International Journal of Sensors and Sensor Networks
2013; 1(5): 55-60
Published online September 20, 2013 (http://www.sciencepublishinggroup.com/j/ijssn)
doi: 10.11648/j.ijssn.20130105.12

Differentiated service for smart grid neighbourhood area networks via optimal resource allocation

Yifeng He*, Mohammad Shams Yazdi

Electrical and Computer Engineering, Ryerson University, Toronto, Canada

Email address:
yhe@ee.ryerson.ca (Yifeng He)

To cite this article:
Yifeng He, Mohammad Shams Yazdi. Differentiated Service for Smart Grid Neighbourhood Area Networks via Optimal Resource Allocation. *International Journal of Sensors and Sensor Networks.* Vol. 1, No. 5, 2013, pp. 55-60. doi: 10.11648/j.ijssn.20130105.12

Abstract: Smart grid is a modern electric system which uses advanced information and communication technologies to improve efficiency, reliability, and safety in electric power distribution and management. Smart grid communication architecture is typically comprised of three interconnected networks: Wide Area Network (WAN), Neighborhood Area Network (NAN), and Home Area Network (HAN). This paper studies the resource allocation problem for NAN. Specifically, we propose an optimal resource allocation scheme to provide differentiated service, in terms of end-to-end delay, to different classes of traffic in the NAN. The resource allocation problem is formulated into a Linear Programming (LP) problem, which can be solved efficiently. The simulation results demonstrate that the proposed scheme can provide a lower delay to the prioritized class by optimally allocating the resource at each node in the NAN.

Keywords: Quality of Service, Smart Grid, Differentiated Service, Resource Allocation, Neighbourhood Area Network

1. Introduction

Smart grid is a modern electric system which uses advanced information and communication technologies to improve efficiency, reliability, and safety in electric power distribution and management [1]. Smart grid applications generate a large volume of data, which is required to be transferred to the control center in time. Therefore, reliable and prompt data communications are critical for smart grid. Smart grid communication architecture is typically comprised of three interconnected networks: Wide Area Network (WAN), Neighborhood Area Network (NAN), and Home Area Network (HAN) [2]. HAN collects the data from the home appliances. NAN transmits the data from HANs and other collectors to WAN. WAN forwards the data from NANs to the data centers.

This paper focuses on NAN. The NAN can be formed in a tree or mesh topology. In the tree based NAN, data is transported from the leaf to the upper levels towards the root node. In the mesh based NAN, data is transported by establishing the ad hoc communications with the neighboring nodes. In tree based NAN, a failed node will cause the disconnection between its descendant nodes and the root node. On the contrary, the mesh based NAN has multiple connections with its neighbors, so a node failure will not cause the isolation of its descendant nodes. Therefore, we choose mesh based NAN in our study.

Multiple applications, such as Plug-in Hybrid Electric Vehicle (PHEV) Charging, distributed generation, community energy storage, are running simultaneously in the smart grid. The data communications for each application have different requirements in terms of delay. For example, the power failure messages have a higher priority, thus requiring a lower delay, compared to the regular operation data. However, it is quite challenging to meet such delay requirements for different applications by optimally utilizing the network resources. The existing works [3-5] on Quality of Service (QoS) supports for Wireless Sensor Network (WSN) cannot be directly applied into smart grid communications, since they do not consider the specific requirements of the smart grid.

In this paper, we propose an optimal resource allocation scheme to provide Differentiated Service (DS) in end-to-end delay to different classes of data flows in the smart grid. We apply the queuing theory to model the data transmission at each node, and then formulate the resource allocation problem into a Linear Programming (LP) problem, which can be solved efficiently. The proposed scheme can provide guidance to the design and configuration of smart grid NANs.

The rest of the paper is organized as follows. Section 2 discusses the related work. Section 3 presents the resource optimization problem for differentiated service. The simulation results are provided in Section 4, and the conclusion is drawn in Section 5.

2. Related Work

QoS for wireless sensor networks has been investigated in the literature. Liao *et al.* maximized the network utility for wireless sensor network under the constraint of end-to-end delay [3]. The optimization problem was solved using duality decomposition approach. A scheduling algorithm was proposed for slot assignment in clustered WSNs, and the slot reuse concept was used to significantly reduce the end-to-end latency [4]. A routing protocol was proposed to achieve moderate energy consumption and high packet delivery ratio even with high link-failure rates [5]. Aalsalem *et al.* proposed a Multiple Level Stateless Protocol (MLSP) [6] which enables the data to be delivered in time. SPEED [7] is a location based real-time routing protocol that aims to reduce the end-to-end deadline missing ratio in wireless sensor network by utilizing geographic locations. Multi-path and Multi-SPEED Routing Protocol (MMSPEED) [8] is a packet delivery mechanism for wireless sensor networks to get service differentiations and probabilistic QoS guarantees in terms of latency and reliability. Barve *et al.* presented a solution to predict the percentage of the lost data packet in the indoor and outdoor wireless sensor networks, by using the Artificial Neural Network (ANN) [9].

QoS has been an important issue in smart grid communications. Worldwide Interoperability for Microwave Access (WiMAX) standard provides five-layer QoS architecture [10]. The data traffic in the smart grid can be classified into different classes with different QoS requirements in terms of delay, throughput and reliability [11]. Levorato *et al.* proposed an algorithm which dynamically allocates traffic with different QoS requirements in terms of throughput, delay, and failure probability to information networks with different performance characteristics [12]. An adaptive admission control algorithm was proposed to provide QoS support for fiber-wireless Smart Grid communications networks [13]. A QoS-aware admission control scheme was proposed for the PHEV charging infrastructure [14]. Vallejo *et al.* proposed the use of a QoS broker device to enhance the QoS in the smart grid electrical distribution access domains by providing a centralization of QoS management [15]. Sun *et al.* presented an improved routing protocol based on the Ad hoc On-Demand Distance Vector (AODV) for the ad-hoc network that is suitable for the urban distribution grid [16]. QoS support was added to the low-cost protocols, like ZigBee, to provide differentiated service for traffic of different priority at the Medium Access Control (MAC) layer [17].

3. Resource Optimization Problem for Differentiated Service

In this section, we will apply the graph theory and queuing theory to study the resource optimization problem for differentiated service in the NAN.

3.1. Network Models

There are multiple classes of data flows in the smart grid NAN. The set of the classes of data flows is denoted by the set K. Each class has a different delay requirement. We assume that the sensors belonging to class-k have a common source rate denoted by $R^{(k)}$. We also assume that there is only one collector, which receives the data and then forwards it to the WAN.

All sensors form a mesh-based wireless sensor network for data delivery. The mesh-based wireless sensor network can be modeled as a directed graph $G = (N, L)$, where N is the set of sensor nodes and L is the set of directed wireless links. Among the node set N, one node is the collector, denoted as t, while the other nodes belong to source-node set V. The source node set V consists of multiple sub-sets $V^{(k)}$ $(\forall k \in K)$ where $V^{(k)}$ represents the sub-set of the class-k source nodes. We assume that each source node generates only one flow session from the source node to the collector. We use H to denote the set of flow sessions. The session-set H consists of multiple sub-sets $H^{(k)}$ $(\forall k \in K)$ where $H^{(k)}$ represents the sub-set of the flow sessions originating from the class-k source nodes. Each node can also serve as a relay node to forward the traffic of the other nodes toward the collector. Any two nodes are connected by a link if they can directly communicate with each other.

The relationship between a node and its connected links is represented by a *node-link incidence matrix A*, whose elements are given by

$$a_{il} = \begin{cases} 1, & \text{if link } l \text{ is an outgoing link from node } i, \\ -1, & \text{if link } l \text{ is an incoming link into node } i, \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

Sensor node i $(\forall i \in N)$ generates data traffic with a source rate R, where $R = R^{(k)}$ if $i \in V^{(k)}$. Session h $(\forall h \in H)$ can go through multiple intermediate nodes towards the collector. We use f_{hl} to denote the link rate at link l for session h $(\forall h \in H)$. Also, we use η_{hi} to denote the generated rate at node i for session h, which is given as below:

$$\eta_{hi} = \begin{cases} R, & \text{if node } i \text{ is the source node of session } h, \\ -R, & \text{if node } i \text{ is the sink of session } h, \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

If node i is the source node of session h, it generate a rate which is equal to the source rate of the session, and hence, $\eta_{hi} = R$. If node i is the sink of session h, it absorbs the source rate of session h, and hence, $\eta_{hi} = -R$. The other nodes have $\eta_{hi} = 0$ since they neither generate nor absorb any rate.

Flow conservation holds at each node for any session. Flow conservation means that the total outgoing rate from a node is equal to the sum of the total incoming rate into the node and the generated rate at this node for a session. The *flow conservation law* is given by

$$\sum_{l \in L} a_{il} f_{hl} = \eta_{hi}, \ \forall h \in H, \ \forall i \in N, \quad (3)$$

where the term $\sum_{l \in L} a_{il} f_{hl}$ in Equation (3) represents the difference between the total outgoing rate and the total incoming rate at node i for session h, and η_{hi} represents the generated rate of session h at node i.

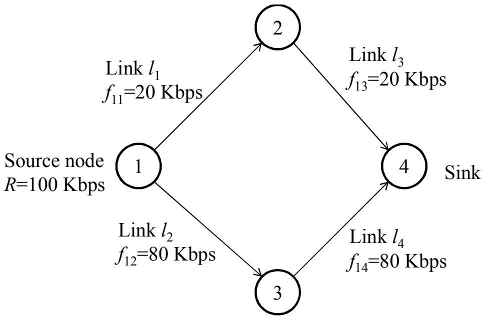

Figure 1. *A network topology with four nodes.*

We will use an example to explain the *node-link incidence* relationship and the *flow conservation law*. The network topology in the example is shown in Figure 1. The network consists of four nodes. A session, denoted as session 1, is generated from the source node (node 1) to the sink (node 4). The flow of the session is traveled via two paths. The first path is: node 1 --> node 2 --> node 4, and the second path is: node 1 --> node 3 --> node 4. The source rate of the session is 100 Kbps, which is split into 2 parts, with part 1 (20 Kbps) over path 1 and part 2 (80 Kbps) over path 2. There are four links, denoted as l_1, l_2, l_3, and l_4, in the topology. The link rates for the session are then given by: f_{11} = 20 Kbps, f_{12} = 80 Kbps, f_{13} = 20 Kbps, and f_{14}= 80 Kbps. Figure 2 shows the *node-link incidence matrix* for the network given in Figure 1. We can verify the flow conservation law in the topology. Node 1 is the source node for session 1. Therefore, we have η_{11} = 100 Kbps. At node 1, $\sum_{l \in L} a_{1l} f_{1l} = a_{11} f_{11} + a_{12} f_{12} = 100$ Kbps. Hence, $\sum_{l \in L} a_{1l} f_{1l} = \eta_{11}$, which means that the flow conservation holds at node 1. The flow conservations at the other three nodes (e.g., nodes 2 - 4) also hold.

Time Division Multiple Access (TDMA) and Carrier Sense Multiple Access (CSMA) are two major mechanisms to resolve the link interference in wireless sensor networks [18]. The CSMA mechanism is based on collision avoidance. Each node listens to the channel before the transmission. If the channel is clear, the node starts the transmission. Otherwise, the node waits while trigging a back-off timer, then tries again. In TDMA scheme, each node transmits data in the assigned time slots, thus eliminating transmission collision. Compared to CSMA, TDMA is more appropriate for delay-sensitive smart grid applications. Therefore, we choose TDMA at the MAC layer in our study.

	l_1	l_2	l_3	l_4
i_1	1	1	0	0
i_2	-1	0	1	0
i_3	0	-1	0	1
i_4	0	0	-1	-1

Figure 2. *Node-link incidence matrix for the four-node network.*

We assume that the transmission power at each link, denoted by P, is constant. The number of the links in the NAN is denoted by $|\boldsymbol{L}|$. The link capacity C_l at link l is modeled by :

$$C_l = \tau_l W log_2 \left(1 + \frac{h_l P}{N_0 W}\right), \ \forall l \in L, \quad (4)$$

where τ_l is the fraction of time allocated to link l. W is the channel bandwidth, h_l is the channel gain at link l, and N_0 is the noise power spectral density.

Since each link is shared by multiple classes of data flows, we model link l as $|K|$ parallel M/M/1 queues [19], among which the k-th M/M/1 queue is used to buffer and forward class-k traffic. The bandwidth allocated to the k-th M/M/1 queue is denoted by $b_l^{(k)}, \forall k \in K$. The sum of allocated bandwidths should be no larger than the link capacity, which means $\sum_{k \in K} b_l^{(k)} \le C_l$. The class-k aggregate rate at link l is given by $y_l^{(k)} = \sum_{h \in H^{(k)}} f_{hl}$. In order to maintain the stability of the k-th M/M/1 queue, the following condition is required: $y_l^{(k)} < b_l^{(k)}$.

The expected queuing delay at the k-th M/M/1 queue at link l is given by [19]: $d_l^{(k)} = 1/(u_l^{(k)} - \lambda_l^{(k)})$, where u_l is mean service rate in packets per second at the queue, which is given by $u_l^{(k)} = b_l^{(k)}/S$ where $b_l^{(k)}$ is the bandwidth allocated to the k-th M/M/1 queue at link l, and S is the average packet length in bits, and $\lambda_l^{(k)}$ is mean arrival rate in packets per second at link l, which is given by $\lambda_l^{(k)} = y_l^{(k)}/S$ where $y_l^{(k)}$ is the aggregate link rate of class-k traffic. Therefore, the average queuing delay at link l for class-k traffic is given by

$$d_l^{(k)} = \frac{1}{(b_l^{(k)}/S) - (y_l^{(k)}/S)} = \frac{S}{b_l^{(k)} - y_l^{(k)}}. \quad (5)$$

A session is the end-to-end flow through multiple links. Therefore, it consists of multiple connected M/M/1 queues. We assume that the M/M/1 queues in the session are independent with each other. Hence, the end-to-end delay for session h ($\forall h \in H$) is given by

$$d_h^{e2e} = \sum_{l \in L} \frac{f_{hl}}{R} d_l^{(k)} = \sum_{l \in L} \frac{S f_{hl}}{R(b_l^{(k)} - y_l^{(k)})}, \quad (6)$$

where f_{hl}/R represents the fraction of the source rate that travels through link l, and $d_l^{(k)}$ is the queuing delay at link l.

3.2. Resource Optimization Problem

In this sub-section, we optimize the network resources to provide dedifferentiated service in end-to-end delay to multiple classes of traffic in the NAN. The end-to-end delay for a flow is typically caused by the congestion at a link. We introduce a metric, *emptiness level* (denoted by $q_l^{(k)}$), to represent the congestion at link *l* for class-*k* traffic. We define the emptiness level as: $q_l^{(k)} = b_l^{(k)} - y_l^{(k)}$ where $b_l^{(k)}$ represents the service capacity of the M/M/1 queue, and $y_l^{(k)}$ represents the traffic-arrival rate of the M/M/1 queue. A higher *emptiness level* indicates a lower congestion at the queue. In other words, a higher *emptiness level* $q_l^{(k)}$ indicates a lower queuing delay at link *l* for class-*k* traffic. Each link consists of |*K*| parallel M/M/1 queues, each of which is used to forward a class of traffic.

In smart grid, each class of traffic has a different delay requirement. We introduce a *delay control coefficient* $\rho^{(k)}$ for each class to provide differentiated queuing delays. Specifically, at the *k*-th M/M/1 queue of each link, we impose a delay constraint: $\rho^{(k)}y_l^{(k)} - b_l^{(k)} \le 0$ where $\rho^{(k)}$ ($\rho^{(k)} > 1$) is the *delay control coefficient* for class-*k* traffic. For the class with a lower delay requirement, we assign it a higher $\rho^{(k)}$, which leads to a higher *emptiness level* at each link. For the class with a higher delay tolerance, we assign it a lower $\rho^{(k)}$, which leads to a lower *emptiness level* at each link. With different *delay control coefficient* for different class, we can have a differentiated queuing delay at each link for different class of traffic.

We optimize the resource at each node to provide differentiated service, in terms of delays, among multiple classes of traffic in the NAN. The *resource optimization problem* for differentiated service is formulated as: to maximize the sum of the *emptiness levels* of all links for all classes of traffic, by optimizing the aggregate link rate at each link, the link rate at each link for each session, the time fraction for each link, and the bandwidth allocated to each class at each link. Mathematically, the *resource optimization problem* is formulated as follows:

$$
\begin{aligned}
\text{maximize} \quad & \textstyle\sum_{k\in K}\sum_{l\in L}(b_l^{(k)} - y_l^{(k)}) \\
\text{subject to} \quad & \textstyle\sum_{l\in L} a_{il} f_{hl} = \eta_{hi},\ \forall h \in H,\ \forall i \in N, \\
& y_l^{(k)} = \textstyle\sum_{h\in H^{(k)}} f_{hl},\ \forall l \in L,\ \forall k \in K, \\
& C_l = \tau_l W log_2\left(1 + \frac{h_l P}{N_0 W}\right), \forall l \in L, \\
& \rho^{(k)} y_l^{(k)} - b_l^{(k)} \le 0,\ \forall l \in L,\ \forall k \in K, \\
& \textstyle\sum_{k\in K} b_l^{(k)} < C_l, \forall l \in L, \\
& \textstyle\sum_{l\in L}\tau_l \le 1, \\
& f_{hl} \ge 0,\ \forall h \in H,\ \forall l \in L, \\
& b_l^{(k)} \ge 0,\ \forall l \in L, \forall k \in K, \\
& \tau_l \ge 0,\ \forall l \in L, \\
& R^{(k)} \ge 0,\ \forall k \in K.
\end{aligned} \tag{7}
$$

In the optimization problem (7), the objective function is the sum of the *emptiness levels* of all links for all classes of data, the optimization variables are $\{y_l^{(k)}, f_{hl}, \tau_l, b_l^{(k)}\}$, among which $y_l^{(k)}$ represents the aggregate link rate of class-*k* data at link *l*, f_{hl} represents the link rate at link *l* for session *h*, τ_l is the time fraction for link *l*, and $b_l^{(k)}$ is the bandwidth allocated to class-*k* traffic at link *l*.

The optimization problem (7) contains the following constraints. The first constraint $\sum_{l\in L} a_{il} f_{hl} = \eta_{hi}$ represents the flow conservation law at each node for each session. The second constraint $y_l^{(k)} = \sum_{h\in H^{(k)}} f_{hl}$ means that the aggregate link rate of class-*k* traffic is equal to the sum of the individual link rates of the sessions belonging to class-*k*. The third constraint $C_l = \tau_l W log_2(1 + h_l P/N_0 W)$ represents the link capacity of the link. The fourth constraint $\rho^{(k)}y_l^{(k)} - b_l^{(k)} \le 0$ is the delay constraint with the introduction of *delay control coefficient* at each link for each session. The fifth constraint $\sum_{k\in K} b_l^{(k)} < C_l$ is the link capacity constraint, which means that the sum of the allocated bandwidths to all classes should be no larger than the link capacity at each link. The sixth constraint $\sum_{l\in L}\tau_l \le 1$ is the TDMA constraint, which means that the sum of the time fractions assigned to all links should be no larger than 1.

Maximizing $\sum_{k\in K}\sum_{l\in L}(b_l^{(k)} - y_l^{(k)})$ is equivalent to minimizing $\sum_{k\in K}\sum_{l\in L}(y_l^{(k)} - b_l^{(k)})$. By replacing the aggregate link rate $y_l^{(k)}$ with $\sum_{h\in H^{(k)}} f_{hl}$, the objective of the optimization problem can be changed to minimize $\sum_{k\in K}\sum_{l\in L}\left(\sum_{h\in H} f_{hl} - b_l^{(k)}\right)$. By letting $\alpha_l = W log_2(1 + h_l P/N_0 W)$, the optimization problem (7) is converted to the following equivalent problem:

$$
\begin{aligned}
\text{minimize} \quad & \textstyle\sum_{k\in K}\sum_{l\in L}(\sum_{h\in H^{(k)}} f_{hl} - b_l^{(k)}) \\
\text{subject to} \quad & \textstyle\sum_{l\in L} a_{il} f_{hl} = \eta_{hi},\ \forall h \in H,\ \forall i \in N, \\
& \rho^{(k)} y_l^{(k)} - b_l^{(k)} \le 0,\ \forall l \in L,\ \forall k \in K, \\
& \textstyle\sum_{k\in K} b_l^{(k)} \le \tau_l \alpha_l,\ \forall l \in L, \\
& \textstyle\sum_{l\in L}\tau_l \le 1, \\
& f_{hl} \ge 0,\ \forall h \in H,\ \forall l \in L, \\
& b_l^{(k)} \ge 0,\ \forall l \in L,\ \forall k \in K, \\
& \tau_l \ge 0,\ \forall l \in L, \\
& R^{(k)} \ge 0,\ \forall k \in K.
\end{aligned} \tag{8}
$$

The optimization problem (8) is a LP problem, which can be solved efficiently using the simplex method or the interior point method [20].

4. Simulations

The simulation settings are described as follows. The wireless sensor nodes are randomly placed in a square region of 150m-by-150m. The transmission range of each node is 50 m. There are two classes of sensor nodes in the NAN. Class-1 is the Smart Meter (SM) sensors, which provide real-time meter readings to the data center of the utility company. Class-2 is the Power Monitoring (PM) sensors, which provide real-time power quality measurements to the data center of the utility company. Class-2 traffic has a higher priority than class-1 traffic, thus requiring a lower delay in the NAN. The data of both classes is transmitted to a common collector, which further forwards the data to the WAN. The bandwidth of the wireless channel is set to W = 200 KHz, the noise power spectral density is $N_0 = 10^{-13}$ W/Hz. The transmission power at each link is set to 200 mW. The channel gain at link l is given by $h_l = 10^3/d_l^4$, where d_l is the distance from the transmitting node to the receiving node of the link. The *delay control coefficients* for class-1 data and class-2 data are set to 1.1 and 1.8, respectively. The location of the collector is determined by minimizing the mean squared distances between the collector and the sensors.

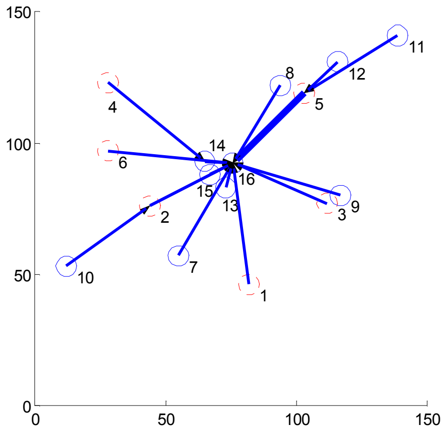

Figure 3. Data flows for the NAN with 15 sensors.

Figure 3 shows the data flows for the NAN with 15 randomly located 15 sensors and one collector (e.g., node 16). The thickness of an edge is proportional to the amount of link rate at the corresponding wireless link. Among the 15 sensor nodes, nodes 1-6 are class-1 nodes with a lower priority, while nodes 7-15 are class-2 nodes with a higher priority. The routing flows in Figure 3 are determined by the solution to the optimization problem (8). In the proposed solution, a higher *emptiness level* is assigned to class-2 traffic, which leads to a higher link bandwidth to be allocated to class-2 flows, thus leading to a lower delay. On the other hand, a lower *emptiness level* is assigned to class-1 flows, thus leading to a higher delay.

We compare our method to our prior work without DS [21]. In [21], an optimal scheme was proposed to maximize source rate for the NAN. However, it does not consider the service differentiation among different classes of traffic [21]. When the two schemes are compared, the network topology, the network parameters, and the source rates are set to the same. The end-to-end delays of all sessions are shown in Figure 4. The proposed method can provide lower end-to-end delays for the class-2 sessions (e.g., sessions 7-15), while higher end-to-end delays for the class-1 sessions (e.g., sessions 1-6). On the other hand, the en-to-end delays among all sessions are random in the scheme without DS [21].

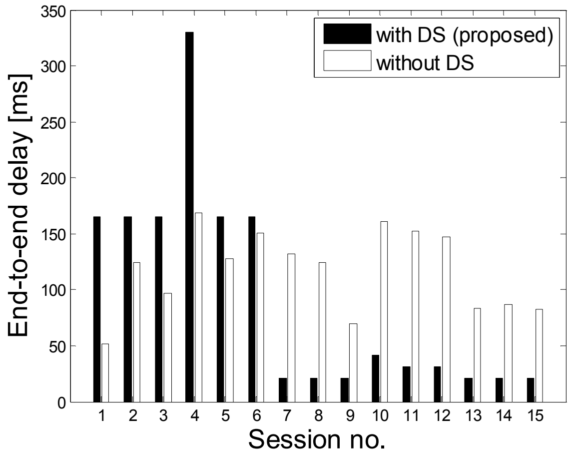

Figure 4. Comparison of end-to-end delays in the NAN with 15 sensors.

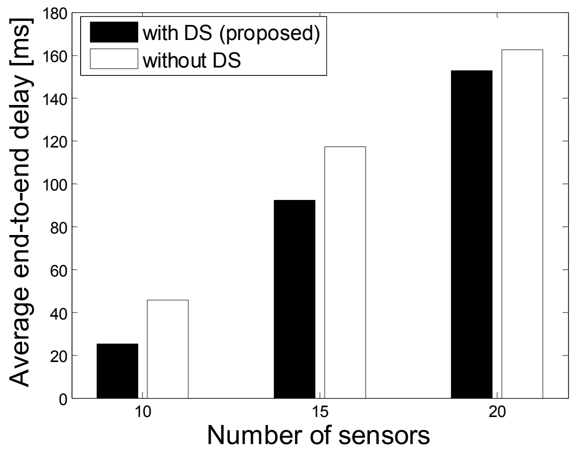

Figure 5. Comparison of average end-to-end delay in the networks with different sizes.

We also conducted simulations on the different networks with different number of sensors. The comparison of average end-to-end delay is shown in Figure 5, from which we can observe that the proposed scheme can obtain a lower average end-to-end delay compared to the scheme without DS [21].

Figure 6 shows the differentiation in average end-to-end delay between the two class of traffic for different networks with different number of sensors. We can see that the proposed scheme can provide a lower delay to class-2 traffic. When the number of the sensors is increased, the difference in average end-to-end delay between two classes becomes larger.

5. Conclusion

In this paper, we proposed an optimal resource allocation scheme to provide differentiated service in terms of end-to-end delay in the NAN for different classes of smart grid traffic. By applying the graph theory and the queuing theory, we formulated the resource optimization problem into a LP problem. By solving the LP problem, we can optimally allocate the network resources to provide differentiated service. We demonstrated in the simulations that the proposed scheme can not only provide differentiated service but also a lower overall end-to-end delay compared to the existing scheme.

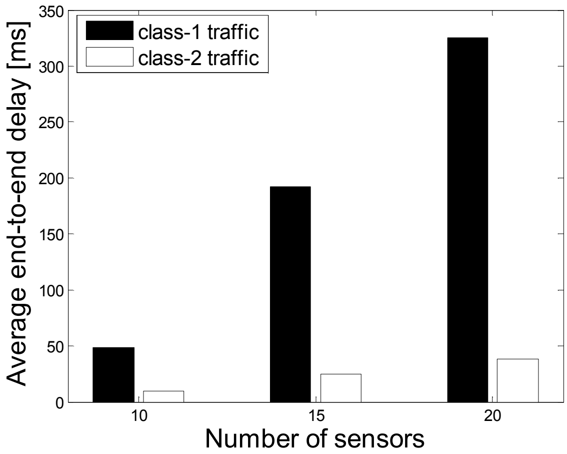

Figure 6. *Differentiated service in end-to-end delays between two classes of traffic in the networks with different sizes.*

References

[1] F. Li, W. Qiao, H. Sun, H. Wan, J. Wang, Y. Xia, Z. Xu, and P. Zhang, "Smart Transmission Grid: Vision and Framework," *IEEE Transactions on Smart Grid*, vol. 1, no. 2, pp. 168-177, 2010.

[2] A. Ghassemi, S. Bavarian, and L. Lampe, "Cognitive Radio for Smart Grid Communications," in *Proc. of IEEE International Conference on Smart Grid Communications (SmartGridComm)*, pp. 297-302, Oct. 2010.

[3] S. Liao, W. Cheng, W. Liu, and Z. Yang, "Distributed Optimization Based on Utility with Delay Constraints in Wireless Sensor Networks," in *Proc. of International Conference on Wireless Communications, Networking and Mobile Computing,* Sept. 2009.

[4] L. Shi and A. Fapojuwo, "TDMA Scheduling with Optimized Energy Efficiency and Minimum Delay in Clustered Wireless Sensor Networks," *IEEE Transactions on Mobile Computing,* pp. 927- 940, Jul. 2010.

[5] K. Daabaj, M. Dixon, T. Koziniec, and D. Murray, "Reliable Data Delivery in Low Energy Ad Hoc Sensor Networks," in *Proc. of Asia-Pacific Conference on Communications*, pp. 324-329, Mar. 2010.

[6] M. Aalsalem, J. Taheri, A. Zomaya. "A Framework for Real Time Communication in Sensor Networks," in *Proc. of ACS/IEEE International Conference on Computer Systems and Applications,* pp. 245-250, Jul. 2010.

[7] T. He, J. Stankovic, C. Lu, and T. Abdelzaher, "SPEED: A Stateless Protocol for Real-Time Communication in Sensor Networks," in *Proc. of IEEE International Conference on Distributed Computing Systems,* pp. 46-55, 2003.

[8] S. Darabi, N. Yazdani, and O. Fatemi, "Multimedia-aware MMSPEED: A routing solution for video transmission in WSN," in *Proc. of International Symposium on Advanced Networks and Telecommunication Systems,* pp. 202-207, Dec. 2008.

[9] Y. Barve, "Neural Network Approach to the Prediction of Percentage Data Packet Loss for Wireless Sensor Networks," in *Proc. of Southeastern Symposium on System Theory,* pp. 143-150, Apr. 2009.

[10] P. Rengaraju, C. Lung, and A. Srinivasan, "Communication Requirements and Analysis of Distribution Networks Using WiMAX Technology for Smart Grids" in *Proc. of Wireless Communications and Mobile Computing Conference (IWCMC),* Jun. 2012.

[11] R. Brown, "Impact of Smart Grid on distribution system design," in *Proc. of IEEE. Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century*, Jul. 2008.

[12] M. Levorato and U. Mitra, "Optimal Allocation of Heterogeneous Smart grid Traffic to Heterogeneous Networks Communication Networks for Smart Grid," in *Proc. of IEEE International Conference on Smart Grid Communications,* pp. 132 - 137, Oct. 2011.

[13] M. Lévesque and M. Maier, "The Über-FiWi Network: QoS Guarantees for Triple-Play and Future Smart Grid Applications," in *Proc. of International Conference on Transparent Optical Networks,* pp.75-81, Jun. 2012.

[14] M. Erol-Kantarci, J. Sarker, and H. Mouftah, "Quality of Service in Plug-in Electric Vehicle Charging Infrastructure," in *Proc. of IEEE International Electric Vehicle Conference (IEVC),* pp. 301-309, Jan. 2012.

[15] A. Vallejo, A. Zaballos, J. Selga, and J. Dalmau, "Next-Generation QoS Control Architectures for Distribution Smart Grid Communication Networks," *IEEE Communications Magazine,* vol. 50, pp. 128 - 134, May 2012.

[16] W. Sun, J. Wang, C. Zhang, and Z. Qian, "Research on the wireless ad-hoc network for power distribution network communication in medium-small cities," in *Proc. of International Conference on Sustainable Power Generation and Supply.* pp.293-299, Apr. 2009.

[17] W. Sun, X. Yuan, J. Wang, D. Han and C. Zhang, "Quality of Service Networking for Smart Grid Distribution Monitoring," in *Proc. of IEEE International Conference on Smart Grid Communications (SmartGridComm)*, pp.293-299, Oct. 2010.

[18] I. Demirkol, C. Ersoy, and F. Alagoz, "MAC protocols for wireless sensor networks: a survey," *IEEE Communications Magazine,* vol. 44, no. 4, pp. 115-121, 2006.

[19] N.U. Prabhu, *Foundations of Queueing Theory*, Springer Press, 1997.

[20] R. J. Vanderbei, *Linear programming: Foundations and Extensions*, 2nd Edition, Springer, 2001.

[21] Y. He and L. Guan, "Source rate maximization for smart meter mesh networks using distributed algorithm", to appear in *Journal of Communications and Information Sciences*, 2013.