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QoS-Aware MAC protocols utilizing sectored antenna for wireless sensor networks-based smart grid applications

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SUMMARY

Wireless sensor networks (WSNs) are the most commonly deployed technology in smart grid environments owing to their advantages including low cost and successful adoption in various harsh smart grid environments. However, providing the quality of service (QoS) requirements of smart grid applications with WSNs is difficult because of the power constraints of sensor nodes and unreliable wireless links. In order to meet the QoS requirements of smart grid applications using WSNs, in this paper, we first propose a QoS-aware omnidirectional antenna-based medium access control (QODA-MAC). Then, in order to investigate the impact of using sectored antennas on meeting QoS requirements, we also propose another QoS-aware four-sectored antenna-based MAC protocol (QFSA-MAC). The aim of the proposed approaches is to increase channel utilization with efficient service differentiation considering traffic flows with different requirements as well as providing reliable and fast delivery of data. We measure the performance of QODA-MAC and QFSA-MAC by making extensive simulations and compare them with each other. The results show that QFSA-MAC outperforms the QODA-MAC protocol and satisfies QoS requirements of smart grid applications by achieving significant improvement in terms of latency, energy consumption and data delivery.

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KEY WORDS: wireless sensor networks; smart grid; service differentiation; directional antenna

1. INTRODUCTION

The smart grid is a modern electric power system that integrates many devices with a state-of-the-art communication infrastructure and energy management techniques on the existing power grid. Many technologies are used for meeting the reliability, security, and efficiency requirements of smart grids. In this respect, accurate and real-time (RT) collection of information from generators, transmission equipment, transformers, and substations, which are illustrated in Figure 1, are the most critical issues for smart grid applications [1].

Wireless sensor networks (WSNs) are widely used in smart grid applications owing to their many advantages. QoS requirements of many smart grid applications summarized in Table I [2, 3], such as plug-in hybrid electric vehicle (PHEV), distribution generation, community energy storage, distribution automation, and outage alarming, vary in terms of delay and throughput. For instance, PHEV provides the information of electricity distribution system [1], and if the information related to status of the transformers is delayed or not correctly transformed, unnecessary load control can occur and can make it difficult to provide the stability of the power grid. Although PHEV is not

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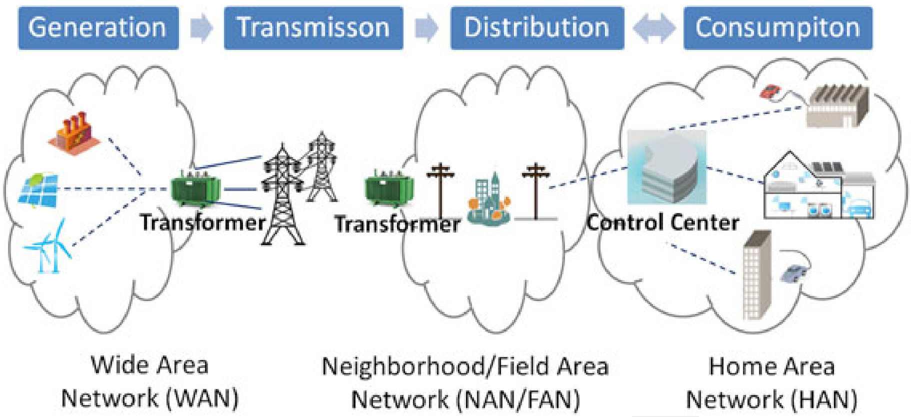

Figure 1. Architecture of wireless sensor network-based smart grid communication network.

Table I. Quality of service requirements of smart grid applications.

Application	Delay	Throughput
Advanced metering infrastructure	2 s	14–100 kbps
Demand response	2 s	56 kbps
Wide-area situational awareness	15–200 ms	600–1500 kbps
Distributed energy resources and storage	100 ms–2 s	9.6–56 kbps
Plug-in hybrid electric vehicle	2 s–5 min	9.6–56 kbps
Distribution automation	20–200 ms	9.6–56 kbps
Substation automation	15–200 ms	9.6–56 kbps
Emergency response	0.5 s	40–250 kbps
Outage management	2 s	56 kbps
Building automation	1–2 s	16–32 kbps

latency-tolerant, other smart grid applications, such as metering, are latency-tolerant. In addition, all of the collected data are not important for smart grid applications. Some of them are auxiliary control packets sending general information such as location information about the sensor nodes and do not require real-time communication [4].

Various types of traffic, such as best effort (BE), non-real-time (NRT), and RT, are delivered by WSN-based smart grid applications. Management of these traffic types can be performed by making prioritization and service differentiation based on the requirements of various traffic types with different requirements [5]. Medium access control (MAC) layer mechanisms can support the QoS requirements of these applications because they manage the sharing of medium and have the capability to affect the performance of the smart grid communication networks. Therefore, implementing an efficient MAC protocol and a compatible routing protocol is important for QoS. However, there exist many design challenges while designing an efficient MAC protocol and a routing protocol. One of these challenges is that high latency can occur during data collection process because of variable channel capacity of WSNs. In WSNs, the interference level perceived at the receiver determines the capacity of each wireless link. Hence, the capacity of each link is environment-dependent, providing QoS provisioning a compelling issue. Second, sensor nodes are resource-constraint, and therefore, they have limited memory, processing capability and data rate. These make it difficult to develop QoS-aware scheduling for smart grid applications. Finally, each smart grid application has specific QoS requirements because some of them are delay-sensitive or need high bandwidth. Therefore, designing an efficient protocol that meets requirements of each application is a challenging task.

In this paper, we present two protocols that aim to address prioritization, delay, and reliability-aware data transmission for smart grid communication networks. The proposed protocols make service differentiation (prioritization) between the traffic classes based on their requirements in order to achieve better performance. Our first approach, the QoS-aware omnidirectional antenna-based MAC protocol (QODA-MAC), uses omnidirectional antennas for neighbor discovery. The

QODA-MAC retrieves neighbor information and makes scheduling according to the traffic types including BE, NRT, and RT. The second approach, named QoS-aware four-sectored antenna-based MAC protocol (QFSA-MAC), utilizes directional antennas, as opposed to QODA-MAC, to discover the neighbors by concentrating the transmission power towards a certain direction [6]. In QFSA-MAC, the use of the directional antenna enhances the spatial reuse of the wireless channel that provides simultaneous communication between the nodes without interference. In this way, it can connect the nodes far away from each other and decreases the number of hops from source node to sink node when compared with omnidirectional antennas. Similar to QODA-MAC, QFSA-MAC makes the scheduling by making service differentiation and uses the same routing protocol for forwarding packets towards the sink node. In addition, both QODA-MAC and QFSA-MAC have two modes of operation, prioritized and unprioritized modes, that provide switching from one mode operation to another according to the application requirements. For instance, if RT traffic occurs, prioritized mode can become active; otherwise, unprioritized mode can be used to provide fairness by allowing other nodes to access the channel. Although many studies have been proposed to meet the QoS requirements of smart grid applications [1, 7–9], QODA-MAC and QFSA-MAC are the first QoS-aware MAC protocols that consider service differentiation of different traffic classes by considering the impact of antenna for smart grid communication networks. Performance of QODA-MAC and QFSA-MAC is evaluated with comprehensive simulations for various traffic classes such as BE traffic, NRT traffic and RT traffic, similar to [4], and their performance are compared with each other for smart grid communication networks. The key contributions of this work are listed as follows:

- Quality of service-aware MAC protocols that aim service differentiation have been explored. QFSA-MAC, has been proposed to handle the challenges and communication requirements of smart grid applications by making service differentiation. The efficiency of sectored antennas and service differentiation in terms of delay, throughput and energy compared with omnidirectional antennas and without QoS-aware scheduling has been demonstrated for smart grid applications.
- Our simulation results show that the QFSA-MAC protocol yields adequately service differentiation and meets the QoS requirements of smart grid applications. It provides better performance from the point of delay, throughput and energy compared with QODA-MAC protocol for both the prioritized and unprioritized modes of operation.
- Efficiency of service differentiation is also demonstrated by comparing the average source with sink delays of proposed MAC protocols with and without delay-aware scheduling.

The remainder of the paper is organized as follows: In Section 2, previous existing works on QoS-aware omnidirectional and directional medium access protocols are summarized and shortcomings of the existing work are identified that motivate the design of QODA-MAC and QFSA-MAC protocols. Important preliminary information to understand the basics of QODA-MAC and QFSA-MAC is provided in Section 3. In Sections 4 and 5, system design details and key properties of QODA-MAC and QFSA-MAC are described. Simulation parameters and an application scenario are presented in Section 6. In Section 7, performance evaluation results are discussed. Finally, the paper is concluded, with a brief summary of simulation results and future research issues in Section 8.

2. RELATED WORKS

In this section, we review QoS-aware MAC protocols and then discuss the features of directional antenna-based MAC protocols for smart grid communication network. We compare all the MAC protocols described in Table II.

2.1. *Quality of service-aware medium access control protocols with service differentiation*

The choice of MAC protocol used plays a crucial role in the resulting delay and communication efficiency. Although there are protocols to meet the QoS requirements of general WSNs [5], there are

Table II. Comparison of existing QoS-aware WSN-based MAC protocols.

Protocol	Purpose	Type	Latency	Data delivery	Energy awareness	Complexity	QoS awareness
RT-MAC [7]	Provide RT data streaming for WSNs.	CSMA	Yes	No	Yes	High	Low
MaxMAC [8]	Guarantee high throughput and low latency for WSNs.	CSMA	Yes	Yes	No	High	Low
QoS-MAC [9]	QoS support for IEEE 802.15.4 and IEE802.15.1	CSMA/CA	Yes	No	No	Low	High
DRX and FDRX [1]	Support delay and service requirements of smart grid.	CSMA/CA	Yes	Yes	No	Low	High
PCF-based medium access [18]	Reduces latency for WLANs under high traffic loads.	TDMA	Yes	Yes	No	High	Low
WRT-Ring [11]	Guarantees timeliness for WSNs.	CDMA/TDMA	Yes	No	No	High	Low
Tree-based TDMA-MAC [16]	An MAC for smart grid Home area network (HAN) network.	TDMA	Yes	Yes	Yes	Low	High
Rate allocation algorithms [19, 20]	Minimize the average delay of the system.	TDMA	Yes	No	No	High	Low
EQ-MAC [22]	Provide QoS for single-hop sensor networks.	TDMA/CSMA	Yes	No	Yes	High	High
CSS and MR-CSS [14, 15]	Decreasing the data collection latency of mobile elements in WSNs	Scheduling	Yes	Yes	No	Low	No
NJN and NJNC [13]	Increasing the data collection performance of mobile elements.	Scheduling	Yes	No	No	High	Low
iHEM with OREM scheme [17]	Minimizing the energy bills of the consumers	Yes Scheduling	Yes	Yes	High	High	
DaaS [31]	Increases the network lifetime in WSNs.	SMAC	No	No	Yes	High	Low
D-STAR [32]	Provide energy efficiency for WSNs.	STAR MAC	Yes	No	Yes	High	Low
[34]	Improve the throughput and energy consumption.	S-MAC	No	Yes	Yes	High	Low
[35]	An energy-efficient MAC protocol for WSNs.	Scheduling	No	No	Yes	High	Low
SAMAC [6]	Guarantees energy efficiency and timeliness for WSNs.	CSMA/TDMA	Yes	Yes	Yes	High	High

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only a few MAC protocols that consider QoS and service differentiation for smart grid. MAC protocols are generally categorized into three classes as contention-based, schedule-based and hybrid schemes [10]. In contention-based MAC protocols, also known as random access protocols, nodes try to access the channel, which can cause higher delays because of the collisions. To reduce these delays, the RT-MAC protocol was proposed in [7]. Although RT-MAC avoids the false blocking problem, which occurs while Request to Send/Clear to Send (RTS/CTS) are exchanged, to increase the spatial channel reuse, RT-MAC cannot solve the interference problem of the multi-stream communications. Additional wake-ups are used by the MaxMAC protocol to reduce latency and to increase packet delivery ratio according to the traffic rate [8], but additional wake-ups increase the power consumption for sensor nodes. QoS-MAC protocol for IEEE 802.15.4 was proposed in [9]. The QoS-MAC is based on the IEEE 802.15.4 uns lotted carrier sense multiple access with collision avoidance (CSMA/CA) scheme that exploits service differentiation according to traffic types that have different priorities. delay-responsive cross-layer (DRX) and fair and delay-aware cross-layer (FDRX) are other MAC protocols presented in [1] for smart grid applications. They use application layer data prioritization and MAC layer parameters for estimating delay requirements of smart grid applications. If the delay requirements of an application are lower than the estimated delay, they give higher priority to the node to access the channel. The difference between DRX and FDRX is that FDRX provides fairness by periodically giving channel access to the nodes having lower priority. Although these contention-based protocols reduce delays, they cannot prevent the effect of collisions.

Many QoS-aware schedule-based MAC protocols were also proposed in [11–20]. WRT-Ring is another schedule-based distributed RT MAC protocol, which works in the slotted virtual ring network [11]. WRT-Ring provides real-time communication according to the control signal, which rounds into the virtual ring. However, addressing the urgent alarm in WRT-Ring is difficult because the control signal is distributed while traveling. Time division multiple access (TDMA) is one of the important schedule-based MAC protocols. In [16], a tree-based TDMA protocol was proposed for home area networks in the smart grid. Even though TDMA protocols are adequate when there is no collision in the medium, they are inefficient to meet different traffic loads. Rate allocation-based protocols proposed in [19, 20] are another schedule-based MAC protocol. These algorithms assign different rates to the users on demand according to their delay requirements. However, they suffer from abundant information exchange that causes extra overhead for providing QoS. Some studies are performed to increase the data collection performance for WSNs with mobile elements. In [14, 15], a combine-skip-substitute (CSS) and multirate CSS (MR-CSS) schemes are proposed. The main purpose of these schemes is that reducing the data collection latency of WSNs with mobile elements. CSS combines the data collection sites and then skip and substitute some sites for reducing the tour length of mobile elements. The other approach, MR-CSS, is designed for providing multirate communication model to mobile elements. MR-CSS allows the mobile elements to collect data from longer distances with a lower rate. The performance of these schemas is evaluated with extensive simulations to show their efficiency and effectiveness. In [13], an *M/G/1/c-NJN* queuing system is modeled with using nearest-job-next (NJN) discipline to schedule the data collection requests that come to mobile elements in WSNs. Different combination of data collection requests can come to mobile element. Therefore, NJN is extended to NJN-with-combination, *M/G/1/c-NJNC*, to measure the gain when possible request combinations arrive at the mobile element. The performance of these models is evaluated through both theoretical analysis and simulations. Furthermore, the proposed models are compared with first-come-first-serve discipline. The simulation results show that the proposed models outperform the first-come-first-serve. In [17], the performance of an in-home energy management (iHEM) application is evaluated with an optimization-based residential energy management (OREM) scheme. The main purpose of this assessment is minimizing the energy outgoings of the consumers. In order to achieve this purpose, OREM schedules the appliances to hours, which are less expensive, according to the time-of-use tariff. Furthermore, the iHEM performance is also evaluated under the existence of local energy management capability, on the use of priority-based appliance scheduling and RT pricing. Simulations are performed to show the performance of iHEM application with OREM. Results show that energy consumption cost and carbon emissions iHEM application. In addition, iHEM application with the OREM scheme also decreases delay and increases delivery ratio with the priority-based scheduling. In the literature, there are also many scheduling approaches and issues for smart grids in WSNs. In [12], a survey is presented on demand response in smart grids. Existing mathematical models and state-of-the-art studies are summarized in this survey to which the reader can refer.

Hybrid MAC protocols combine multiple schemes to overcome drawbacks of using a single scheme. IEEE 802.15.4 uses a hybrid scheme that is formed by combining of CSMA/CA and TDMA [21]. However, this scheme is not efficient for time-critical smart grid applications because of the limited number of available slots and congestion of the CSMA contention period under high traffic loads. EQ-MAC provides QoS for delay-sensitive smart grid applications by integrating a hybrid medium access scheme with service differentiation [22]. Contention-based medium access is used by EQ-MAC for sending messages, and therefore, EQ-MAC suffers from congestion and is inefficient for delay-sensitive smart grid applications.

Although there are many QoS-aware MAC protocols based on service differentiation and include sensor nodes equipped with different antenna types, there have been no studies that explored the performance of their protocols by designing different antenna models. Furthermore, no cross-layer QoS-aware sectored antenna-based MAC protocol has been proposed for smart grid applications in the literature. Within this context, in this paper, two novel cross-layer QoS-aware and priority-based MAC protocols, QFSA-MAC and QODA-MAC, are explored for smart grid communication networks. Aim of QFSA-MAC and QODA-MAC is maximizing the network utilization and reducing the collision on different traffic loads for meeting the requirements of smart grid application.

2.2. *Quality of service-aware directional antenna-based medium access control protocols*

Many wireless sensor network MAC protocols, including S-MAC [23], T-MAC [24] and Z-MAC [25], use an omnidirectional physical layer, and therefore, they have limited channel capacity due to restricted state of the omnidirectional antenna. The use of directional antennas with wireless ad hoc networks [26–28] and mesh networks [29, 30] has been well explored in the literature; however, none of those approaches are suitable for smart grid communication networks because of their higher energy consumption. Currently, there is no study in the literature that uses directional antennas for smart grid communication networks. In this section, we review the studies on MAC protocols that use directional antennas designed for general WSNs.

Authors in [31] propose a scheme where the sink node is equipped with a directional antenna that broadcasts its schedule to its relaying sensor nodes in the network. Their proposed approach increases the network lifetime when the directional antenna is used only at the sink node. Manes *et al.* in [32] also show that a MAC protocol using directional antennas reduces power consumption more than a MAC protocol that uses omnidirectional antennas. Additionally, in [33], it is shown that the network lifetime increases with the use of directional antennas by reducing the duty cycle.

Authors in [34] propose an approach for using directional antenna for WSNs. In this approach, a directional antenna mounted on the sink node is used to transmit beacon to all the nodes. When the nodes receive the signal, they choose the best beam to transmit the data packets towards the sink node. However, this protocol is not suitable for sensor networks because it can limit the spatial span of the sensor nodes. Authors in [35] proposed another approach where each node computes a time schedule to organize directional communications with its neighbors. Each node exchanges its time schedule with its neighbors after they exchange neighboring information. If the time schedule of the node does not change after a few exchanges, the node can send the data packets through the sink node. However, nodes wait until their time schedule has been stabilized, which takes too much time and is not applicable for delay-sensitive applications. Sectored antenna-based MAC (SAMAC) protocol [6] is an MAC protocol that uses directional antenna for sensor networks. It is a protocol equipped with sectored antennas. The authors also claim that SAMAC improves the throughput and end-to-end delay features of sensor networks by using the spatial reuse capability of directional antennas. Although SAMAC is advantageous for efficiency and predictable delay in sensor networks, service differentiation for delay-critical applications is not considered in this protocol. Moreover, the performance of SAMAC is not analyzed under different traffic loads such as high and low loads.

Our proposed directional antenna-based MAC protocol, named QFSA-MAC, uses sectored antennas and service differentiation to meet the requirements of time-sensitive smart grid applications. QFSA-MAC prioritizes the packets and schedules the nodes according to delay requirements of the packets. QFSA-MAC is also efficient under all traffic loads.

3. PRELIMINARIES

3.1. Antenna model

Impact of antennas, which are sectored and omnidirectional antennas, are explored in this study while designing the MAC protocols. The main purpose of using different types of antennas is to explore the impact of antenna type on meeting the QoS requirements of smart grid applications and use it as a parameter for service differentiation.

The omnidirectional antenna architecture is assumed for the QODA-MAC protocol in which sensor nodes are equipped with antennas that radiate the radio frequency electromagnetic fields uniformly in all directions in a plane. One major advantage of omnidirectional antennas compared with other types of antennas is they are easy to install and do not need steering to cover the area because their radiation cone covers 360°. On the other hand, QFSA-MAC is designed by using sectored antenna that is a type of directional antenna with a sector-shaped antenna pattern. K non-overlapping sectored antenna is used to cover the entire 360°range. Packets are transformed by selecting a sector and immediately received by the active sector. Concurrently, inactive sectors buffer the coming signals to transmit them when they become active. Nodes use a switch to select different sectors, and each one of them can activate one sector at a time [6].

The QFSA-MAC and QODA-MAC are both designed to reduce interference and collisions for meeting the QoS requirements of smart grid applications. However, QFSA-MAC is more efficient than the QODA-MAC because directional antennas reduce the interference and allow parallel transmissions between the neighbors by increasing spatial reuse of the radio resources [36].

3.2. Network model

3.2.1. Network model of QODA-MAC protocol. Network is modeled as a graph $G = (V, E)$ in which set of nodes and set of wireless links are represented with V and $E = \{(i, j)|i, j; \in V\}$, respectively.

Interference causes cumulative effects in a wireless network. To solve this, we use a physical interference model that uses signal to interference noise ratio (SINR) to make a successful transmission. Packets are received by the nodes if SINR values of the nodes exceed a definite threshold value. More information about the SINR calculation can be found in our previous study [38]. To measure link qualities, we will use a real physical layer model utilizing the log-normal shadowing model based on the measurement showed in Table III. All the nodes except the sink node generate the packets according to different traffic loads. An example is presented in Table IV. RT packets are collected more frequently than BE and NRT packets because they are more delay-critical. Therefore, interarrival times of the NRT and BE packets are higher than RT. Traffic loads are calculated by calculating the number of sent RT, NRT, and BE packets in every second. For instance, in Type 1 load, in every second, one RT packet and in every 12 s, one NRT and one BE packets are sent. Total number of packets sent by one node is first computed, and then it is multiplied by the total number of nodes that is deployed in the area. Equation (1), which is used for calculating the traffic load, is also shown as follows:

Table III. Path loss and shadowing deviation in electric power environments [37].

Propagation environment	Path loss (η)	Shadowing deviation (X_σ)
500 kv substation	2.42	3.12
Underground transformer vault	1.45	2.45
Main power room	1.64	3.29

Table IV. Loads in simulations.

	Packet rate	Interarrival time	Average created load
Types	Real-time (pkt/s)	Non-real-time and best effort(s)	Traffic load (pkt/s) for 180 nodes
Low traffic load – Type I	2	12	390
High traffic load – Type II	12	2	2340

$$TrafficLoad = \left(\left(\frac{\#OfRTPackets}{RT\_IAT} \right) + \left(\frac{\#OfNRTPackets}{NRT\_IAT} \right) + \left(\frac{\#OfBEPackets}{BE\_IAT} \right) \right) * \#OfNodes \tag{1}$$

where

- *RT_IAT* is the interarrival time of RT packets
- *NRT_IAT* is the interarrival time of NRT packets
- *BE_IAT* is the interarrival time of BE packets

There are some constraints in our data collection model. One of them is using half-duplex transceivers in which the nodes cannot make transmission while another node is making transmission. Another constraint is the physical interference model that focuses on the SINR value to avoid cumulative effects of interference in wireless links. Therefore, nodes can be scheduled to make transmission if their SINR value is larger than a certain threshold.

In our previous study [38], a TDMA-based multi-channel scheduling algorithm is used to schedule the nodes without service differentiation by considering interfering nodes and link qualities (packet reception rate (PRR)). However, in this study, time slots are assigned to the nodes according to delay requirements of coming packets, which can be RT, NRT, or BE. This means that RT packets have the highest priority, and therefore, time slots are primarily assigned to them. In this way, our aim is to provide QoS-aware schedule assignment while eliminating the impact of interference.

3.2.2. Network model of QFSA-MAC protocol. In QFSA-MAC, the network is modeled as a graph similar to the network model of the QODA-MAC protocol. A predetermined high capable sink node is served to this graph. Within the graph, the topology is random and nodes access the sink node over multiple hop. QFSA-MAC does not use a multi-cluster network as the one proposed in [6] because communication between clusters needs additional dedicated channels, increases the interference, and causes packet collisions. QODA-MAC and QFSA-MAC protocols use the same interference model and the physical layer model to determine the link qualities among nodes.

A dynamic TDMA scheduling algorithm that allocates a changeable number of time slots according to traffic load of each data stream is used as an MAC protocol in our QFSA-MAC approach. In this way, QFSA-MAC can meet all traffic types such as high and low loads by dynamically assigning time slots to each node. Furthermore, QoS-aware scheduling has been achieved by the QFSA-MAC with service differentiation in which the packets are prioritized into three classes, RT, NRT, and BE, according to their QoS requirements. Within this context, QFSA-MAC protocol is the first protocol that uses sectored antenna with service prioritization for smart grid communication networks.

3.3. Calculation of link qualities

We consider all the factors including path loss, shadowing deviation, and noise for link quality function. Link qualities are calculated for each link from nodes to other remaining nodes. We use the following log-normal shadowing path loss model, the same function with our previous study [38], for defining quality of links between the nodes:

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$$\gamma(d)_{db} = P_{\tau} - P_L(d_0) - 10_{\eta} \log_{10} \frac{d}{d_0} - X_{\sigma} \tag{2}$$

where

- $\gamma(d)$ is the signal to noise ratio at a distance d from the transmitter,
- P_{τ} is the transmit power in dBm,
- $PL(d_0)$ is the path loss at a reference distance d0,
- η is the path loss exponent, and
- X_{σ} is a zero mean Gaussian random variable with standard deviation (σ).

The parameters including path loss and shadowing deviation are selected from the field studies explained in [37]. These experiments have been carried out in different electric power system environments such as 500 kv substation, main power room, and underground transformer vault by using IEEE 802.15.4 compliant wireless sensor nodes. Within this context, channel parameters that we use in our simulations are shown in Table III.

4. QUALITY OF SERVICE-AWARE OMNIDIRECTIONAL ANTENNA-BASED MEDIUM ACCESS LAYER PROTOCOL DESIGN AND ARCHITECTURE

In this section, we focus on convergecasting data towards the sink node with and without service differentiation in the context of periodic data collection where each node generates different number of packet types, that is, RT, NRT, and BE, at the beginning of every frame. We assume that the size of each packet is the same and the same channel is used by all the nodes in the network. Our main objective is to achieve the minimum schedule length and the maximum packet delivery ratio to meet the QoS requirements of smart grid applications. To this end, we use cross-layer QoS-aware TDMA-based MAC protocol. This protocol differs from other existing cross-layer TDMA-based solutions because it constructs the routing tree and makes different periodic scheduling using our previously proposed CMST with PRR routing tree algorithm [38]. Within this context, we first consider the scheduling of the nodes without service differentiation, and then we introduce a QoS-aware scheduling algorithm named as QODA-MAC with service differentiation.

4.1. Quality of service-aware omnidirectional antenna-based medium access layer without service differentiation

In this section, we present the QODA-MAC without service differentiation and its important properties for adjustment of different types of traffic. In our previous study [38], we used a multi-channel scheduling algorithm to minimize the schedule length and to maximize the throughput in smart grid communication networks, but we did not consider the impact of periodic data generation and different traffic types on schedule length. Within this context, in this study, we aimed to assess influence of different traffic types on the schedule length of TDMA-based scheduling algorithm.

Many smart grid applications, such as advanced metering infrastructure (AMI) and capacitor bank control, must support RT traffic under different traffic loads. Therefore, we consider the AMI application where different traffic types are possible. We assume that RT, NRT, and BE packets are generated by AMI application and their transmission rates are different. For instance, RT packets are sent more frequently than the NRT and BE packets in an emergency situation because NRT and BE packets are not time-critical packets. NRT and BE packets are respectively the control packets including environment information such as vibration and the auxiliary packets including location information of the sensor nodes.

The QODA-MAC without service prioritization firstly constructs the routing tree by using capacitated minimum hop spanning trees considering link qualities (PRR) named as CMST with PRR routing tree algorithm that has been proposed in our previous study [38]. CMST with PRR algorithm is used in QODA-MAC protocol because it is more efficient compared with other routing tree protocols such as minimum hop spanning tree and considers the PRR values, calculating by using log-normal shadowing propagation model while constructing routing tree. The reader can refer to [38] for detailed explanation of the CMST with PRR routing tree algorithm. After the routing tree is constructed, time slots are assigned to the nodes. We use the same time slot assignment algorithm as used in our previous study called as TDMA scheduling where time is divided into time slots. Proposed interference-aware TDMA scheduling algorithm uses breadth-first-search time slot assignment algorithm for time slot assignment. In each iteration, an edge is selected from the breadth-first-search order and is assigned minimum time slot that is different from the adjacent edges considering the SINR values. While sending packets, QODA-MAC without service differentiation does not make priority-based data forwarding, which means that it gives the same priority to all the packets.

4.2. Priority and delay-aware quality of service-aware omnidirectional antenna-based medium access layer

In this section, we describe QODA-MAC with service differentiation and its properties for QoS provisioning with respect to various traffic types shown in Table IV. QODA-MAC with service differentiation protocol is an extension of QODA-MAC without service differentiations because it is based on QoS-aware TDMA medium access protocol that prioritizes the packets according to their production time and deliver them immediately to the sink node.

Figure 2 shows the flow chart for the operation of the QODA-MAC protocol with service differentiation. Firstly, PRR values of each nodes are measured, and then the routing tree is constructed using CMST routing tree algorithm considering the PRR values. After the routing tree is constructed, in every iteration, each node generates RT, NRT, and BE packets with different rates. Non-interfering nodes are found to decide which nodes can make transmission without interfering their adjacent nodes. Within this context, nodes have two types of mode including transmission and idle mode.

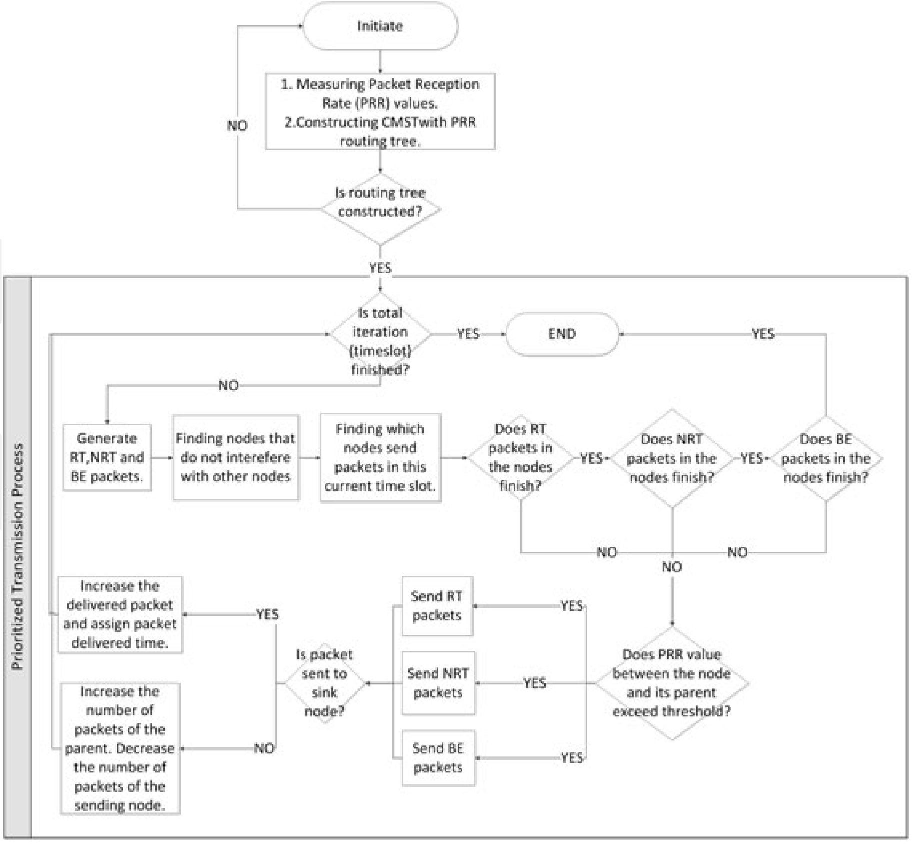

Figure 2. Flow chart of QODA-MAC with service differentiation protocol. NRT, non-real-time; RT, real-time; BE, best effort; CMST, capacitated minimum hop spanning trees.

For instance, if the children, parent, and siblings of the node do not transmit, the node enters the transmission mode; otherwise, it stays idle to avoid interference among the other nodes. When the node is in transmission mode and has RT, NRT, and BE packets, the node firstly schedules the RT packets if the PRR value between the node and its parent exceeds a certain threshold. After then, the node respectively sends the NRT and BE packets when all the RT packets are transmitted. In this way, QODA-MAC with service differentiation protocol transmits the RT packets more rapidly than NRT and BE packets and achieves the QoS-aware scheduling by prioritizing packets according to their delay requirements.

5. QUALITY OF SERVICE-AWARE FOUR-SECTORED ANTENNA-BASED MEDIUM ACCESS LAYER DESIGN AND ARCHITECTURE

The QFSA-MAC protocol is designed for enabling QoS-aware and reliable communication between the sink node and the sensor nodes. Data transmission at uplink traffic is in the direction of sensor nodes to the sink node. The QFSA-MAC protocol is based on the dynamic TDMA protocol and formed in two ways: one prioritize the packets according to their traffic class shown in Table IV and the other does not prioritize the packets and do not make service differentiation for QoS provisioning. In this respect, the QFSA-MAC protocol with service differentiation is the first protocol that combines sectored antennas with service differentiation to meet the requirements of QoS provisioning for smart grid applications.

The QFSA-MAC protocol is designed with using sectored antennas as opposed to QODA-MAC protocol that operates with omnidirectional antennas and groups the sensors together to form the multiple sensor groups. Contention may occur because of the directional beamforms of the sensor nodes in case of simultaneous transmission made by both sensor groups. To avoid the contention events, the QFSA-MAC protocol determines the contending groups by considering the directions of sectored antenna beamforms and properly assigns the time slots. Each sensor node in QFSA-MAC protocol is active in a certain time slot when they are scheduled for communication and enters in a sleep mode at all other times for saving energy. Sensor nodes within the individual groups are scheduled by using our proactive contention avoidance scheme shown in Algorithm 2, which controls the time slots of siblings and children of each node during time slot assignment, at upstream nodes in smart grid communication networks. Calculating the neighborhood information for assigning time slots may be difficult owing to changing environment conditions or to its overhead. In this respect, a contention-based MAC scheme can be used. However, in this work, our aim is to show the effect of service differentiation (prioritization) and the effect of using directional antenna for meeting the QoS requirements when the same type of MAC scheme is used, slotted in our case.

Complete neighborhood information is required before assigning time schedules to the sensor nodes. Our first protocol, QODA-MAC, uses omnidirectional antenna, and therefore, it can simply access all the neighborhood information by sending broadcast message. However, the proposed QFSA-MAC protocol uses sectored antennas, and hence, it can cover $360/numberOfSectors$ azimuth degree, and the neighbor discovery process must be repeated for each sector to cover all directions. In the literature, some of the neighbor discovery protocols [35] using directional antennas utilize an omnidirectional antenna to find the neighbors. But using an omnidirectional antenna coupled with a directional antenna increases the cost of sensor networks and decreases the efficiency of neighbor discovery process because it has less communication range than the directional antenna when the same transmission power is used. Therefore, the QFSA-MAC protocol does not use omnidirectional antenna and utilizes a directional neighbor discovery mechanism. On the other hand, directional antennas have also some possible problems including deafness and interference due to higher gain [39]. Deafness is one of the problems that may occur when a node receives the transmission coming from its particular sector and does not receive the signals coming from its other sectors. The node is locked in a specific sector and becomes deaf in all the other sectors. A second possible problem of the directional antennas is the interference due to higher gain that occurs because of the strength of the focused beam. This culminates in larger range of the signal that can reach the other ongoing transmissions in the same direction and may cause the interference. The QFSA-MAC protocol solves all these problems caused by the directional antennas by using buffers for coming packets to other sectors and by utilizing an efficient interference model.

In the following parts of this section, the steps of the QFSA-MAC protocol, which are also shown in Figure 3, are described.

5.1. Neighbor discovery and routing tree construction

Complete neighborhood information is required for the efficient operation of the QFSA-MAC protocol. Network architecture is initially set up by randomly deploying sensor nodes without having any neighborhood and location information. Each sensor node has multiple sectored antennas that cover

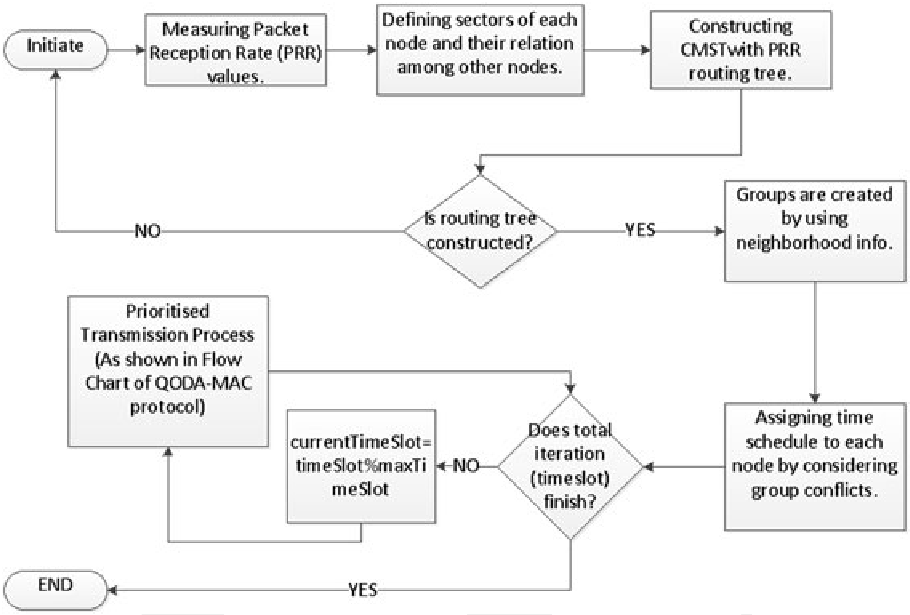

Figure 3. Flow chart of quality of service-aware four-sectored antenna-based medium access layer with service differentiation protocol.

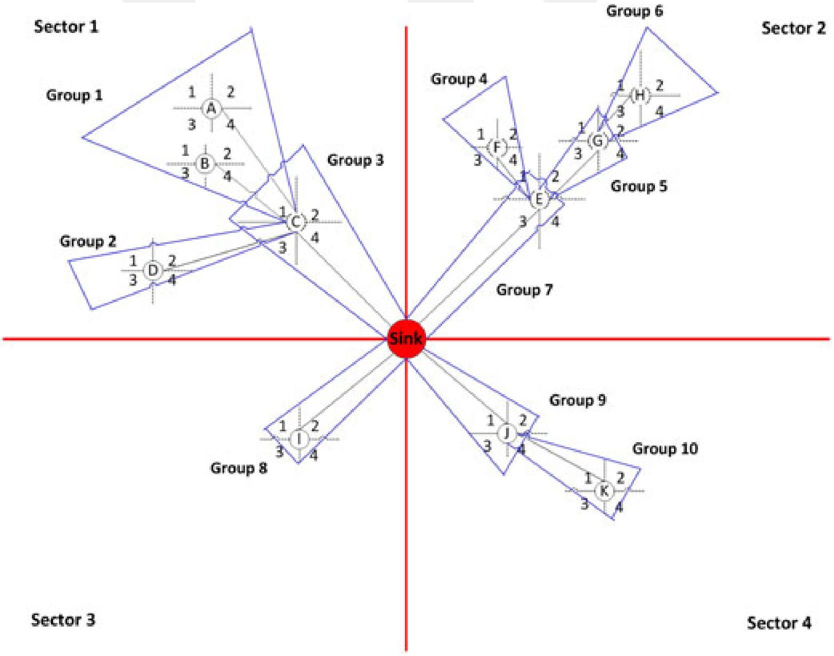

Figure 4. Group creation.

the whole azimuth. A sensor can sense the packet transmission from its two or more sectors, but the packet is actually received over a single sector. This is achieved by selecting the sector that has the maximum reception power level while receiving a packet. Therefore, in Algorithm 1, received signal strength indicator, which is a measurement of the power received from the radio signal, is measured for each node pair by considering path loss. Then, neighborhood relations between two nodes and the sectors that these nodes can communicate on are found by exploring sectors having the maximum power. For instance, Figure 4 describes the neighbor–sector relation algorithm that firstly finds that the node C sends and receives packets on its sector 1, and the node A communicates with C on its sector 4, then add node–sector pairs $(C, 1)$ and $(A, 4)$ that are neighbors of each other to $RelationMatrix$. After all the neighborhood relations are found by each sector, a routing tree is constructed by using our previously proposed CMST with PRR routing algorithm. The process of constructing $RelationMatrix$ is carried out at the beginning of simulation and when the topology changes. It is therefore a rare operation.

Algorithm 1: QFSA-MAC node-sector relation algorithm

```
Input: s (#sectors), nnodes (#nodes), pathL (path loss), outP (output power), rssi (received
       signal strength indicator)
Output: Create relation holder matrix as $RelationMatrix(N, N)$
initialization
for $i \leftarrow 1, nnodes$ do
    for $j \leftarrow i + 1, nnodes$ do
        $maxPower_i \leftarrow 0$
        $maxPower_j \leftarrow 0$
        for $k \leftarrow 1, s$ do
            $rssi(i, j) \leftarrow outputP(i) + pathL$
            $secPower_i \leftarrow rssi(i, j) + rand(1)$
            if $secPower_i > maxPower_i$ then
                $maxPower_i \leftarrow secPower_i$
                $maxPowerIndex_i \leftarrow k$
            $rssi(j, i) \leftarrow outputP(j) + pathL$
            $secPower_j \leftarrow rssi(j, i) + rand(1)$
            if $secPower_j > maxPower_j$ then
                $maxPower_j \leftarrow secPower_j$
                $maxPowerIndex_j \leftarrow k$
        RelationMatrix(i,j) $\leftarrow maxPowerIndex_i$
        RelationMatrix(j,i) $\leftarrow maxPowerIndex_j$
```

However, while constructing our $RelationMatrix$, the side-lobe effect, which reduces the radiated signal strength to zero, is not considered. Many methods [40–42] exist for eliminating problems related to the side-lobe effect. Authors in [40] propose a technique that selects the nodes for collaborative beamforming in WSNs to provide a low level side-lobe beampattern in the directions of unintended base stations (BSs). Authors in [41] present the multiple interest dissemination with directional antenna scheme that transmits multiple disinterest packets to control the coverage area to combat side-lobe effects. Authors in [42] propose a distributed beamforming scheme with side-lobe control, which receives feedbacks from unintended BSs, to maximize the beamforming gain at the main BS while keeping the side-lobe levels below a threshold at the unintended BSs. We plan to solve the problem about the side-lobe effect by integrating these existing methods with our proposed method as future work.

The CMST with PRR routing algorithm considers the variable link qualities and uses neighborhood information retrieved from Algorithm 1 while constructing the routing tree. PRR values of each node in the network are measured, and nodes connect to the neighbors nearest the sink node with highest PRR value and capacity constraint c. This increases the reliability of CMST with PRR

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algorithm because it considers real channel conditions. Constructed subtrees are connected to the root node r if the PRR value of the link between the nodes exceeds a threshold. Nodes are searching closest neighbors having the highest PRR except the sink node. Neighbors are merged after the computation of tradeoff function instead of connecting them directly to the sink node for having some potential savings. As a result, parent–child relations are specified and routing tree is constructed. A more detailed explanation about the tradeoff function and how the PRR values are calculated can be found in our previous study [38].

5.2. Group creation

The QFSA-MAC protocol divides the nodes and creates groups using neighborhood information for increasing slot reuse and for minimizing schedule length. We are inspired from [6], using sectored antenna for WSNs and utilizing the Bellman–Ford shortest path algorithm while creating groups of the QFSA-MAC protocol. Our group creation algorithm differs from the group formation algorithm of [6] in routing tree construction and the network architecture. Felemban *et al.* [6] use the Bellman–Ford shortest path algorithm for determining parent–child relation; however, we utilize from CMST with PRR algorithm and consider real channel conditions while constructing paths. Furthermore, Felemban *et al.* [6] divide the sensors into clusters, but they do not consider communication between cluster heads. On the other hand, we also divide the network into a set of clusters and take care of communication between clusters until the sink node receives the information sent from sensor nodes.

Group creation starts with the determination of paths from sensor nodes to the sink node. These paths are constructed utilizing CMST with PRR routing tree algorithm using the collected neighborhood information. As a result of routing tree algorithm, a capacitated minimum hop spanning tree is created specifying parent–child relations. A common node conflict can occur in case of simultaneous transmission when two nodes, A and B shown in Figure 4, communicate with another node, C, on the same sector of C. This can be avoided if AC and AB communicate in different time slots. When the node pairs are allocated time slots using this strategy, conflicts among the node pairs are avoided. However, assignment of new time slot in case of conflict situation reduces delay performance. Therefore, we dynamically allocate the time slots and use the same time slot if the nodes do not interfere with each other. In this way, we reduce the schedule length and increase delay performance while eliminating conflicts.

In the QFSA-MAC protocol, a group is defined as a set of sensor nodes that has the same time slot and parent–child neighborhood relation. In each group, there is only one parent node, and all the other nodes are the children of the parent node. The QFSA-MAC protocol firstly starts the group formation from the sink node. Each sector of sink node is related with a different group, and each member of these groups is the children of the sink node. In the second phase of the group creation, new smaller groups are created considering the sectors of child nodes. For instance, if a child node C is not inside in a group for each of its sector and has a child node communicated with C over a sector, the node in this sector and the node C create a group. This process continues from parents to child nodes until all of each sector of all nodes are included in a group. Figure 4 illustrates this process for node C. Because sector 1 of the C is already included in a group named as group 1, other sectors of the node C form additional groups including groups 2 and 3.

5.3. Dynamic time slot assignment

Time slot assignment of the QFSA-MAC protocol algorithm consists of two phases: one is the assignment of time slots to the constructed groups and the other is the assignment of time slots to the nodes inside the groups. The hop distance of the parent node of each group to the sink node is specified. Then, groups are sorted in descending order according to their distance to the sink node. Groups are sorted in descending order because time slot assignment begins from the farthest group to the sink node. If some groups have the same distance to the sink node, groups that have larger number of child nodes is firstly considered. After the groups are sorted, time slots are assigned to each group inside the sorted group by considering conflicts among the groups. Time slot assignment process continues until time slot is assigned to all the groups. After time schedule assignment of the groups is finished, time slot assignment begins for the nodes inside the groups.

Nodes inside the groups are scheduled while considering interference between the sensor nodes. Algorithm 2 shows how time slots are assigned to the sensor nodes. The main purpose of this algorithm is assigning the least number of time slot to each node while preventing interference for reducing time schedule length. Firstly, the node inside a group is marked as current visited node. Time slots of children and siblings of the nodes are controlled before assigning the time slot to the node for providing interference-free time slot assignment. If its children and the siblings do not have the same time slot, time slot is assigned to the node; otherwise, time slot is increased by 1 and assigned to the node. In each iteration, time slot (named as $preAssigned$ in Algorithm 2) is set to 1 to minimize the schedule length and to increase the slot reuse if it does not cause interference when assigned to a node. Furthermore, the preassigned group schedules can be also changed in this algorithm because it reorganizes all the nodes that can be parents of the groups for scheduling all the nodes and for constructing complete node schedule matrix.

Algorithm 2: QFSA-MAC time slot assignment and contention avoidance algorithm

```
Input: sg (sorted groups)
Output: Computed $nodeScheduleMatrix$
initialization
preAssigned ← 1
nodeScheduleMatrix ← empty matrix with size of number of nodes
childrenOfNode ← find children of the current visited node
siblingsOfNode ← find siblings of the current visited node
for $g \leftarrow 1, sg$ do
    for $node \leftarrow 1, g$ do
        preAssigned ← 1
        currentVisitedNode ← node
        for $c \leftarrow 1, childrenOfNode$ do
            if timeslot of c == preAssigned then
                preAssigned ← preAssigned + 1

        for $s \leftarrow 1, siblingsOfNode$ do
            if timeSlot of s == preAssigned and s ≠ currentVisitedNode then
                preAssigned ← preAssigned + 1

        nodeScheduleMatrix (currentVisitedNode) ← preAssigned
```

5.4. *Quality of service-aware data transmission*

After time slots are assigned to all the nodes, data transmission phase starts. In this phase, a node makes transmission in its own schedule by turning on its corresponding sector and enters sleeping mode by turning off its antenna in other times until its time schedule begins. When the node is active, it can communicate only one of its sectors at a given schedule. In addition, received packets from other sectors of the node are buffered and sent when the time slot of the corresponding sector comes.

The QFSA-MAC protocol has two modes of operation; one is sending all type of packets without service differentiation and the other is assigning the priorities of the packets according to their traffic class for providing QoS provisioning. These modes of the QFSA-MAC protocol are described as follows:

Unprioritized QFSA-MAC: In the literature, sectored antennas have been used to increase the performance of WSNs [6]. However, until this time, no study utilizing the benefits of sectored antennas for smart grid applications for QoS-aware communication has been proposed. Within this context, the QFSA-MAC protocol is the first protocol wherein the sensor nodes are equipped with sectored antennas and deployed in a smart grid communication environment. Furthermore, studies about the sectored antennas or the directional antennas [6, 31] also do not consider the impact of periodic data generation and different traffic types (low/high load traffic) on the performance of WSNs. However, the QFSA-MAC protocol takes into consideration all of these issues because they are important for providing QoS requirements of smart grid applications.

The QFSA-MAC protocol categorizes the packets into three different classes, RT, NRT, and BE, and generates each class of the packets in different times; an example scenario is shown in Table IV. Because the RT packets are generated in an emergency situation, these types of packets are generated more frequently than the other types to inform the central point as quickly as possible. For instance, when the AMI application of the smart grid is considered, it continuously monitors the system and rarely sends the control packets and auxiliary packets about the system situation. However, in case of emergency, it generates time-critical emergency packets and immediately sends them to utilities. Therefore, the QFSA-MAC protocol considers the real-world conditions by generating different packet types in variable traffic loads.

The QFSA-MAC protocol without service differentiation has the same flow with QFSA-MAC with service differentiation until it enters the data forwarding phase. It firstly measures the PRRs of the nodes, defines the sectors and their relations between the other nodes, then constructs the routing tree using CMST with PRR algorithm. After it constructs the routing tee, it forms the groups using the neighborhood information and assigns the time slot to each nodes and their each sector by considering the interference among the nodes. However, the QFSA-MAC without service differentiation does not prioritize the packets according to their QoS requirements. It forwards the packets towards the sink node when the schedule of the node comes on one of its sector. Therefore, it is not as efficient as the QFSA-MAC with service differentiation mode for providing the QoS requirements of time-sensitive smart grid applications.

The QFSA-MAC with service differentiation: In the literature, many protocols based on the QoS-aware with service differentiation have been proposed for smart grids, but none of them do not use the sectored antennas with service differentiation together. Therefore, the QFSA-MAC protocol with service differentiation is the first protocol that prioritize the packets according to their traffic class by utilizing the sectored antennas for smart grid applications. In this way, QFSA-MAC with service differentiation benefits from all the advantages of sectored antennas such as power efficiency and delay reduction to provide QoS provisioning.

Figure 3 shows the flow chart operation of the QFSA-MAC protocol with service differentiation. Same as the QFSA-MAC protocol without service differentiation, it firstly measures the PRR values of each node, defines the sectors and relations of the nodes, and constructs the routing tree. Then, groups in which each consists of a parent node, child nodes and their sectors, which are the sectors of the nodes used for communication with their parent, are created. After the groups are formed, time slots are assigned to all groups and the nodes inside the groups by considering interference among the nodes and conflicts between the groups. Afterwards, the data forwarding phase of QFSA-MAC protocol with service differentiation starts. Firstly, the PRR value between the node and its parent is controlled. If the PRR value among the node and its parent exceeds a threshold, the node initially sends the RT packets towards to its parents or the sink node if the node is a child of the sink node; otherwise, the node sends the NRT packets if all the RT packets are sent. When the node transmits all the RT and NRT packets, it sends the least time-critical BE packets last. In this way, the QFSA-MAC protocol with service differentiation sends the time-critical RT packets faster than the NRT and BE packets and meets requirements of different traffic classes.

6. APPLICATION SCENARIO AND SIMULATION PARAMETERS

6.1. Application scenario

The QoS requirements of WSN-based smart grid applications described in detail in [2] vary in terms of delay, reliability, and data rate, which are explained in [3]. We choose the AMI WSN-based smart grid application as an example scenario because low latency and higher bandwidths are important for some AMI applications such as real-time metering application. AMI enables two-way communication between the utilities and the meters and is an integrated system of smart meters, data management systems, and communication networks [2]. In this way, it provides the participation of customers while collecting and distributing the information among meters and utilities. However, not all the collected or distributed information is important for the application. Some of the packets are control packets including environment information such as vibration, and some of them are auxiliary packets including location information of the sensor nodes. Accordingly, first traffic class is the metering packets, which are the most prioritized packets to be scheduled for relaying packets towards the sink node, transmitted by our network. Second priority is given to control packets because these packets are the periodic packets and less important than the metering packets. Auxiliary control packets, which forms the third traffic class, are transmitted by the network. As a result, we categorize the packets into three traffic classes, which are BE, NRT, and RT, in the order of least to high priorities. All types of packets are generated periodically according to their generation time that is shown in Table IV. For instance, in Type 1, each node generates two RT packets in every second and NRT/BE packets in every 12 s. This is a real-world scenario because packets interarrival times vary according to condition of the network in the AMI application. Furthermore, higher traffic load, Type 2, is also presented to the network to analyze the performance of proposed algorithms by increasing the number of packets and reducing interarrival times of each traffic class. We will use this application scenario for evaluating the performance of QODA-MAC and QFSA-MAC.

6.2. Simulation parameters

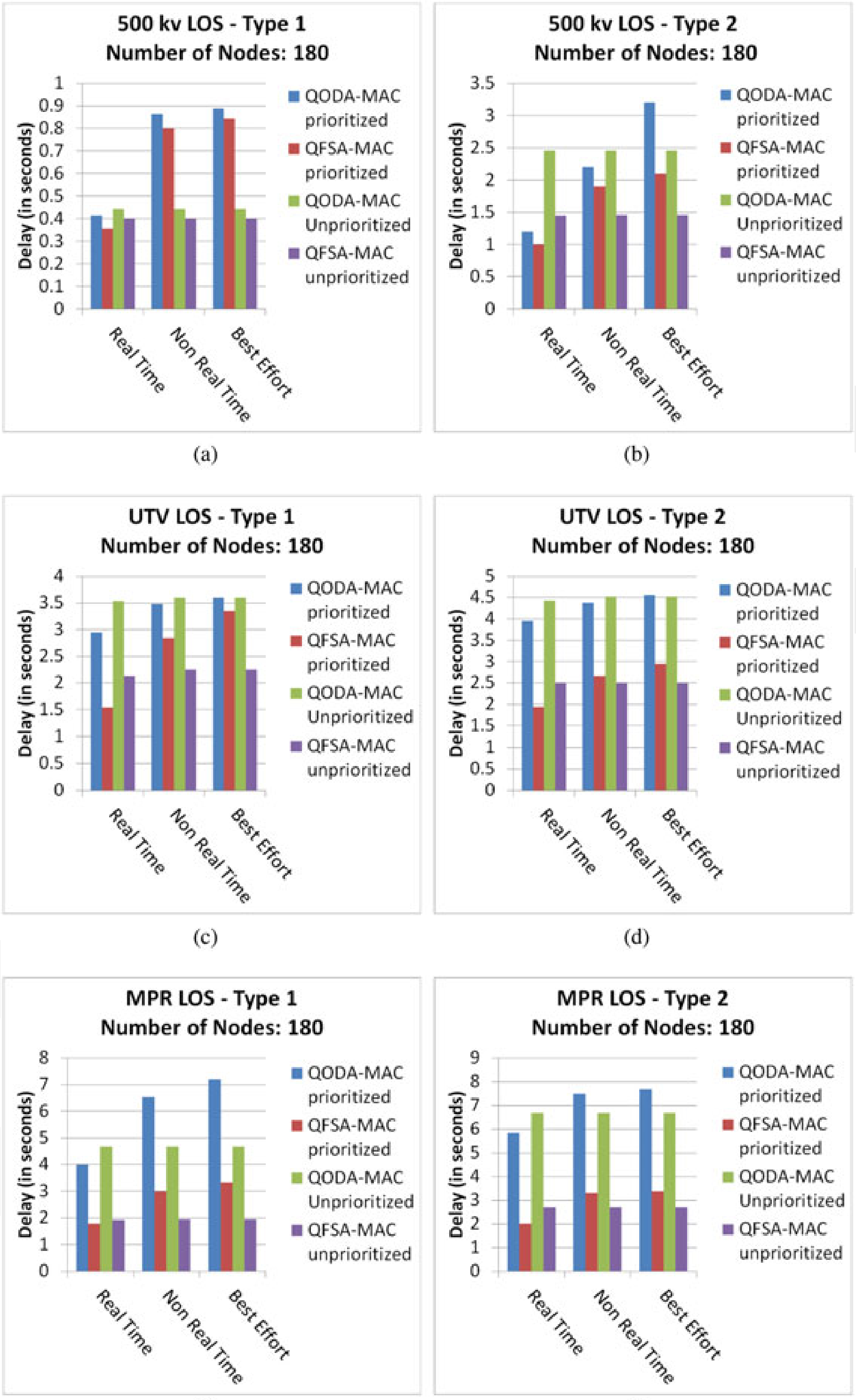
In this study, extensive simulations of the proposed protocols, QODA-MAC and QFSA-MAC, have been performed by using Matlab (MathWorks in Natick, Massachusetts, USA) environment. Simulations have been performed 100 times with different seeds in different smart grid environments [37]. Log-normal shadowing model is used for making the simulations more realistic by using parameters shown in Table III. Square shape area, 200 × 200 m^2 is used in the simulations. The payload of the sensory data is 50 bytes. The number of nodes in the network is 180 nodes unless otherwise specified. Deployed sensor nodes are equipped with two types of antennas: one is an omnidirectional antenna utilized by the QODA-MAC protocol and the other is a sectored antenna used by the QFSA-MAC protocol. We are inspired with the work in [6] that uses four-sectored antennas and proves that it provides the lowest of slot needed, and therefore, we use the four sectors in our sectored antennas. High and low traffic loads presented in Table IV are offered to the network to evaluate the performance of the proposed protocols under different traffic loads. Because QODA-MAC and QFSA-MAC have routing capability, CMST with PRR routing tree algorithm is used as the routing protocol, and the significant parameters, which are used in the simulations, are shown in Table V.

Performance evaluations have been carried out to evaluate the performance of QODA-MAC and QFSA-MAC protocols, respectively described in Sections 4 and 5, according to different performance metrics. The performance metrics utilized during the simulations are the end-to-end delay, throughput, and average energy consumption. Delay is the elapsed time for transmission of packets from a source node to the sink, Throughput is the number of delivered packets in a specified amount of time, and average energy consumption is the energy consumption of the protocols for each successfully transmitted packet at the sink node.

Table V. Simulation parameters.

Number of nodes	180
Size of the topology	200 × 200 m^2
Radio propagation model	Log-normal shadowing model
Algorithms	QODA-MAC, QFSA-MAC
Antenna models	Omnidirectional antenna, sectored antenna
Number of sectors	4
Distance between the nodes	Randomly distributed
Modulation	Non-coherent frequency shift keying
Encoding	Manchester
Output power	4.0 dBm
Noise floor	−93.0 dBm
Asymmetry	Symmetric links
Topology	Random

QODA-MAC, quality of service-aware omnidirectional antenna-based medium access control protocol; QFSA-MAC, quality of service-aware four-sectored antenna-based medium access layer.



(a) (b)

(c) (d)

(e) (f)

Figure 5. Comparative average source to sink packet delay of all the protocols for two types of traffic in different smart grid environments. QODA-MAC, quality of service-aware omnidirectional antenna-based medium access control protocol; QFSA-MAC, quality of service-aware four-sectored antenna-based medium access layer; MPR, main power room; UTV, underground transformer vault.

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7. PERFORMANCE EVALUATION

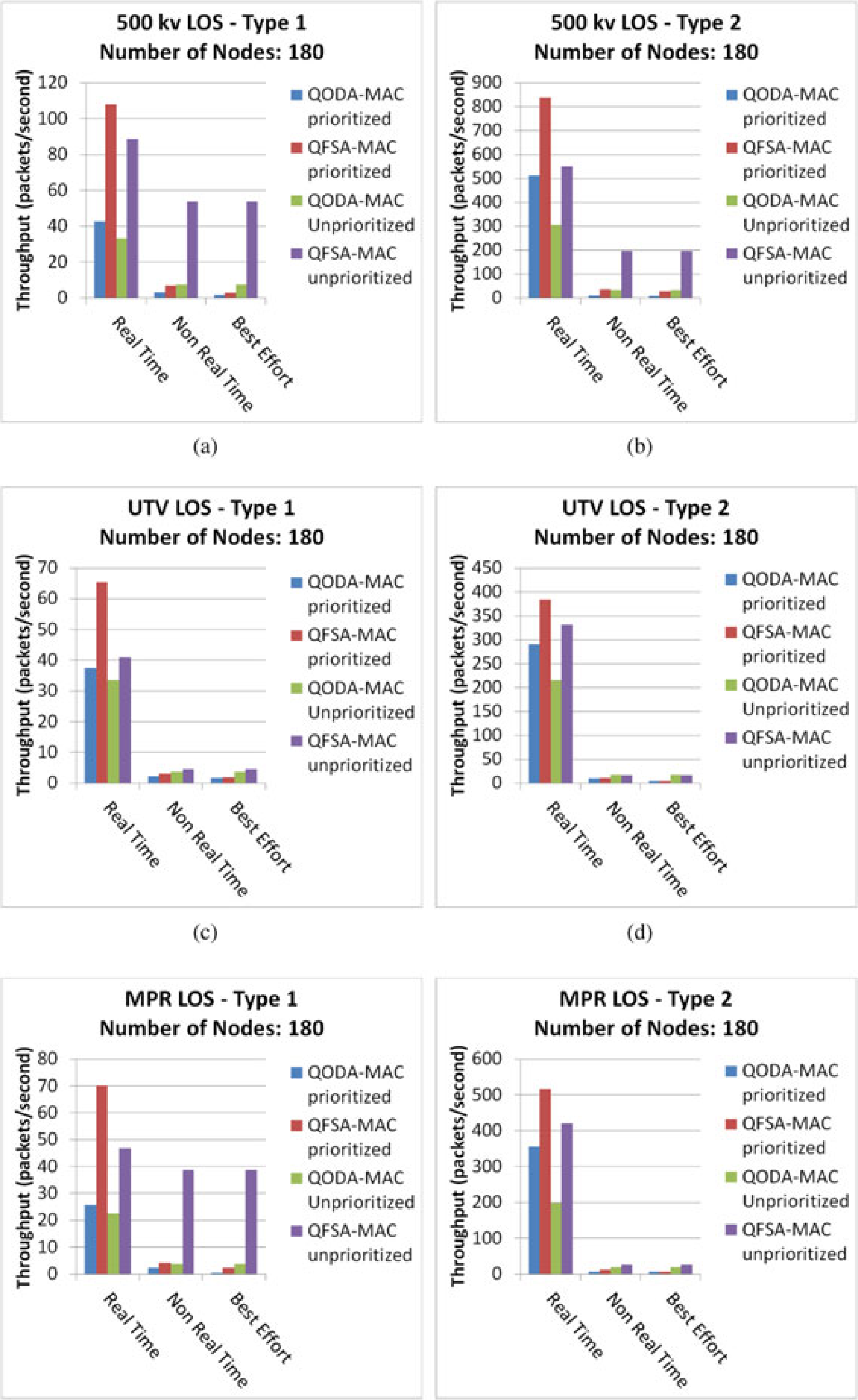
In this section, performance analysis of the QODA-MAC and QFSA-MAC protocols is provided. The analysis includes comparison of the all modes (with/without prioritization) of QODA-MAC protocol running on omnidirectional with the QFSA-MAC protocol on sectored antennas for varying data generation rates and traffic loads. The simulations have been performed in different smart grid environments such as 500 kv substation, underground transformer vault, and main power room, where the parameters *path loss* and *shadowing deviation* have been obtained from [37].

Fast data transmission from sensor nodes to the sink node is crucial for RT applications. Therefore, this is the primary goal of our proposed MAC protocols including QODA-MAC and QFSA-MAC. Each proposed protocol has two types of modes: one prioritizes the packets and sends them according to their QoS requirements and the other prioritizes the packets and transmits them without giving precedence. Within this context, comparative analysis has been carried out for all modes of MAC protocols for showing their efficiency with and without service differentiation. Furthermore, performance of the algorithms is measured for two different traffic loads, low load (type 1) and high load (type 2), shown in Table IV.

Figure 5 shows the average end-to-end delay for all protocols. Prioritized QFSA-MAC protocol reduces end-to-end delay and achieves fast data transmission for all traffic classes when compared with prioritized/unprioritized QODA-MAC protocol and unprioritized QFSA-MAC protocol for all traffic classes. Delay performance of prioritized QODA-MAC protocol is better than the unprioritized QODA-MAC protocol shown in Figure 5 for RT traffic for all traffic loads. On the other hand, unprioritized QFSA-MAC protocol achieves lower delay for all RT, NRT, and BE traffic classes in all traffic loads. This means that all modes of QFSA-MAC protocol is more efficient than the modes of QODA-MAC protocol for time-critical or non-time-critical smart grid applications because the QFSA-MAC protocol utilizes the spatial reuse capability of the directional antennas and in this way, reduces the end-to-end delay. When the traffic load increases from low load (type 1) to high load (type 2), end-to-end delay of QFSA-MAC and QODA-MAC protocol increases because the number of generated and sending packets of all traffic classes increases too. Delay of NRT and BE traffic classes decreases when QODA-MAC and QFSA-MAC are in the unprioritized mode because no precedence is given to packet types. However, their delay is still higher than the RT traffic class in unprioritized mode of the protocols because interarrival time of the RT packets is smaller than them. As a result of the delay measurements of the protocols performed in different smart grid environments, 500 kv substation, underground transformer vault, and main power room, we observed that the lowest delay is achieved by all the proposed protocols in 500 kv substation smart grid environment as shown in Figure 5a and b.

Figure 6 shows the throughput of all the protocols in various smart grid environments. Throughput is based on the delivery ratio and inversely proportional to the delay. Because the delay performance of the prioritized QFSA-MAC protocol is better than its unprioritized mode and all the modes of the QODA-MAC protocol for RT traffic class, it has the highest throughput in all different smart grid environments, which is an advantage of the spatial reuse provided by the sectored antenna. On the other hand, for the NRT and BE traffic classes, unprioritized QFSA-MAC protocol achieves better performance than the others because it does not give precedence to RT packets and fairly sends all types of packet with minimum latency. Throughput of RT packets is higher than the throughput NRT and BE packets because sensor nodes more frequently generate the RT packets and their interarrival times are smaller than the other packet types. Furthermore, we also observed that although the prioritized QODA-MAC protocol gives precedence to RT packets, throughput performance of unprioritized QFSA-MAC protocol is better than it for all the traffic classes in terms of RT, NRT, and BE. This is because unprioritized QFSA-MAC protocol provides high packet delivery ratio by minimizing interference and packet collisions in the shared medium while utilizing the dynamic TDMA medium access protocol.

Average energy consumption for each successfully received packet at the sink node of the protocols is compared in Figure 7. It is seen that prioritized QFSA-MAC protocol consumes notable less energy than all modes of the OQDA-MAC protocol for all traffic loads. This is because of

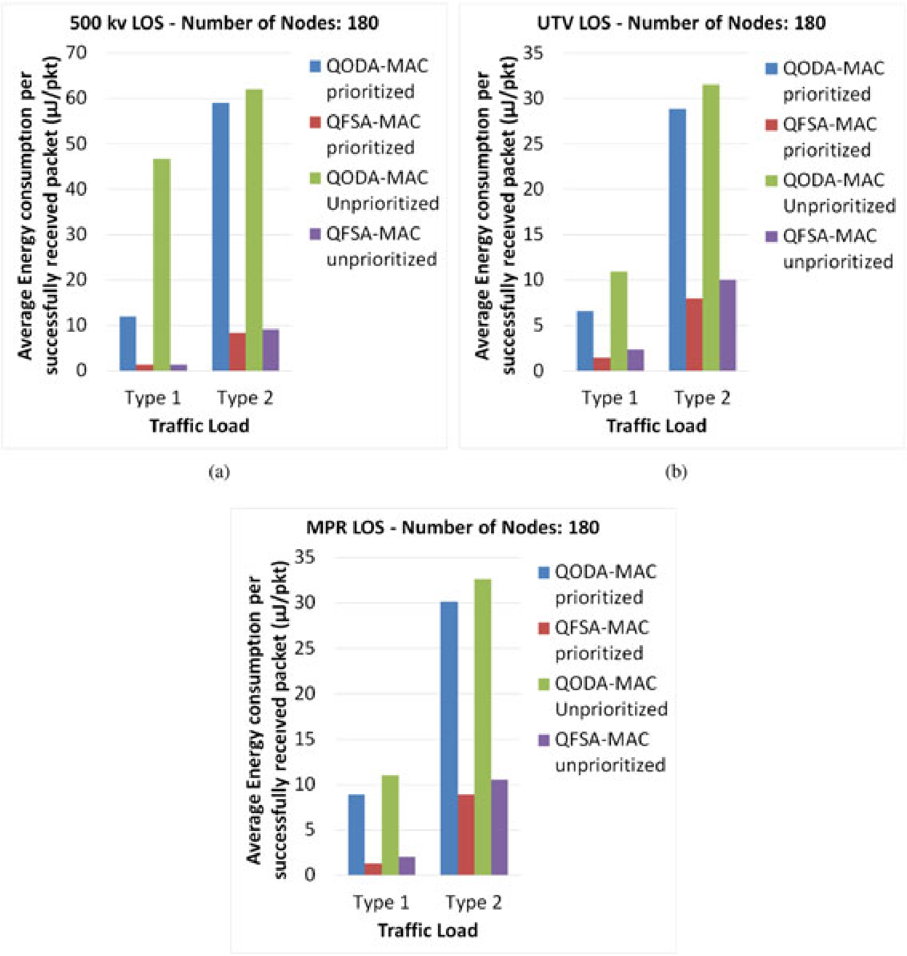


(a) (b)

(c) (d)

(e) (f)

Figure 6. Comparative average throughput of all the protocols for two types of traffic in different smart grid environments. QODA-MAC, quality of service-aware omnidirectional antenna-based medium access control protocol; QFSA-MAC, quality of service-aware four-sectored antenna-based medium access layer; MPR, main power room; UTV, underground transformer vault.



(a) (b)

(c)

Figure 7. Comparative average energy consumption of all the protocols for two types of traffic in different smart grid environments. QODA-MAC, quality of service-aware omnidirectional antenna-based medium access control protocol; QFSA-MAC, quality of service-aware four-sectored antenna-based medium access layer; UTV, underground transformer vault; MPR, main power room.

the dynamic nature of the QFSA-MAC protocol where it allocates the time slots dynamically and avoids waste of energy by waiting for other nodes. It is also shown that energy efficiency of all protocols increases when they are in prioritized mode. The reason behind is that the sink node receives more packets with low delay when the protocols are in prioritized mode as shown in Figures 5 and 6. Furthermore, we observed that unprioritized QODA-MAC protocol shows the worst performance because it uses TDMA-based MAC protocol in which the nodes wait for their slots in making transmission and consume energy during waiting time.

In summary, as shown in the results, the QFSA-MAC protocol is proven to outperform the QODA-MAC protocol because the QFSA-MAC protocol takes the advantage of sectored antennas. Sectored antennas strengthens the receiver power and reduces variance of fading rate. Furthermore, sectored antennas also extend the range for reaching far-away nodes, and their power requirements are less than the omnidirectional antennas in covering the same range. Because of these benefits of sectored antennas, the number of transmitted packets increases with low delay and less energy in the QFSA-MAC protocol.In this way, the QFSA-MAC protocol overcomes several challenges such as application-specific QoS requirements and variable channel capacity [10] that influence the design of WSNs. Furthermore, the QFSA-MAC protocol yields many open research issues [43] with accurate delay modeling and suitable utility functions.

From the simulations, the following results can be obtained:

- Prioritized QFSA-MAC protocol achieves better performance than either unprioritized QFSA-MAC or all modes of the QODA-MAC protocol.
- Compared with prioritized QODA-MAC protocol, which utilizes the omnidirectional antenna, prioritized QFSA-MAC protocol can effectively allocate the limited wireless channel resources of RT traffic, which is the reason why the performance of RT packet is better, but NRT and BE packets are worse than unprioritized QFSA-MAC protocol.
- Compared with the prioritized and unprioritized QODA-MAC protocol, unprioritized QFSA-MAC protocol realized better throughput, delay, and energy performance.
- As a result of the simulations, prioritized QFSA-MAC protocol achieves QoS provisioning for time-critical smart grid applications by exploiting the spatial reuse and collision avoidance capabilities of sectored antennas.

8. CONCLUSION AND FUTURE WORK

This paper presents QODA-MAC and QFSA-MAC, two new priority-based and QoS-aware MAC protocols that coordinate the medium access based on the traffic class with efficient service differentiation mechanism to support QoS for smart grid applications. In the first scheme, named QODA-MAC protocol, sensor nodes are equipped with omnidirectional antennas and assign the time slots by considering the interference and channel conditions. On the other hand, the second approach, named QFSA-MAC protocol, uses sectored antennas and dynamically assigns the time slots as opposed to the QODA-MAC protocol. Both QODA-MAC and QFSA-MAC protocols have two types of mode in terms of prioritized and unprioritized. The comparative performance evaluations of proposed MAC protocols have been carried out, and our results reveal that all modes of QFSA-MAC protocol outperform QODA-MAC by providing lower latencies and higher throughput with less energy consumption in all smart grid environments. Furthermore, results also show that prioritized QFSA-MAC protocol successfully satisfies the QoS requirements of smart grid applications.

As future work, optimization studies to enhance the performance of QODA-MAC and QFSA-MAC will be considered, which include multi-channel scheduling and finding the optimum physical layer parameters.

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