IEEE Access
The journal for rapid open access publishing

Received June 29, 2015, accepted July 17, 2015, date of publication August 7, 2015, date of current version August 26, 2015.

Digital Object Identifier 10.1109/ACCESS.2015.2466077

Delay Critical Smart Grid Applications and Adaptive QoS Provisioning

IRFAN AL-ANBAGI[1], (Senior Member, IEEE), MELIKE EROL-KANTARCI[2], (Senior Member, IEEE), AND HUSSEIN T. MOUFTAH[1], (Fellow, IEEE)
[1]School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON K1N 6N5, Canada
[2]Department of Electrical and Computer Engineering, Clarkson University, Potsdam, NY 13699, USA

Corresponding author: H. T. Mouftah (mouftah@site.uottawa.ca)

ABSTRACT Wireless sensor networks (WSNs) are anticipated to be widely adopted in the various monitoring and control applications due to their versatility and low cost. One of the most promising and emerging WSNs applications is their use in monitoring smart grid assets. Although WSNs can provide cost efficient and reliable solutions, they are not suitable for delay critical application, because they were initially designed for low data rate applications and they may be challenged when sudden faults or failures occur in the monitored environments. Therefore, to prevent extensive delays of critical data, appropriate quality of service (QoS) techniques should be used. In this paper, we present an adaptive QoS scheme (AQoS) and an adaptive guaranteed time slot (AGTS) allocation scheme for IEEE 802.15.4-based WSNs used in high traffic intensity smart grid monitoring applications. Both AQoS and AGTS schemes can adaptively reduce the end-to-end delay and flexibly tune the GTS to provide the required QoS differentiation to delay critical smart grid monitoring applications.

INDEX TERMS IEEE 802.15.4, WSNs, cluster-tree topology, mesh topology, reliability, delay-critical, QoS.

I. INTRODUCTION

Monitoring and controlling smart grid assets with severe risks of damage due to the occurrence of certain events or faults have strict Quality of Service (QoS) requirements, including requirements on the functional behavior, robustness, reliability, and timeliness [1]–[5]. Therefore, a real-time smart grid monitoring system should not only manage system resources and offer a well-defined set of services to application programs, but should also provide guarantees about the timeliness of such events, that is, its behavior must be predictable. Thus, for example, the maximum latency to monitor and control a substation in a power grid should be known in advance and should also satisfy the functional requirements set by power utilities.

The use of different wireless networking technologies in general and the use of Wireless Sensor Networks (WSNs) in specific to monitor and control various smart grid assets is highly desired for emerging smart grid applications. WSNs are preferred due their low cost, rapid deployment, low power consumption. However, using WSNs for some delay critical smart grid applications may require these networks to fulfill the real-time requirements of these applications. In addition to that, condition monitoring using WSNs may involve the deployment of the sensor nodes in harsh and hostile environments [6]–[10]. As a result, it is possible for these WSNs to crash or malfunction due to external environmental factors. Hence, any QoS solution should be based on failure models that account for such possibilities. Furthermore, failure of few nodes should not bring down the network. In addition, WSNs are expected to be deployed in high numbers, thus, scalability is a critical issue in designing an effective QoS scheme for WSNs. Sensor nodes are generally equipped with a limited battery supplied energy and since these nodes spend more energy in communication than local computations, an efficient QoS scheme should also consider energy consumption. Using hard-wired sensors could meet the real-time requirements better than WSNs. However, they are not preferred due to their high installation cost, insulation problems, high failure rates and long repair times.

Certain smart grid monitoring applications generate intense traffic and require strict delay and reliability requirements. For example, monitoring partial discharge activities in high voltage equipment can generate data rates in the vicinity of 300 kbps [11] and [12]. The IEEE 802.15.4 standard is solely designed for low data rate monitoring application [13]. Therefore, such high data rates and delay requirements make the default IEEE 802.15.4-based WSNs inefficient for such applications.

In this paper, we present an Adaptive QoS (AQoS) scheme to reduce the delay of high priority data in WSNs smart grid monitoring applications. We design the AQoS to be suitable for high and low data rate smart grid condition monitoring applications. AQoS adaptively modifies the Guaranteed Time Slot (GTS) based on requests made from the end devices after probabilistically estimating the WSN operating conditions. Furthermore, we enhance the AQoS scheme by presenting an Adaptive Guaranteed Time Slot (GTS) allocation scheme (AGTS)for IEEE 802.15.4-based WSNs in high data rate smart grid monitoring applications. The AGTS scheme can adaptively reduce the end-to-end delay and flexibly tune the GTS to achieve the required QoS differentiation to delay critical smart grid monitoring applications. The AGTS scheme can adaptively allocate the needed GTS to nodes transmitting high priority traffic or draw back the unneeded GTS. This is done without impacting other network traffic and without critically impacting the entire network performance in multi-hop WSNs. Both the AQoS and the AGTS schemes utilize hybrid channel access mechanisms (i.e. using Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and time slot allocation). We show that the use of the traditional channel access schemes individually will not be sufficient to provide the required QoS guarantees.

We also present a comprehensive performance evaluation of the two schemes and compare their effectiveness in a smart grid monitoring scenario. Compared to AQoS scheme, the AGTS scheme shows more flexibility and versatility in reducing the end-to-end delay and providing the required QoS guarantees to high priority traffic. In addition to that, in the AGTS scheme we present multipath solution in mesh topologies were the traffic can be rerouted through alternative paths to achieve the desired operating conditions. Both the AQoS and the AGTS schemes build on the mathematical model described in [14]. However, they presents major improvements to the model by solving the issue of excessive latency by using hybrid channel access mechanisms and adaptively providing QoS guarantees to delay critical condition monitoring and control applications.

The remainder of this paper is organized as follows. In Section II, we present the related work. In Section III, we present scenario description, model assumptions and the delay and reliability analysis. In Section IV, we describe the AQoS and the AGTS schemes. In Section V, we present the simulation and the analysis. Finally, Section VI concludes this work.

II. QoS DEMANDING SMART GRID APPLICATIONS

A. OVERVIEW

WSN requirements associated with smart grid applications play a considerable role in determining how to implement the WSN technology into the power grid infrastructure. QoS requirements vary depending on the criticality of the monitored power grid component. These requirements can be one or a combination of the following requirements; latency, reliability, availability, security and spectrum availability. In this paper we focus on the latency and the reliability requirements. Such applications vary from teleprotection systems, emergency power restoration to substation monitoring and control. Therefore, latency requirements in smart grid monitoring applications may vary from several seconds for smart metering to less than 10 ms for protection operations. Table 1 shows some typical latency requirements of some common smart grid monitoring applications [15]. In the literature there are many studies that discuss the use of QoS WSNs protocol from delay and reliability critical applications. In [16], a spectrum-aware and cognitive sensor networks have been proposed to overcome spatio-temporally varying spectrum characteristics and harsh environmental conditions for WSN-based smart grid applications. In [17] the feasibility of a public LTE network in supporting worst case smart grid communications has been investigated. In [18] a distributed algorithm to minimize the data aggregation latency under the physical interference mode has been proposed in a smart grid scenario. In [19], the performance of a WSN system in the measurement of partial discharge signals and data flow optimization and management from the monitoring sensors to the base station has been optimized and evaluated.

Application	Maximum Latency
Teleprotection	$\leq$10 ms
Synchrophasor	$\sim$ 20 ms
Control and data acquisition	(100-200) ms
Smart metering	(2-3) s

TABLE 1. Latency requirements for some smart grid applications [15].

Sun et al. [20], have proposed to use a private wireless network dedicated for power distribution system monitoring. The authors have introduced a QoS support for IEEE 802.15.4 by the differentiated service for data traffic with different priorities. They have used additional queues in the MAC to store different priority traffic. Therefore, high priority data will have higher probability of channel access, and can interrupt the service to the low priority traffic by forcing it to backoff (BO). They have assumed N sensor nodes to monitor power distribution devices and report back to a coordinator using the IEEE 802.15.4 protocol and that all nodes can hear each other. When operational data arrives at any node, it will be pushed into the queue at MAC layer if there is a packet in service. When the emergency data arrived, it will be queued in the high priority queue if there is high priority packet in service. Otherwise, it will interrupt the service of an operational data packet. They have assumed that no operational data will be serviced until the emergency data queue is empty. They have modelled the delay of QoS-MAC and the BO process using the Markov chain queue model for two classes of traffic. They have assumed that the packet arriving rate for all nodes is the same, and set the maximum number of BO stage as 5, the value of the BO for high priority traffic ranges from 0 to 3 and for low priority data ranges from 2 to 5. The authors have not presented the impact of the buffer or queue size on the performance of the network. The queue size of each sensor node will affect the waiting duration of the packet and hence may affect the overall network performance.

Ruiyi et al. [21], have proposed an Adaptive Wireless Resource Allocation (AWRA) algorithm with QoS guarantee in communication network of smart grid. The authors have addressed adaptive wireless resource allocation, where they have assumed that if the delay of the packets is greater than the delay threshold, then the packet is discarded, while for non-real-time services, as long as the queue does not overflow, the packet will not be discarded. They have assumed that the queue is infinite and do not consider the discarded packet caused by queue overflow and the problem of retransmission and that the total transmission power of the base station in the sub-channels is average distribution. The authors have proposed that the system of the smart grid contains 19 plots, each plot has 3 sectors and that each sector has N sub-channels and K packets. They have defined an optimization problem based on different stages of base station tasks. The first stage is detect stage where the base station measures the user's SNR; the second stage is the feedback stage where the user feedbacks the channel state information and the final stage is when the base station collects the feedback information and allocate space, time, frequency resource for the user to transmit data based on certain scheduling criteria.

In [22], the authors have introduced a medium access scheme, delay-responsive, cross-layer (DRX) data transmission that addresses delay and service differentiation requirements of the smart grid. The DRX scheme is based on delay-estimation and data prioritization procedures that are performed by the application layer for which the MAC layer responds to the delay requirements of a smart grid application and the network condition. In [14], the authors have proposed a Markov-based model for cluster-tree WSN topologies that enhances the stability of the WSNs in smart grid monitoring and control application.

In addition to the above surveyed papers, some papers discuss delay tolerant smart grid applications which include Automatic Meter Reading (AMR), billing, routine data measurement and switching of appliances. These applications tolerate delays and can perform adequately with some data loss. In [23] a WSN-based intelligent light control system for indoor environments have been proposed. In [24] new field tests using open source tools with ZigBee technologies have been proposed for monitoring photovoltaic and wind energy systems and energy management of buildings and homes. In [25] the performance of an in-home energy management application has been evaluated. In [26] an experimental study on the statistical characterization of the wireless channel in different electric-power-system environments was presented.

The concept of using adaptive WSN protocols for delay sensitive applications has been considered in the literature [22], [27], [28]. In addition to that, the use of an adaptive WSN protocols to control other WSN parameters has been discussed in [20], [29], and [30].

In [31], we have presented an adaptive QoS scheme for WSNs that provides service differentiation and reducing the delay of critical data in smart grid applications. In that scheme, we have considered that a single GTS may not be sufficient to reduce the delay especially in high traffic intensity monitoring applications such as monitoring partial discharge activities. Furthermore, the whole idea of an adaptive scheme is that it can show more flexibility in allocating and withdrawing different number of GTSs based on varying network and traffic conditions. In this paper, we propose that a sensor node can request and give back multiple GTSs to achieve the minimum delay in WSNs with mesh topologies.

In [32], the authors have proposed a technique to schedule the Super-Frames (SF) of cluster-tree IEEE 802.15.4 networks over multiple channels to avoid beacon frame collisions as well as GTS collisions between multiple clusters. Their technique allows multiple clusters to schedule their SFs simultaneously on different radio channels. Our scheme also uses SF scheduling to avoid beacon frame collisions. However, we have not used multichannel scheduling, since that scheme requires significant changes to the hardware platform in addition to changes to the IEEE 802.15.4 protocol. Instead, we have proposed that the communication within a cluster take place using CSMA/CA, and the communication between Cluster-Heads (CHs) takes place using mutual scheduling of interfering CHs which requires minimal changes to the hardware as well as the communication protocol. We have also added a QoS scheme based on a Markov chain-based model that can reduce the end-to-end delay of high priority traffic.

In [33], the authors have proposed a tree-cluster-based data-gathering algorithm for WSNs with a mobile sink and introduced a weight-based tree-construction method. They have defined the root nodes of the constructed trees as Rendezvous Points (RPs) and selected special nodes Sub-Rendezvous Points (SRPs) according to their traffic load and hops to root nodes. RPs and SRPs are viewed as stop points of the mobile sink for data collection, and can be reselected after a certain period. The authors have shown that their algorithm can balance the load of the, reduce the energy consumption and prolong the network lifetime. The authors have not considered the impact of their algorithm on the end-to-end delay and also the reliability of data transmission. In addition to that the impact of data arrival rates on the performance of the network.

In [34], the authors have developed a delay-optimal anycasting scheme under periodic sleep wake patterns. They have showed that periodic sleep wake patterns result in the smallest delay among all wake-up patterns under given energy constraints. The use of hybrid WSN MAC protocol based on scheduling and contention has been discussed in [35] where

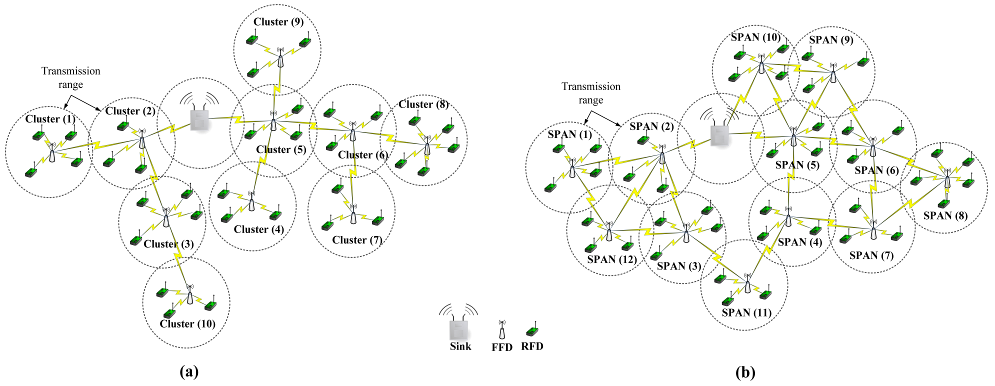

FIGURE 1. ***The proposed WSNs. (a) Cluster-tree topology. (b) Mesh topology.***

the authors have presented hybrid MAC protocol, called Z-MAC, for WSNs that combines the strengths of TDMA and CSMA.

B. OPEN RESEARCH ISSUES

The development of delay critical approaches for WSNs for smart grid applications faces many challenges and open issues. Some of these open issues are common in many WSNs application. Others are related to the nature of the smart grid environment itself, We highlight some of the important open issues and challenges for implementing QoS approaches in WSNs for smart grid applications.

The limitation on the resources including available energy, computational power and available bandwidth in the entire network represent the main challenging issues for QoS in WSNs for smart grid applications. A balance between energy efficiency and a QoS protocol design in smart grid applications is an interesting problem where simple QoS models are required to identify the architecture for QoS support in WSNs.

The investigation of various data dissemination protocols such as directed diffusion and their ability to support QoS constrained traffic to allow these protocols to support priority smart grid applications is another important open research issue. The effects of high network traffic intensities on the QoS mechanism is also interesting issue to be investigated for such applications.

Maintaining consistent performance throughout the network life while considering optimizing the energy consumption in WSNs is an open research issue that has not been studied for smart grid applications.

Defining the criteria of QoS differentiation for specific smart grid application that can maintain more than one differentiation criteria while considering WSN resources such as energy, memory and processing capability still needs to be developed. In addition to that, an efficient QoS mechanism should be able to adaptively balance between the amount of transmitted traffic, application requirement and the available resources.

Scalability and the limits of the QoS for delay critical smart grid applications is also considered an open issue which needs to be further investigated. This challenge becomes obvious when considering different scenarios, for example when comparing the number of nodes in a small scale deployment to wider area deployment scenario.

WSNs pose several vulnerabilities in implementing robust security algorithms because sensor nodes are generally resource constrained. In addition to that, WSNs may be deployed in public hostile locations, which make sensor nodes vulnerable to physical attacks. Therefore, any security algorithm should consider the limited resources, the environment where they are deployed and also take into considerations the QoS requirements, specifically in delay and reliability sensitive applications.

In this work, we address some of these issues by proposing the AQoS scheme which is designed to handle the delay issue of high priority data in WSNs smart grid monitoring applications. The AQoS is designed to be adaptive to high and low data rate applications. AQoS is also adaptive in allocating GTS based on applications' requirements. In addition, we improve the AQoS scheme by presenting AGTS for WSNs, the AGTS scheme is fully adaptive and scalable. Which means that it can grant and and withdraw the GTS based on the application needs, traffic conditions and network topology.

III. SYSTEM MODEL AND ASSUMPTIONS

A. SYSTEM MODEL

In a cluster-tree topology, the network consists of multiple coordinators, also called CHs. These CHs generate periodic beacon frames to synchronize with their end nodes and with higher or lower level CHs. Figure 1-(a) shows an example of a cluster-tree topology that we adopt to implement our model. In Figure 1-(a), CH2 is the parent of CH1 and CH3, while being child of the Personal Area Network (PAN) Coordinator (PC) or the sink, which is also the root of the tree. In this scenario and in similar cluster-tree scenarios if the transmission of the beacon frames are not properly synchronized, (i.e. not properly scheduled), beacon frames could collide either with other beacon frames from different coordinators or with data frames from different clusters. Collision of beacon frames leads to loss of synchronization between communicating CHs, which results in the disconnection of the colliding CHs from the network.

The 15.4b Task Group [36] propose two general methods to avoid beacon frame collisions. These methods are the time division approach and the beacon-only period approach. In the time-division approach, each CH schedules its SF during the inactive period of the other coordinators. This is achieved by setting an offset in time for the beacon frame transmission in each CH. This approach requires minor modification to the current IEEE 802.15.4 MAC protocol. There are several limitations associated with this approach. These limitations can be summarized as follows: the first is the constrains in the duty-cycles, since duty cycle is dependent on the number of interfering CHs (i.e. interfering CHs must operate in different time windows), the second, is that direct communication between sibling CHs (CHs connected to the same parent) is not possible, because each of these CHs operates in a time window different from its adjacent clusters. In the beacon-only period approach, the SF structure is modified by introducing a period at the beginning of each SF, during this period CHs transmit their beacon frames [37]. Each CH should select a proper time slot so that its beacon frame does not collide with the ones from adjacent CHs. This approach allows multiple clusters to share the active period, so it is more scalable than the time division approach. The main disadvantage of this approach is that the beacon-only period depends on the size of network and the parent-child relationship. Most importantly, in this approach, the GTS mechanism cannot be implemented, since transmission from nodes belonging to different clusters may collide [13].

Similarly, in the mesh based WSN, we divide sensor nodes into two categories, namely, Reduced Function Devices (RFDs) and Full Function Devices (FFDs). A RFD can only communicate with an FFD (i.e its parent FFD) and can not perform routing. Therefore, its main role is to collect data and forward it to the FFD. A FFD can communicate with its own RFDs and can perform routing through neighbouring FFDs within its transmission range. We group a number of RFDs depending on their location and functionality into a single Sub-Personal Area Network (SPAN). Figure 1-(b) shows the proposed mesh topology.

B. MODEL ASSUMPTIONS

In our proposed models, we assume that either a CH or an FFD (we refer to it as ''FFD'' in the rest of the paper) communicate with its end nodes or RFD (we refer to it as ''RFD'' in the rest of the paper) using the CSMA-CA mechanism. In smart grid monitoring applications, this is a more practical and reliable scenario, since generally end devices connected to a single FFD are located close to each other within the same PAN. In addition to that, the number of RFDs connected to their FFD is expected to be in the order of tens of nodes, hence using time division approach [38] would be impractical. Each FFD forward packets from the RFD to upper level devices until the sink is reached.

We denote the traffic from the RFDs to their FFD as a local traffic and the traffic between low level and high level devices as the forwarded traffic. As shown in Figure 1-(a) and (b), we assume that RFDs belonging to a certain cluster or SPANs are placed in such a way that they do not suffer from co-channel interference from the transmissions in neighbouring clusters. To avoid beacon frame collisions between neighboring FFDs, we use the beacon frame collision avoidance approach described in [37]. In this approach the time is divided such that beacon frames and the SF duration of a given coordinator are scheduled in the inactive period of its neighbour coordinators. We implemented this approach by carefully selecting the duty cycle of each FFD in the network. This is done by selecting a specific Beacon Order (BeO) and SO.

Each FFD maintains a buffer ($\mathcal{B}$) to store the received packets, which can be either from its own RFDs or forwarded from the lower level nodes. We assume that these buffers can accommodate all of the incoming traffic. We also abide by the following additional assumptions;

- Packet arrival at MAC sub-layer is the same for all RFDs in the network.
- The traffic received by a node in an upper level ($l + 1$) is equal to the aggregate of traffic from nodes at lower levels (l).
- All nodes have M/G/1/L queues; the difference between nodes is in the packet arrival rate (λ).

C. DELAY AND RELIABILITY ANALYSIS

In this section, we consider the inter-FFD (i-FFD) transmission delay to compute the total end-to-end delay from an RFD to the sink. We classify FFDs into two categories based on their distance from the sink; first level FFDs and intermediate level FFDs. First level FFDs are one hope away from the sink, higher level FFDs are at a distance of more than one hop from the sink. We first compute the delay from first level FFDs to the sink then compute the i-FFD delay between higher level FFDs.

In WSNs with multi-hop topologies (cluster-tree or mesh) data packets experience excessive delays in relaying nodes especially in applications similar to the one described in this paper. The main cause of this delay is that when data packets are forwarded from lower level relaying nodes at a high traffic intensity, upper level relaying nodes cannot fit all of the packets in the current SF. Therefore, upper level FFDs have to buffer these packets until the next SF duration.

In a general monitoring and control scenario, certain data packets may require high priority. Thus, in the proposed schemes the application layer tags packets that require QoS provisioning with a flag. When a packet is tagged with high priority, the MAC sub-layer then estimates the reliability (R) using the analytical model described in [14] and briefly described below:

The reliability (R) is defined as the probability of successful packet reception, the approximate value of R is given given by the following relation [14]:

$$R \approx 1 - x^{m+1}(1+\tilde{y}) - \tilde{y}^{n+1} \tag{1}$$

where, $\tilde{y}$ is given by:

$$\tilde{y} = (1-(1-\tilde{\tau})^{N-1})(1-x^2) \tag{2}$$

and

$$\tilde{\tau} = (1+x)(1+\tilde{y})\tilde{b}_{0,0,0} \tag{3}$$

where, $\tilde{\tau}$ is the approximate value of the probability of starting the first Clear Channel Assessment (CCA1). N is the number of nodes in a cluster or a SPAN, $b_{0,0,0}$ is the probability of being at state (0, 0, 0) in the Markov chain and is derived in [14] and x is given by:

$$x = \alpha + (1-\alpha)\beta \tag{4}$$

where, α is the probability of finding the channel busy after CCA1 and is given by [14], [39]:

$$\begin{aligned} \alpha &= LP_c(1-\alpha)(1-\beta) \\ &\quad + L_{ack}\frac{N\tilde{\tau}(1-\tilde{\tau})^{N-1}}{1-(1-\tilde{\tau})^N}P_c(1-\alpha)(1-\beta) \end{aligned} \tag{5}$$

where, L is the packet length, L_{ack} is the acknowledgement packet length, P_c is the the probability of collision and β is the probability of finding the channel busy after the second Clear Channel Assessment (CCA2), and is given by:

$$\beta = \frac{P_c + N\tilde{\tau}(1-\tilde{\tau})^{N-1}}{2-(1-\tilde{\tau})^N + N\tilde{\tau}(1-\tilde{\tau})^{N-1}} \tag{6}$$

and finally P_c is given by:

$$P_c = 1-(1-\tilde{\tau})^{N-1} \tag{7}$$

Following the estimation of R, the MAC sub-layer estimates the number of full SF (δ) a packet is expected to wait in a next hop node before it is forwarded to an upper level node towards the sink. The estimation of δ depends on the level of the node, therefore we base our schemes on a node with level (k) to generalize the scheme for the entire network.

We assume that $\mathcal{O}_k$ be the occupancy of $\mathcal{B}_k$, $\mathcal{M}_k$ be the number of packets received from RFDs in the SPAN during the Contention Access Period (CAP) and $\mathcal{P}_k$ be the number of the forwarded packets from k^{th} level FFDs. Therefore, we get:

$$\mathcal{O}_k = \mathcal{M}_k + \mathcal{P}_k \tag{8}$$

We can obtain $\mathcal{M}_k$ from λ_k and R_k. Furthermore, we assume that $\mathcal{G}_k$ and π_k be the maximum number of data packets that can be transmitted and received from and to a relaying FFD during a single SF duration respectively. The values of $\mathcal{G}_k$ and π_k depend on the packet length and the Contention Free Period (CFP) length. We follow the same procedure followed in [38], therefore we assume $(\mathcal{Q}-1)$ be the number of data packets present in $\mathcal{B}_k$ when the tagged packet arrives in $\mathcal{B}_k$. The values of $\mathcal{Q}$ depend on $\mathcal{O}_k$ in equation (8). For the sake of uniformity, we assume that all the packets in $\mathcal{B}_k$ experience the same single hop delay between FFDs ($\mathcal{D}_{FFD}$). The value of $\mathcal{D}_{FFD}$ (in time slots) is given by:

$$\mathcal{D}_{FFD} = \delta D_{SF} + \mathcal{G}_k \tag{9}$$

where, D_{SF} is the SF duration in time slots. The value of δ can simply be found by the following equation:

$$\delta = \left\lceil \frac{\mathcal{O}_k}{\mathcal{G}_k} \right\rceil - 1 \tag{10}$$

Based on Equation (10) and [38], the average single hop delay of all the packets incoming to $\mathcal{B}_k$ ($\mathcal{D}_{SH}$) is giving by the following equation:

$$\mathcal{D}_{SH} = \frac{\sum_{n=1}^{\mathcal{O}_k}\left[\left(\left\lceil \frac{n}{\mathcal{G}_k}\right\rceil - 1\right)\mathcal{D}_{SF} + \mathcal{G}_k\right]}{\mathcal{O}_k} \tag{11}$$

As in [38], a special case is considered where the FFD is the sink, in this case, $\mathcal{D}_{FFD}$ of the tagged packet in time slot is:

$$\tilde{\mathcal{D}}_{FFD} = \delta D_{SF} + \mathcal{V} \tag{12}$$

where, $\mathcal{V}$ represents the number of data packets serviced in the same SF of the tagged packet and is given by [38]:

$$\mathcal{V} = \pi - \delta\mathcal{G}_k \tag{13}$$

Therefore, as in [38], the average single hop delay of all the packets incoming to B_k ($\tilde{\mathcal{D}}_{SH}$) in the last hop is giving by the following equation:

$$\tilde{\mathcal{D}}_{SH} = \frac{\sum_{n=1}^{\mathcal{O}_k}\left\{\left(\left\lceil \frac{n}{\mathcal{G}_k}\right\rceil - 1\right)\mathcal{D}_{SF} + \left[n - \left(\left\lceil \frac{n}{\mathcal{D}_k}\right\rceil - 1\right)\mathcal{G}_k\right]\right\}}{\mathcal{O}_k} \tag{14}$$

Finally, to find the value of $\mathcal{M}$ we use the value of the reliability R given by equation (1).

After calculating i-FFD, we calculate the delay from an RFD to its local FFD. We assume that the total end-to-end delay to transmit a packet from an RFD to the sink in a multi-hop topology is equal to the sum of the delays along the path from the RFD to the sink. The total end-to-end delay (D_T) depends on the number of nodes and the packet arrival rate in each level k. It also depends on the location of the RFD (i.e. its depth in the network), the total number of FFDs in the network and how much traffic they are generating. The value of (D_T) is given by the following equation:

$$D_T = T + \sum_{i=0}^{l-1} \acute{D}_{SHi} \tag{15}$$

where, T is the delay from an RFD to its FFD and $\acute{D}_{SH}$ represents the i-FFD delay and is given by the combination of (11) and (14).

Similar to [14] and [39], we consider the delay (T) to be resulting from the time spent during backoff (D_{bo}), the time wasted due to experiencing j collisions (jL_c), and the time needed to successfully transmit a packet (L_s) and is given by:

$$T = L_s + jL_c + D_{bo} = (1+j)L + D_{bo} \tag{16}$$

D_{bo} can be found by knowing the probability of being in the backoff state and is given in [14]. For simplicity, in (16), we assume that $L = L_s = Lc$.

Finally, we present the approximate model to calculate the average power consumption. The average power consumed to transmit a packet from an end node to the sink in a multi-hop topology ($\tilde{E}_{tot}$) is equal to the sum of the power consumed in transmitting the packet from an RFD to its immediate FFD (E_{tot}) and the power consumed in transmitting this packet to the FFDs along the path to the sink. Since we initially assume that all the FFDs use scheduling to transmit their packets then there is no power consumed in backoff (E_{bo}), channel sensing (E_{sc}), and retransmissions packet transmission (E_{rt}). Therefore, the total power consumed in transmitting a packet from an RFD to the sink along multiple hops is given by the following equation:

$$\tilde{E}_{tot} = E_{tot} + \sum_{i=0}^{k-1}(E_{ti} + E_{Bi}) \tag{17}$$

where, k represents the total levels of the cluster-tree network.

We find E_{tot} [14] by summing the average E_{bo}, E_{sc}, packet transmission (E_t), packet reception (E_r) idle state (E_Q), buffering (E_B), and wake-up (E_w) and is given by:

$$E_{tot} = E_{bo} + E_{sc} + E_t + E_Q + E_B + E_w + E_r \tag{18}$$

According to [14], each of the terms in equations (17) and (18) can be computed by knowing the probability of being at a certain state and the amount of average power consumed at that state. Since we assume that each end node only receives ACK traffic from the coordinator, therefore, the packet consumed in packet reception is negligible due to the size of the ACK packet (Refer to [14] and [39] for the complete details).

IV. AQoS AND AGTS SCHEMES

A. THE AQoS SCHEME

In multi-hop WSNs with high traffic generation rates (i.e. higher than 20 $pkts/s$), data packet transmissions experiences excessive delays. The reason behind these delays is that when data packets are forwarded from a lower level FFDs at high rates, upper level FFDs cannot fit these packets in the current SF. Therefore, they have to be buffered until the next SF. These delays are common in multi-hop topologies where the GTS is used to avoid beacon frame collisions. We address this issue to allow WSNs to be utilized in delay critical environments with high traffic generation rates. The AQoS scheme, can be implemented in WSNs with multi-hop topologies and can provide QoS guarantees in an adaptive manner.

The AQoS scheme works as follows; the application layer tags packets that require QoS provisioning with a flag indicating the criticality of the data. The node then uses equation (1) to estimate the reliability (R) and then estimates the number of full SF δ this packet is expected to wait in the FFD before it is serviced and forwarded to an upper level FFD. The estimation of δ depends on several factors such as the number of RFDs in each cluster, packet arrival rates, the depth of the FFD in the network, the packet size and other MAC parameters such as the maximum number of backoffs (*macMaxCSMABackoffs*) and the maximum number of frame retries (*macMaxFrameRetries*).

In the AQoS scheme, the tagged RFD (i.e. a node generating high priority data) estimates δ using equation (10) and if it finds the value of δ more than zero, which means that the packet is expected to wait for more than one D_{SF}, and hence the deadline is not going to be met. In this situation the tagged RFD application layer inserts a flag in its frame to request its FFD to double its GTS period so that it can accommodate the increasing λ and to allow the high priority packets to be transmitted to the next FFD in the current D_{SF}. Upon arrival of the data packets to the tagged FFD, the latter coordinates with its higher level FFDs to accommodate the request of its RFD. We found out that after implementing this scheme, other end nodes sharing the same cluster with the tagged RFD take advantage of this scheme even if they are transmitting less urgent data. This happens because all the nodes in the same PAN use CSMA/CA scheme to gain access to the channel and hence all the RFDs are treated with high priority. Therefore, to solve this problem and increase the probability of the tagged RFD in acquiring the medium and transmitting its data, we implement the DRX scheme [22] on top of the AQoS scheme. In the DRX scheme the tagged RFD performs CCA in 64 μs instead of 128 μs defined in [13]. Furthermore, to further increase the probability of the tagged RFD in acquiring the medium, the tagged RFD implements linear backoff period [10], where the RFD uses random $delay = random\_int(2BE - 1)$ instead of random $delay = random\_int(2^{BE} - 1)$ (defined by IEEE 802.15.4 standard [13]). This linear backoff period allows the tagged RFD to come out of its backoff duration before other RFDs and then it would have higher probability in sensing the medium with a reduced CCA duration. Algorithm 1 shows the details of the AQoS algorithm.

B. THE AGTS SCHEME

Compared to the AQoS, the AGTS scheme can adaptively allocate more than one time slot to RFDs transmitting high priority traffic or draw back the unneeded time slots. This is done without impacting other network traffic and without critically impacting the entire network performance in multi-hop WSNs.

In AGTS, if the packet is marked with high priority, the value of δ is estimated, if δ is more than zero, then the tagged RFD's MAC sub-layer inserts a flag in its frame to request its FFD to double its GTS period so that it can accommodate the increase in λ. When the FFD receives the packets from the tagged node, it coordinates with its higher level FFD to accommodate the request of its tagged RFD. When a RFD receives its request of doubling the GTS it performs the revaluation of δ based on the new GTS value and if it finds that δ still higher than 1 it repeats the request for GTS from its FFD. If the FFD has enough GTS it will further

Algorithm 1 AQoS Algorithm

```
//Arrival of data packets to the MAC sub-layer//
$NB \leftarrow 0, CW \leftarrow 2, BE \leftarrow macMinBE$
// Frame is marked from the Application layer//
if High priority flag = on then
    //Run the reliability estimation algorithm //
    $E(R)$
    //Estimate the number of full SF a packet can wait before being forwarded to the next FFD//
    $\delta = \left\lceil \frac{\mathcal{V}_i}{\mathcal{M}_i} \right\rceil$
end if
if $\delta > 0$ then
    //insert a flag to request FFD to double GTS//
    $GTS_{NEW} \leftarrow 2GTS$
    //Use linear random delay and reduced CCA duration//
    $Randomdelay \leftarrow random\_int(2BE - 1)$
    $CCA \leftarrow 64\mu s$ //on BO period boundary//
    (Execute IEEE 802.15.4 CSMA-CA Algorithm)
else
    //Use Exponential random delay and normal CCA duration Run the remaining of the CSMA-CA normally//
    $Randomdelay \leftarrow random\_int(2^{BE} - 1)$
    $CCA \leftarrow 128\mu s$
end if
(Execute IEEE 802.15.4 CSMA-CA Algorithm)
```

increase the GTS until the (δ) condition of the tagged RFD is satisfied. If the RFD finds that it is receiving more GTS than its requirements it alerts its FFD to withdraw the extra GTS. In other words, the AGTS scheme allows the FFD and the RFD to adaptively fine tune the time slot allocation until the minimum delay is reached.

The AGTS schemes allows FFDs receiving high priority packets to halt GTS allocation to nodes that have no high priority. Therefore, if such situation takes place, nodes with low priority data seek GTS from an alternative FFD. In this way, low priority traffic will be forced to take a different route to the sink.

In AGTS, the adaptive tuning of the GTS between the FFD and the RFD is done based the revaluation of the estimated number of full SFs a packet is expected to wait in the FFD (i.e. depending on the new value of δ). This is achieved every time an RFD receives an updated values of λ (when a difference in the measured data is sensed) and a new tuning factor (ω) for different traffic conditions. The tuning factor is defined as the ratio of the granted number GTSs to the original GTS. The value of ω is exchanged between the RFD and the associated FFD until the minimum delay is reached.

To prevent RFDs transmitting less critical data and sharing the same SPAN with the tagged RFD from taking advantage of additional GTSs. We increase the probability of the tagged RFD in acquiring the medium and transmitting the high priority data, we implement the DRX scheme [22] on top of the AGTS scheme. Furthermore, to enforce additional data differentiation and further decrease the delay, the AGTS scheme force the tagged node to implement linear backoff period [10]. Algorithm 2 shows the details of the AGTS algorithm.

Algorithm 2 AGTS Algorithm

```
//Arrival of data packets to the MAC sub-layer//
$NB \leftarrow 0, CW \leftarrow 2, BE \leftarrow macMinBE, n \leftarrow 2$
// Frame is marked from the Application layer//
if High priority flag = on then
    //Run the reliability estimation algorithm //
    $E(R)$
    //Estimate the number of full SF a packet can wait before being forwarded to the next FFD//
    $\delta = \left\lceil \frac{\mathcal{V}_i}{\mathcal{M}_i} \right\rceil$
end if
if $\delta > 0$ then
    //insert a flag to request FFD to increase GTS by n//
    $GTS_{NEW} \leftarrow n \times GTS$
    if $\delta > 0$ then
        $GTS_{NEW} \leftarrow (n + 1) \times GTS$
    end if
    //Use linear random delay and reduced CCA duration//
    $Randomdelay \leftarrow random\_int(2BE - 1)$
    $CCA \leftarrow 64\mu s$ //on BO period boundary//
    (Execute IEEE 802.15.4 CSMA-CA Algorithm)
    if High priority flag = off then
        //insert a flag to request FFD to reduce GTS//
        $GTS_{NEW} \leftarrow GTS$
    end if
else
    //Use Exponential random delay and normal CCA duration Run the remaining of the CSMA-CA normally//
    $Randomdelay \leftarrow random\_int(2^{BE} - 1)$
    $CCA \leftarrow 128\mu s$
end if
(Execute IEEE 802.15.4 CSMA-CA Algorithm)
```

V. SIMULATION AND ANALYSIS

A. SIMULATION SETTINGS

We use QualNet [40] network simulator to simulate the network topology presented in Figures 1-(a) and (b), and compare the simulation results with the analytical results of the AQoS and AGTS schemes. We set all the simulation parameters similar to the mathematical model environment. In both the simulation and the analytical models, we use Poisson traffic arrivals. We assume that all of the nodes (RFDs and FFDs) are operating in the 2.4 GHz band with a maximum bit rate of 250 kbps. We run each simulation for 400 seconds and repeat each simulation 10 times. We assume that all RFDs within an individual cluster transmit and sense the medium with sufficient power, which means that all RFDs in a single cluster can hear each other. We also assume that the noise level is constant throughout the entire network

Parameter	Value
Transmission power (dBm)	3.5
Noise factor (dB)	10.0
Contention window	2
Packet size (Byte)	120
Beacon order	1
Super frame order	1
Antenna gain (dBi)	0

TABLE 2. **Initial simulation parameters.**

(i.e. constant noise factor). We activate the acknowledgement mechanism in both the simulation and the mathematical model to improve the reliability of the system. Table 1 shows some of our simulation parameters, we acquire the rest of the parameters from the IEEE 802.15.4 standard document [13] and the actual specification document of MicaZ platform.

B. AQoS PERFORMANCE EVALUATION

We test the performance of the AQoS scheme in different network scenarios. We do this by assuming that the tagged node is either located in cluster(5) or cluster(6) in Figure 1-(a). In addition to that, we assume CH5 receives high priority packets from either a single CH (e.g. CH4) or from two CHs (e.g. CH4 and CH6) at the same time. Another scenario is when the tagged node is located in cluster(6) and cluster(6) receives high priority packets from either CH7 or from CH7 and CH8 at the same time. We simulate the following four scenarios: Scenario (a); when the tagged node is located in cluster(5) and CH5 receives high priority data from CH4 at the same rate. Scenario (b); when the tagged node is located in cluster(6) and CH6 receives high priority data form CH7 at the same rate. Scenario (c); when the tagged node is located in cluster(5) and CH5 receives high priority data from CH4 and CH6 at the same rate. Scenario (d); when the tagged node is located in cluster(6) and CH6 receives from high priority CH7 and CH8 at the same rate. Figure 2 shows the end-to-end delay of packet transmission from a tagged node versus λ for the different network scenarios. We show that the AQoS scheme outperforms the default IEEE 802.15.4 MAC setting by reducing the delay by more than 50% for high priority traffic for all network scenarios and traffic rates. We also show that this delay reduction becomes highly significant as λ increases and as the tagged node is located further away from the sink (i.e. the depth of the tree increases). We also note that in both cases the delay increases in steps, this behavior takes place because every time a packet misses the SF it waits for one or more SF to be transmitted.

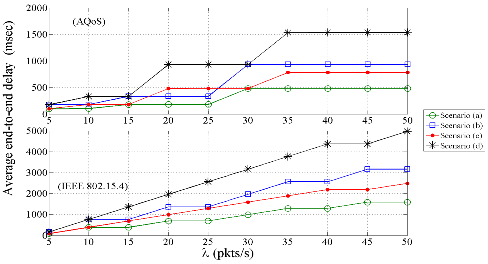

FIGURE 2. **End-to-end delay for different network scenarios.**

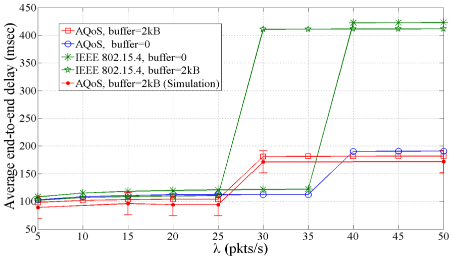

FIGURE 3. **End-to-end delay for different MAC buffer values.**

Figure 3 shows the end-to-end delay of packet transmission from the tagged node to the sink versus λ for different MAC buffer sizes and for the AQoS scheme and the default IEEE 802.15.4 settings, (we assume that the tagged node is located in cluster(5). We assume that there are 20 end nodes in all clusters in the network. We show that for λ values between 5 *pkts*/*s* and 20 *pkts*/*s*, the AQoS scheme outperforms the IEEE 802.15.4 for all MAC buffer sizes [14]. We also show that when λ is higher than 25 *pkts*/*s* and the MAC buffer size is 2 kB the end-to-end delay drops from 420 ms to 170 ms. This significant delay reduction is due to the extended GTS period, which is adaptively granted to the node by upper level CHs. We also show that when λ is between 25 *pkts*/*s* and 35 *pkts*/*s*, the end-to-end delay when the MAC buffer is 0 B is lower than the MAC buffer is 2 kB. This is behaviour is normal because when the MAC buffer size is 2 kB, the reliability is higher [14] and hence there will be more packets arriving to the tagged CH and hence miss the current SF. However, in AQoS we show that the end-to-end delay is always lower when the MAC buffer is 2 kB. We show that simulation results of AQoS agree with the analytical results of AQoS for all λ values.

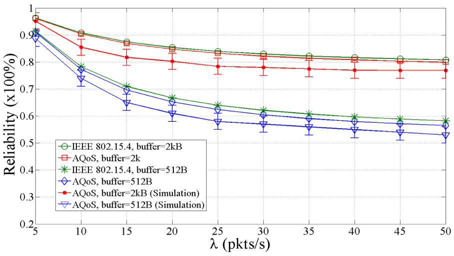

FIGURE 4. **Reliability for different MAC buffer sizes.**

Figure 4 shows the end-to-end reliability versus λ for different MAC buffer sizes and when the tagged node is located in cluster (5). We assume that there are 20 end nodes in each cluster. We show that the reliability is always higher when the MAC buffer size is 2 kB compare to 512 B. This is because as the MAC buffer size increases, the nodes will momentarily buffer the packets before contending and thus collisions are reduced [14]. We also show that as λ increases the reliability drops. From Figure 4, we see that there is no significant drop in the reliability when a node implements the AQoS scheme. We show that the simulation results of the AQoS scheme agree with the analytical results of AQoS for all λ values.

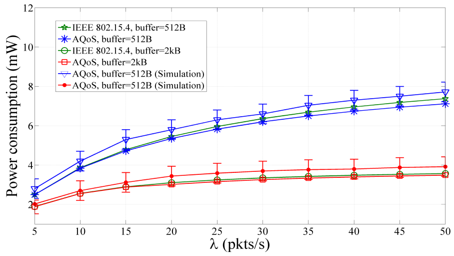

FIGURE 5. **Total power consumed for different MAC buffer values.**

Figure 5 shows the total power consumed in transmitting a packet from the tagged node to the sink versus λ for different MAC buffer sizes when the AQoS and the default IEEE 802.15.4 setting are used (assuming that the tagged node is located in cluster(5)). We show that there is virtually no difference in the power consumption when a node implements the AQoS scheme. We show that the AQoS scheme does not affect the total power consumption as it significantly reduces the end-to-end delay. Simulation results of the AQoS scheme agree with the analytical results for all λ values.

C. AGTS PERFORMANCE EVALUATION

To evaluate the performance of the AGTS scheme, we use the same simulation environment used to evaluate the AQoS scheme. However, we simulate a WSN with mesh topology presented in Figure 1-(b) with various network and traffic conditions to investigate the multipath solution. We simulate a single scenario and compare the AGTS scheme with the AQoS scheme and the default IEEE 802.15.4. We assume that the tagged RFD is located in SPAN(7) and the associated FFD is receiving high priority traffic from the the FFD of SPAN(8) at the same time.

We compare the performance of the AGTS scheme with the AQoS scheme and the default IEEE 802.15.4 setting in the same network scenarios and traffic conditions and observe the improvements to the end-to-end delay reduction when the AGTS is implemented. Figure 6 shows the average end-to-end delay in transmitting a packet from the tagged FFD to the sink for different packet arrival rates. We show that there is a significant delay reduction (compared to the IEEE 802.15.4 protocol and the AQoS scheme) when the AGTS scheme is implemented. We show that the AGTS scheme outperforms the AQoS scheme for high traffic intensities, this is due to the additional time slots that are adaptively granted to the tagged node when it implements the AGTS scheme.

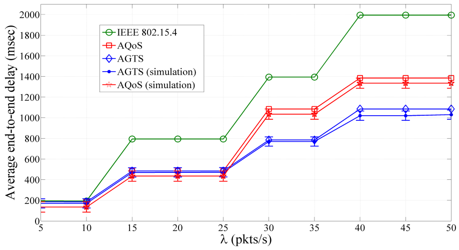

FIGURE 6. **AGTS & AQoS average end-to-end delay.**

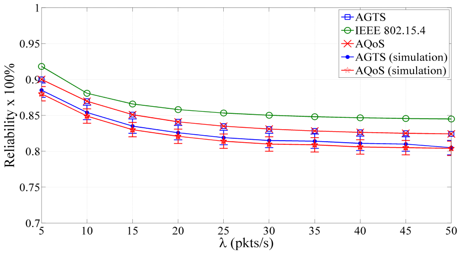

FIGURE 7. **AGTS & AQoS end-to-end reliability.**

Figure 7 shows the reliability in transmitting a packet from the tagged RFD to the sink. Since we assume that FFDs communicate with each other using the CFP then there will be no packets lost due to collision during the communication between FFDs. Therefore, the location of the FFD in the network does not impact the reliability values. We show that there is no noticeable difference in the values of the reliability when a node implements the AGTS scheme compared to the other schemes.

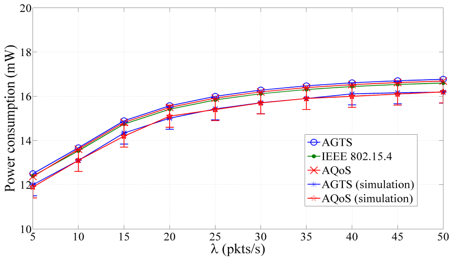

FIGURE 8. **AGTS & AQoS average power consumed.**

Figure 8 shows the average power consumed in transmitting a packet from the tagged RFD to the sink. We show that the difference in the average power consumption between the AGTS scheme and the IEEE 802.15.4 settings is very low there is a slight increase in the average power consumed when the AGTS scheme is implemented. There is a slight increase in the power consumed, this takes place because the tagged RFD and the tagged FFD are transmitting more frequently when AGTS is implement. Furthermore, there is no difference between AGTS and AQoS schemes.

VI. CONCLUSION

In smart grid monitoring applications, occurrence of faults of failures trigger frequent packet generation rates which cannot be handled by the conventional IEEE 802.15.4.

In this paper, we addressed this challenge with adaptive, cross-layer delay reduction schemes for cluster-tree and mesh Wireless Sensor Networks (WSNs). Through analytical and simulation results, we showed that our schemes significantly reduce the end-to-end delay for high traffic intensity event monitoring in the smart grid. The first scheme, namely Adaptive Quality of Service scheme (AQoS) for cluster-tree WSNs could solve the excessive latency by adaptively modifying the Guaranteed Time Slot (GTS) based on requests made from the end devices after probabilistically estimating the WSN operating conditions. We showed that a delay reduction of more than 50% could be achieved when the AQoS scheme is implemented, and at the same time, high reliability and low power consumption values are maintained.

We presented an improvement to AQoS scheme by presenting an Adaptive Guaranteed Time Slot (GTS) allocation scheme (AGTS) that can dynamically tune the time slots according to varying traffic and network conditions in mesh-based WSNs. The AGTS scheme could adaptively grant multiple number of time slots to sensor nodes with high priority data until the minimum delay is achieved. Furthermore, a sensor node can also adaptively surrender the unused time slots to its coordinator when they are not needed. Simulation results showed that the AGTS scheme could reduce the end-to-end delay of high traffic intensity and delay critical data while maintaining acceptable reliability and energy efficiency values.

The delay reduction achieved by implementing the AQoS and the AGTS schemes will enhance the performance of the WSNs in monitoring smart grid environments. The AQoS and AGTS can achieve this QoS differentiation with minimal modifications to the IEEE 802.15.4 MAC protocol.

REFERENCES

[1] I. Bekmezci and F. Alagöz, "Energy efficient, delay sensitive, fault tolerant wireless sensor network for military monitoring," in *Proc. IEEE Sensors Appl. Symp. (SAS)*, Feb. 2008, pp. 172–177.

[2] M. M. Bhuiyan, I. Gondal, and J. Kamruzzaman, "CODAR: Congestion and delay aware routing to detect time critical events in WSNs," in *Proc. Int. Conf. Inf. Netw. (ICOIN)*, Jan. 2011, pp. 357–362.

[3] A. Koubaa, M. Alves, and E. Tovar, "i-GAME: An implicit GTS allocation mechanism in IEEE 802.15.4 for time-sensitive wireless sensor networks," in *Proc. 18th Euromicro Conf. Real-Time Syst.*, Jul. 2006, pp. 188–192.

[4] C. Shanti and A. Sahoo, "DGRAM: A delay guaranteed routing and MAC protocol for wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 9, no. 10, pp. 1407–1423, Oct. 2010.

[5] J. Kim, X. Lin, N. B. Shroff, and P. Sinha, "Minimizing delay and maximizing lifetime for wireless sensor networks with anycast," *IEEE/ACM Trans. Netw.*, vol. 18, no. 2, pp. 515–528, Apr. 2010.

[6] R. Zurawski, *Embedded Systems Handbook: Networked Embedded Systems*. Boca Raton, FL, USA: CRC Press, 2009.

[7] I. Al-Anbagi, M. Erol-Kantarci, and H. T. Mouftah, "A low latency data transmission scheme for smart grid condition monitoring applications," in *Proc. IEEE Elect. Power Energy Conf. (EPEC)*, Oct. 2012, pp. 20–25.

[8] H. Denkilkian *et al.*, "Wireless sensor for continuous real-time oil spill thickness and location measurement," *IEEE Trans. Instrum. Meas.*, vol. 58, no. 12, pp. 4001–4011, Dec. 2009.

[9] A. Depari, A. Flammini, D. Marioli, and A. Taroni, "USB sensor network for industrial applications," *IEEE Trans. Instrum. Meas.*, vol. 57, no. 7, pp. 1344–1349, Jul. 2008.

[10] I. Al-Anbagi, M. Erol-Kantarci, and H. T. Mouftah, "A delay mitigation scheme for WSN-based smart grid substation monitoring," in *Proc. IEEE Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Jul. 2013, pp. 1470–1475.

[11] *International Electrotechnical Commission, High-Voltage Test Techniques—Partial Discharge Measurements*, IEC Standard 60270, 2000.

[12] H. Mota and F. H. Vasconcelos. *Partial Discharge Signal Processing Using Wavelets*. [Online]. Available: http://labplan.ufsc.br/congressos/cba2010/artigos/64852_1.pdf

[13] IEEE Standard 802.15.4-2006.

[14] I. Al-Anbagi, M. Erol-Kantarci, and H. T. Mouftah, "A reliable IEEE 802.15.4 model for cyber physical power grid monitoring systems," *IEEE Trans. Emerg. Topics Comput.*, vol. 1, no. 2, pp. 258–272, Dec. 2013.

[15] J. Deshpande, A. Locke, and M. Madden, "Smart choices for the smart grid: Using wireless broadband for power grid network transformation," in *Proc. Alcatel-Lucent Technol.*, 2010.

[16] A. O. Bicen, O. B. Akan, and V. C. Gungor, "Spectrum-aware and cognitive sensor networks for smart grid applications," *IEEE Commun. Mag.*, vol. 50, no. 5, pp. 158–165, May 2012.

[17] J. Markkula and J. Haapola, "Impact of smart grid traffic peak loads on shared LTE network performance," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2013, pp. 4046–4051.

[18] B. Wang and J. S. Baras, "Minimizing aggregation latency under the physical interference model in wireless sensor networks," in *Proc. IEEE 3rd Int. Conf. Smart Grid Commun. (SmartGridComm)*, Nov. 2012, pp. 19–24.

[19] I. S. Hammoodi, B. Stewart, A. Kocian, S. G. McMeekin, and A. Nesbit, "Wireless sensor networks for partial discharge condition monitoring," in *Proc. 44th IEEE Univ. Power Eng. Conf. (UPEC)*, Sep. 2009, pp. 1–5.

[20] W. Sun, X. Yuan, J. Wang, D. Han, and C. Zhang, "Quality of service networking for smart grid distribution monitoring," in *Proc. 1st IEEE Int. Conf. Smart Grid Commun. (SmartGridComm)*, Oct. 2010, pp. 373–378.

[21] Z. Ruiyi *et al.*, "An adaptive wireless resource allocation scheme with QoS guaranteed in smart grid," in *Proc. IEEE Innov. Smart Grid Technol. (ISGT)*, Washington, DC, USA, Feb. 2013, pp. 1–6.

[22] I. Al-Anbagi, M. Erol-Kantarci, and H. T. Mouftah, "Priority- and delay-aware medium access for wireless sensor networks in the smart grid," *IEEE Syst. J.*, vol. 8, no. 2, pp. 608–618, Jun. 2014.

[23] M.-S. Pan, L.-W. Yeh, Y.-A. Chen, Y.-H. Lin, and Y.-C. Tseng, "A WSN-based intelligent light control system considering user activities and profiles," *IEEE Sensors J.*, vol. 8, no. 10, pp. 1710–1721, Oct. 2008.

[24] N. C. Batista, R. Melício, J. C. O. Matias, and J. P. S. Catalão, "Photovoltaic and wind energy systems monitoring and building/home energy management using ZigBee devices within a smart grid," *Energy*, vol. 49, pp. 306–315, Jan. 2013.

[25] M. Erol-Kantarci and H. T. Mouftah, "Wireless sensor networks for cost-efficient residential energy management in the smart grid," *IEEE Trans. Smart Grid*, vol. 2, no. 2, pp. 314–325, Jun. 2011.

[26] V. C. Gungor, B. Lu, and G. P. Hancke, "Opportunities and challenges of wireless sensor networks in smart grid," *IEEE Trans. Ind. Electron.*, vol. 57, no. 10, pp. 3557–3564, Oct. 2010.

[27] M. Di Francesco, G. Anastasi, M. Conti, S. K. Das, and V. Neri, "Reliability and energy-efficiency in IEEE 802.15.4/ZigBee sensor networks: An adaptive and cross-layer approach," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 8, pp. 1508–1524, Sep. 2011.

[28] V. Jelicic, M. Magno, D. Brunelli, G. Paci, and L. Benini, "Context-adaptive multimodal wireless sensor network for energy-efficient gas monitoring," *IEEE Sensors J.*, vol. 13, no. 1, pp. 328–338, Jan. 2013.

[29] Y. Wang, M. C. Vuran, and S. Goddard, "Cross-layer analysis of the end-to-end delay distribution in wireless sensor networks," *IEEE/ACM Trans. Netw.*, vol. 20, no. 1, pp. 305–318, Feb. 2012.

[30] Z. D. Shakir, K. Yoshigoe, and R. B. Lenin, "Adaptive buffering scheme to reduce packet loss on densely connected WSN with mobile sink," in *Proc. IEEE Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2012, pp. 439–444.

[31] I. Al-Anbagi, M. Erol-Kantarci, and H. T. Mouftah, "An adaptive QoS scheme for WSN-based smart grid monitoring," in *Proc. 3rd IEEE Int. Conf. Commun. Workshops (ICC)*, Jun. 2013, pp. 1046–1051.

[32] E. Toscano and L. Lo Bello, "A multichannel approach to avoid beacon collisions in IEEE 802.15.4 cluster-tree industrial networks," in *Proc. IEEE Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2009, pp. 1–9.

[33] C. Zhu, S. Wu, G. Han, L. Shu, and H. Wu, "A tree-cluster-based data-gathering algorithm for industrial WSNs with a mobile sink," *IEEE Access*, vol. 3, pp. 381–396, May 2015.

[34] J. Kim, X. Lin, and N. B. Shroff, "Optimal anycast technique for delay-sensitive energy-constrained asynchronous sensor networks," *IEEE/ACM Trans. Netw.*, vol. 19, no. 2, pp. 484–497, Apr. 2011.
[35] I. Rhee, A. Warrier, M. Aia, J. Min, and M. L. Sichitiu, "Z-MAC: A hybrid MAC for wireless sensor networks," *IEEE/ACM Trans. Netw.*, vol. 16, no. 3, pp. 511–524, Jun. 2008.
[36] IEEE Standard 802.15. [Online]. Available: http://www.ieee802.org/15/pub/TG4b.html
[37] A. Koubaa, A. Cunha, and M. Alves, "A time division beacon scheduling mechanism for IEEE 802.15.4/Zigbee cluster-tree wireless sensor networks," in *Proc. 19th Euromicro Conf. Real-Time Syst. (ECRTS)*, Jul. 2007, pp. 125–135.
[38] W. Liu, D. Zhao, and G. Zhu, "End-to-end delay and packet drop rate performance for a wireless sensor network with a cluster-tree topology," *Wireless Commun. Mobile Comput.*, vol. 14, no. 7, pp. 729–744, May 2014.
[39] P. Park, P. Di Marco, P. Soldati, C. Fischione, and K. H. Johansson, "A generalized Markov chain model for effective analysis of slotted IEEE 802.15.4," in *Proc. IEEE 6th Int. Conf. Mobile Adhoc Sensor Syst. (MASS)*, Oct. 2009, pp. 130–139.
[40] *QualNet Network Simulator*. [Online]. Available: http://www.scalable-networks.com/content/

IRFAN AL-ANBAGI received the Ph.D. degree in electrical and computer engineering from the University of Ottawa, in 2013. He was a Senior Lecturer and a Program Leader with the Caledonian (University) College of Engineering, Oman, from 2002 to 2010. He was also the Honours Project coordinator, Research Committee Member, and Student Mentor. From 2007 to 2010, he was a Visiting Researcher with the School of Engineering and Built Environment, Glasgow Caledonian University, U.K. He designed and developed a wireless sensor networks (WSN)-based partial discharge monitoring system for high-voltage transformers in the smart grid. He is currently a Post-Doctoral Fellow and the Product Development Manager of SecCharge Project with the School of Electrical Engineering and Computer Science, University of Ottawa. His current research interests include embed networked systems, WSN, cyber-physical systems, smart grids, vehicle-to-grid systems, intelligent transportation systems and quality of service in wireless networks. He is also the Co-Chair of the IEEE Ottawa Section Membership Development and the Co-Chair of the Reliability Society in the IEEE Ottawa Section.

MELIKE EROL-KANTARCI received the B.Sc. degree from the Department of Control and Computer Engineering, Istanbul Technical University, in 2001, and the M.Sc. and Ph.D. degrees in computer engineering from Istanbul Technical University, in 2009 and 2004, respectively. During her Ph.D. studies, she was a Fulbright Visiting Researcher with the Computer Science Department, University of California at Los Angeles. She was the Coordinator of the Smart Grid Communications Laboratory and a Post-Doctoral Fellow with the School of Electrical Engineering and Computer Science, University of Ottawa, Canada. She is currently an Assistant Professor with the Department of Electrical and Computer Engineering, Clarkson University, Potsdam, NY. She has co-authored the book *Wireless Sensor Networks for Cost-Efficient Residential Energy Management in the Smart Grid* which is selected to the IEEE ComSoc Best Readings on Smart Grid Communications. Her main research interests are wireless sensor networks, smart grid, cyber-physical systems, electrification of transportation, underwater sensor networks, mobility modeling, localization, and Internet traffic analysis. She received a Fulbright Ph.D. Research Scholarship (2006) and the Siemens Excellence Award (2004), and she has won two Outstanding/Best Paper Awards. She is an Occasional Reviewer of transactions and journals, and a TPC Member of various conferences. She is an editor of the *International Journal of Distributed Sensor Networks* published by Hindawi and the IEEE Multimedia Communications Technical Committee E-letter. She was the Chair of Women in Engineering at the IEEE Ottawa Section. She is currently the Vice Chair of Green Smart Grid Communications special interest group of IEEE Technical Committee on Green Communications and Computing.

HUSSEIN T. MOUFTAH (F'90) is currently a Distinguished University Professor and the Tier 1 Canada Research Chair of Wireless Sensor Networks with the School of Electrical Engineering and Computer Science, University of Ottawa, Canada. He has been with the ECE Dept, Queen's University (1979-2002), where he was prior to his departure a Full Professor and the Department Associate Head. He has authored or co-authored ten books, 65 book chapters, and more than 1400 technical papers, 14 patents, and 143 industrial reports. He has six years of industrial experience mainly at Bell Northern Research of Ottawa (then known as Nortel Networks). He served as the Editor-in-Chief of the *IEEE Communications Magazine* (1995-97) and the *IEEE ComSoc Director of Magazines* (1998-99), the Chair of the Awards Committee (2002-03), the Director of Education (2006-07), and a member of the Board of Governors (1997-99 and 2006-07). He has been a Distinguished Speaker of the IEEE Communications Society (2000-2008). He is the joint holder of 19 Best Paper and/or Outstanding Paper Awards. He has received numerous prestigious awards, such as the EIC 2014 K. Y. Lo Medal, the 2007 Royal Society of Canada Thomas W. Eadie Medal, the 2007-2008 University of Ottawa Award for Excellence in Research, the 2008 ORION Leadership Award of Merit, the 2006 IEEE Canada McNaughton Gold Medal, the 2006 EIC Julian Smith Medal, the 2004 IEEE ComSoc Edwin Howard Armstrong Achievement Award, the 2004 George S. Glinski Award for Excellence in Research of the U of O Faculty of Engineering, the 1989 Engineering Medal for Research and Development of the Association of Professional Engineers of Ontario (PEO), and the Ontario Distinguished Researcher Award of the Ontario Innovation Trust. He is a fellow of the Canadian Academy of Engineering (2003), the Engineering Institute of Canada (2005), and the Royal Society of Canada RSC Academy of Science (2008).

• • •