Network Coding Based QoS-Provisioning MAC for Wireless Smart Metering Networks

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Abstract. The advanced metering infrastructure (AMI) with smart metering networks, which enables the two-way information exchange between utilities and end-users, is the critically important component of the overall smart grid architecture. In this paper, we propose a network coding based QoS-provisioning MAC protocol for wireless smart metering networks, which aims at providing reliable and low-latency communications services between smart meters and coordinator of the utilities. In particular, to efficiently utilize the limited bandwidth resource, we develop our proposed MAC protocol based on the contention-free orthogonal frequency division multiple access (OFDMA) methodology. Our proposed MAC protocol incorporates the opportunistic resource allocation, cooperative grouping, and network coding technique. Under our proposed MAC protocol, the coordinator adaptively allocates the resource blocks to each smart meters based on the channel conditions between the coordinator and the smart meter and among the smart meters. Also conducted are simulations to verify and evaluate our proposed MAC protocol.

Keywords: Advanced metering infrastructure (AMI), medium access control (MAC) network coding, orthogonal frequency division multiple access (OFDMA), smart grid.

1 Introduction

Recently, the smart grid, which delivers both energy and information, has receives intensive research interests from academia, industry, and military. The motivation behind the smart grid is to improve power reliability and quality, increase the generation and transmission efficiency, and enable a wide adoption of renewable energy and electric vehicles. Due to the two-way information exchange between the utilities and the power end-users (industrial or home consumers), the smart grid enables the new load shifting and energy efficiency programs at the side of end-users that have power usage and price awareness and choice.

The novel power demand managements [1] are one of the most import applications of the smart grid, which impact the energy flow towards the end-user endpoints. With the help of smart metering networks, the end-user consumption

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can now possibly be controlled at energy access point level. Smart meters with the features of power-line connect/disconnect allow end-users automatically to disconnect homes from the grid, in case of a security issues. The power demand managements also encourage end-users to reduce their energy consumption, especially during the power grid's peak loads. This can be achieved by implementing the smart metering networks which enable the two-way information exchange between utilities and end-users.

The smart metering networks, which consist of advanced wireless/wireline communications and networking technologies as well as new and improved solid-state metering devices, plays the critical important role in the smart grid, as shown in Fig. 1. The smart metering networks allow the utilities to not only record and analyze the end-users' utility usage, but also keep end-users informed of updated utility prices and perform remote utility management, all in a reliable and real-time manner. Furthermore, cooperating with the intelligent supervisory control and data acquisition (SCADA) system, the smart metering networks can minimize the unplanned end-user outages and ensures the optimum power distribution network configuration.

To implement the above functionalities and guarantee the efficient power management, the design criteria of the smart metering networks include low latency, reliable and robust information exchange between utility and end-users. In this paper, we propose a network coding based QoS-provisioning MAC protocol for wireless smart metering networks. The proposed MAC protocol aims at providing reliable and low-latency communications services between smart meters and coordinator of the utilities. In particular, to efficiently utilize the limited bandwidth resource, we develop our proposed MAC protocol based on the contention-free orthogonal frequency division multiple access (OFDMA) methodology. Our proposed MAC protocol incorporate the opportunistic resource allocation, cooperative grouping, and network coding technique. Under our proposed MAC protocol, the coordinator adaptively allocate the resource blocks to each smart meters based on the channel conditions between the coordinator and the smart meter and among the smart meters. Also conducted are simulations to verify and evaluate our proposed MAC protocol.

The rest of this chapter is organized as follows. Section 2 presents the related work. Section 3 describes the system model. Section 4 proposes the network coding based QoS-provisioning MAC protocol. Section 5 evaluates our scheme based on simulation experiments. The chapter concludes with Section 6.

2 The Related Works

The communications and networking technology plays the key role in the smart grids. The authors of [2] discussed the applications of communications and networking on smart grids from the industry perspective. The authors of [3] proposed a routing protocol for the AMI in smart grids based on the framework of the IPv6 routing protocol for low power and lossy networks. The authors of [4] implemented a ZigBee-based AMI which employs a multichannel frequency

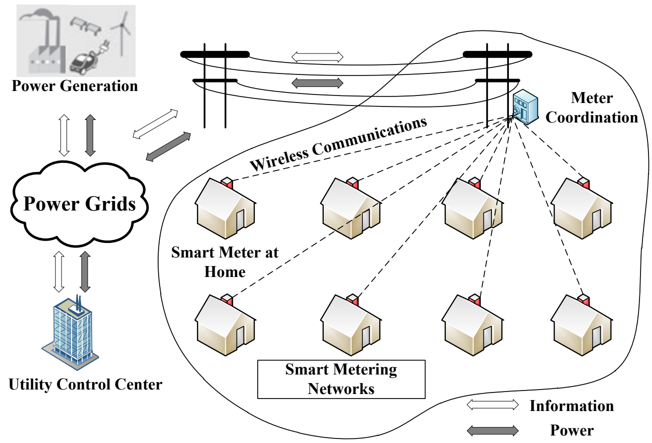

Fig. 1. Illustration of the smart metering networking in the smart grid

hopping system to tackle the co-existence problem with the WiFi and Bluetooth networks.

The network coding is a powerful tool to improve the network throughput and delay performance. The concept of network coding was first coined in [5] in the context of wired multicast communications. The conventional wireless-network coding [6,7], which takes advantage of the broadcast nature of wireless medium to reduce the number of transmissions, were proposed to enhance the network throughput under the 2-way relay scenarios. By not only utilizing the broadcast nature of wireless medium, but also exploiting the inherent physical-layer coding capability through analogously mixing the simultaneously arrived radio waves at the relay nodes, the analog network coding [8, 9] can further increase the network throughput. However, the analog wireless network coding requires the strict synchronization among the source, destination, and relay, and thus is difficult to implement in practice. In this paper, we use only the conventional wireless network coding technique to further improve the network throughput and reliability of the smart metering networks.

3 System Model

To efficiently exploit the previous bandwidth resource, we propose to use the OFDMA as the access methodology for the wireless smart metering networks. The smart meters conduct two-way communications with the coordinator. The smart meters report the utility usage periodically to the coordinator while the coordinator periodically broadcasts utility price to the smart meters. The frequency resources is divided into $M = aN$ resource blocks, where a is a positive integer. For notational convenience, we let M be an even number. The transmission across time is assumed to be independent, and smart meters have independent channels towards the coordinator. We assume the transmission on each resource block uses the same transmit power, modulation and channel coding. The transmission bit rate of the modulated signal over one resource block is R bits/second. Let α be the channel path loss exponent, and c be some constant, then the packet success rate for a transmission of ℓ bits using a single resource block is $e^{-cd^{\alpha}}$. The transmission time in this case is ℓ/R. Alternatively, through resource block multiplexing, a transmission can use 2 resource blocks to transmit ℓ bits in $\ell/(2R)$ seconds. Using the independence assumption, we assume that the packet success rate in this case is also $e^{-cd^{\alpha}}$.

For the same source and destination node pair, the channel allows a maximum of D_0 independent resource blocks, that is the maximum diversity order. Therefore, if a smart meter transmits ℓ bits of data over $r \geq 2$ resource blocks, the increased diversity order improves the probability of success to

$$P_s(d, r) = 1 - (1 - e^{-cd^{\alpha}})^{\min(r, D_0)}. \tag{1}$$

We assume the same probability of success for transmitting L bits of data over $2r \geq 4$ resource blocks.

Let $d_{i,0}$ be the distance between smart meter i and the coordinator, and $d_{i,j}$ be the distance between smart meter i and smart meter j. We denote the probability of success for sending a packet from smarter meter i to the coordinator over a single resource block by $P_s(d_{i,0}, 1)$, and the probability of success for smarter meter j to overhear the transmission by $P_s(d_{i,j}, 1)$. We assume that these probabilities are known at the coordinator, who uses the information for group assignment and scheduling uplink transmissions.

In this paper, to guarantee the real-time information exchange between the smart meters and coordinator, we concentrate on the amount of time that is required to guarantee that all uplink transmissions are received successfully at the coordinator. The uplink transmissions are broken down into multiple transmission opportunities to guarantee reliability. This strategy to improve reliability is to provide two transmission opportunities to an uplink transmission to improve packet success rate as illustrated in Fig. 2. In particular, the time is divided into

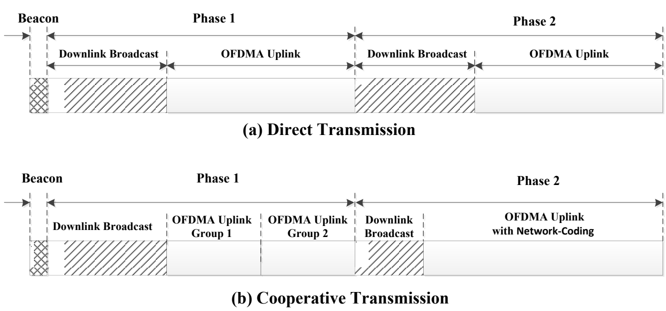

Fig. 2. The illustration of the transmission schemes of our paper

superframes each with fixed length. Each superframe starts with the beacon signal. Besides the beacon signal, the rest of the superframe is partitioned into two transmission phases, which aims at increase the reliability of message delivery. In each transmission phase, we employ the time-division duplex (TDD) for the downlink and uplink communications.

Between the two consecutive uplink transmissions, the coordinator broadcasts a downlink message to all smart meters to acknowledge packet receptions, and send resource assignment information (e.g., channel assignment etc.) for the next uplink transmission.

4 Our Proposed Transmission Schemes

4.1 The Basic Direct Transmission Scheme

We use the basic direct transmission scheme as the baseline for comparison. As shown in Fig. 2(a), in the first transmission opportunity, every smart meter transmits their data using frequency diversity order $a = M/N$. No control overhead is used. The probability of success for transmission from smart meter i is $P_s(d_{i,0}, a)$.

After each transmission opportunity, if the coordinator still fails to decode some packets from some smart meters, the coordinator requests in the feedback those failed smart meters to retransmit their packets again. To meet the time budget during the subsequent transmission opportunities, at most X, with $X \leq M$, nodes may retransmit. Let K be the number of packets that are still missing from the coordinator. If $K \geq X$ and $X = M/2$, then only $M/2$ smart meters can retransmit, and each retransmission uses 2 resource blocks, and thus the diversity order is 1. If $K < X$, the system guarantees that each smart meter has at least 2 resource blocks to transmit its data at diversity order 1. The coordinator successively allocates 2 resource blocks at a time to increase the diversity order of the node that has the worst effectively probability of success. We list the detailed algorithm as follows:

Initialization: Let E be the set of nodes with failed transmission. Let the remaining number of resource blocks be $r = M - 2K$, the effective success probability of node i be

$$P_i = \begin{cases} 1, & \text{if } i \notin E, \\ P_s(d_{i,0}, 1), & \text{otherwise,} \end{cases} \tag{2}$$

and the diversity order of node i be $D_i = I_{\{i \in E\}}$, where $I_{\{\cdot\}}$ is the indicator function.

Step 1) Find the node with the lowest effective probability of success $\tilde{i} = \arg\min_{i:D_i<D_0} P_i$. If $D_i < D_0$ for all i, then find the retransmitting node with the lowest diversity order $\tilde{i} = \arg\min_{i \in E} D_i$.

Step 2) Assign a resource block to increase the diversity order of the transmission from $\tilde{i}$. Update $P_{\tilde{i}} := P_s(d_{\tilde{i}}, D_i + 1)$, and then $D_{\tilde{i}} := D_{\tilde{i}} + 1$, and $r := r - 2$.

Step 3) If $r > 0$, go to step 1).

Step 4) Node i retransmits data using $2D_i$ resource blocks, at diversity order D_i.

4.2 The Basic Grouping Transmission Scheme

Instead of having all smart meters to transmit simultaneously during the first transmission opportunity. As shown in Fig. 2(b), we divide the N smart meters into two groups, namely $\mathcal{A}$ and $\mathcal{B}$, with each group having exactly $N/2$ nodes. The grouping algorithm will be discussed in the next section. During the first transmission time phase, group $\mathcal{A}$ nodes first transmit their packets to the coordinator while group $\mathcal{B}$ nodes overhearing the transmissions; and then group $\mathcal{B}$ nodes transmit while group $\mathcal{A}$ nodes overhearing. Since each node is equipped with a single transceiver, nodes within the same relay group cannot overhear packets from those in the same group. Since group $\mathcal{B}$ nodes transmit their packets after group $\mathcal{A}$, each node in group $\mathcal{B}$ can include a $N/2$-bit control overhead to specify whether it has correctly received the packets from the nodes in group $\mathcal{A}$. When node i in group $\mathcal{A}$ transmits, it transmits the packet at diversity order $a = M/N$ over $2a$ resource blocks. The coordinator receives a packet successfully with probability $P_s(d_{i,0}, a)$, and a smart meter j in group $\mathcal{B}$ overhears the packet successfully with probability $P_s(d_{i,j}, a)$. In this sense, node j in group $\mathcal{B}$ transmits its packet at diversity order $a = M/N$ over $2a$ resource blocks. The coordinator receives the packet successfully with probability $P_s(d_{j,0}, a)$. Similar to the basic transmission scheme, in subsequent retransmissions, the system allocates its available resources so that each failed transmission has at least one direct or relay retransmission. Thus, the system allocates resources to improve the weakest effective probability of success. We list the detailed algorithm as follows:

Let E be the set of up to $M/2$ nodes that have failed previous transmissions and have the shortest distance to the coordinator Let $Y(i)$ be the set of nodes that successfully overhear the packet from node i. Since only the nodes in group $\mathcal{B}$ overhear the packet from the nodes in group $\mathcal{A}$, $Y(i) =$ for $i \in B$. Then, for each node $i \in E$, the system chooses a node $\tilde{j}(i) = \arg\max_{j \in \{i\} \cup Y(i)} P_s(d_{j,0}, 1)$ to retransmit the packet for node i, using 2 resource blocks and diversity order of 1.

Let $r = M - 2K$, and

$$P_i = \begin{cases} 1, & \text{if } i \notin E, \\ P_s(d_{\tilde{j}(i)}, 1), & \text{if } i \in E. \end{cases} \tag{3}$$

Also, let $D_{ij} = I_{\{i \in E\}} I_{\{j = \tilde{j}(i)\}}$ be the diversity order of the transmission from node j to relay for node i (Index ii means that node i transmits its own packet). The algorithm proceeds as follows.

Step 1) Find the node with the lowest effective probability of success $\tilde{i} = \arg\min_{i: D_{ij} < D_0 \forall j} P_i$. If $D_{ij} < D_0$ for all i and j, then find the retransmitting relaying node with the lowest diversity order $\tilde{j} = \arg\min_{i \in E} \min_j D_{ij}$.

Step 2) Find the best relay for retransmitting the packet from node $\tilde{i}$.

$$\tilde{j}(\tilde{i}) = \arg \max_{j \in \{\tilde{i}\} \cup Y(\tilde{i}) : D_{\tilde{i}j} < D_0} P_s(d_{j,0}, 1). \tag{4}$$

Step 3) To assign a resource block, perform

$$D_{\tilde{i}\tilde{j}(\tilde{i})} := D_{\tilde{i}\tilde{j}(\tilde{i})} + 1. \tag{5}$$

$$P_{\tilde{i}} := 1 - \prod_{j}[1 - P_s(d_{j,0}, D_{\tilde{i}j})]. \tag{6}$$

$$r := r - 2. \tag{7}$$

Step 4) If $r > 0$, go to step 1).

Step 5) Node j retransmits data from node i using $2D_{ij}$ resource blocks with diversity order of D_{ij}.

4.3 The Network Coding Based Grouping Transmission Scheme

Similar to the basic grouping transmission scheme, the network coding based grouping transmission scheme also divide the transmissions into two groups, as shown in Fig. 2(b). In the network coding based grouping transmission scheme, we employ the network coding to improve the reliability of message delivery. The coordinator assigns the resource blocks to the smart meters with good channel condition in transmission phase 2. Since the smart meters in group $\mathcal{B}$ can overhear the packets sent from the smart meters in group $\mathcal{A}$ and receive the packets sent from the coordinator to all other smart meters in transmission phase 1, as shown in Fig. 3. Based on the relay report, smart meters in group $\mathcal{B}$ will report to the coordinator on which smart meters in group $\mathcal{A}$ it can successfully overhear and whether it receives the message sent from the coordinator to the other smart meters. Thus, the coordinator is aware of the set of smart meters in group $\mathcal{B}$, denoted by $\mathcal{R}$, which successfully receive the packets sent from/to the smart meters which fail to communicate with the coordinator.

At the beginning of the transmission phase 2, the coordinator chooses the relay smart meters from those in $\mathcal{R}$ to help the smart meters which fail to transmit/receive packets to/from the coordinator. The coordinator allocates the resource blocks to the relay smart meters in the downlink slot of the transmission phase 2. The relay smart meters conduct the XOR operations to combine the

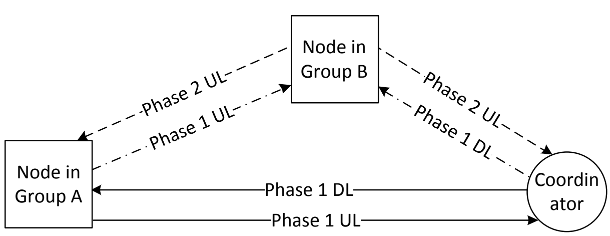

Fig. 3. The network coding aided relay

downlink and uplink packets for the smart meters which fail to transmit/receive packets, and then broadcast the combined packets by using the allocated resource blocks during the transmission phase 2, as shown in Fig.3. Upon the coordinator and the smart meters receive the combined packets, they can successfully decode the missing messages by conducting the XOR operations on the combined packets and their own packets.

The resource allocation in Phase 2 transmission is similar to the basic grouping transmission scheme. The difference between them is the selection criteria for the relay node. In the 2-way-relay network-coding transmission scheme, we need to consider the both the link between the relay and the coordinator and the link between the relay and the source node. Thus, for each smart meter $i \in E$, the system chooses the relay $\tilde{j}(i) = \arg\max_{j \in \{i\} \cup Y(i)} P_s(d_{j,i}, 1) P_s(d_{j,0}, 1)$ to retransmit the packet for node i, using 2 resource blocks and diversity order of 1. The effective probability of success, denoted by P_i, for the network coding based grouping transmission scheme can be written ad

$$P_i = \begin{cases} 1, & \text{if } i \notin E, \\ P_s(d_{\tilde{j}(i),i}, 1) P_s(d_{\tilde{j}(i),0}, 1), & \text{if } i \in E. \end{cases} \tag{8}$$

Also, let $D_{ij} = I_{\{i \in E\}} I_{\{j = \tilde{j}(i)\}}$ be the diversity order of the transmission from node j to relay for node i (Index ii means that node i transmits its own packet).

The details of the network coding based grouping transmission scheme are as follows:

Step 1) Find the node with the lowest effective probability of success $\tilde{i} = \arg\min_{i : D_{ij} < D_0 \forall j} P_i$. If $D_{ij} < D_0$ for all i and j, then find the retransmitting relaying node with the lowest diversity order $\tilde{j} = \arg\min_{i \in E} \min_j D_{ij}$.

Step 2) Find the best relay for retransmitting the packet from node $\tilde{i}$. Considering the maximum diversity order, redefine

$$\tilde{j}(\tilde{i}) = \arg \max_{j \in \{\tilde{i}\} \cup Y(\tilde{i}) : D_{\tilde{i}j} < D_0} P_s(d_{j,0}, 1) P_s(d_{j,i}, 1). \tag{9}$$

Step 3) To assign a resource block, perform

$$D_{\tilde{i}\tilde{j}(\tilde{i})} := D_{\tilde{i}\tilde{j}(\tilde{i})} + 1. \tag{10}$$

$$P_{\tilde{i}} := 1 - \prod_j [1 - P_s(d_{j,0}, D_{\tilde{i}j}) P_s(d_{j,i}, D_{\tilde{i}j})]. \tag{11}$$

$$r := r - 2. \tag{12}$$

Step 4) If $r > 0$, go to step 1).

Step 5) Smart meter j combines the data from the source i and coordinator by using XOR operation, and then broadcasts the combined data using $2D_{ij}$ resource blocks with diversity order of D_{ij}.

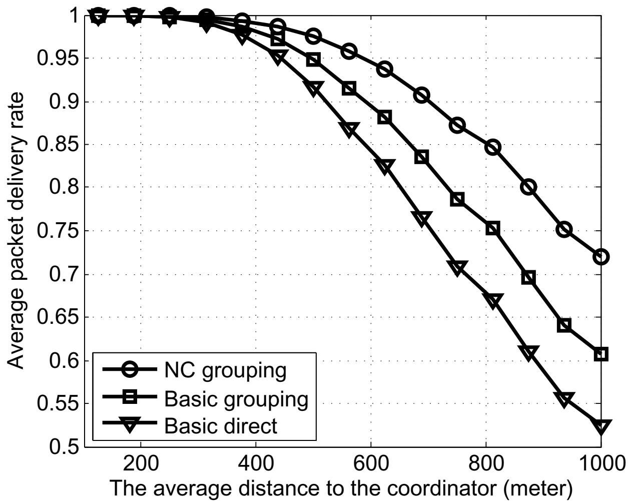

Fig. 4. The impact of the average distance to the coordination on the average packet delivery rate

4.4 The Grouping Algorithm

Since the smart meters is divided into two groups to proceed the cooperations, we develop a simple, but effective, grouping algorithm. Assume that the system only knows $P_s(d_{i,0}, 1)$ for all i. Since only the nodes in group $\mathcal{B}$ in direct transmission scheme may help relay packets of the nodes in group $\mathcal{A}$, the system may benefit from direct transmission scheme only if group $\mathcal{B}$ nodes are better performing than the nodes in group $\mathcal{A}$. Hence, the grouping algorithms simply assigns the $N/2$ smart meters with the poorest P_i to group $\mathcal{A}$, and the $N/2$ smart meters with the best P_i to group $\mathcal{B}$.

5 Performance Evaluations

To meet the delay requirement of the meter reading defined by NIST [10], we set the length of the superframe to be equal to 30 ms. The simulation results shown in this section is the average results of the 100 simulation runs.

Figure 4 shows the impact of the average distance to the coordination on the average packet delivery rate with different schemes. As the average distance to the coordination increases, the average packet delivery rate decreases. Our proposed network coding based grouping scheme decreases at the slowest speed. When the average distance to the coordination keep increasing, the advantage between our proposed network coding based grouping scheme over the other two schemes becomes larger. When the average distance to the coordinator reaches 1000 meters, the packet delivery rate of our proposed network coding based grouping scheme can still be 0.72, while the basic grouping transmission scheme

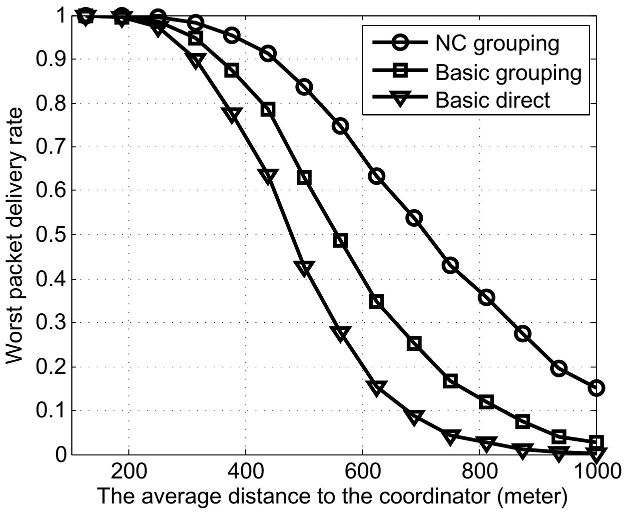

Fig. 5. The impact of the average distance to the coordination on the worst packet delivery rate among all smart meters

achieving less than 0.61 packet delivery rate and the basic direct transmission scheme having less than 0.53 packet delivery rate.

We proceed to study the worst packet delivery rate, which is defined as the worst packet delivery rate achieved among all smart meters. Generally speaking, the worst packet delivery rate is achieved by the smart meter with the worst channel condition. As shown in Fig. 5, when the average distance to the coordination is large, the worst packet delivery rates of all schemes are small. If setting the threshold for the worst packet delivery rate to be 0.9, then the maximum average distance to the coordination achieved by our proposed network coding based grouping transmission scheme is 446 meters, while the maximum average distances for the basic grouping transmission and the basic direct transmission scheme are 357 and 312 meters, respectively, which shows the superiority of our proposed network coding based grouping transmission scheme.

6 Conclusions

This paper proposed a network coding based QoS-provisioning MAC protocol for wireless smart metering networks to provide reliable and low-latency communications services between smart meters and coordinator of the utilities. Our proposed MAC protocol combine together the opportunistic resource allocation, cooperative grouping, and network coding technique. In particular, We developed our proposed MAC protocol based on the contention-free orthogonal frequency division multiple access (OFDMA) methodology, which aims at efficiently utilizing the limited bandwidth resource. Specifically, our proposed MAC protocol enables the coordinator to adaptively allocate the resource blocks to each smart meters based on the channel conditions between the coordinator and the smart meter and among the smart meters. The extensive simulation results showed that our proposed MAC protocol significantly outperforms the basic transmission protocols in terms of packet reliability.

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