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MAC Protocol Design for Smart Meter Network

Yue Yang

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Abstract

The new generation of power metering system—that is advanced metering infrastructure (AMI)—is expected to enable remote reading, control, demand response and other advanced functions, based on the integration of a new two-way communication network, which will be referred as Smart Meter Network (SMN). In this chapter, we focus on the design principles of multiple access control (MAC) protocols for SMN. First, we list several features of SMN relevant to the design choice of the MAC protocols. Next, we introduce some performance evaluation metrics and give a survey of the associated research issues for the SMN MAC protocols' design. In addition, we also note progress within the new IEEE standardization task group (IEEE 802.11ah TG) currently working to create SMN standards. After that, in order to emphasize the importance of the performance metrics mentioned before, we give several MAC protocol design examples which could solve the associated research issues and challenges for the SMN.

Keywords: Smart Meter, MAC protocol, AMI, Smart Metering Network, Grouping

1. Introduction

Since the Smart Meters application crucially depends on two-way networks, denoted as Smart Meter Network in this chapter, communication aspects of Smart Meter Network design have begun to draw attention [1–4]. Some of those discuss the choice of communication architectures [5] that are appropriate for the various AMI applications, so as to achieve the traditional goals of communication reliability, efficiency and security. On the other hand, some papers talk about the pros and cons of multiple different communication technologies, such as power line communications [6], ZigBee [7] and WiFi [8], and compare their suitability to the AMI applica-

tions. Furthermore, one new IEEE 802 standardization task group (802.11ah TG) [9] has been established and aims to create new standards to provide a guideline for the design of Smart Meter Network. In addition, as an important part of network design issue, the multiple access control (MAC) protocols' design, which is used to regulate the data transmission on the shared channel and largely determines the efficiency of end-to-end data collection process, starts to become the research focus recently. Therefore, in this chapter, we first discuss some SMN unique features that will significantly impact the choice of MAC protocols in Section 2. After that, we discuss several MAC protocols' performance metrics and design challenges especially in Smart Meters Network in Section 3. In Section 4, the progress of the IEEE 802 standardization task group (802.11ah TG) in the aspect of MAC protocols' design is also reviewed. After that, we present several solutions and examples of the MAC protocols' design, presented in [10, 11], which adapt to the special requirements of Smart Meter Network and solve the challenges mentioned below.

2. Smart Meter Network features

There are several features in Smart Meter Network that have significant impact on the MAC protocol design. These features are listed in **Table 1**, and two of them are introduced in more details in the following subsections.

Important features	Brief discussions
Smart Meter Network architecture	• Smart Meter <-> Local Collector <-> Central Collector
	• MAC protocols' design mainly focuses on Neighbourhood Area Network (NAN), that is Smart Meter <-> Local Collector.
	• Many Smart Meters are associated with one Local Collector
Candidate communication technologies	• Power line communications
	• ZigBee
	• Machine-type communications in cellular communications
	• WiFi-based communications
Fixed location	• Smart Meters are implemented in fixed location without mobility concern in MAC protocol design.
Information redundancy	• Smart Meters information has nearly zero redundancy but may be highly correlated. This feature should be considered in MAC protocol design with respect to accurate data aggregation or information estimation.

Table 1. Smart Meter Network features outline.
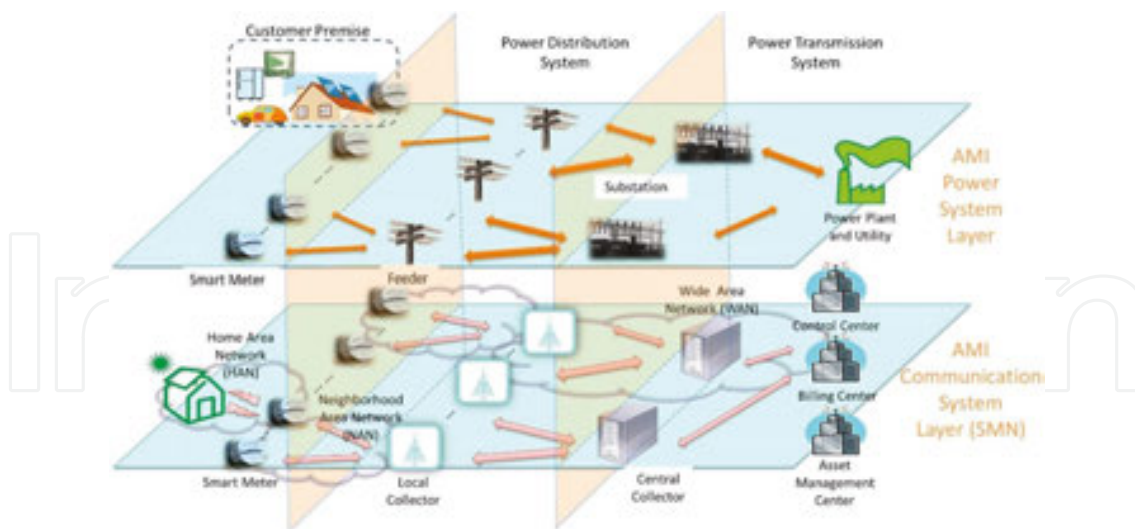
Figure 1. Smart Meter Network system architecture.

2.1. Smart Meter Network system architecture

Figure 1 presents an SMN system based on the Smart Grid architecture given in [12]. A short overview of its main components is as follows:

- Smart Meter (SM): This device has three different roles. First, the Smart Meter is a multi-utility instrument measuring electric power consumption (and possibly in future, gas, water and heat). It can thus act as an energy control centre, that is as a point of aggregation for usage information collected using a home area network (HAN) that connects home appliances. Finally, the Smart Meter also serves as the gateway between HAN and external network; it reports on energy consumption, sends out urgent data, receives remote commands from the utility and is responsible for security of the above transactions. It is noted that SMs' nodes are fixed as they are deployed in customer premises. They are usually powered from the main supply, and hence, power-saving issue is not as important as in traditional battery-powered wireless sensor network nodes.

- Home Area Network (HAN): This is composed of multiple interconnected electric appliances, such as air conditioner, dish washer, plug-in hybrid electric vehicles (PHEV), and the Smart Meter. All the components inside HAN share information or deliver control commands to each other. For example, the dish washer may send a signal to Smart Meter, requesting it to send a 'postpone' command to the charging PHEV, so that it may operate without incurring excessive energy cost at that time.

- Local Collector (LC): Between the Smart Meter and Utility Centre, there could be multiple layers of intelligent electronic devices (IEDs) that act as data concentrators. For example, a data collection node closer to customer premises—named as Local Collector—collects SM data from multiple premises and relays it to the Central Collector. Additional functions at the Local Collector may include simple data processing and distributed decision and intelligence using its own data. The network segment between Smart Meter and Local

Collector is called neighbourhood area network (NAN), while that above Local Collector belongs to wide area network (WAN).

• Central Collector: A centralized data repository for the entire region operated by the utility that acts as the interface with Control Centre, Billing Centre and Asset Management Centre. These centres may use this data to conduct analysis and evaluate system status, and make decisions or deliver control commands to other components.

The mapping between the SMN components and their prospective physical deployments is also shown in **Figure 1**. For example, the Local Collector could be located at a distribution transformer because it would be easy to power the Collector and obtain measurements from other feeder devices. On the other hand, the independent deployment for Local Collector may provide more flexibility to adjust its coverage range. The Central Collector is likely to be deployed closer to the centres. If the utility's coverage region is not very large, only one Central Collector located close to the centres may suffice. Otherwise, Central Collectors may be placed at the distribution substation as the second tier data relay. Since the HAN consists of electric appliances which are manufactured by different vendors and has much flexibility in implementation especially on application layers, the utility operating SMN may leave it open and focus their design on the upper level network. On the other hand, the design of network from the Local Collector to the Central System does not only depend on the communication requirements of SMN because it also includes the electrical devices which serve the power systems other than AMI. Therefore, the main focus of the MAC protocols' design for SMN lies on the segment from Smart Meter to Local Collector (NAN), which is exactly also the focus in this chapter.

2.2. Candidate communication technologies

A large amount of literature discusses the feasibility of several optional bi-directional communication technologies applied on the SMN. We summarize the various options and highlight their pros/cons in **Figure 2**.

Technology	Applications	Benefits	Limitations
Power Line Carrier	WAN, NAN, HAN	No Extra Cabling Fee, High Security	High Noisy Medium, Low Scalability
Messaging over Cellular Network	HAN, NAN, WAN	Mature Development, Long Range	Low Data Rate, Low Robustness, Low Security, Costly Spectrum Fees, Low Scalability
WiFi	HAN, NAN, WAN (with multi-hop)	Mature Development, Free License, High Robustness	Low Security, Low Scalability
ZigBee	HAN	Low Cost	Short Range, Low Security, Low Data Rate

Figure 2. Comparison among optional communication technologies for SMN.

In power line carrier (PLC), the data are transmitted over electricity transmission lines along with electrical power [13]. Its communication performance depends on several factors, such as frequency, propagation distance and existence of transformers because the data signals cannot go through the transformers. PLC has gained a lot of attractions because it uses the existing power lines as signal carrier and no extra cabling fee is needed. Therefore, many countries (e.g. Singapore) adopted it for broadband communication services. However, PLC also suffers from several disadvantages, such as high-signal attenuation, high noisy medium and lower scalability, which lead to the termination of deployment in some countries (e.g. US) [14].

ZigBee is a wireless communication technology that consumes low power at the device side [13]. Thanks to its low cost and easy implementation, this technology has already been widely used in the Smart Home Network by many AMI vendors, such as Itron and Landis Gyr. They produce Smart Meters and measuring devices integrated with ZigBee protocol to monitor and control the Home Energy Status. On the other hand, there are still some constraints on ZigBee for its practical application on the SMN. For example, its short range confines this protocol in the application domain of HAN. Furthermore, the processing capabilities and memory size of the ZigBee device are expected to be improved for more advanced functions and communication requirements of the SMN.

Machine-type communications over cellular network allows the Smart Meters and Local Collector to exchange information via low data load communication service, which has been supported by multiple mature cellular network standards, such as LTE [15]. It is the popularity and easy implementation that make this technology become an attractive candidate option. Furthermore, the long range and high data rate provide the utility more flexibility to design and implement the SMN. However, the concern about reliability, security and delay performance makes a barrier for the implementation of this technology in practice, especially under the condition of heavy traffic load.

Finally, WiFi is a communication technology that allows devices to exchange data wirelessly based on IEEE 802.11 Standards. Its popularity, mature development and unlicensed spectrum make it on the top of the candidate technology list. Furthermore, it is also a cost-efficient network with dynamic self-healing and distributed control, which makes it easier to be implemented. On the contrary, the capacity, scalability and security issues are the main challenges for its application on the SMN. Therefore, in order to solve these challenges, a new standardization task group IEEE 802.11ah is established and aimed at creating a WiFi-based standard to support wireless communication between Smart Meters and Local Collector as one of its primary use cases. In the following sections, we also regard this WiFi-based communication technology as our main foundation of MAC protocols' design.

3. MAC protocols design performance metrics and important research issues

MAC protocols must be designed to match the different objectives for the various types of Smart Meter data as well as adapt to the different network topology scenarios. Furthermore,

the special features and applications in Smart Meter Network also address some new challenges to the suitable MAC protocols' design. In this section, we outline the broad performance metrics for MAC protocols as they relate to Smart Grid operations and identify some specific challenges for MAC protocols' design in Smart Meter Network.

3.1. Different data types

Usually, the data transmitted over Smart Meter Network may be classified according to the latency requirements. For example, energy consumption information is delay tolerant compared to fault reports or other control actions in response to some urgent events that must be communicated as soon as possible [16]. On the other hand, the Smart Meter traffic may also belong to two different classes: periodical and event-triggered data. The former includes energy consumption information, while the latter is largely data from protection devices (relays, reclosers, etc., that monitor local fault status) or electric vehicle charging stations. We list a table of several representative traffic examples with their important properties in **Figure 3**.

Traffic Examples	Delay Requirements	Trigger Type
Outage Alert	Seconds	Event Triggered
Billing Information	Minutes to Hours	Periodical
Demand Response	Seconds or Minutes	Periodical
Real-time Pricing Information	Seconds or Minutes	Periodical
EV Charging Information	Seconds or Minutes	Event Triggered

Figure 3. Examples of data with different communication requirements.

3.2. Scalability

Scalability requires that MAC protocols continue to perform well as the number of Smart Meters offering data scales, which is the top challenge to MAC protocols' design in Smart Meter Network. Referring to [17], one Local Collector is required to support a network associated with a large number of Smart Meters, which are much higher than that covered in the traditional WLAN network, such as WiFi. For example, as specified in the Use Case 1a: Smart Grid—Meter to Pole requirement in [17], the capacity of one Local Collector (AP) is required to be upto 6000, which is usually the network scenario in densely populated urban city in Asia. According to [18], the urban outdoor path loss model for 900 MHz RF in dB is as follows

$$P_{L,dB}(r) = 8 + 37.6 \times \log_{10} r, \tag{1}$$

where r denotes the distance between the Smart Meter and Local Collector. Then based on the parameters listed in the table (**Figure 4**) [9], the received power and noise power at the receiver terminal are given as follows:

$$P_{RX,dB}(r) = P_{TX,dB} + G_{dB} - P_{L,dB}(r) = 0 + 3 - (8 + 37.6 \times \log_{10} r) \tag{2}$$

$$P_N = k \times T \times W = 1.3 \times 10^{-23} J / K \times 290K \times 2MHz \tag{3}$$

Referring to the AWGN capacity derivation with BPSK modulation in [19], we may draw a figure of the transmission rate and received power with respect to r. As shown in **Figure 5**, the RX received power at 1200 m satisfies a reasonable received power threshold (−120 dB) and achievable transmission rate at 4500 m exceeds 100 kbps, the minimal required data rate set in IEEE 802.11ah Use Case [17]. This implies that one Local Collector may need to communicate with individual Smart Meters located 1200 m away using a star topology. Given typical SM density ρ (1000–6800 SMs per km²) [20, 21], it is possible to have in excess of 6000 Smart Meters communicating to one Local Collector. Clearly, the design of MAC protocols for such large number of nodes invites challenges about scalability of any chosen MAC protocol for SMN as discussed next.

Parameter	Value	Parameter	Value
Channel Bandwidth W	2 MHz	Transmitter Power $P_{TX,dB}$	30 dBm
Antenna Gain G_{dB}	3 dB	Temperature T	290 K
Transmission Frequency	900 MHz	Boltzmann's Constant k	1.38×10^{-23} J/K
SM Density ρ	1000 per km^2	Cell Radius R	1200 m
$SINR_{dB,th}$	14 dB	$P_{RX,dB,th}$	-129 dB

**Figure 4.** Parameter list for transmission rate and hidden node calculation.

Taking random access protocols based on carrier sensing as an example—such as DCF (CSMA/CA) in IEEE 802.11—such a large coverage area corresponding to a single Collector cell will lead to significant hidden nodes. In the traditional random access protocols, such as CSMA/CA, all nodes listen to estimate channel status (busy/idle) based on energy threshold. If the node observes the channel to be continuously idle for a specific interval, it starts contending for the channel via a random back-off process.

However, when the coverage of the Local Collector is enlarged, one Smart Meter (hidden node) may not be able to detect ongoing transmission of other meters due to the degenerated radio channel condition. Then, this hidden node may initiate its own transmission because it determines the channel as idle, which leads to a collision.
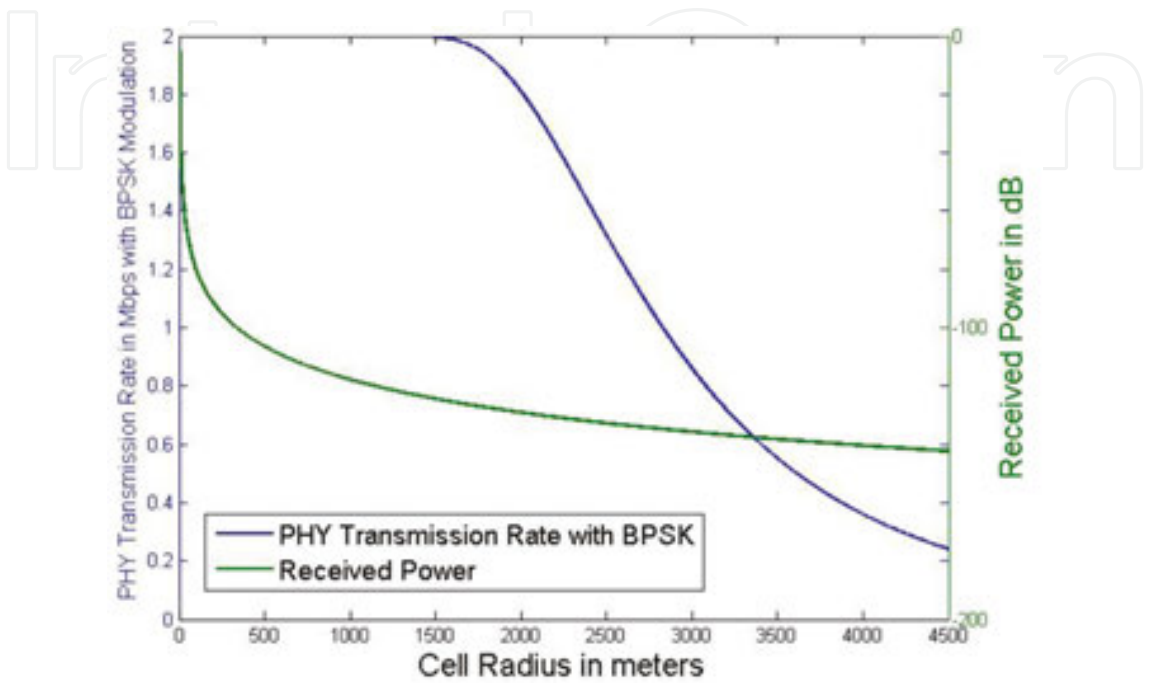
Figure 5. PHY transmission rate of the communication with BPSK modulation and received power at Local Collector with respect to their distance.
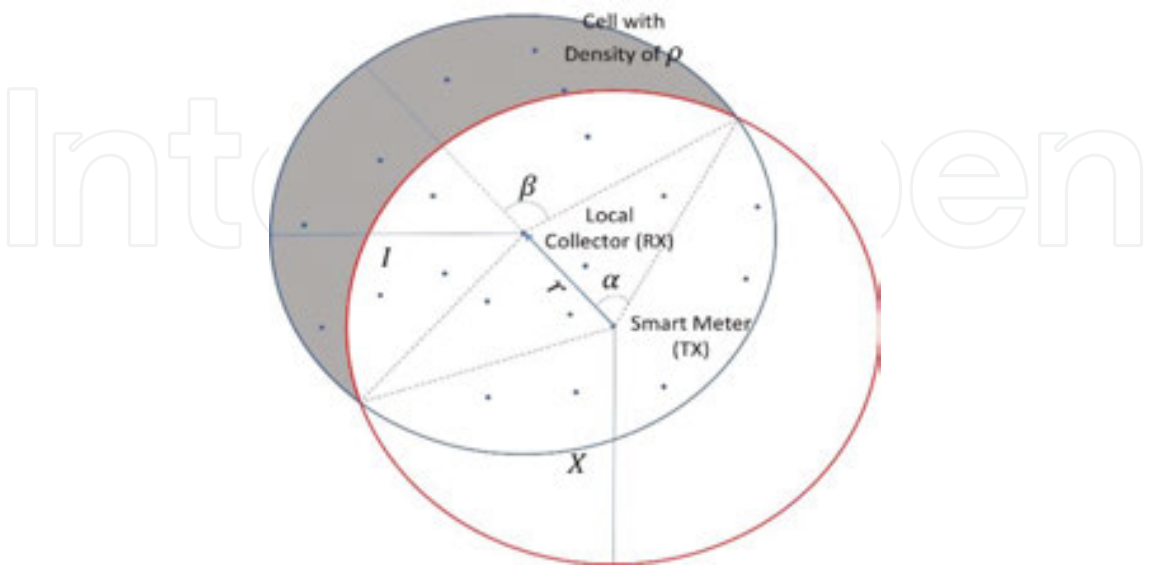
Figure 6. Network topology for hidden node calculation.
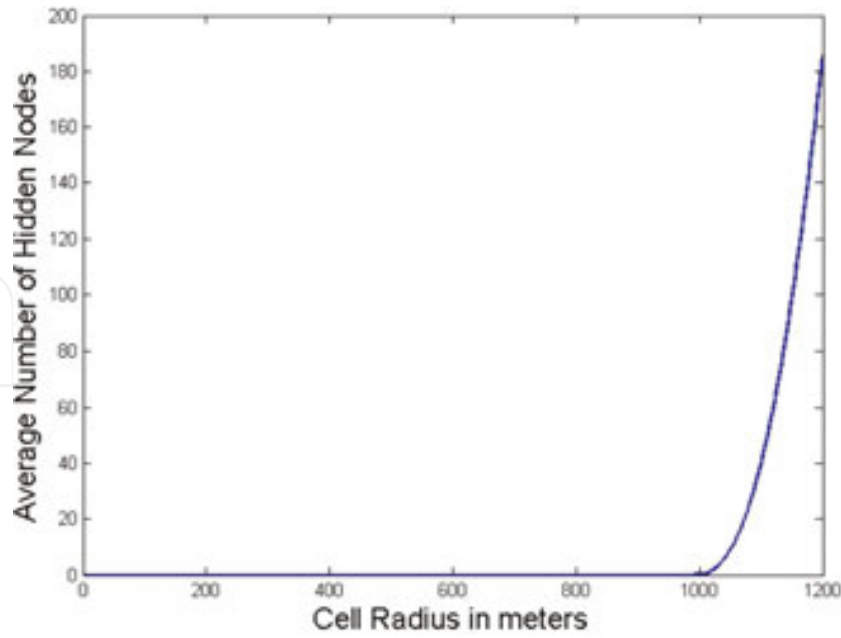
Figure 7. Results for hidden node calculation.

In order to investigate the number of hidden nodes with growing Local Collector coverage, we consider the network topology of a disk with radius of R and uniformly distributed SM density ρ (**Figure 6**) and the distribution of Smart Meter deployment with respect to r is $f(r) = 2r/R^2$, where $0 \leq r \leq R$. Since the down-link communication from Local Collector may cover all the Smart Meters successfully, thus the hidden node only exits in up-link communications where Smart Meter is always the transmitter (TX) and Local Collector is always the receiver (RX). According to [22], the area inside the interference range of the receiver I and outside the carrier sensing range of the transmitter X is defined as the hidden area $A(r)$ (shadowed zone) for a given Smart Meter, which is given as follows:

$$If \ r \leq X - I, \ A(r) = 0$$

$$If \ r > X - I, \qquad A(r) = \beta I^2 + rX \left| \sin(\alpha) \right| - \alpha X^2 \tag{4}$$

where $\alpha = \cos^{-1}(X^2 + r^2 - I^2/2rX)$ and $\beta = \pi - \cos^{-1}(I^2 + r^2 - X^2/2rI)$.

The carrier sensing range X can be calculated based on the equation $P_{TX,dB} + G_{dB} - P_{L,dB}(X) = P_{X,dB,th}$, where $P_{X,dB,th}$ is the carrier sensing threshold for the received power such that the received signal can be detected. Furthermore, the interference range I can be derived based on the following equation:

$$I(r) = \min\left[R, \left\{ y \middle| P_{RX,dB}(r) - 10\log_{10}\left(P_N + P_{RX}(y) \right) = SINR_{dB,th} \right\} \right] \tag{5}$$

where $SINR_{dB,th}$ is the threshold for signal noise interference ratio such that received signal can be decoded successfully.

After that, we use $N_{hidden} = \int_0^R \rho A(r) f(r) dr$ to obtain the mean number of hidden nodes inside the network and plot it with respect to cell radius R based on the parameters listed in **Figure 4**. As shown in **Figure 7**, the number of hidden nodes increases dramatically when the coverage of the network is enlarged.

Although the DCF in 802.11 proposes the RTS/CTS algorithm to reduce the occurrence probability of hidden nodes event, its effect on such a large area network still needs to be investigated. On the other hand, the increasing number of Smart Meters may also increase the data load in the Smart Meter Network, which basically results in stronger competition for the medium access. Then, the collisions and following retransmissions happen more frequently, which directly aggravate the performance. Therefore, whether the MAC protocols may guarantee the latency requirements of the event-driven and delay sensitive data under the case of large network is also a critical metric to evaluate the designed MAC protocols.

3.3. Delay

Different types of data induce different communication requirements within a Smart Meter Network. For example, delay sensitive data—such as those reporting a fault and protection related messages—should have higher priority over others, so as to minimize end-to-end latency. Therefore, how to minimize the Smart Meter Network latency—such as that of the last hop between the Smart Meter and the Local Collector is a primary concern. In general, several factors impact the delay, such as the choice of the communication technology, the network architecture, and most notably, the MAC protocol.

A good MAC protocol can coordinate the uplink transmissions of multiple communication nodes to reduce the collision probability significantly, resulting in lower delay. Usually, it is convenient to design MAC protocols for one type of traffic—for example, random access MAC protocols such as distributed coordination function (DCF) in 802.11 have been designed to provide reasonable efficiencies in terms of throughput at low-to-moderate loads, but the delays escalate rapidly as the average load increases. On the other hand, a polling-based (taking-turns) protocol such as point coordination function (PCF) defined in 802.11 is well-suited to reporting data with bounded delay guarantees. The total duration of one polling cycle increases only linearly with the number of nodes (in contrast to exponential increase in delay with random access systems as the aggregate load increases) and provides a guaranteed delay bounds. However, the efficiency of such protocols declines rapidly with the number of nodes, providing a different trade-off to random access protocols.

However, most Smart Grid scenarios comprise of a mix of traffic, for example regular traffic and emergency traffic. To serve both types within a DCF framework, the notion of traffic classes were introduced via enhanced distribution channel access (EDCA) defined in 802.11e [23], to prioritize low latency data over non-time-critical data applications (such as billing informa-tion). A combination of EDCA and PCF, hybrid coordination function controlled channel access (HCCA), tries to serve multiple traffic types by granting higher priority to some

particular kinds of data via polling algorithm, which is centralized controlled by access point (AP). On the other hand, the performance against scalability issue of these hybrid MAC protocols under densely populated network still needs to be evaluated.

3.4. Fairness

This seeks to measure whether each node in the Smart Meter Network obtains a fair share of system resources. Fairness can be quantified in terms of the access probability to the shared channel by each node—ideally, this should be equal (independent of the node) assuming that all Smart Meters require identical data rates. In general, the notion of proportional fairness should be applied, based on different data rate requirements by different nodes.

3.5. Security

Data security in Smart Meter Network is an extremely vital issue as it relates to household or customer information (e.g. energy consumption profile) that is considered private.

Therefore, it is necessary to encrypt the message to prevent eavesdroppers from intercepting the message. Although cryptographic tools and algorithms are relatively mature, these will result in extra load on the Smart Meter Network. An open question is whether the known features of Smart Meter data may be exploited to develop simplified yet effective cryptographic approaches. Secondly, end-point authentication is also indispensable for Smart Meter Network; whenever the data collector receives a message of energy consumption report, it has to authenticate the identity of the sender.

Specifically, defences against two common types of attacks will be of high priority. Integrity in data communications between Smart Meter and Local Collector may be compromised by a relay or man-in-middle attacker. And such communications may be targeted for disruption via denial-of-service (DoS) attacks by saturating the Local Collector with a large number of spurious external communications, so that it cannot respond to the legitimate traffic [24]. Within this context, it is noted that most Smart Meter communications are regular as it reporting actions are typically scheduled. Therefore, we may exploit such features to filter out malicious accesses by an attacker, by identifying anomalous access traffic patterns.

On the other hand, a good design of the MAC protocol with the aid of pseudo-random algorithm can also effectively protect the privacy of the customer data.

3.6. Expandability

For Smart Meter Network, the expandability means the ability of this network to accommodate the new communication nodes (Smart Meters) to its existing capacity. It is noted that the deployment of Smart Meters will not occur according to a fixed schedule; for example, whenever a house is built, a newly installed Smart Meter will need to be introduced into the existing NAN covered by the corresponding Local Collector. This introduction procedure, which may include registration, identity authentication, geographical location identification, etc., has to be conducted automatically and is used for the Local Collector to determine the

newly installed Smart Meter is ready to work inside its coverage. Therefore, how to realize this introduction procedure should be a part of the MAC protocols' design. For example, whenever one newly installed Smart Meter is online, it sends a request to its associated Local Collector to report its own identification and geographical location. After that, the collector registers this new meter and replies it via a message with some necessary setting information. Then, how to automatically modify the parameters of current communication systems due to the newly registered Smart Meter still needs to be analysed.

3.7. Fault detection

For Smart Meter Network, the fault can be categorized into two kinds of cases. The first one is data fault, which means the data involved in the message has some errors. These data errors may be caused by monitoring errors or malicious message altering. Fortunately, the data collector may detect such kind of fault by some statistical algorithms, such as comparison between the current data and historical data. This kind of fault and corresponding solutions mainly occur at application layer. What the MAC protocols' designers need to consider is another one, communication fault, which means that some Smart Meters cannot communicate with the Local Collector directly. These communication problems may be caused by the malfunction of Smart Meters or the degeneration of wireless communication environment since communication fault leads to the Smart Meter Network as quickly as possible. For example, the Local Collector may exploit the idle communication intervals to poll every Smart Meter and expect its feedback. After that, the collector may detect the silent meters by checking the missing feedbacks.

Furthermore, how to schedule the poll-feedback actions in detail and improve its efficiency still need to be investigated.

4. IEEE 802.11ah standardization task group

The success and popularity of IEEE 802.11 (WiFi) enabled communication devices have led to a new standardization task group IEEE 802.11ah, aimed at creating a WiFi-based standard to support wireless communication between Smart Meters and Local Collector as one of its primary use cases. According to [9], IEEE 802.11ah compliant devices will utilize multi-input, multi-output-orthogonal frequency division multiplexing (MIMO-OFDM) at frequencies below 1 GHz, where there are no licensing and regulatory issues. The most discussed channelization for 802.11ah in the US focuses on the 902–928 MHz band, which is currently free. The 802.11ah Working Group appears to have settled on 1 and 2 MHz as the possible channel bandwidth [25]. Besides the benefit of free spectrum, the signal transmission below 1 GHz generally suffers less propagation path loss, enabling the network to achieve larger coverage, as verified above.

With respect to the MAC protocols' design for the use case of Smart Meter—Local Collector communications—the IEEE 802.11ah TG is considering using improved DCF and PCF [9]. Since the area of a cell for one Local Collector may cover thousands of Smart Meters that far

exceed the current capabilities of base DCF protocol that was intended for small, indoor cells serve 20 users on average. Hence, the scalability issue of DCF is one of their main discussion areas. The modified DCF with contention factor and prohibition time is one of the suggestion new options. Before the contention phase, the Local Collector broadcasts a prohibition time T and contention factor $0 < Q < 1$, according to the current network congestion status. After that, each Smart Meter generates a random number r which follows a uniform distribution on the unit interval and compare it to Q. Then, the Smart Meter may contend for the channel if $r > Q$ and, otherwise, it keeps silent until the prohibition time T passes. In order to further relieve contention congestion, the MAC scheme may also divide all the Smart Meters within a cell into several groups and provide different groups with different parameters Q and T or allow them to contend for the channel group by group. The collision probability is expected to decrease dramatically (compared to traditional DCF applied to all Smart Meters), as a result.

In order to solve the scalability challenge for PCF, IEEE 802.11ah TG proposes a modified PCF scheme, Probe and Pull MAC (PP-MAC) [9]. After partitioning all the Smart Meters into groups, the Local Collector broadcasts a probe message to a certain group of Smart Meters before the contention free phase. After that, the Smart Meters having data to send reply a short Probe-ACK concurrently with the use of Zadoff–Chu sequences. By assigning these orthogonal sequences to each Smart Meter and multiplying their own messages with their respective sequences, the cross-correlation of the simultaneous short probe-ACK transmissions is reduced, so that the Local Collector is able to resolve these parallel ACKs and identify the different transmitters. After that, the Collector schedules and only polls the Smart Meters with Probe-ACK, which leads to a shorter polling cycle and a more efficient taking-turns MAC protocol.

5. MAC protocols design example I: grouping-based MAC protocols for EV charging data transmission in Smart Meter Network

As mentioned above, the number of Smart Meters involved in Smart Meter Network (a single Local Collector coverage) is much larger than those in today's local area networks, the traditional random access MAC protocols such as DCF in IEEE 802.11 does not work well on event-triggered data communication, for example EV charging data transmission, due to the scalability issue. Therefore, we propose two grouping-based MAC protocols: TDMA-DCF (TDCF) and Group Leader DCF-TDMA scheme (DCFT) in the paper [11]. These two schemes are directed at 802.11 type networks operating at the frequencies below 1 GHz that has been adopted by a new IEEE 802.11ah standardization task group.

In TDMA-DCF, all Smart Meters are divided into several groups and separating network channel access into two-tiers: inter-group and intra-group tier. During each periodic frame in the contention phase, the Local Collector allocates one mutually exclusive sub-frame to each group by broadcasting a control message.

Once a generic group has been allocated the sub-frame and obtains the transmission rights, all the Smart Meters inside this group compete for the channel by DCF. Therefore, the number of

meters involved in the contention concurrently is the number of Smart Meters per group at most. The random access at intra-group tier lasts until the sub-frame duration passes or the channel keeps idle for a continuous interval, defined as 'idle interval'. After that, the Local Collector broadcasts another control packet to allocate a new sub-frame to another group. It is noted that there may exist some communications not finishing at the end of sub-frame, and then it may collide with the random access of next group nodes if they do not detect the ongoing transmission. Therefore, in order to avoid such collision, the sub-frame allocation is only controlled by the Local Collector's broadcasting message. The scheme is operated as shown in **Figure 8**.
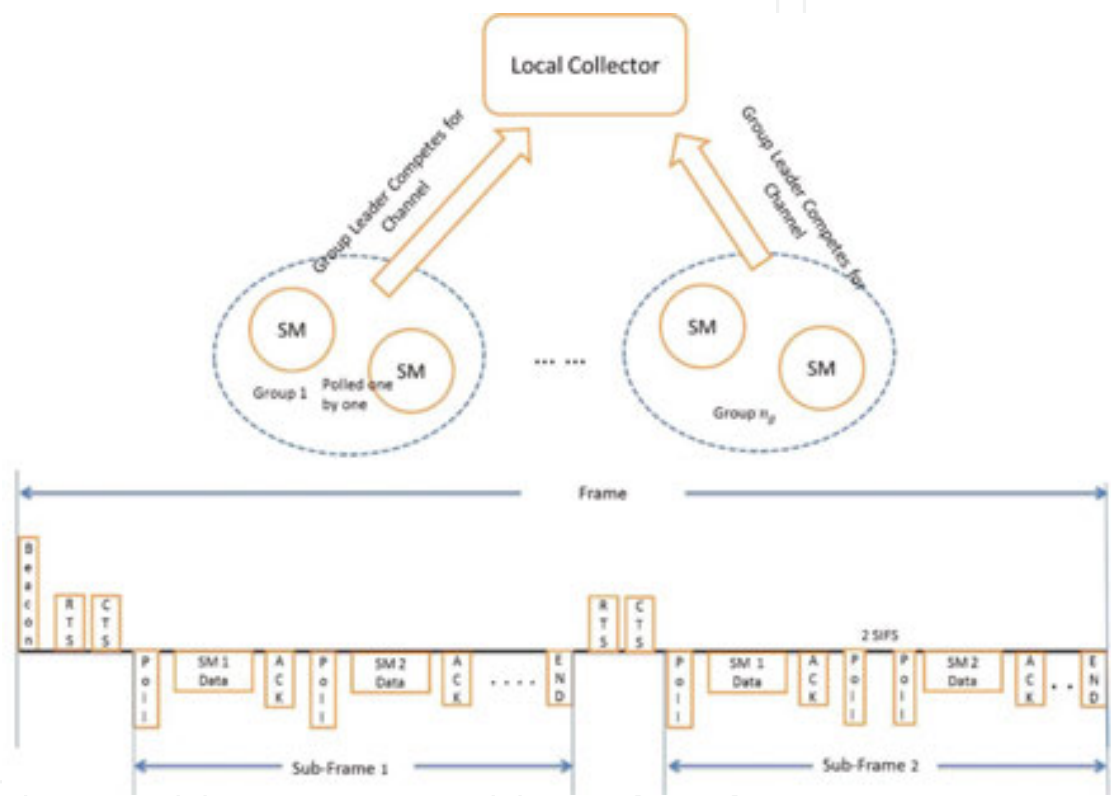
Figure 8. TDMA-DCF scheme operations.

In order to reduce the hidden node events of the random access at intra-group tier, we divide all the Smart Meters into several groups according to their deployment proximity and optimal group size. After the division, as shown in **Figure 9**, the grouping status is recorded in the Registration Table.

On the other hand, in the Group Leader DCF-TDMA scheme, we divide all the Smart Meters into groups according to a different rule which is mentioned below. Furthermore, the Group Leader DCF-TDMA scheme applies DCF at the inter-group tier and Polling protocol at the intra-group tier, which is opposite to the TDMA-DCF scheme. First, Local Collector assigns a group leader for each group. At the beginning of the periodic frame of the contention phase, all the group leaders compete for the channel via RTS/CTS exchange based on the DCF scheme.

Therefore, the number of Smart Meters involved concurrently in the random access at most equals to the number of groups which is much less than the total number of meters. If a generic group leader wins the competition, that is this leader reserves a sub-frame for its associated group via the RTS message and informs other group leaders of the expected duration via the CTS responded by the Local Collector, and then the Local Collector polls all the meters inside the 'winner' group one by one; the Smart Meter replies to the Local Collector with its own data sequentially. The reserved sub-frame lasts until the Local Collector broadcasts an 'END' message when all the meters inside the group finish the transmissions. If any meter in the group has nothing to transmit and keeps silent to the Polling message, the Local Collector is able to detect this case and starts to poll next sequential meter after two continuous idle SIFS. Accordingly, the collector may broadcast the 'END' signal earlier. After that, all the group leaders start to compete for the channel again. It is noted that in this scheme, the Polling operation is centralized controlled by the Local Collector. Therefore, our scheme is more suitable for the use case of SMN, because the group leader in SMN is just the normal Smart Meter with simple infrastructure. The operation of this scheme is outlined in **Figure 9**.
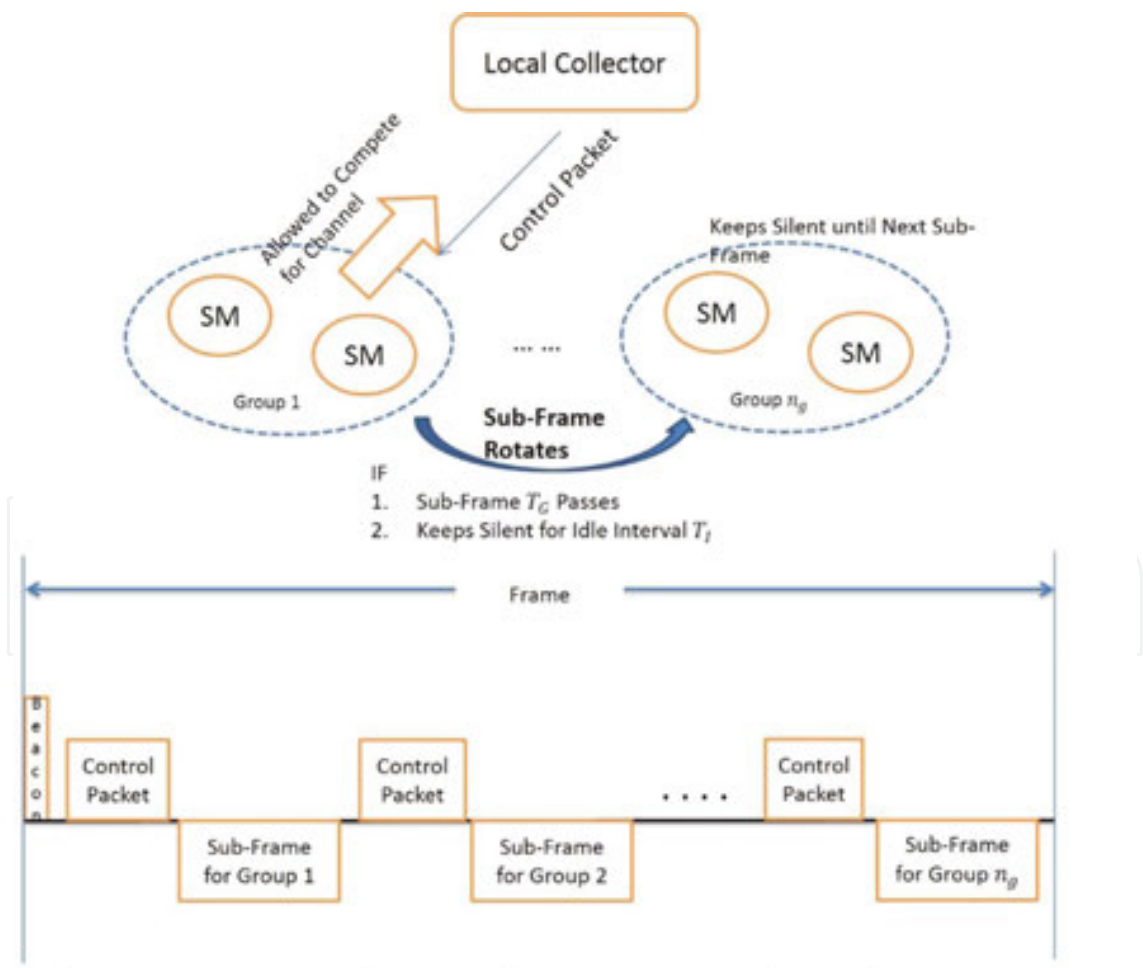

Figure 9. DCF-TDMA scheme operations.

On the contrary to the TDMA-DCF scheme, in order to reduce the hidden node events of the random access at inter-group tier, we have to select the Smart Meters located close to the Local Collector to act as the group leaders, among which there is no hidden node problem. After that, all other Smart Meters may be randomly picked to associate to each group leader and form the group. After division, as shown in **Figure 10**, the grouping status is also recorded in the Registration Table.
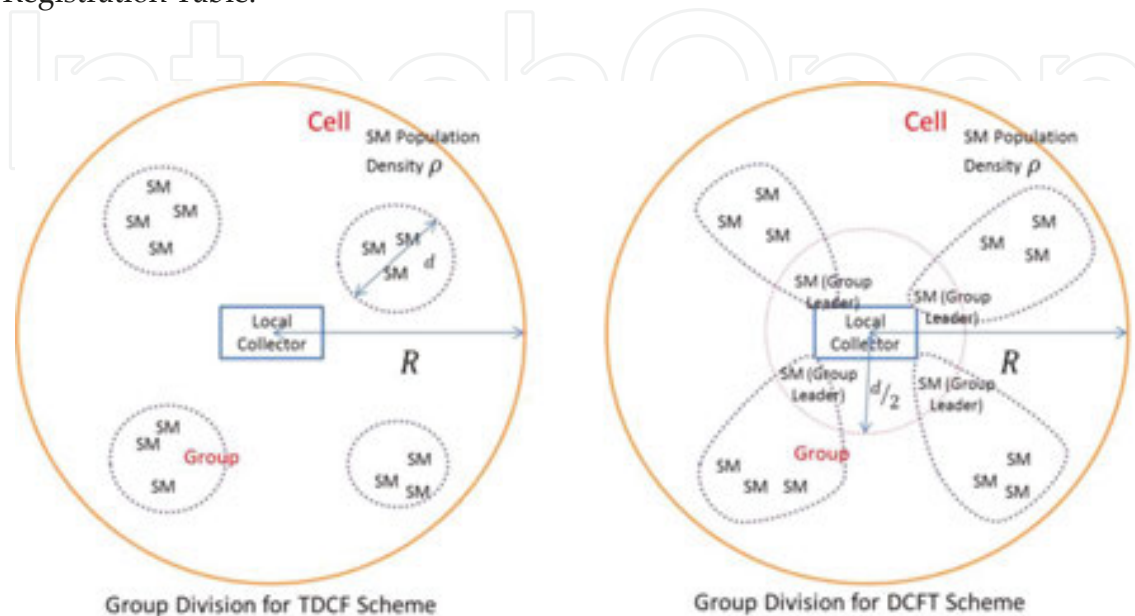
Figure 10. Network topology after group division.

Furthermore, from the calculation in [11], the approximate value of successful transmission distance is 1600 m. If we model it as a disk with radius 800 m, the number of Smart Meters within this area is about 2000. That means, as long as the group size for TDMA-DCF scheme and the number of group leaders for DCF-TDMA scheme is smaller than 2000, it is believable to assume that there are few hidden nodes in these two grouping-based schemes.

The protocol details and comprehensive throughput and delay analysis on these schemes are presented in [11]. The numerical results show that these two grouping-based MAC protocols significantly outperform the traditional random access protocol DCF in a densely populated network with large coverage like Smart Meter Network.

6. MAC protocols design example II: enhanced PCF scheme for periodic data transmission in Smart Meter Network with cognitive radio

In order to solve the scalability issue for periodic data transportation, the authors in [10] propose a modified PCF scheme with the aid of cognitive radio technology (CR-PCF), in which the Smart Meters are allowed to use the white space to report the periodic data to the Local Collector as secondary users.

In the initialization phase of this algorithm, all the Smart Meters and Local Collector stay in the dedicated channel for the control signalling exchange. Local Collector senses all the candidate channels in the white space and then detects the available channels not occupied by Primary Users. After that, it distributes all the available channels to its associated Smart Meters with the broadcasting Poll message. After receiving the message, the Smart Meters having been allocated transmission resources are tuned to the allocated channels and transmit their packets to the Local Collector. Then, the Local Collector checks whether the received packets have been corrupted due to the collision with Primary Users. At the same time, it senses the current available channels and distributes them to the Smart Meters for the next round transmission together with the acknowledgement. It is noted that all the Smart Meters tune back to the dedicated channels so as to be able to receive the acknowledgement and Poll messages. This operation runs until all the Smart Meters finish the transmission of all the pending packets.

On the other hand, the fairness among all the Smart Meters is also quite important in the protocol design. For example, the Local Collector first serves the specific several Smart Meters in a generic group and does not allocate channels to the rest of the Smart Meters until the first several Smart Meters finish their transmission of all their packets. After that, the Local Collector focuses on serving other Smart Meters until they finish their pending packet transmissions. As a consequence, there may exist a situation that the number of Smart Meters which still need to be served is smaller than the number of available channels when approaching the end of contention-free frame. It is obvious that this case is a waste of channel resource, which will also lead to increasing the duration to finish the entire reporting transmission. In order to avoid this situation, we propose a Least Completed First Served Principle as shown in [10]. In brief, at each round of channel sensing and allocation, the Local Collector prefers to allocate the channels to the Smart Meters with the least completed transmissions so as to try to guarantee the fairness among all the Smart Meters.
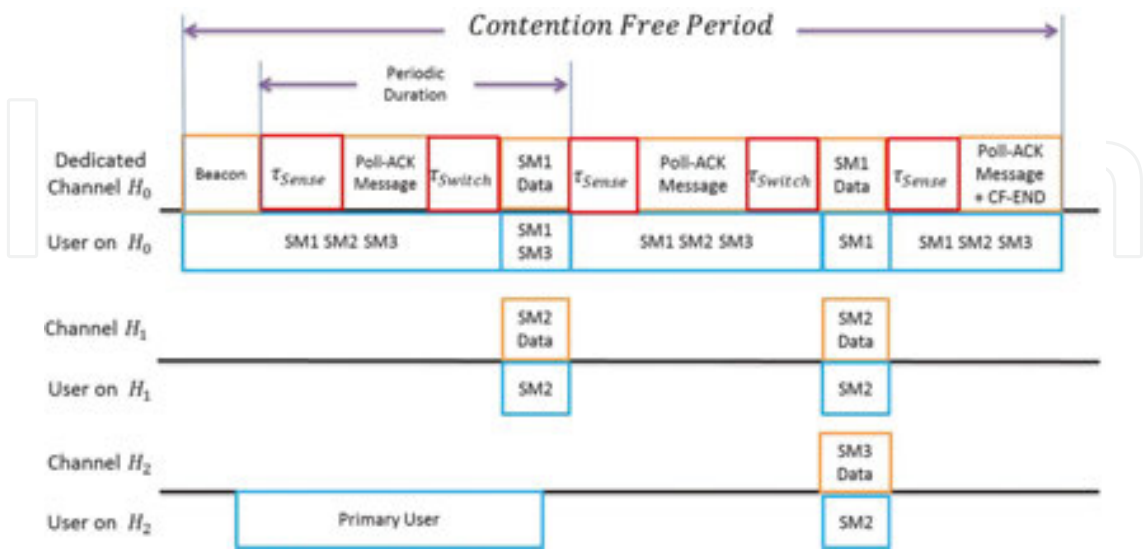

Figure 11. CR-PCF scheme operation example.

The detailed protocol scheme is exemplified in **Figure 11**. In addition, through comprehensive numerical and simulation in [10], the modified PCF with cognitive radio is shown to significantly outperform the traditional one in Smart Meter Network.

7. Conclusion

In this chapter, we briefly introduced the Smart Meter Network architecture and candidate communication technologies, which is quite important to the MAC protocols' design of Smart Meter Network. After that, we highlighted several significant MAC protocol design metrics and the associated research issues in the Smart Meters Network, including different data types, scalability, delay, fairness, expandability, security, etc. In order to solve the challenges and issues, we proposed two MAC protocol design solutions, grouping-based schemes and enhanced PCF scheme with the aid of cognitive radio. Furthermore, a short summary of MAC protocol improvement in IEEE 802.11ah TG is also included.

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References

[1] Khalifa T., Naik K., and Nayak A., "A Survey of Communication Protocols for Automatic Meter Reading Applications," IEEE Communications Survey and Tutorials, vol. 13, no. 2, Second Qtr, 2011, pp. 168–182.

[2] Yang Y., and Roy S., "PMU Deployment for Three-Phase Optimal State Estimation Performance," IEEE International Conference on Smart Grid Communications, Vancouver, Canada, 2013.

[3] Yang Y., and Roy S., "PMU Deployment for Optimal State Estimation Performance," IEEE GLOBECOM 2012, Anaheim, CA, USA, 2012.

[4] Gungor V.C., Sahin D., Kocak T., and Ergut S., "A Survey on Smart Grid Potential Applications and Communications Requirements,"IEEE Transactions on Industrial Informatics, vol. 9, no. 1, 2011, pp. 28–42.

[5] Wang W., Xu Y., and Khanna M., "A Survey of the Communications Architectures in Smart Grid," Computer Networks, vol. 55, no. 15, 2011, pp. 3604–3629.

[6] Park B., Hyun D., and Cho S., "Implementation of AMR System Using Power Line Communication, IEEE/PES Transmission Distribution Conf. Exhibition, Yokohama, Japan, Oct. 2002.

[7] Peizhong Y., Iwayemi A., and Zhou C., "Deveploing Zigbee Deployment Guideline Under WiFi Interference for Smart Grid Applications," IEEE Transactions on Smart Grid, vol. 2, no. 1, 2011, pp. 110–120.

[8] Yarali A., "Wireless Mesh Networking Technology for Commercial and Industrial Customers," Proceeding Electrical Computing Engineering CCECE, Niagara Falls, Ontario, Canada, May 1–4, 2008, pp. 000047–000052.

[9] IEEE 802.11ah TG, "Specification Framework for TGah," IEEE 802.11-11/1137r15, May 2013.

[10] Yang Y., and Roy S., "PCF Scheme for Periodic Data Transmission in Smart Metering Network with Cognitive Radio," IEEE GLOBECOM 2015, San Diego, CA, USA.

[11] Yang Y., and Roy S., "Grouping Based MAC Protocols for EV Charging Data Transmission in Smart Metering Network," IEEE Journal of Selected Area on Communications, vol. 32, no. 7, 2014, pp. 1328–1343.

[12] Yang Y., Yin Y., and Hu Z., "MAC Protocols Design for Smart Metering Network," Automation, Control and Intelligent Systems, vol. 3, no. 5, 2015. pp. 87–94.

[13] Lewis R.P., Igic P., and Zhongfu Z., "Assessment of Communications Methods for Smart Electricity Metering in the UK," IEEE PES/IAS Conference of Sustainable Alternative Energy (SAE), Valencia, Spain, Sept. 28–30, 2009.

[14] Gungor V.C., Sahin D., Kocak T., Ergut S., Buccella C., Cecati C., and Hancke G.P., "Smart Grid Technologies: Communications Technologies and Standards," IEEE Transactions on Industrial Informatics, vol. 7, no. 4, 2011, pp. 529–539.

[15] Tan H., Lee H., and Mok V., "Automatic Power Meter Reading System Using GSM Network," IEEE International Conference on Control Application, Singapore, Oct. 1–3, 2007.

[16] AEIC Team, "AEIC/Smart Grid AMI Interoperability Standard Guidelines for ANSI C12.19 Communications," Association of Edison Illuminating Companies, Birmingham, AL, USA Version 2.0, November 19, 2010.

[17] IEEE 802.11ah TG, "Potential Compromise for 802.11ah Use Case Document," IEEE 802.11-11/0457r0, Mar. 2011.

[18] IEEE 802.11ah TG, "TGah Channel Model Proposed Text," IEEE 802.11-11/0968r3, Nov. 2011.

[19] Proakis J.G., "Digital Communications, Fifth Edition," McGraw Hill Publishing House, New York, NY, USA, 2009.

[20] Electric Power Research Institute, "Summary of EPRI Test Circuits," www.epri.com.

[21] IEEE 802.11ah TG, "Association ID Management for TGah," IEEE 802.11-11/0088r1, Jan. 2011.

[22] Ma H., Alazemi H., and Roy S., "A Stochastic Model for Optimizing Physical Carrier Sensing and Spatial Reuse in Wireless Ad Hoc Networks," IEEE International Conference on Mobile Adhoc and Sensor Systems, Washington DC, USA, Nov.7, 2005.

[23] IEEE 802.11 WG, IEEE 802.11e/D5, "Draft Supplement to Standard for Telecommunications and Information Exchange between Systems—LAN/MAN Specification Requirements—Part 11: Wireless Medium Access Control and Physical Layer Specifications: Medium Access Control Enhancements for Quality of Service," 2003.

[24] Kurose J., and Ross K., "Computer Networking A Top-Down Approach, Fifth Edition," Pearson Education Inc, New York City, NY, USA, 2010.

[25] Aust S., and Prasad R., "IEEE 802.11ah: Advantages in Standards and Further Challenges for Sub 1 GHz Wi-Fi," 2012 IEEE International Conference on Communications, Ottawa, Canada, Jun. 10–15, 2010.