Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

Effect of data aggregation on the delay of demand-response communications within a Wi-Fi home area network with and without other traffic

N. S. Weerakoon [1, *], K. M. Liyanage [2]

[1]*Department of Computing, Rajarata University of Sri Lanka, Mihintale, Sri Lanka*
[2]*Department of Electrical and Electronics Engineering, University of Peradeniya, Peradeniya, Sri Lanka*

ARTICLE INFO

Article history:
Received 26 January 2022
Received in revised form
29 April 2022
Accepted 16 May 2022

Keywords:
Smart grids
Demand-response
Home area networks
Data aggregation
Energy efficiency
Delay

ABSTRACT

Home area networks play an important role in the demand-response function of smart grids. It is responsible for responding to requests received from the grid by controlling the devices in the home in a predefined manner. Communication within a Home Area Network should be efficient in terms of both delay and energy. Delay matters since the devices need to respond to the request within the stipulated delay. Energy matters since thousands of Home Area Networks are likely to create a significant energy footprint on the global level. In order to reduce energy consumption, the number of communications needs to be reduced and data aggregation can achieve this goal. However, data aggregation introduces a prolonged delay and may thus render the system unfit for its purpose. Therefore, it is required to determine the variation of delay when data aggregation is performed at different levels. This paper presents algorithms for data aggregation and device clustering optimization. Finally, the delay distribution was studied in a simulation environment with one level of data aggregation. The results show that an existing Wi-Fi network can be used for Smart Grid communications with in-network data aggregation provided that there is a spare (unused) bandwidth of 3 Mbit/s in the network.

1. Introduction

Smart Grid is an energy generation and distribution system that is expected to be more reliable and efficient in supplying energy that is affordable at a globally competitive level, and especially, capable of accommodating distributed renewable energy sources (DOE, 2008). The Smart Gird, unlike the traditional power grid, is accompanied by a massive intelligent information system, which encompasses all subsystems of the energy grid. Therefore, the Smart Grid is envisaged to have self-healing capabilities in the event of breakdowns, cybersecurity to ensure customer safety, and real-time capabilities of reconfiguration, demand-side management, and demand response (Momoh, 2018).

Demand-Response (DR) is the main function of Smart Grids (SG) as defined by NIST (Gopstein et al., 2021). DR is the modification of electricity demand at the customer premises in response to price, rebates, or directives from the utility to maintain stability, reliability, and consistent pricing (Herberg et al., 2014). The primary actor in the DR function is the Customer Subdomain, which represents the energy users in the SG. With respect to DR, the Customer is expected to modify the energy usage according to signals from the energy grid. For this purpose, the Customer Subdomain is required to be equipped with a communication infrastructure, which is generally known as Home Area Network (HAN) (Momoh, 2018), that could independently make decisions on the instantaneous energy usage so as to be able to participate in DR.

DR is generally divided into two levels: Slow DR and Fast DR (Herberg et al., 2014). While slow DR signals are sent significantly before the events occur, Fast DR programs, which include load balancing and frequency stabilization, require faster response times in the range of a few seconds. However, with more distributed energy resources, which have variable outputs, incorporated into the grid, these delay requirements may become more stringent

---

* Corresponding Author.
Email Address: nsw@rjt.ac.lk (N. S. Weerakoon)
https://doi.org/10.21833/ijaas.2022.08.006
Corresponding author's ORCID profile:
https://orcid.org/0000-0002-2711-0926

(Momoh, 2018). Therefore, it is required to verify that any communication system used in a HAN is capable of conforming to these real-time response requirements.

Many different communication protocols, including some proprietary protocols, have been proposed to be used in HANs. However, all these proposals are based on establishing a separate network only for the SG traffic (Momoh, 2018). When such a separate network is established, there is an additional energy use (Shih et al., 2001), and with many such networks, there will be a significant energy footprint as well as a carbon footprint globally.

In our research, we study the possibility of an existing Wi-Fi network being used for HAN communications. This would significantly reduce the global energy footprint since it allows the use of already available Wi-Fi networks for SG traffic. We have already established that an excess amount of 10 Mbit/s is sufficient for the SG traffic to be within an acceptable delay when a Wi-Fi network is used with other traffic (Weerakoon and Liyanage, 2020). This result is in relation to a network where there is no data aggregation within the network.

In this paper, we discuss the possibility of using an existing Wi-Fi network, which is used for other communications, for SG traffic with in-network data aggregation. The reason for aggregation is to reduce the energy in communication and to increase the total distance covered by introducing multi-hop communication. In data aggregation, data from many sources will be aggregated at an intermediate node, before being transmitted to the final destination. The communications with the aggregating node will be much shorter than with the destination and therefore, this will result in a reduction in energy usage. By selecting a node closer to the destination as the aggregating node, the total communication distance can be increased. Nevertheless, both the increase in the distance and data aggregation increases the delay in receiving the responses at the destination. Therefore, it is required to optimize these two contending parameters together.

2. Literature review

Since a HAN is similar to a Wireless Sensor Network (WSN), it has the limitations of a WSN except for the power constraint. A common WSN may have sensor nodes that are operating on battery power (Akyildiz et al., 2002), whereas in the HAN, nodes can draw energy from the mains. However, since it is necessary to maintain a low energy footprint, a HAN needs to be configured to operate as a common WSN consuming minimum possible energy. Therefore, it is possible to apply the knowledge of WSNs in designing a HAN.

Data aggregation is considered a crucial task within a WSN as it removes data redundancy and hence reduces the number of communications (Zheng and Jamalipour, 2009). With data aggregation within the network, an extra delay is introduced since a cluster head needs to wait for data from its neighbors before sending data to the HAN controller (Hu et al., 2006). A timing control mechanism needs to be implemented to ensure maximum data reception while maintaining a minimum delay. This is because different nodes may respond to a query with different delays and therefore all the nodes may not respond within a specified interval. Nevertheless, waiting for all nodes to respond may introduce an unnecessarily large delay that may render the data sent useless. In order to control the delay, Hu et al. (2006) introduced an adaptive timing control system. Using this system, the delay can be controlled depending on the priority of accuracy of the results against the maximum allowed latency. With reference to latency, DR signals define a ramp period, which is usually very large (~4s) compared to the possible latency within a HAN (Herberg et al., 2014).

Data aggregation reduces the energy consumption of the node considerably. Research carried out to determine the energy consumption model of a sensor node has demonstrated that the energy consumed in data transmission is much higher compared to the energy consumption for data processing (Pottie and Kaiser, 2000). For low-lying antennas, within a building where line-of-sight is obstructed, the path loss exponent has been measured to range between 4 to 6 (Rappaport, 1996). This means that the energy required for data transmission increases in the fourth to the sixth power of the distance. Hence, data aggregation can reduce energy consumption and the total energy footprint significantly even if the size of the network is small (Rajagopalan and Varshney, 2006). As we can see here, energy consumption and the delay of the responses are two factors that need a compromise. Li and Halpern (2001) showed that relaying information may require less power than transmitting the information directly. They also propose a protocol to construct the minimum energy network called a small minimum-energy communication network – SMECN.

On the contrary, Krishnamachari et al. (2002) suggested that the latency due to aggregation is non-negligible and this is proportional to the number of hops. Therefore, to minimize the delay the number of hops needs to be reduced while keeping each hop short to reduce the energy consumption.

3. The model

For HAN with data aggregation, routing should be among the same class (loads, storages, generators) of devices, since otherwise, aggregation is meaningless. Then the HAN gateway will receive an aggregated value from each class. For the energy, E, to be reduced, it is necessary to minimize the total distance of packet transport. If we take the distance between each two nodes i_{n-1} and i_n as $d_{i_{n-1}i_n}$ and i_0 is the sink, we need to select the path, such that,

$$E = min\left\{\left\{\sum_{n=1}^{D} min\left\{\sum\left(d_{i_n i_{n+1}}\right)^4 \mid \forall\, i_{n+1} + \left(d_{i_{n-1} i_n}\right)^4\right\}\right\} \mid \forall\, i_n\right\}$$

where, *D (≥1)* is the depth of the tree. When D = 1, there is no aggregation. If we consider the case of D=2,

$$E = min\left\{\left\{\sum_{j=1}^{n}\left\{(d_{ij})^4\right\} \forall\, j \neq i + (d_i)^4\right\} \mid \forall\, i\right\}$$

where, i is the cluster head and d_{ij} is the distance between nodes i and j. d_i is the distance from the cluster head to the sink. this can be found using Dijkstra's Algorithm (Dijkstra, 1959) using (fourth power of) distance as the weight function. Building the Minimum Spanning Tree (MST) starting from the HAN gateway for each class of devices will give us the desired result.

Unlike in general WSNs, where some nodes along the path are just forwarders, all the nodes in a HAN are responders, so each node will be an aggregator (aggregating the response generated by itself with the value(s) received from the downstream). Therefore, the longer the path, the longer will be the delay. To minimize the delay, we need to reduce the depth of the path. The delay, Δ can be expressed as,

$$\Delta = max\left\{\left\{\sum_{n=1}^{D} max\left(t_{i_{n-1} i_n} + tp_{i_{n-1}}\right)\right\} \mid \forall\, i_n\right\}$$

where, $t_{i_{n-1} i_n}$ is the delay of communication between i_{n-1} and i_n, $tp_{i_{n-1}}$ is the processing delay at i_{n-1}, and i_0 is the sink. *D (≥ 1)* is the depth of the aggregation tree. We can ignore tp_{i_0}, which is the processing time at the sink. The ultimate delay will be the maximum of delays in all trees. If the depth is 2 (i.e., one intermediate node collects and aggregates all responses from other devices in its own class), the delay is,

$$\Delta = max\left\{(t_i + t_{pi})\ \forall\, i + max\{t_{ij}\} \forall\, i \neq j\right\}$$

where, t_i is the transmission delay from *i to sink*, t_{ij} is the transmission delay from j to i, and tp_i is the processing delay at *i*. Provided that the number of nodes is fixed and data-centric routing is used, tp_i will be a constant value.

Since these two have a trade-off, we need to determine the optimal depth that data aggregation can be done. For this, first, we must build a Maximum Depth-Bound Spanning Tree.

Explanation of the Algorithm (Maximum Depth-Bound Spanning Tree):

- Define each node as unsolved and depth = 0
- Select the unsolved node with the shortest distance to sink and check the distance from it to all solved nodes (including the sink, whose depth is 0) whose depth < n. Mark the node solved and depth as the depth of the shortest distant solved node + 1. Add the connecting edge to the edge list.
- Repeat until all the nodes are solved.

Mathematical Expression:

- Let U be the set of unsolved nodes, S be the set of solved nodes and T as the set of edges in the tree. Initially, $U = V(G)$, and $S, T = \emptyset$□□Let ϕs be the depth of the node and Φ the maximum depth of the tree. The depth of the sink, $\phi s_0 = 0$. Let d_{us} denote the distance from node u to node s.
- Add sink to S.
- Select $u_i \in U$ with the shortest distance from the sink and find $s_j \in S \mid d_{us}$ is minimum and $\phi s_j < \Phi$. Subtract u_i from U and add to S. Set its depth $\phi u_i = \phi s_j + 1$. Add the connecting edge to T.
- Repeat the last step until all the nodes are in S.

Algorithm: Maximum Depth-Bound Minimum Spanning Tree
Input: A weighted, undirected, complete graph, $G = (V, E, w)$, the maximum bound of the spanning tree □
Output: A maximum depth-bound minimum spanning tree *T,*

```
T ← ∅

    Let r be the sink chosen from V,

$\phi r = 0$
$S \leftarrow r$
$V \leftarrow V \setminus r$

while $|S| < n$ do
    find $v \in V$ with the shortest distance to $r$ and $s \in S$ such that the edge $(v, s)$ is a minimum weighted edge between $V$ and $S$, and $\phi s < \Phi$,

    $\phi v = \phi s + 1$
    $S \leftarrow v$
    $V \leftarrow V \setminus v$
    $T \leftarrow T \cup \{(v, s)\}$
```

since G is a complete graph, a solution is guaranteed.

4. Simulation setup

We used a Matlab Simulink simulation to determine the delay characteristics of the SG traffic with one level of aggregation (D = 2). Two separate sets of simulations were carried out with and without other traffic in the network. All simulations were carried out sending 100 DR requests 1s apart and calculating the average delay of responses and acknowledgments separately. In the first set of simulations, the available bandwidth for the communications varied from 56 Mbit/s to 10 kbit/s, whereas in the second set the traffic level varied from 55.99 Mbit/s to 0 while having the bandwidth fixed at 56 Mbit/s so that the effectively available bandwidth varied from 56 Mbit/s to 10 kbit/s.

The packet sizes of the requests, acknowledgments, and responses were 14 bytes, 21 bytes, and 26 bytes respectively, the same as in (Weerakoon and Liyanage, 2020). There was a HAN Gateway that sent out the requests and received the acknowledgments and responses. The total number of devices in the simulated network was 50 with each of them belonging to one of three different types to represent loads, storage, and sources. There were 15 nodes of type 01, 18 of type 02, and 17 of type 03. The requests also belonged to these three types and there were 34 type 01, 36 type 02, and 30 type 03 requests, totaling 100 requests per simulation. Each node only responds to the requests related to its type. However, all nodes acknowledge the receipt of requests. This is intended to notify the HAN controller of the existence of the device. Accordingly, there are 100 responses and 300 acknowledgments in each round of simulation. While the number of devices of each type was randomly selected, the type of requests was randomly determined by the simulation system. According to this setup, there were 100 requests, 100 responses, and 300 acknowledgments since the 50 devices were clustered according to their type and only each cluster head communicated with the HAN Gateway.

5. Results discussion

The distribution of the average of the measured delay of responses when there was no other traffic in the network is shown in Table 1. Similarly, the distribution of the average of the measured delay of acknowledgments under the same conditions as given in Table 2. When we graphically represent both these results together, we get the plots in Fig. 1.

Table 1: Delay distribution of responses without other traffic

Bandwidth (Mbit/s)	0.01	0.015	0.02	0.025	0.05	0.075	0.1	0.2	0.3
Delay (s)	23.0354	19.2995	0.0701	0.0661	0.0597	0.0581	0.0572	0.0562	0.0608
Standard Deviation (s)	22.0199	33.5569	0.0099	0.0082	0.0058	0.0052	0.0050	0.0050	0.0086
Bandwidth (Mbit/s)	0.4	0.5	1	2	3	4	5	10	15
Delay (s)	0.0637	0.0655	0.0688	0.0728	0.0752	0.0750	0.0752	0.0749	0.0760
Standard Deviation (s)	0.0118	0.0113	0.0109	0.0083	0.0050	0.0055	0.0050	0.0056	0.0057
Bandwidth (Mbit/s)	20	25	30	35	40	45	50	56	
Delay (s)	0.0760	0.0758	0.0765	0.0760	0.0756	0.0755	0.0757	0.0763	
Standard Deviation (s)	0.0057	0.0066	0.0074	0.0064	0.0067	0.0073	0.0069	0.0070	

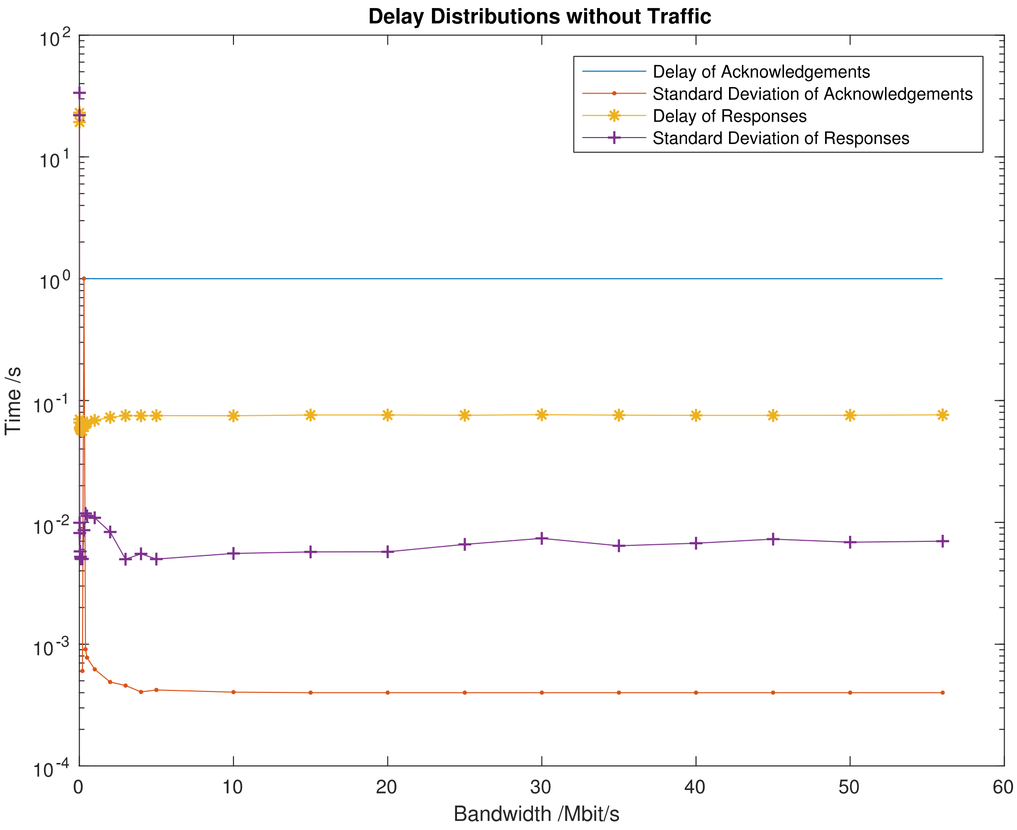

Fig. 1: Delay distributions without other traffic

With other traffic in the network, the distribution of the average of the measured delay of responses is as given in Table 3. The distribution of the average of measured delay of acknowledgments with other traffic in the network is given in Table 4. Fig. 2 shows this result graphically.

Table 2: Delay distribution of acknowledgements without other traffic

Bandwidth (Mbit/s)	0.01	0.015	0.02	0.025	0.05	0.075	0.1	0.2	0.3
Delay (s)	-	-	-	-	-	-	-	1.0055	1.0043
Standard Deviation (s)	-	-	-	-	-	-	-	0.0006	1.0041
Bandwidth (Mbit/s)	0.4	0.5	1	2	3	4	5	10	15
Delay (s)	1.0029	1.0026	1.0018	1.0014	1.0013	1.0012	1.0012	1.0012	1.0011
Standard Deviation (s)	0.0009	0.0008	0.0006	0.0005	0.0005	0.0004	0.0004	0.0004	0.0004
Bandwidth (Mbit/s)	20	25	30	35	40	45	50	56	
Delay (s)	1.0011	1.0011	1.0011	1.0011	1.0011	1.0011	1.0011	1.0011	
Standard Deviation (s)	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	

Table 3: Delay distribution of responses with other traffic

Available Bandwidth (Mbit/s)	0.01	0.015	0.02	0.025	0.05	0.075	0.1	0.2	0.3
Delay (s)	11.8142	11.8142	11.8142	2.7911	2.7911	2.7911	2.7911	2.7911	2.7911
Standard Deviation (s)	17.6614	17.6614	17.6614	3.4651	3.4651	3.4651	3.4651	3.4651	3.4651
Available Bandwidth (Mbit/s)	0.4	0.5	1	2	3	4	5	10	15
Delay (s)	2.7911	2.7911	1.8968	1.3042	0.8042	0.7874	0.8781	0.8482	0.7254
Standard Deviation (s)	3.4651	3.4651	3.2107	2.5034	1.3959	1.8349	1.3024	1.0646	1.1260
Available Bandwidth (Mbit/s)	20	25	30	35	40	45	50	56	
Delay (s)	0.7254	0.5553	0.8235	0.5329	0.5324	0.4226	0.2404	0.0763	
Standard Deviation (s)	1.1260	0.9697	1.5347	0.6650	0.6658	0.5032	0.5818	0.0070	

Table 4: Delay distribution of acknowledgements with other traffic

Available Bandwidth (Mbit/s)	0.01	0.015	0.02	0.025	0.05	0.075	0.1	0.2	0.3
Delay (s)	26.7581	26.7581	26.7581	21.6460	21.6460	21.6460	21.6460	21.6460	21.6460
Standard Deviation (s)	33.0475	33.0475	33.0475	37.8924	37.8924	37.8924	37.8924	37.8924	37.8924
Available Bandwidth (Mbit/s)	0.4	0.5	1	2	3	4	5	10	15
Delay (s)	21.6460	20.7924	10.4366	2.2150	2.2150	2.2150	2.8785	2.8777	3.0907
Standard Deviation (s)	37.8924	36.2041	15.7974	1.7915	1.7915	1.7915	2.7652	2.6454	2.8019
Available Bandwidth (Mbit/s)	20	25	30	35	40	45	50	56	
Delay (s)	2.8978	2.8779	2.6927	2.5005	3.0007	2.4060	2.0018	1.0011	
Standard Deviation (s)	2.7370	1.8110	1.5527	1.0001	1.5527	1.3732	0.9974	0.0004	

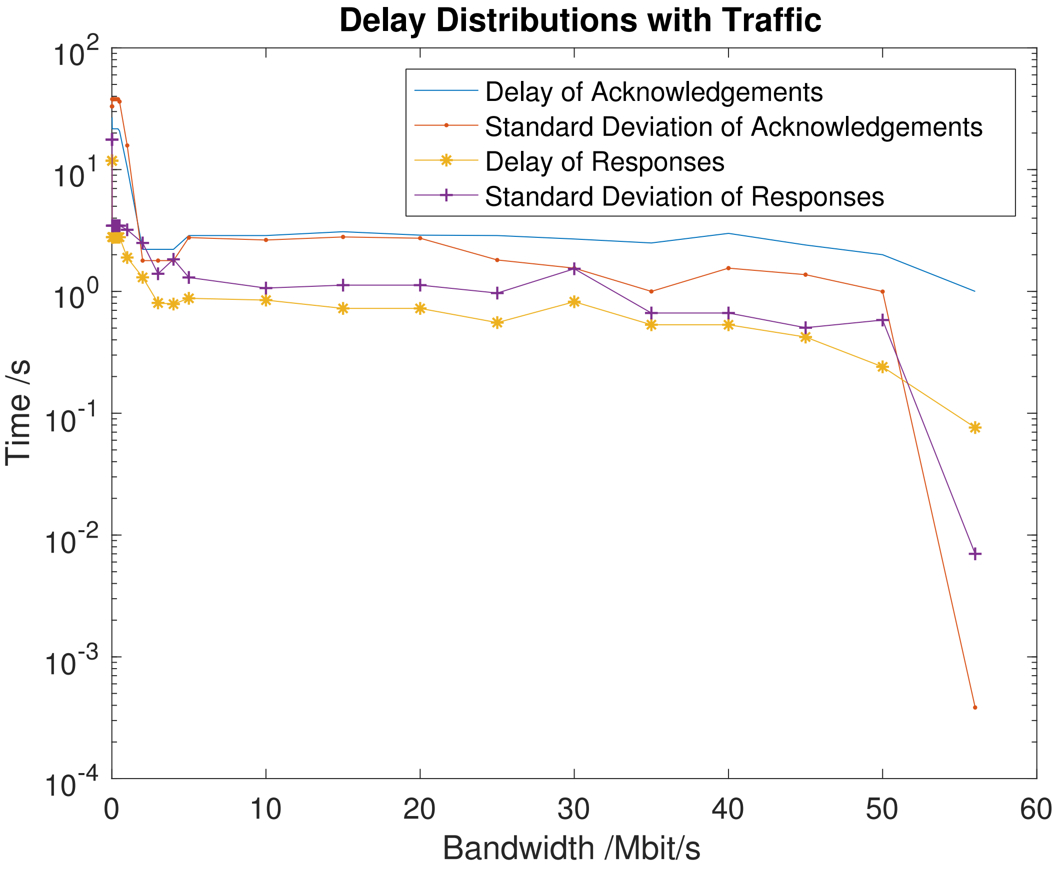

Fig. 2: Delay distributions with other traffic

6. Conclusions and further work

As shown in Fig. 1, when a dedicated network is used, the mean delay of responses falls below 0.1s when the bandwidth of the channel is 20 kbit/s (0.02 Mbit/s). this clearly indicated that when a dedicated network is used the bandwidth has very little influence on the delay. However, in the same scenario, when we consider the acknowledgments, there are no acknowledgments received at the bandwidth values below 200 kbit/s (0.2 Mbit/s). There is a high packet loss of about 40% is experienced for the acknowledgments when the bandwidth is below 1 Mbit/s. The delays as well as the reception become steady when the bandwidth of the network is above 1 Mbit/s.

On the other hand, when an existing network with other traffic in it is considered, the delay of the responses becomes less than 2s when the available bandwidth (excess from the available traffic) is above 1 Mbit/s (Fig. 1). This falls below 1s at the excess bandwidth of 3 Mbit/s. Interestingly, unlike in the case where the bandwidth of the channel is below 0.2 Mbit/s with a dedicated network (Fig. 2), some acknowledgments are received when the available bandwidth is below 0.2 Mbit/s in a shared network. The mean delay of acknowledgments falls to approximately 2s when the available bandwidth is 2 Mbit/s. Since the main purpose of having acknowledgments is to notify the HAN controller the existence of a particular device, this delay does not significantly affect the performance of the network with respect to DR communications.

With these results, we can conclude that an existing Wi-Fi network can be used for SG traffic provided that an excess bandwidth of 3 Mbit/s is available to be used. This conforms with the results we obtained in Weerakoon and Liyanage (2020) without in-network data aggregation. The inherent delay due to data aggregation can be reduced by making sure that an appropriate timeout is applied for the aggregator.

As further work related to this research, it is necessary to verify the obtained results using a physical Wi-Fi network. Once these results are verified, we can reliably use existing Wi-Fi networks for the SG traffic. Since similar researches have not been conducted to study the usability of Wi-Fi for SG traffic, the verification of the obtained result physically is really important. Once this result is verified, the need to set up a different local area network for SG traffic within customer domain can be eliminated.

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Akyildiz IF, Su W, and Sankarasubramaniam Y and Cayirci E (2002). A survey on sensor networks. IEEE Communications Magazine, 40(8): 102–114. https://doi.org/10.1109/MCOM.2002.1024422

Dijkstra EW (1959). A note on two problems in connexion with graphs. Numerische Mathematik, 1: 269–271. https://doi.org/10.1007/BF01386390

DOE (2008). The SMART GRID: An introduction. United States Department of Energy, Washington, USA.

Gopstein A, Nguyen C, O'Fallon C, Hastings N, and Wollman D (2021). NIST framework and roadmap for smart grid interoperability standards, release 4.0. NIST SP 1108r4, National Institute of Standards and Technology, Gaithersburg, USA. https://doi.org/10.6028/NIST.SP.1108r4

Herberg U, Mashima D, Jetcheva JG, and Mirzazad-Barijough S (2014). OpenADR 2.0 deployment architectures: Options and implications. In the 2014 IEEE International Conference on Smart Grid Communications (SmartGridComm), IEEE, Venice, Italy: 782-787. https://doi.org/10.1109/SmartGridComm.2014.7007743

Hu F, May C, and Cao X (2006). Data aggregation in distributed sensor networks: Towards an adaptive timing control. In the 3rd International Conference on Information Technology: New Generations, IEEE, Las Vegas, USA: 256-261. https://doi.org/10.1109/ITNG.2006.46

Krishnamachari L, Estrin D, and Wicker S (2002). The impact of data aggregation in wireless sensor networks. In the 22nd International Conference on Distributed Computing Systems Workshops, IEEE, Vienna, Austria: 575-578. https://doi.org/10.1109/ICDCSW.2002.1030829

Li L and Halpern JY (2001). Minimum-energy mobile wireless networks revisited. In the ICC 2001, IEEE International Conference on Communications, Conference Record (Cat. No. 01CH37240), IEEE, Helsinki, Finland, 1: 278–283. https://doi.org/10.1109/ICC.2001.936317

Momoh JA (2018). Energy processing and smart grid. John Wiley and Sons, Hoboken, USA. https://doi.org/10.1002/9781119521129

Pottie GJ and Kaiser WJ (2000). Wireless integrated network sensors. Communications of the ACM, 43(5): 51-58. https://doi.org/10.1145/332833.332838

Rajagopalan R and Varshney PK (2006). Data aggregation techniques in sensor networks: A survey. IEEE Communications Surveys Tutorials, 8: 48–63. https://doi.org/10.1109/COMST.2006.283821

Rappaport TS (1996). Wireless communications: Principles and practice. Prentice-Hall, Upper Saddle River, USA.

Shih E, Cho SH, Ickes N, Min R, Sinha A, Wang A, and Chandrakasan A (2001). Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks. In the 7th Annual International Conference on Mobile Computing and Networking, Association for Computing Machinery, Rome, Italy: 272-287. https://doi.org/10.1145/381677.381703

Weerakoon NS and Liyanage KM (2020). Delay characteristics of smart grid traffic in Wi-Fi home area networks with and without other traffic. In the 4th World Conference on Smart Trends in Systems, Security and Sustainability, IEEE, London, UK: 484-489. https://doi.org/10.1109/WorldS450073.2020.9210352

Zheng J and Jamalipour A (2009). Wireless sensor networks: A networking perspective. John Wiley and Sons, Hoboken, USA. https://doi.org/10.1002/9780470443521