the details of how the conclusion is drawn are not provided. Therefore, it is necessary to conduct investigation regarding the performance difference between the GFSK and the LECIM modulation schemes (BPSK and O-QPSK). Moreover, for the proposed prototype system, the choice of the spreading factor 32,768 is not justified. The number 32,768 is the maximum spreading factor defined in [16], and it will unavoidably increase the processing power consumption at the transmitter side. Considering that the prototype network only has 5 nodes as transmitter, a more reasonable spreading factor should be used, under the consideration of the energy consumption and the multiple access performance.

Xiong *et al.* [17] also argue that the Aloha-based MAC protocol incurs less overhead than that of the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism due to lack of channel sensing before data transmission. On the other hand, the assumed DSSS PHY enables simultaneous access by multiple end devices to the same channel using different spreading sequences, but with the constraint of limited number of available orthogonal spreading sequences. Nonetheless, the testing results in [17] indicate that the proposed prototype design has acceptable multi-user performance, but the scalability of the spread-spectrum-based PHY and the Aloha-based MAC is still unclear, because just only 5 end devices are tested. It is also worth considering how the interference will impact the DSSS's multiple access performance. The interference mitigation mechanisms, such as the combing scheme of time division multiplexing, frequency division multiplexing and code division multiplexing proposed in [19], can be considered in the prototype system design. The other issue of the medium access performance study of the prototype system is the lack of channel allocation mechanism. The latest IEEE 802.15.4 standard defines 8 or 16 channels for DSSS in the 433 MHz band depending on the channel spacing [16]. In [17], since the channel sensing mechanism is claimed as "neither practical nor useful" and thus not utilized, the Aloha-based MAC will not be able to choose the less congested channels for transmission, and, consequently, the spectrum resources cannot be fully utilized in large scale networks. As a solution, methods of clear channel assessment (CCA) that are specifically developed for LPWA (i.e., LECIM) in [20] can be used.

In [21], a practical LPWA network which is based on the prototype system proposed in [17] is implemented to monitor the urban air quality. Like the LPWA in [17], the PHY is DSSS plus GFSK modulation, and the MAC protocol is still the Aloha-based mechanism. The sensor node in [21] has four major components, which are the power module, the controller module, the LPWA Tx module and the sensor module. More specifically, the LPWA Tx module includes the Texas Instruments CC1125 chip that can transmit the modulated signal, and a baseband signal processor. In order to save energy, the spreading sequences only need to be calculated once and stored in the memory after the node is powered on. When the node gets into Tx mode, the calculated sequences can be read from the memory. The proposed air quality monitoring system also applies the solar panel to charge the battery; however, the energy consumption rate and the network lifetime are not studied.

An evolved frequency-shift keying (FSK) modulation at the transmitter and a turbo-decoder dedicated to the FSK waveforms at the receiver are proposed in [22] to enable the low power UL transmissions for the LPWA networks. According to the simulation results provided in [22], the new mechanism, which is referred to as turbo-FSK, requires lower energy-per-bit-to-noise power spectral density ratio, E_b/N_0 to achieve the same level of performance compared with the spreading sequence based mechanisms (i.e., the 32-FSK with spreading factor 5 and BPSK with spreading factor 32). Hence, the turbo-FSK mechanism transmits at a lower power than the spreading sequence based mechanisms. The limitation of [22] is that it only considers the modulation scheme for the LPWA networks, while the corresponding MAC mechanism is not discussed. It is worth noting that the DSSS allows multiple end devices to be detected and identified simultaneously on one channel [17], which makes the use of low complexity MAC layer mechanism such as the Aloha feasible. Therefore, in order to make the turbo-FSK a practical LPWA solution, first it requires a network overhead study comparing with that of the conventional FSK. Second, a multiple access mechanism should be developed to deal with the massive access requirement.

The spread spectrum PHY is the most common solution for LPWA due to its interference tolerance. Nevertheless, Anteur *et al.* [23] suggest that the UNB principle is also a good candidate for LPWA because it can concentrate the Tx power into narrow frequency bandwidth which is beneficial to the link budget. However, the design of the MAC layer mechanism for such UNB PHY scheme is challenging. Firstly, frequency variation can be observed at the receiver side. Second, local oscillator of the transmitter may also introduce frequency drift to the signal when the moving speed of the transmitter is high [23] (Doppler effect). In order to study the effects of the frequency drift in the medium access performance of UNB LPWA, the network performance metrics, such as the normalized throughput and the packet loss rate of the time/frequency Aloha (TFA), is evaluated considering the frequency variation and drift in [23]. However, the improvement of the TFA, such as using the forward error-correcting codes, is not evaluated.

B. Proprietary LPWA Solutions

Most of the current LPWA solutions are developed for commercial use and, hence, are proprietary. In [24], three proprietary solutions of low throughput networks which are mostly designed for smart metering are discussed. All the three solutions feature low power consumption and long communication range (tens of kilometers according to [24]), therefore they can also be ascribed as LPWA network technologies.

The first solution is from INGENU [25], which has proposed its proprietary RPMA-DSSS (random phase multiple access-direct sequence spread spectrum) scheme. Thanks to the random delay and the spread spectrum, the AP demodulator using RPMA-DSSS can "simultaneously demodulate several thousand or more links received from tags (end devices)" [26]. On the other hand, RPMA-DSSS is deployed at the 2.4 GHz ISM band instead of the Sub-1 GHz ISM band. The benefits of using the 2.4 GHz ISM band over the Sub-1 GHz band are including: higher allowable Tx power and antenna gain, available worldwide, no duty cycle limit, and wider available spectrum [25]. The simulations performed in [24] suggest that, the less the two transmissions in the same time slot are overlapped, the better the bit error rate (BER) performance would be. This is because the effect of the intercode interference (ICI) can be less severe if the simultaneous transmissions are not completely overlapped. It is worth noting that the low overlap level requires the actual Tx time to be short, such that the channel is not fully utilized.

The second proprietary LPWA solution in [24] is proposed by Sigfox, which utilizes the UNB to achieve high sensitivity [24]. The bandwidth of the Sigfox signal is 100 Hz, and it can allow successful demodulation of the received signal at a sensitivity of -142 dBm [24]. The MAC mechanism of the Sigfox is the random frequency division multiple access (R-FDMA) [27]. In [8], the interference model of the R-FDMA is analyzed, such that the closed form of bit error rate (BER) and outage probability (OP) metrics are derived. By using the proposed BER and OP expressions, the network capacity is evaluated in [8]. The communication range of the Sigfox is tested in [28]. The test results suggest that, by using 14 dBm Tx power, the signal-to-noise ratio (SNR) can be higher than 20 dB over the 25 km test link [28]. More details on Sigfox are provided in [29].

The third solution discussed in [24] is the LoRaWAN offered by Long Range (LoRa) Alliance. It operates in the 433, 868 or 915 MHz ISM band, and it either uses GFSK or its proprietary LoRaWAN modulation scheme [24]. LoRaWAN's proprietary modulation scheme is based on the chirp spread spectrum (CSS) that "uses wideband linear frequency modulated pulses whose frequency increases or decreases based on the encoded information" [9]. Because of the broadband chirps, the LoRaWAN modulation can deal with both multipath fading and Doppler effect [9]. On the other hand, in order to improve the spectrum efficiency and the multiple access performance, six orthogonal spreading factors are used to further spread the spectrum, and to enable the use of a pure Aloha MAC layer scheme [9]. According to the analysis in [9], the maximum UL throughput of LoRaWAN is less than 2 kbps, while regarding the scalability, "a single LoRaWAN cell can potentially serve several millions of devices sending few bytes of data per day" [9]. However, the appropriate spreading factors allocation mechanism with respect to the tradeoff between the data rate and the energy efficiency remains unknown.

Among the aforementioned proprietary LPWA solutions, the LoRaWAN has been studied intensively in the literature. The signal coverage of LoRaWAN is investigated in [30] through experiments. In [30], the Kerlink's LoRa Internet of Things (IoT) station with bi-conical D100-1000 antenna from Aerial serves as base station, which is located 24 m above sea-level, while the end device choice is the Semtech SX1272 transceiver with Planar-F type printed circuit board antenna. Both car and boat are used to measure the packet loss ratio and path loss due to the geographical location of Oulu, Finland being close to the sea. The results show that, for the measurements done by the car, the ranges 0 – 2 km, 2 – 5 km, 5 – 10 km and 10 – 15 km have 12%, 15%, 33% and 74% packet loss ratio, respectively, and the path loss exponent is 2.32. As for the measurements done by the boat, for ranges 5 – 15 km and 15 – 30 km, the packet loss ratio is 31% and 38%, respectively, and the path loss exponent is 1.76. The reason why the path loss exponent is less than 2 (free-space) is not discussed in [30]. The performance difference of the two different PHY settings supported by LoRaWAN regarding the communication range is tested in [31]. The results suggest that, for low rate LoRaWAN PHY (i.e., spread spectrum with spreading factor 10, bandwidth 250 kHz, coding rate 4/6 and data rate 1,627.6 bps), the error free transmission ranges of 10-byte payload, 50-byte payload, and 100-byte payload are 7.482 km, 1.346 km, and 2.302 km, respectively. For the high rate LoRaWAN PHY (i.e., FSK modulation with deviation value of 50 kHz and data rate 100 kbps), the error free transmission range of both 16-byte payload and 64-byte payload is 0.276 km. Clearly the communication range of low data rate LoRaWAN is much longer than that of high data rate LoRaWAN, demonstrating the data rate vs. communication range tradeoff. For the indoor performance evaluation of LoRaWAN, a health monitoring system based on LoRaWAN is tested in [32]. The tests are performed in the main campus of the University of Oulu, Finland. By using 14 dBm Tx power, and the spreading factor of 12 in the 868 MHz European Sub-1 GHz ISM band, the packet success delivery ratio is 96.7% [32]. It is worth noting that all the LoRaWAN evaluations surveyed focus on the communication range and packet error rate performance, while the multiple access performance of the LoRaWAN is not studied in the surveyed literature.

Besides the OnRamp, Sigfox and LoRaWAN, there are also other LPWA solutions such as the NWave, Telensa, Weightless-N, Weightless-P, and Amber Wireless as mentioned in [14]. Almost all of them are proprietary. It is challenging to find papers in the literature that systematically study the pros and cons of those technologies under different application scenarios. However, thanks to the patents (e.g., [26]) and specifications (e.g., [33]) that are available to the public, it is possible to evaluate the key techniques which have been adopted by those proprietary LPWA solutions through simulation and/or experimentation using software defined radio (SDR) as a direction for future research.

TABLE I
KEY TECHNOLOGIES OF SURVEYED LPWA SOLUTIONS

Solutions	LECIM-based prototype LPWA	RPMA	Sigfox	LoRa
PHY	DSSS+GFSK	Proprietary RPMA-DSSS	UNB	GFSK/CSS based LoRaWAN proprietary modulation scheme
MAC	Pure Aloha	Pure Aloha	R-FDMA	Pure Aloha

C. Summary of the Reviewed LPWA Solutions

In this section, two types of PHY solutions for LPWA networks namely the spread spectrum and the UNB are reviewed in detail. The spread spectrum mechanism allows a large number of data links to be demodulated simultaneously, such that the simple pure Aloha MAC can be used. The high sensitivity nature of the spread spectrum receiver and the low complexity MAC scheme make the spread spectrum based PHY a popular choice for LPWA networks. To the best of the authors' knowledge, spread spectrum (both DSSS and CSS) and UNB are the mainstream choices of LPWA PHY. For example, the prototype networks in [17] and [21], and the proprietary solutions [26], [33] are all based on the spread spectrum PHY. Meanwhile, the suitability of using the UNB is justified in [23]. The Sigfox is an example of a successful UNB deployment in LPWA.

All the aforementioned LPWA network techniques are targeting the low data rate M2M communications. However, in real life, different application scenarios have different data rate, scalability, communication range, and energy consumption requirements. Hence, more work on performance comparison is required, such that the choice of PHY and MAC protocols for a specific application scenario can be justified. All the enabling technologies of the surveyed solutions are summarized in Table I. For the applications that require both high data rate and long communication range, the IEEE 802.11ah [7] is presented as a solution and reviewed in the next section.

III. HIGH DATA RATE LPWA SOLUTION: IEEE 802.11AH

Recently, the IEEE 802.11ah has been proposed as a Wi-Fi solution specifically for high data rate and long range WLAN-based M2M networks [7], which is reviewed in this section. Note that the IEEE 802.11ah can support a wide range of data rates from 150 kbps to 8 Mbps [34]. Hence, the IEEE 802.11ah can be considered as a high data rate LPWA solution, and it also features the highest maximum data rate among all the low power and long range M2M communication solutions surveyed in this paper.

A. Overview of the IEEE 802.11ah Standard

The Wi-Fi technology has the capability to deal with high data rate requirement. For example, the IEEE 802.11ac can achieve more than 500 Mbps using 80 MHz channels [35]. Despite the fact that Wi-Fi technology is designed primarily for local area coverage, the study of Wi-Fi's long range performance is carried out in [36] through field tests. The testing results indicate that, if the IEEE 802.11n is used, the maximum throughput of 148 Mbps and 40.8 Mbps can be achieved at a range of 800 m and 1,800 m, respectively. Clearly the IEEE 802.11n has much better performance in terms of data rate than its precursors. However, the experimental network in [36] features the MIMO (multiple-input, multiple-output) technique, which may not be available for an M2M network that has low power and low cost requirements, not to talk about the small form factor of the devices in some applications, e.g., biomedical sensors. Furthermore, the performance tests in [36] focus more on the evaluation of the PHY layer techniques, and the MAC layer protocol is not studied. Hence, the suitability of using the IEEE 802.11n for a large scale M2M network is unknown.

The IEEE 802.11ah is an IEEE 802.11 standard amendment that defines the Sub-1 GHz license-exempt operation to support sensors and IoT applications [37]. At the time of writing this survey, the standard is still under development by the IEEE TGah (Task Group ah). Recently, a group of researchers has developed a programmable modem for IEEE 802.11ah research [38]. The objective of this particular Wi-Fi amendment is to provide better support for wireless sensors and metering network, backhaul network for sensors and meters, and the extended range Wi-Fi [37]. In this section, the new features of the PHY and MAC of IEEE 802.11ah which are designed for the aforementioned usage scenarios are discussed.

B. IEEE 802.11ah PHY

1) Sub-1 GHz License-Exempt Band: In North America, the IEEE 802.11ah frequency spectrum is available at the 915 MHz ISM band, and it has totally 26 MHz available bandwidth from 902 MHz to 928 MHz. There are pros and cons of operating a wireless communication system in this band. The benefit lies in the energy efficiency nature (due to the low propagation loss) at the low frequency bands. According to [37], the 915 MHz ISM band has 8.5 dB less free space propagation loss than the 2.4 GHz ISM band. The lower path loss can allow a higher transmission range for a given Tx power and receiver sensitivity or use a lower Tx power to cover a given transmission range. However, the downside of the 915 MHz ISM band is its limited bandwidth. Although it may be sufficient for the low data rate IoT applications [37], to guarantee the throughput of the large scale M2M network is still challenging due to the potentially high collision rate at the MAC layer. As a solution, the TGah proposes a restricted access window (RAW) based mechanism, which will be discussed later.

TABLE II
IEEE 802.11AH MCS SETTING VS. DATA RATE WITH 1, 2 MHZ BANDWIDTH, NSS = 1 AND GI = 8 μm [39]

MCS Index	Modulation	Coding rate	Data rate (kbps)	
			1 MHz	2 MHz
0	BPSK	1/2	300	650
1	QPSK	1/2	600	1300
2	QPSK	3/4	900	1,950
3	16-QAM	1/2	1,200	2,600
4	16-QAM	3/4	1,800	3,900
5	64-QAM	2/3	2,400	5,200
6	64-QAM	3/4	2,700	5,850
7	64-QAM	5/6	300	6,500
8	256-QAM	3/4	3,600	7,800
9	256-QAM	5/6	400	Not valid
10	BPSK	1/2 with 2x repetition	150	Not valid

2) Basic PHY Design: Since the IEEE 802.11ah is a down-clocked version of the IEEE 802.11ac, the orthogonal frequency-division multiplexing (OFDM) scheme is supported by the IEEE 802.11ah. Unlike the IEEE 802.11ac that has maximum 160 MHz bandwidth, the bandwidth of the IEEE 802.11ah ranges from 1 MHz to 16 MHz in the Sub-1 GHz radio band within the 26 MHz available bandwidth of the 915 MHz band. For the 1 MHz bandwidth, 2 pilot sub-carriers and 24 data sub-carriers per OFDM symbol are defined, while for the 16 MHz bandwidth, 16 pilot sub-carriers and 468 data sub-carriers are assigned for each OFDM symbol. Since the IEEE 802.11ah targets mostly M2M communication scenarios compared with the 802.11ac's human type high data rate communication scenarios, only the 1 and 2 MHz bandwidths are mandatory. Other bandwidths can be applied depending on the data rate requirement.

In order to provide different levels of data rate, the IEEE 802.11ah utilizes multiple sets of MCSs, number of spatial streams (NSS) and duration of the guard interval (GI) [39]. In terms of coding schemes, the binary convolutional coding (BCC) and low density parity check (LDPC) are applied to the IEEE 802.11ah [39]. The MCS settings and the corresponding data rates for 1 and 2 MHz bandwidths using 1 spatial stream and 8 μm GI are summarized in Table II. It is observed from Table II that, to achieve a wide range of data rates that are from low to high, multiple modulation schemes, including the BPSK, QPSK, 64-QAM (quadrature amplitude modulation), and the 256-QAM, are available in the IEEE 802.11ah PHY [40]. The higher data rate is achieved at the cost of higher SNR requirement, for example, the allowed error vector magnitude (EVM) of BPSK is -4 dB, while the allowed EVM of 256-QAM is -32 dB. The lower allowed EVM of the higher order modulation is because the higher order modulation schemes feature a denser constellation diagram, hence the signal is less tolerable to the error caused by noise. On the other hand, the minimum receiver sensitivity also depends on the modulation scheme, such that the minimum receiver sensitivity for the BPSK is -98 dBm, which is much higher than the 256-QAM's -72 dBm [40]. The reason is also the denser constellation diagram. On the other hand, by applying narrow bandwidth, e.g., 1 MHz, the SNR can be increased due to the reduced noise power with small bandwidth. Compared with the 2 MHz bandwidth, 1 MHz bandwidth can increase the SNR by 3 dB [37]. Therefore, for different application scenarios, different modulation and multiplexing schemes should be adapted depending on the data rate vs. energy consumption trade-off.

3) PHY Performance Evaluation: In [39], simulations are performed to evaluate the IEEE 802.11ah PHY performance. The PHY parameters of the simulations are: 0 dBm Tx power, 0 dB transmitter antenna gain, 3 dB receiver antenna gain, 3 dB noise figure and the coding method is BCC. The Tx power is limited to 0 dBm because of the low power consumption of the battery powered devices [39]. The simulation results suggest that if the larger MCS index is used for higher data rate transmission, the communication range will be reduced. For example, for the MCS 0 with 1 MHz bandwidth, the communication range is 640 m with 10% error rate, while for the MCS 9 with 1 MHz bandwidth, the communication range is only 130 m at the same error rate [39].

Since the support of the MIMO-OFDM is mandatory for the IEEE 802.11ah [41], the suitability of using MIMO-OFDM with narrow bandwidth channel should be studied. In [41], the performance of the MIMO-OFDM at the Sub-1 GHz band is evaluated on the "Hydra" platform. Nodes in "Hydra" have "flexible RF (radio frequency) front-end and a general purpose machine with software based MAC and PHY" [42]. As a comparison of the data rate performance using MIMO and SISO (single-input, single-output), it is reported in [41] that the highest Internet Control Message Protocol (ICMP) data rate of 2×2 MIMO is 91.31 kbps using QPSK with coding rate 3/4 (which is also the MCS 10 for the IEEE 802.11n), while the highest ICMP data rate of SISO is 87.8 kbps using the same MCS setting. The data rate improvement is trivial according to the results, but Aust *et al.* [41] did not provide any explanation about it. Therefore, considering that the MIMO may introduce computational overhead at the station (STA) or device side, it is unnecessary to apply the MIMO mechanism to the battery powered M2M network STAs, because the data rate improvement is limited. According to the proposal of the new generation Wi-Fi (the IEEE 802.11ax [43]), the orthogonal frequency-division multiple access (OFDMA) will be applied. Thus, the possibility of using OFDMA in the Sub-1 GHz band Wi-Fi could also be an interesting research direction for future study.

C. IEEE 802.11ah MAC

1) Overview of the IEEE 802.11ah MAC: One of the biggest challenges of designing the IEEE 802.11ah is to allow a large number of STAs (e.g., more than 6,000 STAs [44]) to be served by one AP. The RAW mechanism that can divide the large number of STAs into groups is provided as a solution. In each group, the collision is reduced due to small number of STAs competing with each other for accessing the shared channel. To associate the grouping information to the STAs, a hierarchical identification scheme for the STAs is introduced. The STAs are assigned with unique association identifiers (AID) that have a four-level structure: page, block, sub-block and stations [34]. Users can allocate AIDs to the STAs in a way that the network performance metrics, such as throughput, collision rate and energy consumption, are optimized. The AID has 14 bits, which can identify STAs' identifications from 1 to 8,191, while the identifications from 8,192 to 16,383 are currently reserved for future specification [7].

Under the hierarchical MAC framework, three different types of STAs are defined: traffic indication map (TIM) STA, Non-TIM STA, and unscheduled STA [45]. The TIM STA listens to its data transmission schedule (i.e., its own RAW) which is indicated by the TIM beacons [45]. The STA will stay in the sleep mode if there are no transmissions. For the DL transmission, if the AP has pending data for one of its associated STAs, that STA can be notified by listening to both the delivery traffic indication map (DTIM) and TIM which inform the STA to get the message at its own RAW. Likewise, the channel contention for UL transmission of TIM STA should also be constrained in its dedicated RAW. For non-TIM STA, the transmission is not scheduled in the RAW, instead, it occurs in the periodic restricted access window (PRAW) [45]. It is pointed out in [45] that non-TIM STA is suitable for periodical data transmission, while the TIM STA is optimized to handle high-volume data. However, to the best of the authors' knowledge, there is no work dedicated to the optimal TIM and non-TIM STAs designation mechanism for different traffic patterns so far. The unscheduled STA can ask for immediate channel access at any time in an infrequent manner by sending out a poll frame [45]. Upon receiving the poll frame, the AP will send out a response frame to indicate the time interval that is outside of both RAW and PRAW for the unscheduled STA to access the channel [45]. The benefit of using the RAW scheme is to restrict the number of STAs that simultaneously compete for channel access, that is, only the STAs in the same hierarchical level (group) can compete for the channel through the distributed coordination function (DCF). Therefore, the scalability and energy efficiency performance of the IEEE 802.11ah lies in the design of the RAW mechanism, which is discussed next.

2) Performance Analysis and Enhancements of the IEEE 802.11ah RAW Mechanism: Since the most significant feature of the IEEE 802.11ah is the RAW mechanism, several works have been dedicated to its performance and the improvement of the grouping strategy, such as [5], [34], and [46]–[48]. To study its performance, aspects such as the throughput, packet loss rate, collision rate, latency, power consumption and network scalability should all be considered. Moreover, M2M networks also feature different traffic patterns, as described in Section I. Modelling the traffic patterns of the STAs in a specific M2M network is nontrivial because several aspects must be considered: the packet size, packet sending frequency, which is also related with the packet generating interval, and the data rate requirement (including potentially different data rates of the preamble, PHY header and PHY payload). For example, for the alarm-initiated M2M traffic pattern studied in [49], the Beta distribution can be used.

The association procedure of the IEEE 802.11ah STAs is discussed in [50]. According to the simulation results, in a dense network, the "association process may take up to several minutes" [50] due to the fact that the association requesting STAs still need to contend with the STAs in a RAW. The long association time is negligible in static M2M networks because the STAs only need one association procedure. However, for the mobile STAs that require low latency data transmission, several minutes of waiting time is not acceptable. The solution provided by Sthapit *et al.* [50] is to constrain the number of active STAs in a network, which is impractical in a real network because the number of active STAs cannot be determined a-priori by the AP. Therefore, a more realistic solution is to allow the association requesting STAs to have dedicated resources (e.g., channel or time slot) to perform the association, which is similar to the random access channel (RACH) mechanism in the LTE. In future research, a mechanism should be investigated to determine an optimal resource allocation that can both satisfy the throughput requirement and the association latency.

In [51], an analytical model with given collision and error probabilities is developed to compute the saturation throughput and energy efficiency of the IEEE 802.11ah. The numerical results suggest that, for the packets with small payload (e.g., 256 bytes), it is more efficient to use the basic access mechanism instead of the request-to-send/clear-to-send (RTS/CTS) handshaking mechanism. This is to avoid the relatively large overhead caused by the RTS/CTS control frames. Meanwhile, the numerical results of the RAW performance evaluation show that, using the optimal RAW size (i.e., 10 slots for the network in [51]), the RAW can substantially improve the RTS/CTS mechanism's throughput and energy efficiency performance in a dense network, thanks to the reduced collision rate. Note that the optimal RAW size is determined through an exhaustive search. The work [51] demonstrates the performance improvement of using the RAW mechanism. However, only the saturation throughput is evaluated in [51], while the impacts of the heterogeneous traffic patterns are not studied.

Khorov *et al.* [12] claim that the dynamically changing traffic is more suitable to model the M2M communications. Instead of assuming that the number of active STAs remains unchanged, a dynamic set is used for the active STAs, and the number of active STAs decreases through time. By considering the dynamic traffic patterns for the M2M communication, the distribution of the time for completing data transmission is studied in [12], which can be used to determine the RAW slot duration if the network's traffic load can be estimated. However, the method of estimating the number of active STAs and their data amount is not provided in [12]. Furthermore, the grouping strategy is also not investigated in [12].

A study of the IEEE 802.11ah RAW mechanism using the simulation approach is reported in [34] and [39]. In [39], simulations are performed to evaluate the effectiveness of using the RAW in terms of improving throughput and justifying the size (i.e., the number of slots) of the RAW. For the evaluation of throughput improvement introduced by the RAW, two mechanisms, namely the legacy DCF and the RAW with 32 groups, are tested in a network of 512 STAs. Without the RAW, the average throughput during the simulation time is around 0.5 Mbps. Now when the RAW is applied, the average throughput goes up to 0.75 Mbps, as a result of reduced collisions. In [39], simulations are also performed to test the influence of using different RAW sizes. The results show that, for the network that has a small number of STAs, the RAW slot parameter has no effect on performance (including the throughput, latency per packet and packet loss percentage), while for a larger scale network (i.e., network with more than 40 STAs), more slots in a RAW lead to higher throughput, lower latency and less collision. However, the work [39] does not show the relationship between the traffic patterns and the grouping methods. Hence, in [34], by using the same simulation platform, the performance of different grouping strategies is studied. The simulation results of [34] suggest that, for a network that has heterogeneous traffic patterns, evenly splitting the STAs into groups can help to increase the throughput and reduce the latency. This is because the evenly distributed traffic prevents the situation where some groups have low channel utilization while other groups are too congested. In other words, the load is more balanced. The work [34] only proves that the "even" grouping method is optimal for the static heterogeneous traffic patterns. In a real M2M network, it is possible that the traffic patterns will keep changing. Hence, in order to propose a practical grouping mechanism, there must be an efficient way to detect or predict the STAs' traffic patterns by the AP in real time. Besides, the hidden node issue should also be considered in the grouping strategy design.

Hidden node problem is one of the key issues whose solution remains elusive in the context of WLANs, especially for long range outdoor environment [37]. As shown by the outdoor environment scenario provided in [37], the AP is located at the rooftop of a building, and the STAs are deployed near the ground. The result is much higher path loss between STAs, while the path loss between the STA and the AP is lower. For the battery-powered low power and low cost M2M network STAs, in order to save energy, the peer-to-peer communication and relaying are not supported. This is because the buildings or any other obstructions between the STAs that are near the ground may heavily attenuate the signal, while the signal between the STAs and the AP (at an elevated location) is likely to be line-of-sight. Consequently, it is hard for the STAs to detect each other's transmissions, thus they become hidden nodes to each other. In [46], it is justified that the hidden node problem can be mitigated by an "AP assisted medium access using synch frame". If the medium is sensed as idle by the AP, it will send out a synch frame after a predetermined period within a slot. Upon receiving the synch frame, the STA that is allocated to this time slot can then start transmission. The downside of using the synch frame mechanism is that, should the synch frame be lost, the STAs may lose their chance to send data. On the other hand, a portion of the time slot will be used by the STAs to determine the availability of the medium, which will reduce the channel utilization. Therefore, a more practical solution is needed to improve the probability of detecting the ongoing data transmission. As one promising approach, a spatial grouping mechanism is proposed in [47] to allow the STAs to be able to detect ongoing transmissions. The STAs that are geographically close to each other will be grouped together in one RAW. Since the signal attenuation between any two competing STAs is low, the ongoing transmission will be detected with higher probability, such that the hidden node problem can be mitigated. Simulation results show that the throughput achieved using the spatial group RAW scheme is much improved compared with that of using only RAW or DCF. However, a way to realize the spatial grouping is not introduced in [47]. Meanwhile, different traffic patterns are not considered by the grouping mechanism, which may result in only sub-optimal network performance.

The influence of the holding period is studied in [52]. In order to keep the data transmissions of the STAs from one group within the designated RAW, all active STAs should stop and save their backoff counters at the beginning of the holding period, such that no new transmissions will be started. The holding period takes up the channel access time of the STAs, thus if the RAW size (channel access period duration in [52]) and the group counts are not optimal, the throughput will not be improved, according to [52]. Although the importance of finding optimal grouping configuration is emphasized by [52], a practical grouping strategy is not provided other than exhaustive searching. In [53], different holding schemes, namely the "FIXED", "DECREMENTING", "VARIABLE" and "HYBRID" are introduced and evaluated. It is worth noting that the holding scheme in [52] is ascribed as the "FIXED" scheme in [53], because the backoff counters are frozen in the holding period. To improve the channel utilization, it is also pointed out in [53] that the AP should keep track of all the STAs' backoff status, such that the transmissions are spread out in the RAW. However, this idea assumes that the AP has all the STAs' backoff information. Therefore, in order to make the solution applicable, a mechanism that can efficiently acquire large number of STAs' backoff information before the beginning of the following RAW is expected.

In [48], a virtual grouping with power saving method is introduced. By applying random arbitration inter-frame spacing (AIFS), the STAs can be divided into contending STAs' group and non-contending STAs' group. In order to achieve power saving, the STAs that are recognized as non-contending consecutively for longer than a time threshold can transit into sleep mode. There are several drawbacks of the virtual grouping with power saving method presented in [48]. Firstly, the virtual grouping is not developed under the latest RAW framework presented in [12], namely it only has two groups (contending and non-contending), which may not support a large number of STAs. Second, the random AIFS assignment mechanism cannot differentiate the various traffic patterns of M2M networks. Finally, the proposed power saving mode may not be useful in a saturated traffic condition.

A grouping method that can optimize the channel utilization is proposed in [5]. Due to the different sampling rate and packet size, the wireless sensors feature different traffic patterns. In order to achieve load balance, an integer programming optimization problem is presented to maximize the channel utilization of the wireless sensors. The performance evaluation results suggest that the proposed greedy algorithm based solution can improve the channel utilization when the network is almost saturated. However, the network model in [5] is not realistic, because the hidden node problem is not considered. On the other hand, grouping parameters such as the RAW size, number of STAs in a RAW, and number of groups in total are not studied in the problem. To achieve high energy efficiency of the RAW mechanism, another optimization problem is proposed in [54]. The problem is formulated based on the model in [55] and solved by using the simulated annealing method. There are two issues for the work in [54]: first, the potential latency caused by using the simulated annealing method on an AP is not justified. Second, the energy consumption model does not consider the PHY layer attributes.

TABLE III
ENHANCEMENT OF THE IEEE 802.11AH RAW MECHANISM

General concept	Traffic pattern	Hidden terminal issue	Performance evaluation method	Computation technique	Reference
Even grouping method	Yes	No	Simulation	N/A	[34]
Synch frame	No	Yes	Simulation	N/A	[46]
Spatial grouping	No	Yes	Simulation	N/A	[47]
Virtual grouping with power saving	No	No	Simulation	N/A	[48]
Maximize channel utilization	Yes	No	Simulation	Greedy algorithm	[5]

D. Summary of the IEEE 802.11ah Standard Survey

In this section, the IEEE 802.11ah Standard which operates in the unlicensed Sub-1 GHz radio band is reviewed. The RF characteristics of the Sub-1 GHz radio band allow a longer transmission range compared to the higher frequency ISM band. This is because the 915 MHz band has 8.5 dB less free space propagation loss than the 2.4 GHz radio band. For the data rate performance of the IEEE 802.11ah, using MCS 9 and 2 MHz bandwidth, the data rate of up to 7.8 Mbps can be achieved. In the MAC layer of the IEEE 802.11ah, the RAW mechanism allows a large number of STAs (up to 8,191 STAs) to be associated with one AP. However, the IEEE 802.11ah Standard is still under development, therefore new techniques are expected to enhance the performance of the Sub-1 GHz Wi-Fi. Especially, the grouping strategies of the RAW mechanism still cannot fully address the hidden node issue in a practical way. Moreover, a mathematical cross-layer model that enables the formulation of the grouping optimization problem considering both the energy efficiency and the traffic patterns is unavailable. In Table III, all the surveyed IEEE 802.11ah RAW enhancement mechanisms are summarized.

IV. CELLULAR-BASED M2M COMMUNICATION SOLUTIONS

Cellular networks are primarily developed to support H2H communication instead of the M2M communications. Therefore, the cellular technology, such as the LTE, focuses more on the mobile broadband (MBB) communications [56]. However, since the demand for the M2M communication in cellular network is relatively new and still growing, the native support for the M2M communication is one of the key technologies of the next generation cellular networks [57]. In this section, both the current and future technologies that enable M2M communication in cellular network are reviewed.

TABLE IV
NB-IoT CHANNELS AND FUNCTION DESCRIPTION [64]

Channel		Function description
DL	Narrowband Physical Downlink Control Channel (NPDCCH)	UL and DL scheduling information
	Narrowband Physical Downlink Shared Channel (NPDSCH)	DL dedicated and common data
	Narrowband Physical Broadcast Channel (NPBCH)	Master information for system access
	Narrowband Primary / Secondary Synchronization Signal (NPSS/NSSS)	Time and frequency synchronization
UL	Narrowband Physical Uplink Shared Channel (NPUSCH)	UL dedicated data
	Narrowband Physical Random Access Channel (NPRACH)	Random access

A. LTE Based M2M Communication Solutions

The M2M communication enhancements have been added to the 3rd Generation Partnership Project (3GPP) standard since the time when Release-10 was proposed. In the Release-10 and Release-11, the focus was mainly on preventing the network congestion by assigning access priorities to the user equipment (UE) [58]. The 3GPP then started work on standards on low cost UE for M2M communications in Release-12. The first UE of such kind is referred to as Category-0 UE (Cat-0 UE) for which approximately 50% of the bill-of-material (BoM) cost is reduced compared with the conventional UE [58]. To lower the BoM cost, the Cat-0 UE has only one receive antenna, and the peak data rate for UL is constrained to 1 Mbps using the 20 MHz channel. The power saving mode (PSM) is developed for the Cat-0 UE. It allows the UE to sleep when there is no data to transmit. To further improve the power efficiency, the discontinuous reception (DRX) is introduced in the Release-12. The DRX prevents the UE from monitoring the channel continuously [56]. Compared to PSM, the DRX does not need to perform the tracking area update (TAU) procedure every time the UE wakes up, therefore the DRX is more power efficient [56]. In order to enhance the coverage performance of the LTE-based M2M communications, several coverage enhancement techniques, such as repetition, power boosting of data and reference signals, multi-subframe channel estimation, and multiple decoding attempts are proposed in the 3GPP Release-12 [59]. An early work on evaluating the performance of M2M communication specified by 3GPP Release-12 in smart metering application is provided in [60].

The current state-of-the-art of the LTE-based M2M communication standard is provided by the 3GPP Release-13. There are two types of UEs introduced by the Release-13: one is LTE Category M1 (LTE-M) UE that operates on a 1.4 MHz channel bandwidth, and the other one is Narrow Band-IoT (NB-IoT), also known as the Cat-NB1 or Cat-M2 with 180 kHz channel bandwidth. Compared with the Cat-0 UE, both the LTE-M and the NB-IoT UEs use narrower bandwidth for lower BoM and power consumption. The bandwidth of LTE-M covers six LTE resource blocks (RBs), therefore a new machine type communication multi-resource block physical downlink control channel (MPDCCH) that takes six RBs in one LTE subframe is developed [56]. To support longer communication range, the LTE-M requires 15 dB coverage enhancement over the Cat-0 UE through repetition [56]. The LTE-M also supports RF retuning to achieve frequency diversity. More specifically, frequency hopping is applied among different narrowband channels for repeated messages [56]. Similar to the conventional LTE network, the multiple access scheme of LTE-M is the RA operated on the physical random access channel (PRACH). It is worth noting that the waveform of the PRACH is based on OFDM and Zadoff-Chu sequences, which is the same as that in the legacy LTE [56]. This feature allows LTE-M to be deployed without hardware modification at the base station side. On the other hand, thanks to the narrower bandwidth, the power spectral density of LTE-M is higher than that of Cat-0 UE, therefore the LTE-M has longer communication range and lower bit error rate [61] than those of Cat-0 UE. More details of LTE-M can be found in [62] and [63].

To further reduce the BoM cost and enhance the low power and long communication range support for LPWA systems, the concept of using only one LTE RB for M2M communication is first introduced in [10]. Compared with the six RB channels scenario, one RB channel can utilize less expensive RF components, and the communication range can be increased through concentrating transmission power in narrower bandwidth [10]. The one LTE RB-based M2M communication technology is later referred to as NB-IoT in the 3GPP Release-13 [64], [65]. The design requirements of NB-IoT include: ultra-low device complexity, 20 dB improvement of indoor signal coverage compared to general packet radio service (GPRS), support of at least 52,547 low-throughput devices per cell, ten years lifetime of 5 Wh battery, and 10-second maximum latency [64]. To achieve the battery lifetime of ten years, a UE can only send out one packet per day [65]. Due to the one LTE RB constraint, both the DL and UL transmissions can only take up 180 kHz bandwidth. Consequently, the control, RA, and data transmission channels need to be redesigned to fit in one RB. Table IV lists all the NB-IoT channels and provides a summary of their functions. For the NPDCCH (narrowband physical downlink control channel), NPBCH (narrowband physical broadcast channel), NPDSCH (narrowband physical downlink shared channel), and NPSS (narrowband primary synchronization signal) / NSSS (narrowband secondary synchronization signal), the subcarrier spacing is 15 kHz, such that 12 subcarriers occupy a 180 kHz channel. Meanwhile, the NPRACH (narrowband physical random access channel) uses

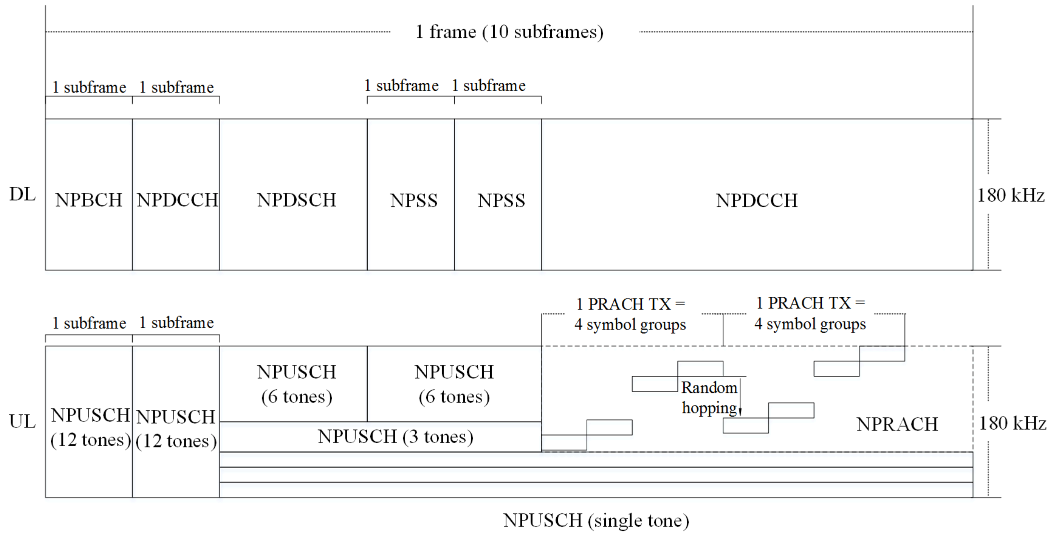

Fig. 2. Example of NB-IoT channel assignment for DL and UL transmissions [64], [67].

3.75 kHz subcarrier spacing, and the NPUSCH (narrowband physical uplink shared channel) allows single tone transmission using either 3.75 kHz or 15 kHz subcarrier spacing. It is worth noting that, in terms of coverage performance, the 3.75 kHz one tone transmission is not necessarily better than the 15 kHz one tone transmission. This is because the 15 kHz subcarrier spacing supports more symbols than that of 3.75 kHz subcarrier spacing, in spite of the noise power of 15 kHz tone being heavier [64]. Fig. 2 gives one example of the NB-IoT channel assignment in one radio frame.

It is seen from Fig. 2 that the NPBCH is assigned at the beginning of a frame, since it contains the narrowband master information block (MIB-NB). Essential information such as system frame number (SFN) is contained in the MIB-NB [64]. Likewise, the NPRACH in Fig. 2 is multiplexed with NPUSCH, therefore the spectrum resource for RA is less than 180 kHz. More study on multiple access of NB-IoT in such a narrow bandwidth is required, since the number of available preambles for RA is limited, and there is limited frequency diversity. To test the RA in an NB-IoT network, the simulation platform introduced in [66] can be used upon modification. For extending the communication range, the NPRACH in Fig. 2 also features repetition with pseudo-random frequency hopping [64]. The NB-IoT only takes up one LTE RB, therefore it is possible to deploy the NB-IoT either within the LTE band, or in the LTE carrier guard band [64]. It is also possible to fit the NB-IoT within one global system for mobile communication (GSM) carrier that has 200 kHz bandwidth [67]. Regarding the coexistence of NB-IoT with conventional LTE, it is pointed out in [67] that the co-channel and adjacent channel interference from neighboring cells can potentially cause problems to the NB-IoT transmission in an asynchronous network.

Several recent works in the literature have focused on improving the performance of NB-IoT. In [68], an UL link adaptation mechanism is proposed to tune the modulation and coding scheme and the repetition number. Compared to the conventional repetition-dominated and straightforward methods, the new mechanism reduces the active time and resource consumption. However, the algorithm in [68] is only a heuristic solution, hence may not be able to generate global optimal results. In order to further improve the energy efficiency and throughput performance, it is beneficial to investigate an analytical model that considers both the link adaptation and modulation and coding schemes in closed-form.

For NB-IoT network, the issue of how to reserve channel resource out of the maximum 180 kHz NPRACH for massive number of UEs needs to be solved. One possible solution is to use the small data transmission (SDT) scheme proposed in [69], in which the NB-IoT radio resource control (RRC) connection setup process is omitted for higher system capacity (i.e., up to 60% of increased maximum supportable devices in NB-IoT). However, the side effects (e.g., the effect to the paging process based DL transmission as mentioned by Oh and Shin [69]) of omitting RRC are yet to be studied in detail.

Due to the large number of devices, the big size of paging message in NB-IoT network may cause energy inefficiency at the UE side. In [70], a binary tree based paging message design is proposed to reduce the message size. The numerical results in [70] show that the binary tree based mechanism performs better than the current state-of-the-art approaches in terms of paging message size. However, the tree searching algorithm performed on the UE may potentially increase the energy consumption. In order to justify the suitability of using binary tree based paging message determination, the energy consumed on receiving a long paging message needs to be compared with the energy consumed on tree searching at the UE side.

There are also several works related with the performance enhancements of legacy LTE-based M2M networks. It is pointed out in [71] that LTE can satisfy the delay requirement of slow (less than 100 ms) automatic interactions, while the fast (less than 20 ms) automatic interactions may not always be satisfied using the LTE [71]. On the other hand, the ultra-low latency applications may require less than 1 ms latency. To reduce the latency of LTE system, the idea of using reserved RA preambles and simplified RA procedures is introduced in [72]. Based on the proposed idea, two mechanisms are designed for delay sensitive critical information transmission in LTE network in [72]. The first one is called short message service (SMS) like RA. It relies on the use of dedicated preambles for LTE RA message 1 (Msg1) transmission, and the encrypted critical message is sent through the LTE RA message 3 (Msg3). The benefit of using this mechanism is to allow data transmission directly in the RA procedure. To further reduce the latency, the other mechanism for delay sensitive transmission is based on sending an array of coded preambles. Emergency information is carried on the coded preamble sequence such that the eNodeB can receive the information at the reception of LTE RA message 1 (Msg1).

In M2M communications, using narrower bandwidth is favorable because it allows lower BoM and power consumption. However in [73], it is pointed out that there are three negative effects to apply a bandwidth that is smaller than the minimum required. Firstly, it will limit the throughput of transmission that has good channel condition (i.e., higher signal-to-noise ratio). Second, the longer transmission time may increase the energy consumption for a fixed power transmitter. Third, it makes the system vulnerable to the carrier frequency offset (CFO) mismatch between the transmitter and the receiver [73]. Therefore, an adjustable UNB pulse for M2M network is proposed in [73]. It can adapt to different settings of data rate by using adjustable signal pulse bandwidth based on the channel conditions and data rate requirements of different application scenarios. According to the numerical evaluations, using adjustable signal pulse bandwidth can support more machine type devices compared with the LTE's repetition scheme. To further improve the performance of the adjustable UNB pulse, the bandwidth determination mechanism proposed in [73] should also consider channel adaptation.

Regarding the M2M devices' energy consumption, the complexity of the communication protocol should also be considered. In [74], a lightweight protocol is proposed to reduce the processing overhead at M2M UEs. The LTE is developed primarily for supporting H2H UEs that have less constrained battery lifetime requirement than that of the M2M communication devices. For example, a H2H UE (i.e., a smartphone) can be recharged every couple of days, whereas a M2M device is expected to have 10 years battery lifetime without recharging. Therefore, further work is required to carry out a performance evaluation that compares the lightweight protocol proposed in [74] for the NB-IoT.

B. Beyond 4G LTE

To date, both the LTE-M and NB-IoT are mature enough to be deployed by wireless service providers around the world. For example, Vodafone has launched its first commercially available NB-IoT network in Spain in January 2017 [75]. The 3GPP is now focusing on standardization of the next generation of cellular communication, in which the M2M communication is facing a new era of development. It is predicted that up to tens of billions of machines will be connected worldwide, and up to 300,000 machine-type devices per cell need to be supported [76]. For the radio access requirement, it is expected to have below 10-ms access delay in the M2M communication network [72].

In the 3GPP Release-14, two radio access design requirements for M2M communication, namely the massive machine-type communication (mMTC) and ultra-reliable and low-latency communication (URLLC), are proposed [77]. The current LTE-based M2M communication mechanisms (i.e., 3GPP Release-13) cannot handle a large number of UEs connecting simultaneously. This is because the preambles available for M2M communication RA is limited, and the large number of simultaneous network access attempts may result in high collision rate [13]. Therefore, a new multiple access mechanism is needed. For URLLC, one of the potential solutions provided by the 3GPP Release-14 is referred to as fast UL grant [77]. Instead of sending out scheduling requests (SRs) for UL grant, the UE can be configured with a periodic UL grant, such that the time of sending the UL grant is saved. Another potential solution provided by 3GPP Release-14 for latency reduction is called shorter transmission time interval (TTI), which is designed to reduce the period of sending control messages for both UL and DL [77]. Furthermore, it is pointed out in [77] that, with a two-OFDM-symbol TTI and fast UL grant working together, the one-way latency is around one millisecond, which is significantly shorter than the 10-ms delay requirement. However, the 3GPP Release-14 does not provide any solution on how to combine the mMTC and URLLC requirements together. In other words, low latency and ultra-reliable communication for massive energy constrained machine-type communication (MTC) devices still requires efforts in development.

The fifth generation infrastructure public private partnership (5GPPP) also has its own vision towards 5G M2M network [78]. In the early project (i.e., the mobile and wireless communications enablers for 2020 information society) of 5GPPP, the massive access support (i.e., mMTC) and ultra-reliable support (uMTC) are expected in the next generation M2M networks [76]. To achieve the ultra-reliable requirement, the latency of the data transmission must also be lower than 10 ms [79]. A way to support both mMTC and uMTC simultaneously is to allow the network access working in overload mode without causing collisions. One potential solution is known as the low density signature-orthogonal frequency-division multiplexing (LDS-OFDM) [80]. The basic idea of the LDS-OFDM is to combine the benefits of avoiding the inter-symbol interference (i.e., contributed by OFDM), and the benefits of supporting overload on one carrier (i.e., contributed by the LDS) [80]. According to the simulation results, the LDS-OFDM supports parallel data streams of up to 400% more than the number of subcarriers [80]. At the receiver side, due to the small number of interferers on each subcarrier, the multi-user detector/decoder (MUDD) designed in [81] only uses a small number of iterations to achieve the optimum performance.

To further improve the performance of the multicarrier code division multiple access (multicarrier CDMA) technique, the sparse code multiple access (SCMA) is developed in [82]. The coding based non-orthogonal multiple access mechanism also allows the network to work in overload mode. As a coding based mechanism, the codebook design of SCMA is proposed in [83]. Compared with LDS-OFDM, SCMA can utilize the constellation shaping gain. SCMA allows a massive number of devices with bursty traffic connecting to the network without the request/grant process [84]. It is worth noting that the control overhead is not negligible in short packet dominated M2M communication networks [85]. The challenge of deploying SCMA for massive M2M communication lies in the computational complexity of the message passing algorithm (MPA) used for the decoding process. In [86], a low complexity decoding method that is based on the list sphere decoding (LSD) for SCMA receiver is proposed. The simulation results in [86] show that the proposed method can reduce the decoding complexity at a cost of only a slight performance loss. However, the latency performance and energy efficiency of SCMA mechanism have not been studied in a massive access scenario, and the current decoding methods are not proven to be applicable at the base station side. Therefore, more studies are still needed in order to deploy SCMA in next generation cellular-based M2M communication network.

C. Summary of the Cellular-Based M2M Communication Solutions

In this section, M2M communication in the context of cellular network framework is surveyed. The cellular-based M2M communication solutions proposed by 3GPP Release-13 include LTE-M and NB-IoT. To achieve low BoM cost, LTE-M UEs only have one antenna for half-duplex data transmission. The bandwidth of an LTE-M channel contains six LTE RBs, thus the power spectral density (PSD) of LTE-M is higher than that of the conventional LTE signal. Combining the high PSD with repetition, LTE-M achieves 15 dB coverage improvement compared with the legacy LTE. To achieve a further lower deployment cost, NB-IoT can be fitted in one LTE RB. Because of the extremely narrow bandwidth, NB-IoT has a high PSD suitable for long range communication. However, there are several drawbacks regarding the narrow bandwidth. First, the data rate of NB-IoT is low, such that the radio on-time of UE could be high for large volume of data, and, consequently, the energy consumption is increased. Second, the limited RA resources in NPRACH can cause a high collision rate in a congested network. Third, the narrow bandwidth cannot provide frequency diversity for both RA and data transmission. Since the LTE-M and NB-IoT are still at early stage of deployment, there is room for further optimization. For example, recently proposed techniques can be used to improve the LTE-M/NB-IoT's performance in terms of increasing energy efficiency, reducing latency, and boosting scalability. Examples of such performance improvement techniques include the new UL link adaptation mechanism proposed in [68], the use of reserved RA preambles for ultra-low latency communication [72], the binary tree based paging message design [70], the adjustable ultra-narrowband pulse [73], and the lightweight protocol design [74].

TABLE V
COMPARISON OF CELLULAR-BASED M2M COMMUNICATION SOLUTIONS

Criteria\Solutions	NB-IoT	LTE-M	Beyond 4G
Outdoor range / Maximum coupling loss	<15 km / 164 dB [62]	<11 km / 156 dB [62]	To be determined (TBD)
Key and Candidate technologies: PHY / Multiple Access	SC-FDMA / PRACH (single-tone transmission with hopping) [87]	OFDM / PRACH [87]	TBD/ candidate: SCMA
Spectrum / bandwidth	Licensed 7-900 MHz / 200 kHz or shared [62]	Licensed 7-900 MHz / 1.4 MHz or shared [62]	TBD
Data rate	<150 kbps [62]	<1 Mbps [62]	TBD
Battery life	>10 years [62]	>10 years [62]	TBD
Availability	2017	2017	Targeting at 2020

For the technologies of next generation M2M communications, two candidate solutions are surveyed. The first one is proposed in the 3GPP Release-14. It brings up the new design requirements of mMTC and URLLC. The fast UL grant and shorter TTI can significantly improve the network's latency performance. However, the simultaneous support of both the mMTC and URLLC is not discussed in the 3GPP Release-14 yet. The other candidate solution is the SCMA which supports a massive number of devices with bursty traffic connecting to the network. The challenge of applying SCMA for massive access is the high decoding complexity at the base station side.

It is also necessary to compare the performance of the cellular based M2M communication solutions with its ISM band counterparts such as the LPWA and the IEEE 802.11ah. A preliminary comparison of Sigfox, LoRaWAN and LTE-M, which is mainly focused on commercial perspective instead of technical details, is provided in [88]. In Table V, specifications such as the outdoor range, key or candidate technologies for both PHY and MAC, spectrum (bandwidth), data rate, battery lifetime and availability are compared among the NB-IoT, LTE-M and future M2M communication solution SCMA, labeled as Beyond-4G. As shown, several values of the criteria for the Beyond-4G solution remain to be determined.

V. DEPLOYMENT STRATEGIES FOR LOW POWER AND LONG RANGE M2M COMMUNICATION NETWORKS

For a specific application scenario, the network deployment consideration usually contains two phases. In the first phase, all the available networking solutions need to be evaluated for suitability study. Particularly, for low power and long range M2M communication network, available technologies surveyed in this paper include: LECIM-based LPWA prototype, RPMA from INGENU, Sigfox, LoRaWAN, IEEE 802.11ah, LTE-M, and NB-IoT. If none of the current solutions meets the requirement of the application scenario, or the candidate solution is unviable on site, then at the second phase, a new network solution needs to be developed.

In Table VI, the specifications (requirements) of the surveyed low power and long range M2M communication

TABLE VI
DEPLOYMENT CONSIDERATION OF THE SURVEYED M2M COMMUNICATION SOLUTIONS

Solutions	LECIM based LPWA prototype	RPMA from INGENU	SigFox	LoRaWAN	IEEE 802.11ah	LTE-M	NB-IoT
Range	20 km in line-of-sight condition and 5 km in non-line-of-sight condition [17]	500 km in line-of-sight condition [89]	50 km rural and 10 km urban [89]	15 km rural and 5 km urban [89]	100 ~ 1,000 m [45]	Less than 11 km [62]	Less than 15 km [62]
Carrier frequency	433 MHz [17], license required in North America	2.4 GHz ISM [25]	Sub-1 GHz ISM [89]	Sub-1 GHz ISM [89]	Sub-1 GHz ISM	Licensed cellular [89]	Licensed cellular [89]
Data rate	0.00153 ~ 125 kbps [17]	UL: 624 kbps DL: 156 kbps [89]	UL: 100 bps [89]	UL 100 kbps DL: 100 kbps [89]	150 kbps ~ 7.8 Mbps [45]	UL: 1 Mbps DL: 1 Mbps [89]	UL: 64 kbps DL: 128 kbps [89]
Latency	LECIM critical message delay tolerance: 15 s [18]	10s of seconds [25]	10s of seconds [25]	10s of seconds [25]	Varies depending on traffic loads, number of STAs, and grouping strategy [34]	Less than 150 ms [61] (handover latency is not considered)	Less than 10 s [64]
TCP/IP support	6LoWPAN required for IPv6	Not clear	Availability depending on service provider	Gateway required [92]	Yes	Yes	Availability depending on service provider
Private network support	Yes	Yes [25]	No [90]	Yes [90]	Yes	No, service provider required	No, service provider required
Suitable applications	Critical infrastructure monitoring, environmental monitoring	Smart metering, parking meter, logistics	Smart metering, parking meter, logistics	Smart metering, parking meter, logistics	WSN backbone network, home automation, smart grid and smart meter, agricultural monitoring	Connected car, fleet management, remote health monitoring, WSN gateway	Smart metering, parking meter, logistics

technologies are summarized. The Table also lists the applications (provided in [11] and [89]) that can be supported by each technology. The LECIM is developed to monitor critical infrastructure, therefore the LECIM-based LPWA prototype can also support critical infrastructure monitoring and other urban applications such as environmental monitoring. If the IPv6 (Internet Protocol version 6) over low power wireless personal area network (6LoWPAN) is used, Internet connectivity can be directly supported by the LECIM-based LPWA prototype network. Smart metering, parking meter, and logistics require wide area network (WAN) connection and low data rates. Hence, solutions such as the RPMA, Sigfox, LoRaWAN, and NB-IoT can be used. For Sigfox and NB-IoT, since the signal coverage relies on the service provider, it is not likely the network is privately deployed. On the other hand, solutions such as the RPMA and LoRaWAN can be privately deployed for the aforementioned applications [90]. As for the higher data rate networks with TCP/IP protocols support, for example the WSN backbone network, home automation, and WSN gateway, these applications can be supported by using the IEEE 802.11ah and LTE-M. The IEEE 802.11ah is a WLAN-based solution whose maximum range is less than 1 km [45]. Hence, the WAN connection required applications, such as the connected car, fleet management, and remote health monitoring, are better supported by LTE-M. Nonetheless, the use of ISM band allows self-deployed and wide WLAN signal coverage (less than 1 km) applications such as the home automation, smart grid, and agricultural monitoring to be realized through the deployment of IEEE 802.11ah. The multiple access performance of the different solutions is not presented in Table VI because multiple access performance is determined by several factors: the maximum allowable devices connected in one cell (e.g., supported by one AP), the maximum capacity of the simultaneous connections, the traffic patterns of wireless devices, and the MAC protocol. Clearly, the multiple access performance of the different solutions can be determined by conducting rigorous analytical and comprehensive simulation studies.

There may be some applications that are not well supported by the currently available solutions. For example, the alarm and critical messages need to be received and processed with very stringent delay requirement [72]. In this case, a new technology is to be developed which will simultaneously enhance the network's energy efficiency, latency, throughput, and transmission reliability. Furthermore, in order to have better support of connected mobility for the road safety use case, the cellular-based M2M communication network performance improvements should also include the "user and control plane latency, handover execution time, and radio signal availability" [91]. Therefore, it is possible that the new technologies are fundamentally different from the current solutions in terms of PHY and MAC mechanisms.

VI. GAPS IN KNOWLEDGE AND THE OPEN CHALLENGES

It is shown in the previous sections that the LPWA, IEEE 802.11ah and the cellular-based M2M solutions have applied different techniques and concepts such as the UNB, DSSS, RAW, SCMA, etc. into their design to enable the low power communications. It is also noted that a user application can be supported by using more than one network solution. Thus, the gaps in knowledge and the open challenges are summarized in this section to stimulate further research and help the development of the future low power and long range M2M communication protocols that support a wide range of M2M application scenarios.

In Section II, several LPWA network solutions have been proposed for both research purpose and real-life industrial applications. They are classified in two categories: the open LPWA network that is for research purpose, and the proprietary LPWA solutions created for commercial applications. For the LECIM-based LPWA prototype designed for research purpose, the DSSS from the IEEE 802.15.4 and the GFSK modulation scheme are used as the PHY protocol, and the pure Aloha is the MAC protocol. Since there is no CCA mechanism in the pure Aloha, collisions may still happen to the prototype system when the short spreading sequence is traded for less computational overhead. If the CCA mechanism (i.e., as in the CSMA/CA) is considered, the networking overhead needs to be compared with that of pure Aloha. On the other hand, the hidden nodes issue in the long communication range network still remains unsolved. As for the UNB technology, which is another candidate PHY for the prototype LPWA network, its corresponding MAC protocol (i.e., the TFA) is facing the challenge of the frequency drift. On the other hand, the investigations of the proprietary LPWA solutions such as the RPMA-DSSS proposed by INGENU and LoRaWAN provided by the LoRa Alliance are rather limited. To the best of the authors' knowledge, there is no analytical work about the RPMA-DSSS performance evaluation, which means it is hard to model the optimization problem for tuning the performance. There are several works dedicated to the performance evaluation of LoRaWAN; however, they are mostly focused on the network capacity and communication range studies. Furthermore, intensive and rigorous analytical studies on energy consumption and network scalability are currently unavailable.

The major challenge for applying the current LPWA solutions to the wide variety of the M2M networks is the constrained data rates. For some M2M communication scenarios such as the wireless sensor network backhaul and the cellular data offloading, both the communication range and the throughput requirements are high. Therefore, for the high data rate M2M network, the IEEE 802.11ah is a promising candidate that features shorter range and higher energy consumption. However, the IEEE 802.11ah standard is an open standard. Thus, for a specific application scenario, its featured RAW mechanism must be tailored to be optimal in that case. According to the survey of the RAW mechanism proposals summarized in Section III, there are several challenges that need to be overcome. Firstly, the association latency is not considered in the RAW mechanism. Second, for the analytical work on the IEEE 802.11ah RAW mechanism, only the saturated throughput is evaluated, while the influence of the diversified traffic patterns are not studied. Third, the way to detect or predict the STAs' traffic patterns by the AP in a timely manner is unavailable. Fourth, hidden nodes issue still exists by applying the current IEEE 802.11ah MAC mechanism. Finally, there is no cross-layer (i.e., PHY and MAC) mathematical model available to formulate the grouping strategy optimization problem that can maximize the energy efficiency.

Unlike the IEEE 802.11ah and most of the LPWA solutions, cellular-based M2M solutions can utilize the currently available cellular infrastructure such as the LTE base stations (eNodeBs) to provide a large coverage area without deploying a new AP or sink node. However, cellular technologies are designed primarily for H2H communications, therefore there are three major gaps in knowledge that may hinder wide deployment of the cellular-based M2M solutions. First, for NB-IoT, the network's energy efficiency for low data rate transmission, lack of frequency diversity, and limited RA resources need to be considered. Second, for the potential next generation M2M communication technologies, the method of realizing massive access, low latency, and high reliability in one system needs to be studied. More specifically, for the 3GPP Release-14, new mechanisms that allow simultaneous support of the mMTC and URLLC with high energy efficiency need to be investigated. As for the candidate M2M communication solution based on SCMA, the emphasis should be put on the design of low latency decoding mechanism. It is worth noting that the low complexity decoding method is not the same as low latency decoding method, especially in overload condition. Third, there is no comprehensive comparison of the cellular-based M2M solutions and the ISM band based solutions (e.g., IEEE 802.11ah, LPWA, etc.).

As a guideline for future research, several directions are proposed in the next section based on the aforementioned gaps in knowledge and open challenges.

VII. Future Research Directions

As summarized in Section VI, challenges exist in the current LPWA, IEEE 802.11ah and cellular-based M2M networks. In order to develop new M2M communication protocols that can meet the requirements of low power, long communication range and wide range of data rate choices, those challenges and gaps in knowledge need to be addressed by solving the following research problems.

A. A Thorough Study of the Relationship Between the DSSS Spreading Factor and the Collision Rate With the Pure Aloha As the MAC Layer Protocol

Compared with the CSMA/CA, the pure Aloha does not need to perform the CCA, which can increase the energy efficiency and have no hidden nodes issue. However, the lack of CCA may have a negative impact on the collision mitigation performance. Therefore, it requires an energy efficient DSSS mechanism (i.e., to have reasonable settings of the DSSS spreading factor) at the PHY layer to allow multiple packets to be demodulated simultaneously. On the other hand, the random phase of the RPMA-DSSS can be used to further reduce the collision rates.

B. Development of an Energy Efficient CCA Mechanism for the Aloha-Based LPWA Networks

Since the CCA is not included in the prototype LPWA network, it is impossible for the network to choose a less congested channel. Therefore, a CCA mechanism should be introduced to the pure Aloha MAC protocol, such that the less congested channel can be chosen to mitigate collision with an acceptable level of energy consumption overhead.

C. Proposal of a New Grouping Strategy and RAW That Can Optimize the Energy Efficiency, Throughput, and Association Latency Performance of the IEEE 802.11ah

In order to support high throughput M2M communications, the current grouping strategy and RAW mechanism of the IEEE 802.11ah need to be improved. First, it requires a cross-layer mathematical model of the IEEE 802.11ah protocol to formulate the optimization problem. Second, an efficient way to detect and predict the STAs' traffic patterns by the AP in a timely manner needs to be developed, since the traffic patterns will be considered by the optimization problem at the AP. Third, the grouping strategy should also mitigate the hidden nodes problem in a way that the probability of detecting the on-going transmissions from other STAs can be increased. Last but not the least, the optimization problem should be solved without introducing latency to the network.

D. An Adaptive M2M Communication Protocol That Can Achieve Long Communication Range With Low Power and Wide Range of Data Rate Choices

The IEEE 802.11ah can support high data rate communications in dense M2M networks. However, when the data traffic is light, the networking overhead introduced by the RAW and the DCF of IEEE 802.11ah is high compared with the simple MAC mechanism such as the pure Aloha. Therefore, it is motivated to have an adaptive communication protocol that can choose to use either DSSS plus pure Aloha with CCA, or IEEE 802.11ah MAC and PHY depending on the traffic pattern. To realize the adaptive M2M communication protocol, an optimization problem should be formulated to generate optimal communication strategies (i.e., the choices of PHY and MAC protocols) that are suitable for the STAs in a long communication range heterogeneous M2M network. Meanwhile, solution to the optimization problem should also consider the latency requirement in a dynamic and delay sensitive network.

E. Improving the Low Latency and Massive Access Capabilities of Cellular-Based M2M Communication Network

The current state-of-the-art cellular-based M2M communication solutions are LTE-M and NB-IoT. Due to the limited RA resources, the massive access and low latency are not well supported by LTE-M and NB-IoT. To solve the problem, first, the analytical model of the SCMA mechanism will be investigated. Based on the analytical model, optimization problems can be formulated to determine optimal SCMA codebook design and subcarrier allocation scheme. Second, to further improve the latency performance and to guarantee ultra-reliable data transmission, a low complexity decoding and multi-user detection method for the base station should be proposed and optimized. It is crucial to evaluate the latency performance of the proposed mechanism. Furthermore, the handover latency of mobile machines (devices) should also be considered.

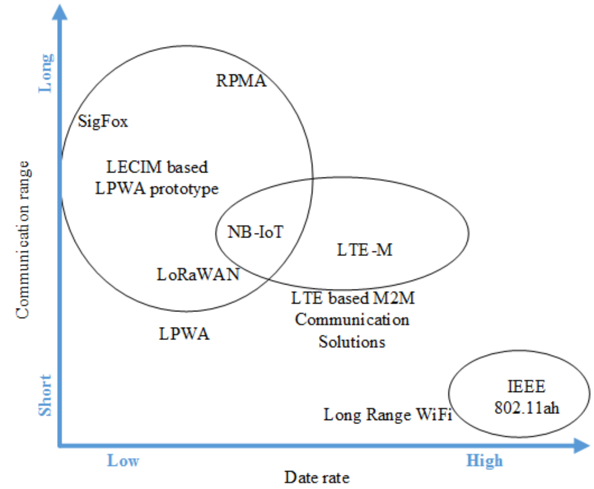

Fig. 3. Inter-relationships among the surveyed technologies.

F. Performance Evaluation and Comparison of the Surveyed LPWA, IEEE 802.11ah, and the Cellular-Based M2M solutions for a Particular Application Scenario

In this survey, three different technologies of low power and long range M2M communications are discussed. The inter-relationships among the surveyed technologies are shown in Fig. 3. The IEEE 802.11ah and most of the LPWA are operated in the ISM radio band, therefore they can be deployed by the user. However, the channel quality is not guaranteed due to the potential mutual interference that exist among the systems operating in the ISM radio band. The maximum communication range of IEEE 802.11ah is not long enough compared with LPWA solutions such as LoRaWAN and Sigfox, while the throughput of IEEE 802.11ah is higher than that of LPWA, as shown in Fig. 3. For the cellular-based solutions, NB-IoT can be considered as LPWA but operated in the licensed band. This is because the NB-IoT has a narrow bandwidth for low data rate communication. Meanwhile, the other LTE-based M2M communication solution, LTE-M, can support higher data rate. For a specific use case, according to the specific design requirement, only the suitable technologies (both PHY and MAC) will be applied. For example, if a network needs to be deployed at a place where there is no cellular coverage, then the IEEE 802.11ah can be used for high data rate communication, while the LPWA can be used for low data rate but long range communication. In order to achieve the design requirements of a specific network deployment, the performance (including power consumption) of the surveyed M2M solutions and enabling technologies should be thoroughly evaluated and compared with each other.

VIII. Conclusion

In this paper, the low power wide area (LPWA) networks, the IEEE 802.11ah and the cellular-based machine-to-machine solutions are surveyed. To achieve low energy consumption, the communication bandwidth of the low power wide area solutions is usually narrow, hence the data rate of the current LPWA solution is low. As such, LPWA solutions are not suitable for high data rate M2M networks. Therefore, in order to support high data rate M2M communications, the IEEE 802.11ah and the cellular-based solutions are introduced. The high data rate feature of the IEEE 802.11ah can be achieved by using the high modulation and coding scheme index at the expense of reduced communication range and energy efficiency. The low power requirement of IEEE 802.11ah is satisfied due to the lower path loss at Sub-1 GHz radio band compared with the 2.4 GHz radio band. As for the support of large number of stations that are connected to one access point, the concept of restricted access window is proposed to reduce the collision rate. In addition, it is also possible to utilize the current cellular infrastructure for M2M communications, several cellular-based M2M solutions (e.g., LTE-M, Narrowband-IoT, etc.) are already available. Similar to the low power and wide area network solutions that have ultra-narrowband physical layer mechanism, the Narrowband-IoT uses narrow bandwidth to achieve better energy efficiency. As an extension to the technological details and the current state-of-the-art performance improving methods surveyed in this paper, the deployment strategies are investigated. Furthermore, the gaps in knowledge and the open challenges are summarized to inform further research and development on the next generation low power and long range M2M communication technologies. The major contribution of this survey is the holistic presentation of the pros and cons of the surveyed technologies with identifying the current gaps in knowledge and the open challenges, and the proposal of new research directions to fill the gaps and tackle the challenges. These research directions can stimulate further research thus leading to better design of the future LPWA technologies.

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