Journal of Network and Computer Applications 71 (2016) 50–58

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

journal homepage: www.elsevier.com/locate/jnca

Channel-aware routing and priority-aware multi-channel scheduling for WSN-based smart grid applications

Melike Yigit [a,*], V. Cagri Gungor [b], Etimad Fadel [c], Laila Nassef [c,d], Nadine Akkari [c], Ian F. Akyildiz [c,e]

[a] Department of Computer Engineering, Bahcesehir University, Istanbul, Turkey
[b] Department of Computer Engineering, Abdullah Gul University, Kayseri, Turkey
[c] Department of Computer Science, King Abdulaziz University, Jeddah, Saudi Arabia
[d] Department of Computer Sciences and Information, Institute of Statistical Studies and Research, Cairo University, Giza, Egypt
[e] Broadband Wireless Networking Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

ARTICLE INFO

Article history:
Received 10 September 2015
Received in revised form
24 May 2016
Accepted 25 May 2016
Available online 4 June 2016

Keywords:
Smart grid
Data prioritization
Multi-channel scheduling
Routing

ABSTRACT

Wireless Sensor Networks (WSNs) are one of the most promising solutions for smart grid applications due to advantages, such as their low-cost, different functionalities, and successful adoption to smart grid environments. However, providing quality of service (QoS) requirements of smart grid applications with WSNs is difficult because of the power constraints of sensor nodes and harsh smart grid channel conditions, such as RF interference, noise, multi-path fading and node contentions. To address these communication challenges, in this paper link-quality-aware routing algorithm (LQ-CMST) as well as the priority and channel-aware multi-channel (PCA-MC) scheduling algorithm have been proposed for smart grid applications. Furthermore, the effect of different modulation and encoding schemes on the performance of the proposed algorithms has been evaluated under harsh smart grid channel conditions. Comparative performance evaluations through extensive simulations show that the proposed algorithms significantly reduce communication delay and the choice of encoding and modulation schemes is critical to meet the requirements of envisioned smart grid applications.

1. Introduction

The smart grid, the modernization of the power grid, utilizes advanced electrical power components, information and communication technologies to collect and process the power grid's operational information (Shah et al., 2013). Smart grids provide bidirectional communications and use advanced control capabilities to generate, distribute and consume the electricity more efficiently, unlike the existing power grid (Saputro et al., 2012). Reliable and timely data transmission from suppliers to consumers is critical in smart grid applications. To this end, wireless sensor networks (WSNs) are one of the most promising communication solutions that can meet the delay and reliability requirements of smart grid applications. However, recent field tests show that the smart grid infrastructure has harsh and complex environmental conditions, noise, interference, connectivity and multi-path fading problems during low-power wireless communications (Gungor et al., 2010). In these field tests, the average noise level was measured as −93 dBm in outdoor 500 kV substation environment. Note that this noise level is much higher than that of outdoor noise levels, which is measured as −105 dBm. In addition, smart grid has some specific system challenges (Bari et al., 2014). One such challenge is interoperability, since the smart grid is a large-scale system in which there are many interconnected power components, generating an enormous amount of data to be transmitted and analyzed. Therefore, interoperability issues need to be investigated while developing new protocols and standards. The second challenge of the smart grid is the security, which is required to realize remote power management in the smart grid. Since energy is a valuable resource, providing security against malicious activities is an important concern in smart grid. The third challenge of the smart grid is optimization and control of the grid. Analyzing the data collected by sensors and controlling the peak loads are difficult for the smart grid. Therefore, optimization algorithms are needed to optimize the power grid's operation.

Furthermore, network traffic loads and data types exchanged in

---

[*] Corresponding author.

E-mail addresses: melike.yigit@stu.bahcesehir.edu.tr (M. Yigit), cagri.gungor@agu.edu.tr (V.C. Gungor), eafadel@kau.edu.sa (E. Fadel), lmohamed@kau.edu.sa (L. Nassef), nakkari@kau.edu.sa (N. Akkari), ian@ece.gatech.edu (I.F. Akyildiz).

http://dx.doi.org/10.1016/j.jnca.2016.05.015
1084-8045/

the smart grid communication infrastructure keep changing and increase exponentially. Collected smart grid data are usually time-critical. However, conventional communication techniques only provide a best-effort service and do not guarantee quality-of-service (QoS) (Yaghmaee et al., 2013). Therefore, the smart grid requires a reliable and efficient communication framework to provide QoS requirements of the envisioned smart grid applications. Moreover, the different types of traffic need to be prioritized based on application-specific delay requirements. Importantly, to improve network performance in smart grid environments, multi-channel communication can be utilized to overcome the impact of RF interference and achieve simultaneous transmissions over multiple channels. With the parallel transmissions, network performance can be improved in terms of delay. Note that although the effect of RF interference might be mitigated with multi-channel communications, recent studies show that network capacity of sensor networks is also constrained by network topology (Yigit et al., 2014; Incel et al., 2012). Hence, it is imperative to construct reliable routing topologies in such environments to take advantage of multi-channel communications.

In the related literature, there have been some QoS-aware communication protocols proposed for wireless sensor networks as shown in Table 1. However, none of these protocols does not meet the application-specific smart grid requirements. To address these challenges, in this paper, link-quality-aware routing algorithm (Link-Quality-Aware Capacitated Minimum Hop Spanning Tree (LQ-CMST)) as well as the priority and channel-aware multi-channel (PCA-MC) scheduling algorithm have been proposed for smart grid applications. Performance evaluations through extensive simulations show that the proposed algorithms significantly reduce communication delay in smart grid environments. Overall, our main contribution is to investigate the performance of multi-channel WSNs for smart grid and to quantify how priority and channel-aware communication will perform under different network traffic loads and the harsh smart grid channel conditions. We expect that the proposed algorithms and performance evaluations shown in this paper will provide valuable understanding of multi-channel scheduling and topology construction for WSNs in harsh smart grid environments. We also expect that the proposed routing and scheduling algorithms are applicable for other applications, such as smart cities, health-care applications and industrial WSNs.

The remainder of the paper is organized as follows. The network model and the proposed algorithms are explained in Section 2. Application scenarios and simulation models are introduced in Section 3. In Section 4, performance evaluations are discussed. Finally, the paper is concluded in Section 5.

Table 1
Comparison of existing QoS-aware routing algorithms for WSNs.

Protocol	Delay	Throughput	Reliability
RTLD (Ahmed and Fisal, 2008)	No	Yes	Yes
Energy-aware QoS routing algorithm (Akkaya and Younis, 2005)	Yes	Yes	Yes
SPEED (He et al., 2003)	Yes	No	No
MMSPEED (Felemban et al., 2006)	Yes	Yes	Yes
RRR (Gelenbe and Ngai, 2008)	Yes	Yes	Yes
OQAP (Lee and Younis,)	No	No	No
MRL-CC (Liang et al., 2010)	No	No	No
DARA (Razzaque et al., 2008)	Yes	No	Yes
OMCR (Li and Zhang, 2010)	Yes	No	No

2. Network model and proposed algorithms

In this study, the Log-Normal Shadowing model is used to model the real channel conditions in smart grid environments. In the related literature, it has been shown that this model is used to model radio propagation environments with obstructions, e.g., smart grid environments (Gungor et al., 2010). The parameters of this model are shown in Table 2. In this model, the path loss at a distance d from the transmitter is given by Gungor et al. (2010) and Yigit et al. (2014):

$$PL_{d_0 \to d} = PL(d_0) + 10\eta \ \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \tag{1}$$

where

- $PL_{d_0 \to d}$ is the path loss in dBm at a distance d from the transmitter,
- $PL(d_0)$ is the path loss at a reference distance d_0,
- η is the path loss exponent, and
- X_σ is a zero mean Gaussian random variable with standard deviation (σ).

Furthermore, the Modified Receiver-Based Channel Assignment (RBCA) algorithm (Incel et al., 2012) is used as a multi-channel MAC protocol. The main motivation of using the RBCA algorithm is that it performs well for WSNs, since it assigns channels statistically to the nodes while considering RF interference. Specifically, the RBCA algorithm schedules the transmissions over multiple branches of the routing tree and uses a TDMA time slot assignment algorithm to avoid packet collisions. In this paper, we also make some modifications to the RBCA's time slot assignment algorithm and scheduled the transmissions in parallel throughout multiple branches while considering data prioritization. Here, it is important to note that although the effect of interference might be mitigated with multi-channel communications, recent studies show that network capacity of sensor networks is also constrained by network topology (Yigit et al., 2014; Incel et al., 2012). Hence, it is imperative to construct reliable routing topologies in smart grid environments to take advantage of multi-channel communications. To address this challenge, in this study the link-quality-aware routing algorithm (Link-Quality-Aware Capacitated Minimum Hop Spanning Tree (LQ-CMST)) has been proposed. In this algorithm, variable link qualities are considered while constructing the network tree, whose root is the sink node. Specifically, the LQ-CMST algorithm obtains a minimum-hop spanning tree in the network so that the cost of each subtree connected to the sink node does not exceed a predefined capacity. The LQ-CMST algorithm is based on the greedy scheme (Yigit et al., 2014; Incel et al., 2012), in which constructed subtrees are connected to the sink node, if the link-quality of the routing tree exceeds a predefined threshold. In addition, to achieve further performance improvement, the priority and channel-aware multi-channel (PCA-MC) scheduling algorithm has been proposed. In Fig. 1, the flow chart of the proposed PCA-MC scheduling algorithm has been shown. The proposed scheduling algorithm is based on the calculation of the minimum schedule lengths by using a TDMA-based multi-channel

Table 2
Log-Normal Shadowing channel parameters of smart grid environments (Gungor et al., 2010).

Propagation environment:	500 kv Substation Line-of-Sight (LOS)
Path loss (η):	2.42
Shadowing deviation (X_σ):	3.12

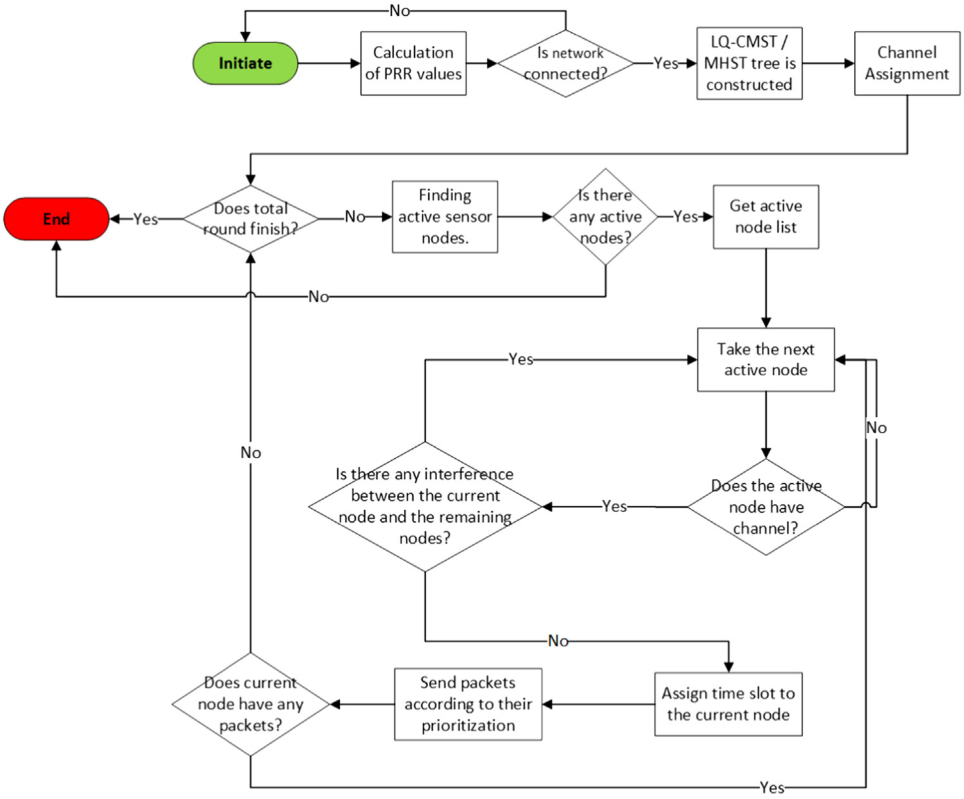
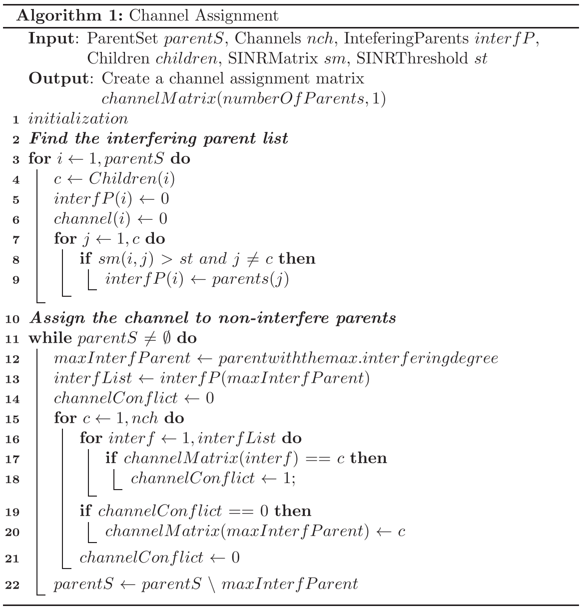


Fig. 1. Flow chart of the proposed priority and channel-aware multi-channel (PCA-MC) scheduling algorithm.

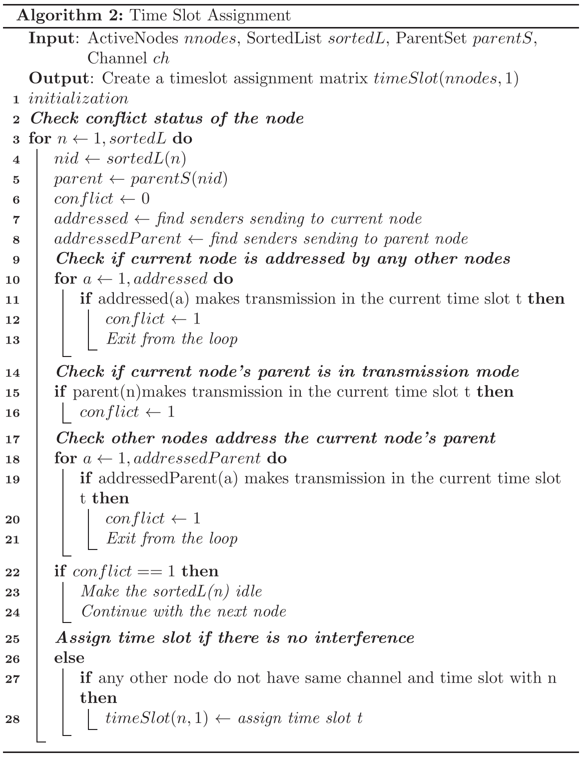
scheduling algorithm. Specifically, after constructing the routing tree, the channel assignment is made by considering RF interference between the nodes. In other words, if the Signal to Interference Noise Ratio (SINR) value between the nodes exceeds the predefined threshold, the same channel can be assigned to these nodes. Otherwise, the same channel cannot be assigned to these nodes. Moreover, the Modified Receiver Based Channel Assignment (RBCA) algorithm is used for assigning a minimum number of frequencies to the receivers. The RBCA algorithm is preferred in this study because according to Incel et al. (2012), if the transmissions are scheduled on different channels, the effects of interference can be mitigated. As illustrated in Algorithm 1, interfering links are found based on the SINR values of the nodes. Specifically, if there is an available channel, the parent, which has maximum interfering degree, has been assigned a channel. If no available channel exists, the parent node is marked as the interfering node, which is resolved in the time slot assignment phase. As a result, Algorithm 1 iteratively assigns the channels to the parent nodes and gives the channel assignment matrix as an output. Furthermore, time slot assignment is done after the channels are assigned to the parent nodes. To this end, Algorithm 3 takes active nodes with packets in transmission mode and creates a list, including the nodes that are sorted in ascending order according to their distance to the sink node, and the parent is set as an input. It also gives an output list of time slots assigned to the nodes. Here, this algorithm first controls the existence of the conflict in the same time slot by considering three cases: Conflict occurs (1) if the current node is addressed by any other nodes, (2) if the parent of current node makes transmission, (3) if the other nodes send packets to the current node's parent. Furthermore, Algorithm 3 also checks channels of other nodes and if the same time slot and channel are used by the other nodes, the time slot is assigned to current active node. Otherwise, the time slot cannot be assigned to the node. This process continues until the nodes in the sorted list finish.

Algorithm 1. Channel assignment.



```
Algorithm 1: Channel Assignment
Input: ParentSet $parentS$, Channels $nch$, InteferingParents $interfP$,
       Children $children$, SINRMatrix $sm$, SINRThreshold $st$
Output: Create a channel assignment matrix
        $channelMatrix(numberOfParents, 1)$
initialization
Find the interfering parent list
for $i \leftarrow 1, parentS$ do
    $c \leftarrow Children(i)$
    $interfP(i) \leftarrow 0$
    $channel(i) \leftarrow 0$
    for $j \leftarrow 1, c$ do
        if $sm(i,j) > st$ and $j \neq c$ then
            $interfP(i) \leftarrow parents(j)$

Assign the channel to non-interfere parents
while $parentS \neq \emptyset$ do
    $maxInterfParent \leftarrow parentwiththemax.interferingdegree$
    $interfList \leftarrow interfP(maxInterfParent)$
    $channelConflict \leftarrow 0$
    for $c \leftarrow 1, nch$ do
        for $interf \leftarrow 1, interfList$ do
            if $channelMatrix(interf) == c$ then
                $channelConflict \leftarrow 1;$

        if $channelConflict == 0$ then
            $channelMatrix(maxInterfParent) \leftarrow c$

        $channelConflict \leftarrow 0$

    $parentS \leftarrow parentS \setminus maxInterfParent$
```

Algorithm 2. Time slot assignment.



```
Algorithm 2: Time Slot Assignment
  Input: ActiveNodes $nnodes$, SortedList $sortedL$, ParentSet $parentS$,
         Channel $ch$
  Output: Create a timeslot assignment matrix $timeSlot(nnodes, 1)$
  initialization
  Check conflict status of the node
  for $n \leftarrow 1, sortedL$ do
      $nid \leftarrow sortedL(n)$
      $parent \leftarrow parentS(nid)$
      $conflict \leftarrow 0$
      $addressed \leftarrow$ find senders sending to current node
      $addressedParent \leftarrow$ find senders sending to parent node
      Check if current node is addressed by any other nodes
      for $a \leftarrow 1, addressed$ do
          if addressed(a) makes transmission in the current time slot t then
              $conflict \leftarrow 1$
              Exit from the loop
      Check if current node's parent is in transmission mode
      if parent(n)makes transmission in the current time slot t then
          $conflict \leftarrow 1$
      Check other nodes address the current node's parent
      for $a \leftarrow 1, addressedParent$ do
          if addressedParent(a) makes transmission in the current time slot
          t then
              $conflict \leftarrow 1$
              Exit from the loop
      if $conflict == 1$ then
          Make the $sortedL(n)$ idle
          Continue with the next node
      Assign time slot if there is no interference
      else
          if any other node do not have same channel and time slot with n
          then
              $timeSlot(n, 1) \leftarrow$ assign time slot t
```

2.1. Data collection model

In this section, we introduce our delay-aware data collection model used in our performance evaluations. This model realizes service differentiation and sends the packets according to their traffic classes as shown in Table 3. Delay-sensitive packets, such as emergency response packets, are marked with high priority, non-real time packets, including periodic control packets, are marked with medium priority and the remaining packets are marked with low priority. Although multiple priority assignments can be done, we only consider three priority assignments, such as real-time (RT), non-real-time (NRT) or best effort (BE) traffic, for simplicity. Specifically, Algorithm 3 takes the parent set, active nodes, Packet Reception Rate (PRR) values of the nodes, total round and hop count as an input and gives delays of RT, NRT and BE traffic as an output. Based on this algorithm, if the transmission of the RT packets is finished, the NRT and BE packets are sent, respectively. When the sink node receives the packets, the number of delivered packets is increased and the packet transmission time is set for all packet types. Otherwise, the number of packets of the parent node is increased and the number of packets of the active node is decreased. This process continues until the total round ends. In this way, the RT packets are transmitted more rapidly than other types of packets and delay-aware data transmission is achieved by using service prioritization. Also note that there are some studies about weighted fair scheduling schemes (Huang and Bi, 2015; Rezaee et al., 2013; Monowar et al., 2008). These studies propose different scheduling algorithms to provide network fairness. On the other hand, the main objective of this study is to prioritize emergency situations requiring delay-sensitive communication in smart grid environments and then allocate the rest of network capacity for the NRT and BE traffic. Therefore, fairness is the second priority for our study. Future work includes integrating the proposed protocol with weighted fair scheduling schemes to achieve fairness in different smart grid application scenarios.

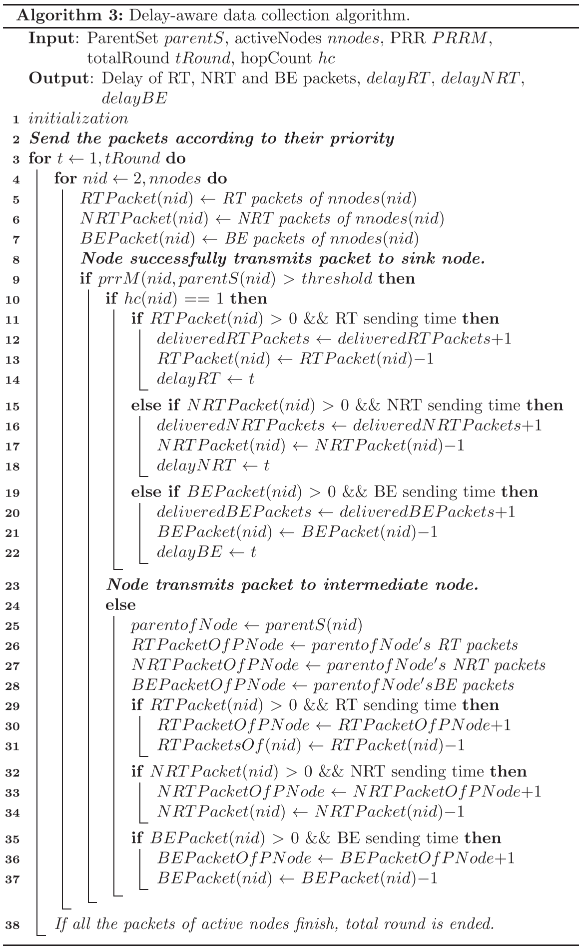
Table 3
Applied traffic loads.

Types	RT (Pkt/s)	NRT & BE (Pkt/s)	Average created traffic (Pkt/s)
Low traffic load – Type I	2	12	260
High traffic load – Type II	12	2	1560

Table 4
Simulation parameters.

Number of nodes	120
Size of the topology	200×200 m^2
Radio propagation model	Log-Normal Shadowing Model
Algorithms	LQ-CMST, PCA-MC
Distance between the nodes	Randomly distributed
Modulation	Non-Coherent Frequency Shift Keying (NCFSK)
Encoding	Manchester
Output power	4.0 dBm
Noise floor	-93.0 dBm
Topology	Random

Algorithm 3. Delay-aware data collection algorithm.



```
Algorithm 3: Delay-aware data collection algorithm.
  Input: ParentSet $parentS$, activeNodes $nnodes$, PRR $PRRM$,
         totalRound $tRound$, hopCount $hc$
  Output: Delay of RT, NRT and BE packets, $delayRT$, $delayNRT$,
          $delayBE$
  initialization
  Send the packets according to their priority
  for $t \leftarrow 1, tRound$ do
      for $nid \leftarrow 2, nnodes$ do
          $RTPacket(nid) \leftarrow$ RT packets of $nnodes(nid)$
          $NRTPacket(nid) \leftarrow$ NRT packets of $nnodes(nid)$
          $BEPacket(nid) \leftarrow$ BE packets of $nnodes(nid)$
          Node successfully transmits packet to sink node.
          if $prrM(nid, parentS(nid) > threshold$ then
              if $hc(nid) == 1$ then
                  if $RTPacket(nid) > 0$ && RT sending time then
                      $deliveredRTPackets \leftarrow deliveredRTPackets{+}1$
                      $RTPacket(nid) \leftarrow RTPacket(nid){-}1$
                      $delayRT \leftarrow t$
                  else if $NRTPacket(nid) > 0$ && NRT sending time then
                      $deliveredNRTPackets \leftarrow deliveredNRTPackets{+}1$
                      $NRTPacket(nid) \leftarrow NRTPacket(nid){-}1$
                      $delayNRT \leftarrow t$
                  else if $BEPacket(nid) > 0$ && BE sending time then
                      $deliveredBEPackets \leftarrow deliveredBEPackets{+}1$
                      $BEPacket(nid) \leftarrow BEPacket(nid){-}1$
                      $delayBE \leftarrow t$
              Node transmits packet to intermediate node.
              else
                  $parentofNode \leftarrow parentS(nid)$
                  $RTPacketOfPNode \leftarrow parentofNode's$ RT packets
                  $NRTPacketOfPNode \leftarrow parentofNode's$ NRT packets
                  $BEPacketOfPNode \leftarrow parentofNode'sBE$ packets
                  if $RTPacket(nid) > 0$ && RT sending time then
                      $RTPacketOfPNode \leftarrow RTPacketOfPNode{+}1$
                      $RTPacketsOf(nid) \leftarrow RTPacket(nid){-}1$
                  if $NRTPacket(nid) > 0$ && NRT sending time then
                      $NRTPacketOfPNode \leftarrow NRTPacketOfPNode{+}1$
                      $NRTPacket(nid) \leftarrow NRTPacket(nid){-}1$
                  if $BEPacket(nid) > 0$ && BE sending time then
                      $BEPacketOfPNode \leftarrow BEPacketOfPNode{+}1$
                      $BEPacket(nid) \leftarrow BEPacket(nid){-}1$
      If all the packets of active nodes finish, total round is ended.
```

Table 5
The parameters and notations.

	Parameter	Description	Values
Radio	SNR	Signal to noise ratio	$\psi = 10^{(rssi(i,j) - noise\ \ floor(j))/10)}$
	$Q(\cdot)$	Standard Gaussian error function	$Q(x) = 0.5 * erfc\left(\frac{x}{\sqrt{2}}\right), erfc(x) = \frac{2}{\pi}\int_x^{\infty} e^{-t^2} d_t$
	Eb/No	The energy per bit to noise power spectral density ratio	$Eb/No = \psi \frac{B_N}{R}$
	Modulation scheme	FSK	$P_b^{FSK} = Q(\sqrt{(Eb/No)})$
		ASK	$P_b^{ASK} = Q(\sqrt{((Eb/No)/2)})$
		O-QPSK	$P_b^{OQPSK} = Q(\sqrt{((Eb/No)_{DS})}),\ (Eb/No)_{DS} = \frac{(2N \times Eb/No)}{(N + 4Eb/No(K-1)/3)}$
	Encoding scheme	NRZ	$PRR_{nrz} = ((1 - Pb)^{8*pL}) * ((1 - Pb))^{8*(fL - pL)}\Big)$
		SECDED	$PRR_{secded} = ((1 - Pb)^{8*pL} * (1 - Pb)^{8}) + (8 * Pb * ((1 - Pb))^{7})\Big)\Big)^{(fL - pL)*3)}$
	P_t	Output power	4 dB
	P_n	Noise floor	−93 dB
	fL	Frame size	400 Bits
	pL	Preamble length	16 Bits
	B_N	Noise bandwidth of Mica 2's transceiver chip	30 kHz
	R	Data rate of Mica2	19.2 kbps
	N	No of chips per bit	16 chips/bit
Topology	*#nodes*	Number of nodes	120
	D_X	Terrain dimension: *X*	200 m
	D_Y	Terrain dimension: *Y*	200 m
	Topology	Topology	Random topology

3. Simulation model

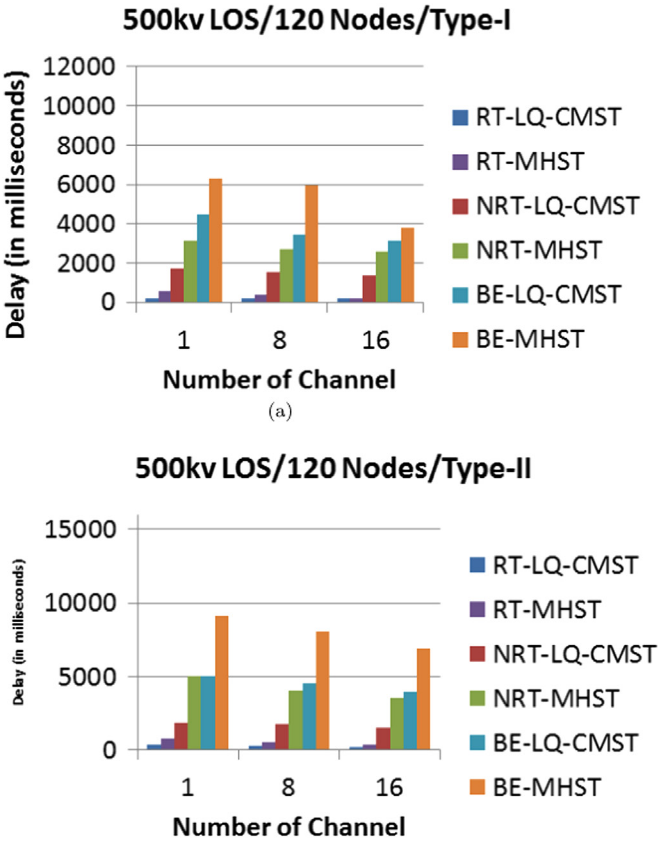
3.1. Application scenario

In general, smart grid applications, including emergency response, periodic power grid monitoring, and wireless meter reading, have different communication delay requirements. For instance, emergency response is one of the time-critical smart grid applications to predict the problems in the power grid before they occur. To this end, the operational power grid problems can be minimized through timely transmission of emergency packets. Therefore, we classify and prioritize data packets into three classes based on their delay requirements. To this end, emergency packets (named as real-time (RT) traffic) will be given the highest priority. The packets, including the temperature, pressure, consumption statistics, are given the second priority (named as non-real time (NRT)). The third class is the control packets (named as best effort (BE)). In this study, three main scenarios are considered by classifying traffic flows based on their priority:

- In the first scenario, traffic flows are classified based on their priority and multi-channel scheduling that is employed.
- In the second scenario, all traffic has been treated in a best-effort manner and all the packets are transmitted without any prioritization.
- In the third scenario, performance evaluations have been conducted under low and high network traffic loads.

3.2. Simulation parameters of the experiments

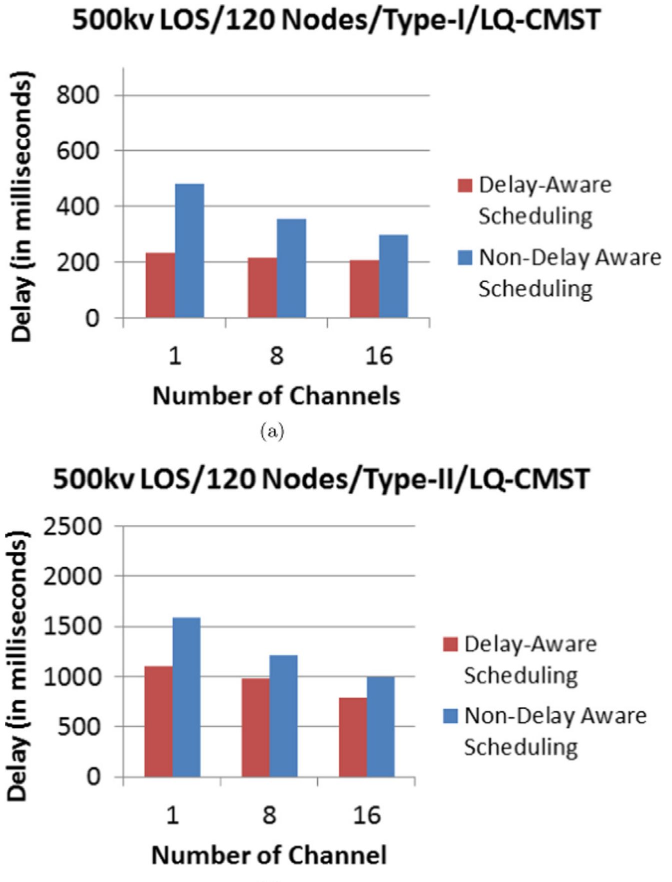
In this paper, to evaluate the proposed approaches, the MATLAB-based network simulator has been used. Simulations have



(a)

(b)

Fig. 2. Comparison of average delay of the two routing algorithms when number of channel increases in 500 kv Substation Smart Grid Environment. (a) Low traffic load, (b) high traffic load.



(a)

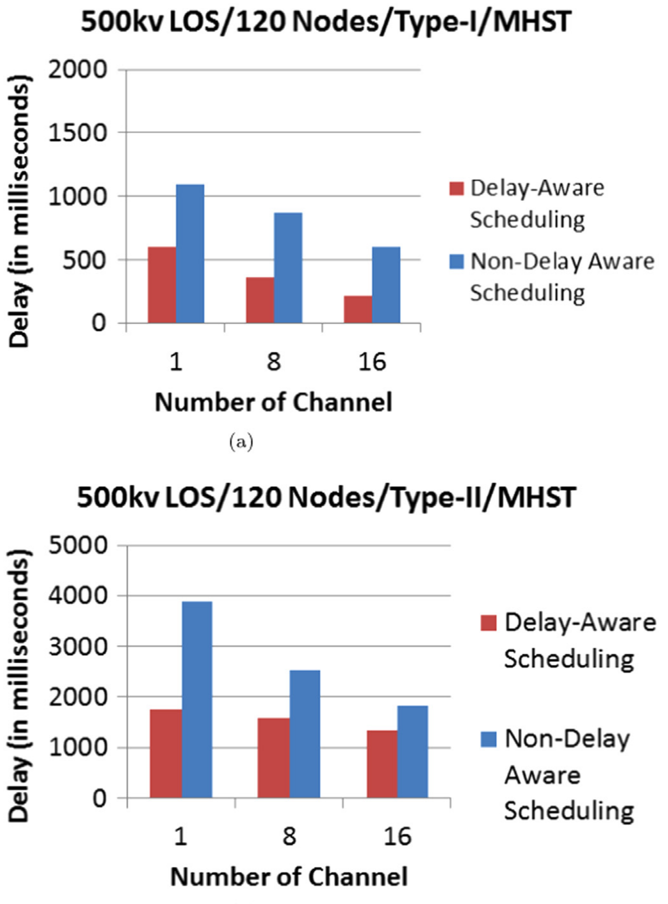
(b)

Fig. 3. Average delay of LQ-CMST routing algorithm with and without prioritization by increasing number of channel in 500 kv Substation Smart Grid Environment. (a) Low traffic load, (b) high traffic load.

been performed 100 times with different seeds. We have a $200 \times 200\ \text{m}^2$ deployment area and a single sink node for gathering information. The number of nodes in the network is 120 unless otherwise is specified. Different numbers of channels, including 1, 8 and 16 channels, have been studied to evaluate the performance of the proposed algorithms. The Log-Normal Shadowing propagation model is also used to realize the real channel conditions in our simulations by using the smart grid path loss and shadowing deviation parameters shown in Table 2. Low and high network traffic loads presented in Table 3 are offered to the network to assess the delay performance of the proposed protocols (Yigitel et al., 2011). All the simulation parameters used in this paper are shown in Table 4.

4. Performance evaluations

The radio parameters, modulation and encoding schemes used in our performance evaluations are listed in Table 5. Note that comparative performance evaluations of the proposed protocols have been conducted based on smart grid channel parameters and modulation and encoding schemes of the existing wireless sensor network platforms. To better evaluate the advantages of the proposed LQ-CMST algorithm, the proposed routing algorithm has been compared to the Minimum Hop Spanning Tree (MHST) algorithm (Incel et al., 2012). Specifically, the MHST algorithm aims to reduce the number of hops to transmit data packets towards the sink and constructs the minimum hop spanning trees in the network.



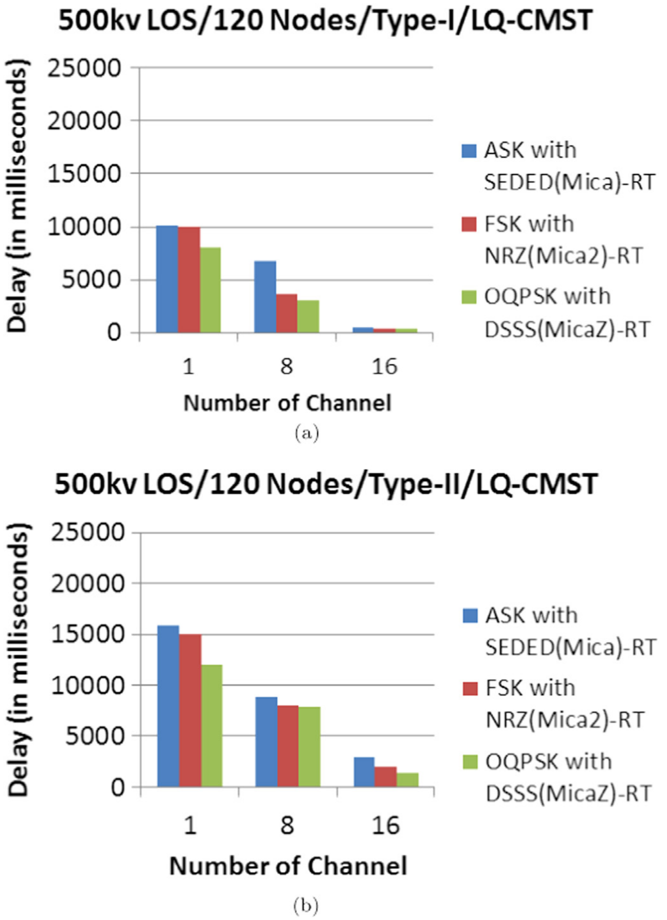
(a)

(b)

Fig. 4. Average delay of MHST routing algorithm with and without prioritization by increasing number of channel in 500 kv Substation Smart Grid Environment. (a) Low traffic load, (b) high traffic load.

4.1. *Analyzing the effect of number of channels on delay performance*

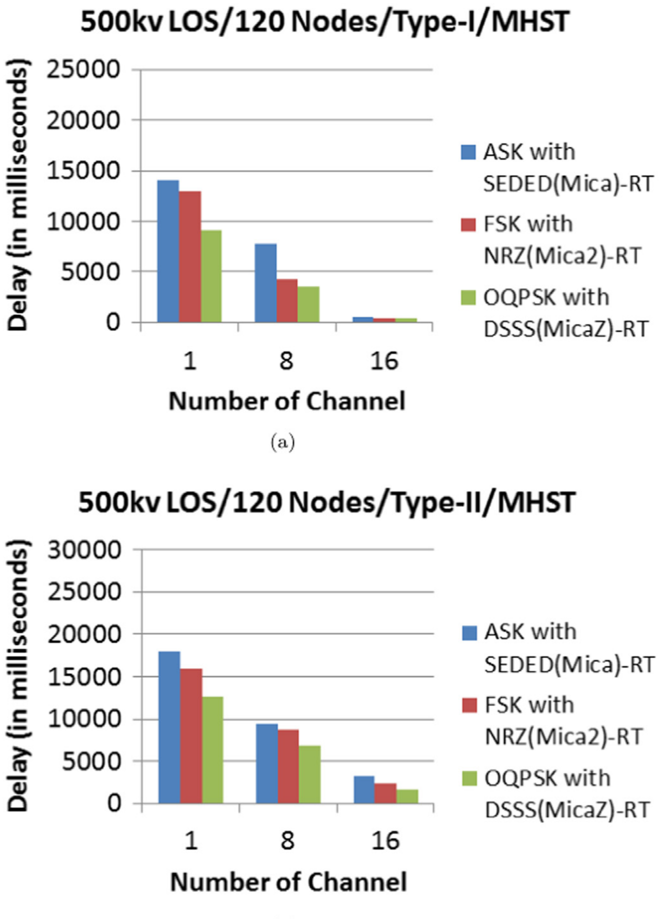
In the first scenario, there are three packet types, real-time (RT), non-real-time (NRT) or best effort (BE) traffic, and different numbers of channels and traffic loads. Fig. 2 shows the average latency when the LQ-CMST and the MHST routing algorithms are used. In this figure, we have observed that the LQ-CMST routing algorithm decreases the average latency of all traffic classes, i.e., the RT, NRT and BE traffics, compared to the MHST routing algorithm. This is because it considers real channel conditions and link-quality variations, while constructing the data paths. Although the LQ-CMST algorithm leads to lower communication delay compared to the MHST algorithm, both the routing algorithms have the same service differentiation mechanism that guarantees that high priority channels, carrying the RT traffic, are preferred compared to the lower priority channels, carrying NRT and BE flows. In order to study the performance of the proposed routing algorithm under different traffic loads, we also run the simulations by congesting the network with more RT data packets. As shown in Fig. 2b, while the number of RT packets increases, the LQ-CMST and MHST algorithms still provide delay requirements of the RT class, since it has the highest priority. Hence, communication delay of the NRT and BE packets increases. However, such increases are not important, since they do not include time-critical packets. Fig. 2 also demonstrates that the communication delay increases with large numbers of contenders. This is because when large numbers of nodes want to access to the network and if there is only one common channel, network bottleneck occurs.



(a)

(b)

Fig. 5. Comparison of modulation schemes for 500 kv Substation LOS in terms of average delay of LQ-CMST routing algorithm vs. number of channel. (a) Low traffic load, (b) high traffic load.



(a)

(b)

Fig. 6. Comparison of modulation schemes for 500 kv Substation LOS in terms of average delay of MHST routing algorithm vs. number of channel. (a) Low traffic load, (b) high traffic load.

Additionally, we also show the impact of multi-channel scheduling on delay performance of routing algorithms. As shown in Fig. 2, communication delay of all classes decreases when the number of channels increases, since packets are scheduled on more channels and therefore, schedule length decreases.

Figs. 3 and 4 illustrate the effect of following priority and delay-aware multi-channel scheduling on the average communication delay, when low and high traffic loads are applied with increasing number of channels. We observe that when the proposed routing algorithms follow delay-aware scheduling, the average latency of the RT packets decreases significantly. It is also important to note that the delay performance of the LQ-CMST algorithm is better than the MHST algorithm with and without delay-aware scheduling, since it considers link qualities while constructing routing paths in the network.

4.2. Analyzing the effect of modulation and encoding schemes on delay performance

In this section, the effect of modulation and encoding schemes on the delay performance of the proposed algorithms is analyzed. To quantify how the proposed algorithms can perform with different wireless sensor network platforms, such as MicaZ, Mica2, Mica, we change the modulation schemes to O-QPSK as in MicaZ, FSK as in Mica2, ASK as in Mica. Figs. 5 and 6 illustrate that the average delay values of the LQ-CMST and MHST routing algorithms for different modulation schemes and number of channels, respectively. Focusing on the results of Figs. 5 and 6, we observe that the O-QPSK shows the best result for both routing algorithms. After the O-QPSK, the FSK provides the second best result and lastly the ASK presents the third best result. We conclude that the modulation scheme is one of the most important design factors to provide QoS requirements of smart grid applications.

5. Conclusions and future work

Recent field tests show that the smart grid infrastructure has harsh and complex environmental conditions, noise, interference, connectivity, and fading problems during low-power wireless communications. To address these communication challenges, in this paper, the link-quality-aware routing algorithm (Link-Quality-Aware Capacitated Minimum Hop Spanning Tree (LQ-CMST)) and the priority and channel-aware multi-channel (PCA-MC) scheduling algorithm have been proposed for smart grid applications. Furthermore, the effect of modulation and encoding schemes on the performance of the proposed algorithms is analyzed under harsh smart grid channel conditions. Comparative performance evaluations through extensive simulations show that the proposed algorithms significantly reduce communication delay in smart grid environments. Overall, our main contribution is to investigate the performance of multi-channel WSNs for the smart grids and to quantify how priority and channel-aware communication will perform under different network traffic loads and harsh channel conditions of smart grid environments. We expect that the proposed algorithms and performance evaluations shown in this paper provide a valuable understanding about multi-channel scheduling and topology construction of WSNs in harsh smart grid environments. As a future work, we plan to integrate the proposed protocols with weighted fair scheduling schemes to provide fairness in different smart grid application scenarios.

Acknowledgment

This project was funded by the National Plan for Science, Technology and Innovation (MAARIFAH) King Abdulaziz City for Science and Technology – the Kingdom of Saudi Arabia award number (12-INF2731–03). The authors also, acknowledge with thanks Science and Technology Unit, King Abdulaziz University for technical support.

References

Ahmed, A.A., Fisal, N., 2008. A real-time routing protocol with load distribution in wireless sensor networks. Comput. Commun. 31 (14), 3190–3203.

Akkaya, K., Younis, M., 2005. Energy and qos aware routing in wireless sensor networks. Clust. Comput. 8 (2–3), 179–188.

Bari, A., Jiang, J., Saad, W., Jaekel, A., 2014. Challenges in the Smart Grid Applications: an Overview, International Journal of Distributed Sensor Networks, vol. 2014, Article ID 974682, 11 pp, http://dx.doi.org/10.1155/2014/974682.

Felemban, E., Lee, C.-G., Ekici, E., 2006. Mmspeed: multipath multi-speed protocol for qos guarantee of reliability and timeliness in wireless sensor networks. IEEE Trans. Mob. Comput. 5 (6), 738–754.

Gelenbe, E., Ngai, E.-H., 2008. Adaptive qos routing for significant events in wireless sensor networks. In: 5th IEEE International Conference on Mobile Ad Hoc and Sensor Systems, MASS 2008. IEEE, Atlanta, GA, pp. 410–415.

Gungor, V.C., Lu, B., Hancke, G.P., 2010. Opportunities and challenges of wireless sensor networks in smart grid. IEEE Trans. Ind. Electron. 57 (10), 3557–3564.

He, T., Stankovic, J.A., Lu, C., Abdelzaher, T., 2003. Speed: a stateless protocol for real-time communication in sensor networks. In: Proceedings of 23rd International Conference on Distributed Computing Systems. IEEE, Providence, RI, USA, 2003, pp. 46–55.

Huang, J., Bi J., 2015. A proportional fairness scheduling for wireless sensor networks. In: 2015 International Conference on Identification, Information, and Knowledge in the Internet of Things (IIKI), pp. 266–271, http://dx.doi.org/10.1109/IIKI.2015.64.

Incel, O.D., Ghosh, A., Krishnamachari, B., Chintalapudi, K., 2012. Fast data collection in tree-based wireless sensor networks. IEEE Trans. Mob. Comput. 11 (1), 86–99.

Lee, S., Younis, M., 2009. Qos-aware relay node placement in a segmented wireless sensor network. In: IEEE International Conference on Communications, ICC'09. IEEE, Dresden, 2009, pp. 1–5.

Li, H., Zhang, W., 2010. Qos routing in smart grid. In: IEEE Global Telecommunications Conference (GLOBECOM 2010). IEEE, Miami, Florida, USA, 2010, pp. 1–6.

Liang, X., Chen, M., Xiao, Y., Balasingham, I., 2010. Mrl-cc: a novel cooperative communication protocol for qos provisioning in wireless sensor networks. Int. J. Sens. Netw. 8 (2), 98–108.

Monowar, M.M., Rahman, M.O., Pathan, A.-S.K., Hong, C.S., 2008. Congestion control protocol for wireless sensor networks handling prioritized heterogeneous traffic. In: Proceedings of the 5th Annual International Conference on Mobile and Ubiquitous Systems: Computing, Networking, and Services, Mobiquitous '08. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), Brussels, Belgium, pp. 17:1–17:8, http://dx.doi.org/10.4108/ICST.MOBIQUITOUS2008.3829.

Razzaque, M.A., Alam, M.M., Mamun-Or-Rashid, M., Hong, C.S., 2008. Multi-constrained qos geographic routing for heterogeneous traffic in sensor networks. IEICE Trans. Commun. 91 (8), 2589–2601.

Rezaee, A.A., Yaghmaee, M.H., Rahmani, A.M., 2013. Optimized congestion management protocol for healthcare wireless sensor networks. Wirel. Pers. Commun. 75 (1), 11–34. http://dx.doi.org/10.1007/s11277-013-1337-z.

Saputro, N., Akkaya, K., Uludag, S., 2012. A survey of routing protocols for smart grid communications. Comput. Netw. 56 (11), 2742–2771.

Shah, G., Gungor, V.C., Akan, O.B., et al., 2013. A cross-layer qos-aware communication framework in cognitive radio sensor networks for smart grid applications. IEEE Trans. Ind. Inform. 9 (3), 1477–1485.

Yaghmaee, M.H., Yousefi, Z., Zabihi, M., Alishahi, S., 2013. Quality of service guarantee in smart grid infrastructure communication using traffic classification. IET Conf. Proc., 0803–0803(1).

Yigit, M., Durmaz Incel, O., Gungor, V.C., 2014. On the interdependency between multi-channel scheduling and tree-based routing for wsns in smart grid environments. Comput. Netw. 65, 1–20.

Yigitel, M.A., Incel, O.D., Ersoy, C., 2011. Design and implementation of a qos-aware {MAC} protocol for wireless multimedia sensor networks. Comput. Commun. 34 (16), 1991–2001. http://dx.doi.org/10.1016/j.comcom.2011.06.006 〈〉.

Melike Yigit received her B.S. and M.S. degrees in computer engineering from Bahcesehir University, Istanbul, Turkey, in 2010 and 2012, respectively. Currently, she is a Ph.D. student in Bahcesehir University, Istanbul, Turkey and works at Turkish Airlines (THY), which is an international airlines in Turkey, as a Business Analyst. Before starting THY, she worked in Huawei Technologies Co. Ltd. and Alcatel-Lucent Teletas as a software developer and San-Tez Project student, respectively. Her current research interests are smart grid communications, power line communications and wireless ad hoc and sensor networks.

V. Cagri Gungor received his B.S. and M.S. degrees in Electrical and Electronics Engineering from Middle East Technical University, Ankara, Turkey, in 2001 and 2003, respectively. He received his Ph.D. degree in electrical and computer engineering from the Broadband and Wireless Networking Laboratory, Georgia Institute of Technology, Atlanta, GA, USA, in 2007 under the supervision of Prof. Ian F. Akyildiz. Currently, he is an Associate Professor and Chair of Computer Engineering Department, Abdullah Gul University (AGU), Kayseri, Turkey. His current research interests are in smart grid communications, next-generation wireless networks, wireless sensor networks. He is also the recipient of the Editor of the Year Award, Ad Hoc Networks Journal (Elsevier Science) in 2015, Turkish Academy of Sciences Distinguished Young Scientist Award (TUBA-GEBIP) in 2014, IEEE Transactions on Industrial Informatics Best Paper Award in 2012, and the European Union FP7 Marie Curie IRG Award in 2009.

Etimad Fadel received her Bachelors degree in Computer Science at King Abdul Aziz University with Senior Project title ATARES: Arabic Character Analysis and Recognition in 1994. She was awarded the Mphil/PhD degree in computer science at De Montfort University (DMU), Liecester, UK. The Thesis title was Distributed Systems Management Service in 2007. Currently she is working as an Assistant Professor at the Computer Science Department at KAU. During this time she was appointed in different administrative positions. She was the Vice-Dean of the Faculty FCIT at the Girls section. This was between 2008 and 2010. Her main research interest is Distributed Systems, which are developed based on middleware technology. Currently she is working on Wireless Networks, Internet of Things and Internet of Nano-Things, and smart grids.

Laila Nassef received the Bachelor of Science Degree in electronics and communications from Ain Shams University, Cairo, Egypt in 1984 and Master of Science Degree in electronics and computers from Ain Shams University, Cairo, Egypt in 1989. She received her Ph.D. degree in computer engineering from Anglia Polytechnic University, England in 1997. She joined the National Telecommunications Institute in Cairo, Egypt in 1985. She joined the Institute of Statistical Studies and Research of Cairo University, Cairo, Egypt in 2001. Currently, she is an associate professor with Department of Computer Science, Faculty of Computing and Information Technology, King Abdulaziz University, Jeddah, KSA. Her research interests include wireless ad hoc and sensor networks, cognitive networks, heterogeneous networks and smart grid communications.

Nadine Akkari received the B.S and the M.S. degrees in Computer Engineering from University of Balamand, Lebanon, in 1997 and 1999, respectively. She received the Master degree in Networks of Telecommunications from Saint Joseph University and the Faculty of Engineering of the Lebanese University, Lebanon, in 2001 and Ph.D. degree in Networking from National Superior School of Telecommunications (ENST), France, in 2006. She is currently an associate professor with the faculty of Computing and Information Technology at King Abdulaziz University, Jeddah, Saudi Arabia. She is a senior member of IEEE. Her research interests are in heterogeneous networks, QoS provisioning, wireless nano-sensors and smart grids communications.

Ian F. Akyildiz received the B.S., M.S., and Ph.D. degrees in Computer Engineering from the University of Erlangen-Nuremberg, Germany, in 1978, 1981 and 1984, respectively. Currently, he is the Ken Byers Chair Professor in Telecommunications with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, the Director of the Broadband Wireless Networking Laboratory and Chair of the Telecommunication Group at Georgia Tech. Dr. Akyildiz is an honorary professor with the School of Electrical Engineering at Universitat Politcnica de Catalunya (UPC) in Barcelona, Catalunya, Spain and the founder of N3Cat (NaNoNetworking Center in Catalunya). He is also an honorary professor with the Department of Electrical, Electronic and Computer Engineering at the University of Pretoria, South Africa and the founder of the Advanced Sensor Networks Lab. Since 2011, he has been a Consulting Chair Professor at the Department of Information Technology, King Abdulaziz University (KAU) in Jeddah, Saudi Arabia. Since September 2012, Dr. Akyildiz has also been a FiDiPro Professor (Finland Distinguished Professor Program (FiDiPro) supported by the Academy of Finland) at Tampere University of Technology, Department of Communications Engineering, Finland. He is the Editor-in-Chief of Computer Networks (Elsevier) Journal, and the founding Editor-in-Chief of the Ad Hoc Networks (Elsevier) Journal, the Physical Communication (Elsevier) Journal and the Nano Communication Networks (Elsevier) Journal. He is an IEEE Fellow (1996) and an ACM Fellow (1997). He received numerous awards from IEEE and ACM. His current research interests are in nanonetworks, Long term evolution (LTE) advanced networks, cognitive radio networks and wireless sensor networks.