Article

An Efficient Algorithm in Computing Optimal Data Concentrator Unit Location in IEEE 802.15.4g AMI Networks

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Abstract. With a view to achieve several goals in the smart grid (SG) such as making the production and delivery of electricity more cost-effective as well as providing consumers with available information which assists them in controlling their cost, the advanced metering infrastructure (AMI) system has been playing a major role to realize such goals. The AMI network, as an essential infrastructure, typically creates a two-way communication network between electricity consumers and the electric service provider for collecting of the big data generated from consumer's smart meters (SM). Specifically, there is a crucial element called a data concentrator unit (DCU) employed to collect the boundless data from smart meters before disseminating to meter data management system (MDMS) in the AMI systems. Hence, the location of DCU has significantly impacted the quality of service (QoS) of AMI network, in particular the average throughput and delay. This work aims at developing an efficient algorithm in determining the minimum number of DCUs and computing their optimum locations in which smart meters can communicate through good quality wireless links in the AMI network by employing the IEEE 802.15.4g with unslotted CSMA/CA channel access mechanism. Firstly, the optimization algorithm computes the DCU location based on a minimum hop count metric. Nevertheless, it is possible that multiple positions achieving the minimum hop count may be found; therefore, the additional performance metric, i.e. the average throughput and delay, will be utilized to select the ultimately optimal location. In this paper, the maximum throughput with the acceptable averaged delay constraint is proposed by considering the behavior of the AMI meters, which is almost stationary in the AMI network. In our experiment, the algorithm is demonstrated in different scenarios with different densities of SM, including urban, suburban, and rural areas. The simulation results illustrate that the smart meter density and the environment have substantially impacted on a decision for DCU location, and the proposed methodology is significantly effective. Furthermore, the QoS in urban area, i.e. a highly populated area for SM, of the AMI network is better than those in the suburban and rural areas, where the SM density is quite sparse, because multiple available hops and routes created by neighboring meters in the dense area can help improve the average throughput and delay with the minimum hop count.

Keywords: Optimal placement algorithm, data concentrator unit, smart grids, IEEE 802.15.4g, AMI.

1. Introduction

Based on the communication of the traditional electricity grid, it is unidirectional communication in nature, and with its limited capability, the grid is impossible to pervasive control and monitoring its equipment. Smart grid (SG), the next generation electricity grid, is emerging as a convergence of information technology and communication technology to allow pervasive control and monitoring [1]. In the smart grid, an advanced metering infrastructure (AMI) network is the foundation of SG as it provides a wealth of information such as load profile, demand, time of use, and power quality data which has the advantage for electric service provider (ESP) to optimize their business planning and collect monthly consumption data used for billing. In addition, the AMI network with two-way communications allows ESP to inform consumers during critical periods of peak pricing through real-time data so that the customer can manage their energy usage more efficiently [2-5]. As shown in Fig. 1, the AMI network is composed of four parts, including 1. smart meters, 2. communication networks, 3. head-end systems (HES), and 4. meter data management system (MDMS). Smart meters collecting customer consumption data will be connected to a central unit, called a data concentrator unit (DCU), via RF networks in order to exchange the data with the head-end system. In addition, the DCU and HES will be linked through a backhaul communication network, such as cellular or optical fiber networks [6-7].
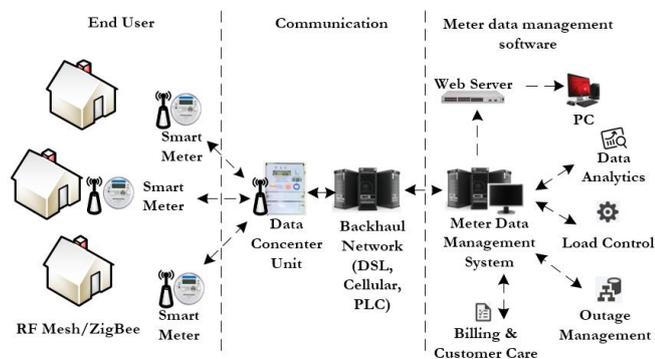

Fig. 1. The architecture of an advanced metering infrastructure (AMI) system.

When deploying and expanding the AMI communication network, the methodology for determining the DCU location and the least number of DCUs for an assigned network to guarantee the coverage area are the challenge problems. In [8], Lu et al. has proposed a distributed minimum packet forwarding algorithm for finding suitable locations at which packet aggregation for a certain destination should be performed in order to minimize a transmission cost. In [9], Tripathi et.al. have proposed a weighted centroid algorithm in providing the optimal base station positioning. The weighting factor of the algorithm has the impact to the average amplifier energy. In [10], the article presents an approximation algorithm that can guarantee (1-ϵ) optimal network lifetime performance for base station placement problem with any desired error bound $\epsilon > 0$. Although this article is not the case in AMI, one can apply some constraints of the algorithm according to the AMI context. In [11] the minimum cover set algorithm to search the optimal DCU locations is utilized, but it was not considered about the latency of the networks. In [12], they proposed the K-means algorithm to solve the DCU location; however, the single hop problem is only considered. In [13], the authors introduced an algorithm that identifies the best position for DCUs based on the number of hops obtained from the Bread-First search, Dijkstra and Bellman-Ford method. In [14], the authors investigated the data aggregation point (DAP) placement problem, and proposed solutions to reduce the distance between DAP and smart meters. In [15], the authors proposed the optimization algorithm to compute data collector locations with the reliability requirement for AMI traffic, based on power line communication technology. In [16], the DAP placement problem and proposed solutions for reducing the distance between DAPs and smart meters are investigated, in which the authors show the concept of network partition with two objectives regarding the distance minimization.

In our preliminary work [17], we have proposed the optimization algorithm for DCU placement based on a minimum hop count metric constraint with the AMI's QoS such as the average throughput and delay.

In this paper, we study on the location optimization for DCU in the AMI network, in which the effect of averaged throughput and delay could play an additional role together with the hop-count optimization to solve such optimization problem. Particularly, the reliably averaged throughput of all SM nodes with the acceptable averaged delay constraint could be considered. The developed algorithm is also conducted in different areas to investigate the impact of the environment and smart-meter density. In addition, we compare the results with the previous work [13], and it demonstrates that the performance analysis of our algorithm is considered in QoS perspective not only in hop count metric but averaged throughput and delay as well while the work [13] only considered the average delay. Moreover, our algorithm is investigated in different scenarios with different densities, but the work [13] ignored in considering the impact of different scenarios to the performance of AMI network.

This paper is organized as follows. In section 2, the advanced metering infrastructure (AMI) topology will be modeled. In section 3, an averaged throughput and delay analysis will be presented. In section 4, the optimal placement algorithm for DCU will be proposed. In section 5, the computer simulation will be examined, and the paper will be concluded in section 6.

2. Advanced Metering Infrastructure (AMI) Network Topology

In the studying AMI network model, a static cluster-tree AMI network of *N* SM nodes, i.e. SM nodes, with one DCU served as a gateway, is considered as shown in Fig. 2. For the cluster- tree network, SM nodes are formed in logical groups, called clusters. SM nodes in each cluster are classified into two types: 1. routers 2.end nodes. The smart meters that have a function in multi-hop routing are known as *routers,* whereas the SM nodes that cannot associated with the other smart meters and do not participate in routing are known as *SM end nodes* [18]. We denote that the x-hop node represents a SM node whose hop-count distance to the DCU is equal to x hop counts. In this study, the ratio of the x-hop SM node in the network is assumed to be known to the system administrator prior to perform any optimization process. Regarding the medium access control (MAC), we consider non-beacon mode 802.15.4g networks with an unslotted CSMA/CA channel access mechanism. In addition, the major communication traffic will be between the SM node and the DCU through cluster to cluster; therefore, the DCU will be the destination of all nodes. Without loss of generality, we consider the upstream traffic from SM nodes to the DCU in the rest of this paper since the routine function of the SM node is to report the load profile in every 15 minutes to the DCU, based on the worldwide utility practice. The downstream traffics, such as a firmware upgrade package, a connect/disconnect command, and the instantaneous value reading, are infrequently flowing in the AMI network.
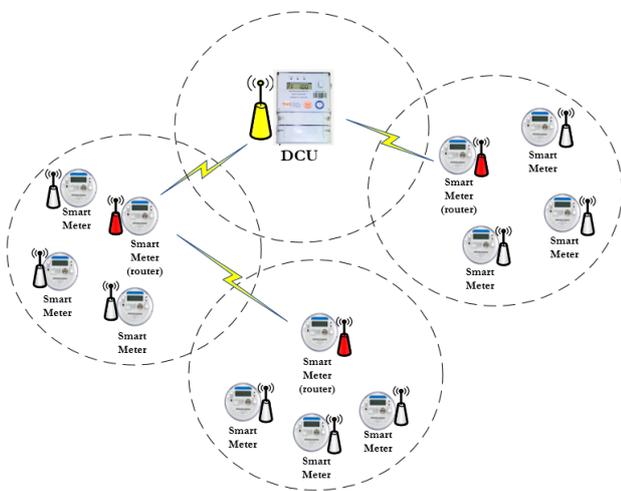

Fig. 2. Advanced metering infrastructure (AMI) network topology.

Let us define x, at each SM node, as a hop count index measuring the hop count distance from the SM node to the DCU. Generally, the traffic loads of (x+1)-hop SM node will affect the packet arrival rate of x-hop SM nodes in the multi-hop scenario because each x-hop SM node is assumed to relay packets from (x+1)-hop SM nodes. We also consider the case that all SM nodes will exhibit the same wireless channel capacity of *W* bits per second, regardless of the number of SM nodes in the network. In our study, we consider the case that each SM node is able

to buffer the incoming data from both neighboring SM nodes and itself in a queue [19]. We consider the standard routing protocol, i.e. an ad hoc on demand distance vector (AODV), that relies on the shortest path algorithm in which the lowest number of hop counts is considered as a constraint for path selection [20]. In addition, the AODV protocol has been widely used in IEEE802.15.4 ZigBee standard. This routing algorithm is considered robust and highly connected, where only one dedicated route will be assigned for data communications through flooding algorithm. The mechanism to avoid the route loop, route request message collision, and route discover error is well designed in this routing protocol.

3. Average Throughput and Delay Analysis

In this section, an averaged throughput and delay analysis are investigated.

3.1. Meter Group Clustering via K-Means Algorithm

In this section, clustering algorithm has been suggested to apply to the DCUs location problem in the AMI network. The objectives of clustering algorithm are to optimally determine the centroid of the SM population and partition the SM nodes into clusters with the intention of better management in the data communications and structure among all of them, which can then be used to generate a hypothesis for each given group [21]. K-means clustering is the simplest clustering algorithm used in many applications in which a sum of squared errors of Euclidian distance between the center of the cluster and each SM node in the coverage area will be minimized. In this paper, the maximum end-to-end delay will be configured first as the acceptable AMI networks' performance metric. Then, the SM node will be classified as a member of the given cluster if and only if it is close to the center of the cluster and meet the given performance criterion. The purpose of this process is to guarantee the quality of service in the designed cluster-tree AMI network. Next, the remaining SM nodes of interest will be grouped to another cluster by setting the new centroid as well as the given performance metric. The same procedure will be repeated until all meters of interest are grouped to the proper cluster. It is worth to note that the more rigid the performance metric, the more number the clusters, which could affect the cost of installation in the practical point of view.

3.2. Throughput Analysis

Let us first define the ratio of x-hop SMs in the network as h(x), and the total number of SM nodes in the network as *N*. It is worth noticing that h(x) depends on the routing protocol, the geographical distribution of SMs, and the transmission coverage range. When the maximum number of hops, i.e. H hops, is specified, the throughput analysis for RF AMI networks is readily derived next. Note that there will be no data traffic sending from the H(x+1)-

hop SM node. In our system, each packet may be lost due to wireless channel error, we define the packet error rate at physical layer as P_{phy} [22]. Hence the probability of packet loss over the wireless channel after L times of packet retransmissions is given by

$$P_{phyloss}=P_{phy}^{L+1} \tag{1}$$

where L denotes the times of packet retransmission and its maximum number is not more than 3.

At the same time, the service rate at the x-hop node is given as

$$\mu(x)=\frac{\left(1\text{-}P_{phy}^{L+1}\right)}{\mu_0\left(1\text{-}P_{phy}\right)} \tag{2}.$$

In this case, t_0 is the effective service time of system without error in the wireless channel which is computed by

$$t_0=t_{CSMA}+t_{DATA}+t_{TURNAROUND}+t_{ACK} \tag{3}$$

where t_{CSMA} denotes the channel access time, t_{DATA} denotes the frame transfer time, $t_{TURNAROUND}$ denotes the turnaround time, and t_{ACK} denotes the acknowledged transmission timing. Typically, the service time is equal to 6.976 milliseconds.[23]

By exploiting the standard NRZ coding, non-coherent FSK, data rate R=19.2kbps and the noise bandwidth $B_N=30$ kHz, we will get the packet error rate at the physical layer, P_{phy} as a function of SNR (γ) as

$$P_{phy}=1\text{-}\left(1\text{-}\frac{1}{2}e^{\frac{-\gamma}{1.28}}\right)^{8f} \tag{4}$$

where f denotes a frame size which is equal to 50 bytes.

Given a transmitting power P_t, the SNR, $\gamma\big(d(x)\big)_{dB}$, at the x-hop node with a distance d(x) is given as

$$\gamma\big(d(x)\big)_{dB}=P_{tdB}\text{-}PL\big(d(x)\big)_{dB}\text{-}P_{ndB} \tag{5}$$

where $PL\big(d(x)\big)$ denotes the log-normal shadowing path loss with a distance $d(x)$ and is given by [24]

$$PL\big(d(x)\big)=PL\big(d_0(x)\big)+10n\log_{10}\left(\frac{d(x)}{d_0(x)}\right)+X_\sigma \tag{6}$$

where $d(x)$ is the transmitter-receiver distance, $d_0(x)$ a reference distance, n the path loss exponent equal to 4, and X_σ a zero-mean Gaussian RV (dB) with standard

deviation σ equal to 4 and P_n denotes the noise floor and is given

$$P_n=(F+1)kT_0B \tag{7}$$

where F is the noise figure, k the Boltzmann's constant, T_0 the ambient temperature, and B the equivalent bandwidth. For our system the Chipcon CC1000 has a noise figure of 13 dB and a system noise bandwidth of 30 kHz. In this case the ambient temperature equals 300 Kelvin; hence, the noise floor is -115 dBm.

As a result, the packet error rate at a distance d(x) is

$$P_{phy}\big(d(x)\big)=1\text{-}\left(1\text{-}\frac{1}{2}e^{\frac{-\gamma(d(x))}{1.28}}\right)^{8f} \tag{8}$$

Substituting (8) into (2), we will receive

$$\mu(x)=\left[\frac{\left[1\text{-}\left(1\text{-}\left(1\text{-}\frac{1}{2}e^{\frac{-\gamma(d(x))}{1.28}}\right)^{8f}\right)\right]^{L+1}}{\mu_0\left(\left(1\text{-}\frac{1}{2}e^{\frac{-\gamma(d(x))}{1.28}}\right)^{8f}\right)^{L+1}}\right] \tag{9}$$

Since each x-hop node will relay packets from $(x+1)$-hop nodes, the relay rate $\lambda(x)$ of the x-hop node is given by [19]

$$\lambda(x)=\begin{cases}\dfrac{h(x+1)\mu(x+1)}{h(x)} & x=1,2,\dots,H\text{-}1 \\ 0 & x=H\end{cases} \tag{10}$$

where $\mu(x+1)$ denotes the service rate of the $(x+1)$-hop node. Then, the amount of traffic in the x-hop node is given by

$$\rho(x)=\begin{cases}\dfrac{h(x+1)\mu(x+1)}{h(x)\mu(x)} & x=1,2,\dots,H\text{-}1 \\ 0 & x=H.\end{cases} \tag{11}$$

Next, the end-to-end traffic throughput will be investigated. From the *M/M/1/K* queuing model in which the system consists of one server and a buffer size *K*, the blocking probability for packets at each hop is given as [25-26]

$$P_b(x) = \begin{cases} \dfrac{[1-\rho(x)\rho(x)^K]}{1-\rho(x)^{K+1}} & \rho(x) \neq 1, \\ \dfrac{1}{K+1} & \rho(x) = 1. \end{cases} \quad (12)$$

The throughput of the x-hop nodes $T(x)$ could be defined by the average number of successfully received packets per unit time at the receiver, which is the DCU is this study. Technically, such throughput $T(x)$ could be viewed as the service rate of packets at x-hop nodes that are not blocked by the intermediate nodes between the given x-hop nodes and the DCU. Hence, the non-blocking packet probability for the x-hop nodes is defined as [1-$P_b(x)$] Considering the end-to-end link in the RF AMI network, the end-to-end non-blocking packet probability is defined as the product of non-blocking probabilities at all intermediate nodes. The throughput of the x-hop nodes, $T(x)$, is given as

$$T(x) = \begin{cases} \mu(1) & x=1 \\ \mu(x) \displaystyle\prod_{i=1}^{x-1}[1-P_b(i)] & x=2,\dots,H. \end{cases} \quad (13)$$

Now, the aggregate throughput per node T_{agg}, which could be used to represent the efficiency of the system, is given as

$$T_{agg} = \sum_{x=1}^{H}[N(x)T(x)] \quad (14)$$

where $N(x)=N\cdot h(x)$ denotes the expected number of x-hop nodes. Finally, the average throughput per node T_{ave}, which could be used to represent the average efficiency per node, is given as $T_{ave} = T_{agg}/N$.

3.3. Delay Analysis

The end-to-end delay, $D(x)$, is defined as the time interval captured in between the beginning time of packet transmission sent by the x-hop SM source node and the finishing time of packet received successfully by the destination. In this study, the propagation delay is assumed to be negligible. Therefore, the end-to-end packet delay is the sum of the transmission time and the delay time in the queues for all intermediate SM nodes. Let us define the queue size in a steady state for the *M*/*M*/*1*/*K* queuing model for an x-hop SM node, $L_r(x)$, as follows [25-26]

$$L_r(x) = \begin{cases} \dfrac{\rho(x)}{1-\rho(x)} - \dfrac{\rho(x)[K\rho(x)^K+1]}{1-\rho(x)^{K+1}} & \rho(x) \neq 1, \\ \dfrac{K(K-1)}{2(K+1)} & \rho(x) = 1. \end{cases} \quad (15)$$

In fact, the delay time in the queue for all intermediate SM nodes could be determined by the sum of the waiting time spent in all intermediate SM nodes, in which the waiting time is defined as the waiting time for a packet in one intermediate SM node captured in between the time that the packet is stored in the queue of such intermediate SM node and the time that such intermediate SM node starts transmitting the first bit of the packet to the next SM node or destination. It could be shown that the waiting time for packets in the x-hop SM node, $W_r(x)$, could be readily derived as [19]

$$W_r(x) = \frac{1}{\mu(x)} + \frac{L_r(x)}{\lambda(x)[1-P_b(x)]} \quad x=1,2,\dots,H\text{-}1. \quad (16)$$

Let us define the transmission time to send the packet crossing over one intermediate SM node as t_c. Hence, the end-to-end delay $D(x)$ could be readily expressed as [19],

$$D(x) = \begin{cases} t_c & x=1 \\ x\cdot t_c + \displaystyle\sum_{i=1}^{x-1} W_r(i) & x=2,\dots,H. \end{cases} \quad (17)$$

It could be shown that the total end-to-end delay of packets generated and successfully received by all x-hop SM nodes is $N(x)\cdot T(x)\cdot D(x)$ where $N(x)$ stands for the number of x-hop SM nodes and $T(x)$ stands for the throughput of the x-hop SM node in (13). Therefore, the end-to-end averaged delay could be readily expressed as

$$D_{ave} = \frac{\sum_{x=1}^{H}[N(x)\cdot T(x)\cdot D(x)]}{T_{agg}} \quad (18).$$

4. The Proposed Optimal Placement Algorithm for DCU

In this section, we will propose the optimal placement algorithm for DCU by examining the optimization algorithm and the DCU location optimization methodology.

4.1. The Proposed Optimization Algorithm

In order to determine the optimal location for DCU, the optimization cost function has to be set up first. In the previous section, the throughput and delay are analyzed by the *M*/*M*/*1*/*K* queuing model, which could be used as the acceptable threshold criteria for ensuring the minimum end-to-end performance of the smart grid networks. In fact, the simple and effective cost function that affects both throughput and delay of the cluster-tree network is the average hop count, denoted as $H_c(l)$, where $l=1,2,\dots,L$ denoting the possible candidate DCU's location in the optimization problem with *L* positions. Hence, the optimization problem for determining the optimal location for DCU could be expressed as follows

$$\hat{l}= \min_{\{z_j\},\{y\}_{ij}} \sum_{j=1}^{N_{pole}} \sum_{x=1}^{H} y_{ij}(x \cdot h(x)_l)_{ij} \qquad (19)$$

$$\text{s.t. } D_{avg} \le D_{th} \qquad (20)$$

$$T_{avg} \ge T_{th} \qquad (21)$$

$$\sum_{j=1}^{N_{pole}} y_{ij}=1; \qquad\qquad 1 \le i \le N_{sm} \qquad (22)$$

$$\sum_{i=1}^{N_{sm}} y_{ij} \le A \; ; \qquad\qquad 1 \le j \le N_{pole} \qquad (23)$$

$$y_{ij} \le z_{ij} \qquad\qquad 1 \le i \le N_{sm} \qquad (24)$$

$$\qquad\qquad\qquad 1 \le j \le N_{pole}$$

$$z_j \in \{0,1\}; \qquad\qquad 1 \le j \le N_{pole} \qquad (25)$$
$$y_{ij} \in \{0,1\}; \qquad\qquad 1 \le i \le N_{sm} \qquad (26)$$
$$\qquad\qquad\qquad 1 \le j \le N_{pole}$$

where $\hat{l}$ denotes the optimal location position, $T_{ave(th)}$ denotes the average throughput threshold, and denotes the average end-to-end delay threshold. Constraints (20) and (21), computed in the previous section, are defined to guarantee that the average QoS of the system would meet the minimum threshold for acceptable QoS. Constraint (22) ensures that a smart meter is served only a DCU. Constraint (23) limits the maximal number of SMs per DCU. Constraint (24) ensures that a smart meter can only be connected to an electrical pole which is chosen for DCU installation.

4.2. The Problem Statement

In this section, we will propose the optimal placement methodology for DCU, taking into account the proposed optimization algorithm and constraint in the previous section. In Fig. 3 the proposed DCU location optimization methodology is shown. The proposed methodology starts from getting the position of all AMI smart meters from the GIS systems. The result is the latitude and longitude position of all meters and poles as the candidate position for DCU with the GIS map on the background. Next, the average throughput and delay as well as the maximum averaged end-to-end delay will be configured. These setting parameters are the minimum system performance guarantee to ensure the effectiveness of the AMI networks. At this stage, the number of DCU is primarily set to n=1, which will be increased if the maximum averaged end-to-end delay constraint is not met for a specific group of meters. After setting such parameters, the meters will be grouped into a cluster by using the k-means algorithm, in which the center position of the cluster will be used as a reference position for determining L candidate pole's positions for DCU. Specifically, L different pole's positions will be selected

within the radius of 100m from the center of meter cluster, in which a span of each candidate pole's position is 20m. In fact, the radius of 100m from the center of meter cluster is good enough to find the possible pole to install the DCU, and the span of 20m is typically equal to 2 poles, which is sufficient to track the dynamic behavior of the RF cluster-tree topology for optimization purposes. In this study, the AODV routing protocol for IEEE 802.15.4 ZigBee network is used, in which the shortest path routing principle will be implemented resulting in minimizing the average number of hops between meters and DCU. Next, the proposed optimization algorithm will be performed by searching for the pole location that results in the minimum averaged hop count with subject to the throughput and delay thresholds. Such thresholds have to reflect the realistic requirements for the minimum performance guarantee of the AMI network that will be varied from systems to systems. In some cases, there are multiple pole's locations that result in the same value of minimum averaged hop counts; therefore, we propose to evaluate another performance metric in order to judge the ultimately optimal DCU location. In fact, the AMI meters are almost stationary at the pole so that the average delay of the network is almost constant. Therefore, the throughput could be naturally considered as the decision-making parameter in such scenario. In this paper, we will select the ultimately optimal location for DCU based on the maximum throughput with the acceptable averaged delay constraint. This selection could, in turns, guarantee the maximum system reliability. The last procedure of the proposed methodology is to determine the average throughput and delay. If the estimated average end-to-end delay is larger than the maximum averaged end-to-end delay, the meters have to be regrouped by increasing the number of DCU by n+1, and the whole procedures for determining the optimal DCU location will be repeating again until the maximum averaged end-to-end delay constraint is met.
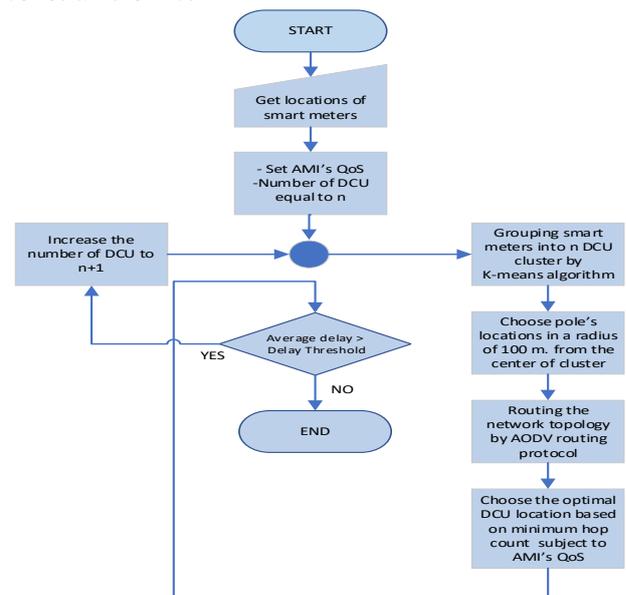

Fig. 3. A flowchart of the proposed optimal DCU placement algorithm.

5. Computer Simulation Results

In this section, the performance evaluation of the proposed optimal placement methodology will be examined by computer simulations. The experiment is tested at our university, King Mongkut's University of Technology North Bangkok, Thailand, in which there are 21 smart meters per transformer in the low-voltage distribution network. Based on the practical performance requirement, the average throughput threshold is 92 kbps, which is 80% of the system service rate, i.e. $\mu(x)=144$ kb/s, the average end-to-end delay threshold is 50 ms, which is 2.5 times of the data transmission delay over one intermediate SM node, i.e. $t_c=20$ms, and the coverage area of IEEE 802.15.4g network per hop is 50m. It is also worth noticing that the payload of information is 200 bytes which is enough for sending all instantaneous measurements, billing, and load profile data. In addition, the buffer size per SM node is $K = 300$ bytes, and the maximum averaged end-to-end delay is 200 ms.

5.1. AMI Network Topology and Performance Analysis

After computing the proposed methodology, we have found that there are 5 poles' locations for DCU placement, as shown in Fig. 4, in which DCU1 is closed to the center on the meter cluster.

Fig. 4. 5 candidate poles' locations for DCU.

Table 1. Averaged hop count, throughput, and delay.

DCU Location	Ave. Hop count	Ave. Throughput	Ave. Delay
1	2.10 hops	144 kb/s	41.9 ms
2	2.10 hops	134.86 kb/s	41 ms
3	2.48 hops	130.29 kb/s	47.8 ms
4	2.43 hops	143.66 kb/s	50.3 ms
5	2.33 hops	137.05 kb/s	44.4 ms

The average hop count, throughput, and delay are shown in Table 1. It is worth to note that there are 4 candidate poles' locations that achieve the minimum averaged hop counts; however, only DCU location 1,2,3,

and 5 are satisfied with the average throughput and delay constraints. Hence, it is necessary to determine the ultimately optimal DCU location by selecting the location that yields the maximum throughput with the acceptable averaged delay constraint. The ultimately optimal location for DCU in this case is DCU location 1. The AMI network topology for DCU location 1 and 2 are shown in Fig. 5 and Fig. 6, respectively. In addition, we compare our algorithm with the algorithm by [13] in this scenario, and its results as demonstrated in table 2 has appeared that the hop count results are the same as our results. Nevertheless, our algorithm can perform not only average delay but also throughput on AMI network whereas the algorithm by [13] focuses only on the average delay.
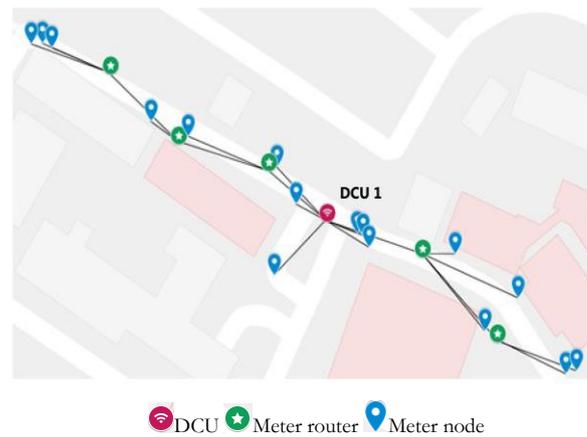

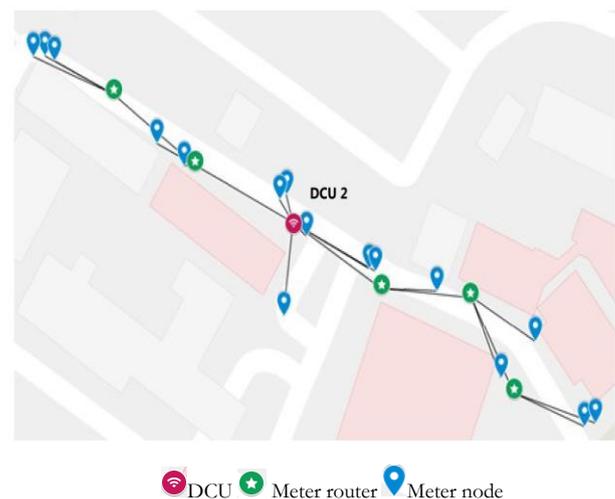Fig. 5. AMI network topology for DCU location 1.

Fig. 6. AMI network topology for DCU location 2.

Table 2. Averaged hop count, and delay.

DCU Location	Ave. Hop count	Ave. Delay
1	2.10 hops	41.9 ms
2	2.10 hops	41 ms
3	2.48 hops	47.8 ms
4	2.43 hops	50.3 ms
5	2.33 hops	44.4 ms

5.2. The Effect of Different Environments to the Performance and DCU Placement Algorithm

In this section, three scenarios of cluster-tree AMI networks with different densities of SM nodes will be demonstrated. Firstly, for urban area at Pattaya city, the candidate pole locations for DCU with 31 SMs are shown in Fig. 7, and from Table 3 the average delay of each DCU candidate attain the delay threshold. However, DCU location 3 as illustrated in Fig. 8 is the optimal position since the average hop count is 1.26 hops, which is the minimum hop count, and its QoS is subjected to the QoS constraints. Secondly, Fig. 9 illustrates the candidate pole locations for DCU with 64 SMs in suburban area at Nakhon Ratchasima city, and DCU location 2 as illustrated in Fig. 10 is chosen due to minimum hop count as shown in Table 4; that is 2.30 hops and meets the constrains. Finally, with 88 SMs in rural area at Nong Khai province as clarified in Fig. 11, Table 5 exhibits that DCU location 4 has the minimum average hop count; however, the average delay of DCU at any candidate position is above the delay threshold. Furthermore, we observe that the average hop counts in urban and suburban area are fewer than those in rural area. It can be explained as follows. In rural area the SM distribution density is quite sparse, while in urban and suburban area, the degree of SM distribution density is dense. In order to alleviate the hop count problem and the QoS not being achieved the threshold in rural area, more DCUs are required in rural area than in urban and suburban area. We will discuss the number of DCU problem in more detail in the next section.
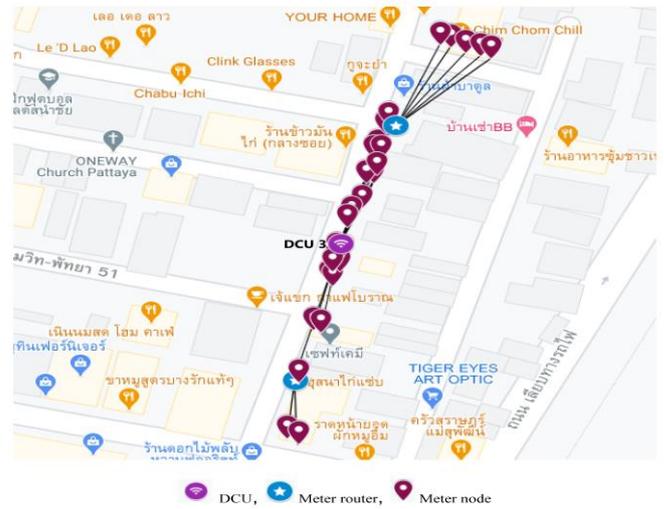

Fig. 8. AMI network topology for DCU location 3 in urban area, Pattaya City.

Table 3. Averaged hop count, throughput, and delay in urban area, Pattaya City.

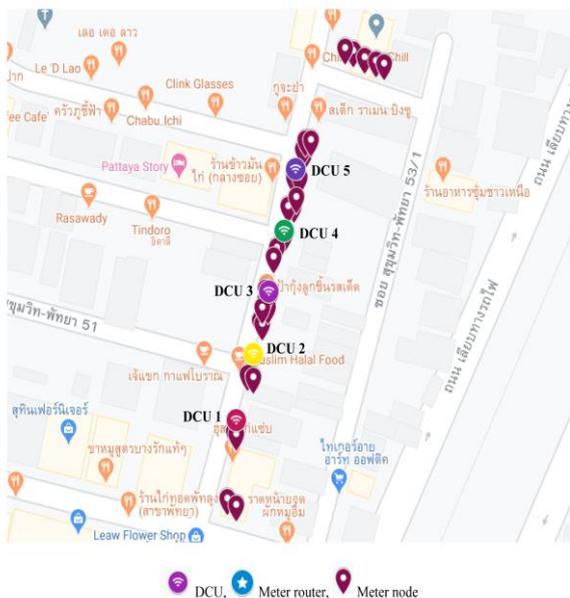| DCU Location	Ave. Hop count	Ave. Throughput	Ave. Delay
1	1.71 hops	144 kb/s	34.2 ms
2	1.52 hops	144 kb/s	30.3 ms
3	1.26 hops	144 kb/s	25.2 ms
4	1.42 hops	144 kb/s	28.4 ms
5	1.32 hops	144 kb/s	26.5 ms

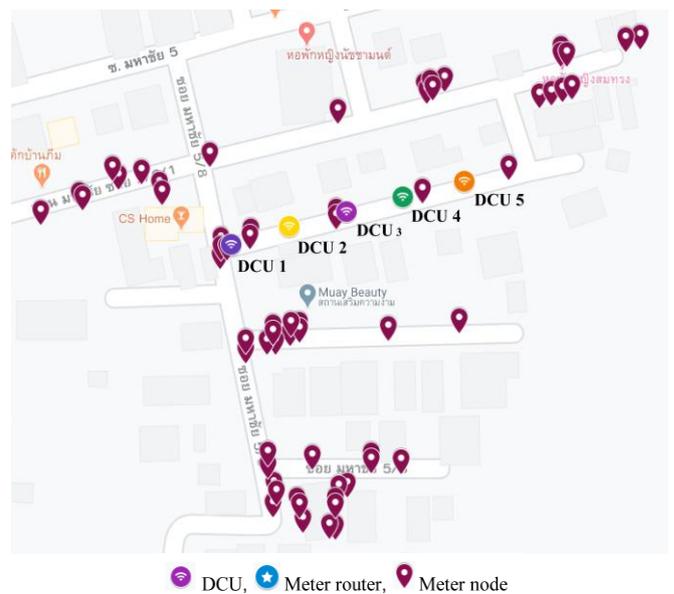Fig. 7. Five candidate poles' location for DCU in urban area, Pattaya City.

Fig. 9. Five candidate poles' location for DCU in suburban area, Nakhon Ratchasima City.

Fig. 10. AMI network topology for DCU location 2 in suburban area, Nakhon Ratchasima City.

Table 4. Averaged hop count, throughput, and delay in Suburban area, Nakhon Ratchasima City.

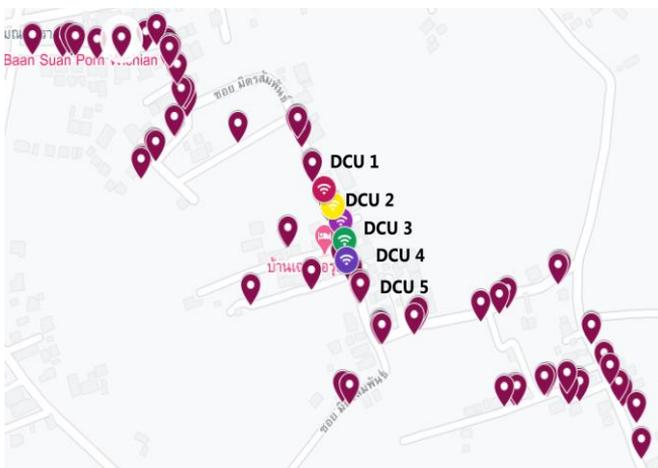| DCU Location	Ave. Hop count	Ave. Throughput	Ave. Delay
1	2.51 hops	95.85 kb/s	39.0 ms
2	2.30 hops	137.25 kb/s	44.7 ms
3	2.69 hops	103.5 kb/s	39.1 ms
4	3.14 hops	68.73 kb/s	39.9 ms
5	3.06 hops	83.57 kb/s	39.4 ms

Fig. 11. Five candidate poles' location for DCU in rural area, Nong Khai Province.

Table 5. Averaged Hop Count, Throughput, and Delay in Rural Area, Nong Khai Province.

DCU Location	Ave. Hop count	Ave. Throughput	Ave. Delay
1	5.22 hops	94.725 kb/s	77.3 ms
2	5.18 hops	75.150 kb/s	68.1 ms
3	5.30 hops	75.522 kb/s	71.1 ms
4	4.81 hops	84.763 kb/s	68.2 ms
5	4.82 hops	75.154 kb/s	53.4 ms

5.3. Delay Analysis for Delay over 50 ms Case

In the previous section, we found that the QoS of AMI networks cannot achieve the threshold, as shown in Table 5. From Table 5, the average delay in the rural area is greater than 50 ms. According to the proposed algorithm, two DCUs for rural area are positioned, as shown in Fig. 12, and the average delay problem is resolved. As shown in Table 6, the average delay of AMI networks in the rural area is improved in comparison with the previous section.

Table 6. Averaged Hop Count, Throughput, and Delay in Rural Area, Nong Khai Province with 2 DCUs.

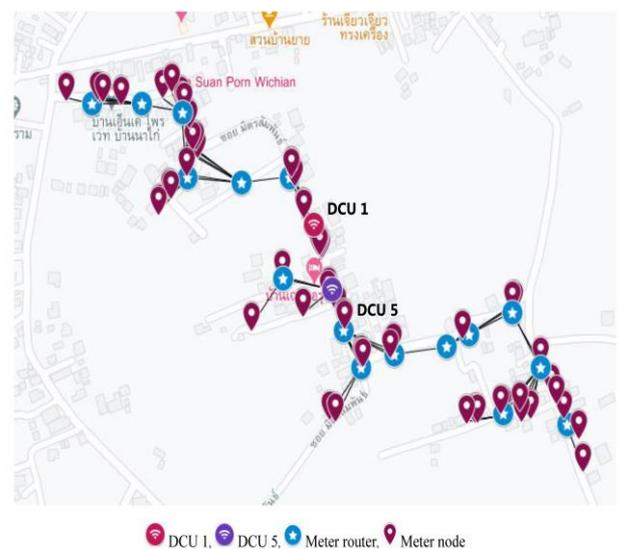| DCU Location	Ave. Hop count	Ave. Throughput	Ave. Delay
1	3.13 hops	60.85 kb/s	36.4 ms
5	5.31 hops	60.33 kb/s	29.5 ms

Fig. 12. AMI network topology for 2 DCUs at DCU location 1 and location 5 in the rural area, Nong Khai Province.

Likewise, the average delay in the highly dense area, Chiang Mai city, is greater than 50 ms.; therefore, more than one DCU are required to achieve the delay threshold. From Fig. 13, the optimal location for 2 DCUs is located at DCU 1 and DCU2, respectively. As shown in Table 7, the average delay of AMI network in the highly dense urban area is improved, i.e. less than 50 ms. We can observe that the average hop count and the average throughput of the highly dense urban area are better than those of the rural area. In addition, it is apparent that the utilization of DCU in the highly dense urban area is superior to that of DCU in the rural area. This follows from the fact that the ratio of x-hop SMs in the highly dense urban area is higher than that in the rural area, especially its ratio in the first hop which significantly affects to the performance of AMI network.

Table 7. Averaged Hop Count, Throughput, and Delay in Highly Dense Urban Area, Chiang Mai City, with 2 DCUs.

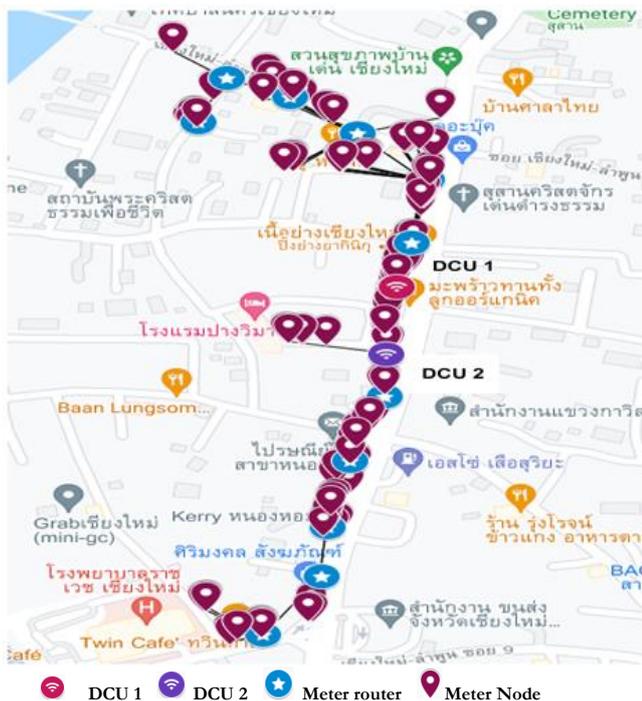| DCU Location	Ave. Hop Count	Ave. Throughput	Ave. Delay
1	2.97 hops	111 kb/s	49.6 ms
2	3.00 hops	98 kb/s	47.7 ms

Fig. 13. AMI network topology for 2 DCUs in the highly dense urban area, Chiang Mai City.

In our simulations, we have found that the proposed algorithm is significantly effective; nevertheless, the error results can occur if the transmission range defined is different from the real scenarios. This is due to the fact that the empirical measurement of the ratio of received to transmitted power has mistaken. For this reason, it is essential that the measurement data shall be elaborately collected to acquire the correct data.

6. Conclusion

In this paper, the optimal location algorithm for the data concentrator unit placement in a non-beacon mode IEEE 802.15.4g smart grid network has been investigated. The $M/M/1/K$ queuing model has been adopted for analyzing the average throughput and delay. The optimization algorithm based on a minimum hop count approach with proper constraints and optimal DCU localization methodology have been proposed. It is worth noting that the optimal location for DCU should be preliminarily determined by a minimum hop count. If the optimization solution is not unique, the DCU location selection process for the ultimately optimal location will be considered based on a maximum throughput with the acceptable averaged delay constraint in order to ensure the maximum system reliability and performance. In addition, three scenarios with different densities of SMs, including urban, suburban, and rural areas, have been examined. From the simulation results, it is obvious that the hop count, throughput, and delay in urban area are better than those metrics in suburban and rural areas because the SM nodes in urban area are densely distributed, while the SM nodes in suburban and rural areas are sparsely distributed. Moreover, it has been observed that the proposed algorithm tends to choose less number of DCUs in urban and suburban areas such that every SM node is covered. Meanwhile, more DCUs are required in rural area to serve every SM node in the desired area. The proposed methodology is significantly effective in all different scenarios, in which the optimal location for DCU yielding the acceptable averaged throughput and delay is achieved.

References

[1] G. W. Arnold, "Challenges and opportunities in smart grid: A position article," *Proceed. IEEE*, vol. 99, no. 6, pp. 922-927, Jun. 2011.

[2] F. Bouhafs, M. Mackay, and M. Merabti, "Links to the future: Communication requirements and challenges in the smart grid," *IEEE Power Energy Mag.*, vol. 10, no. 1 pp. 24-32, Jan.- Feb. 2012.

[3] H. Farhangi, "The path of the smart grid," IEEE Power and Energy Magazine, pp. 18-28, Jan.-Feb. 2010.

[4] R. R. Mohassel, A. Fung, F. Mohammadi, and K. Raahemifar, "A survey on advanced metering infrastructure," *International Journal of Electrical Power & Energy Systems*, vol. 63, pp. 473-484, 2014.

[5] Y. Kabalci, "A survey on smart metering and smart grid communication," *Journal of Renewable and Sustainable Energy Reviews (JRSER)*, vol. 57, pp. 302-318, 2016.

[6] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. P. Hancke, "A survey on smart grid potential applications and communication requirements," *IEEE Transaction on Industrial Informatics*, vol. 9, no. 1, pp. 28-42, Feb. 2013.

[7] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. P. Hancke, "Smart grid technologies: Communication technologies and standards," *IEEE Transaction on Industrial Informatics*, vol. 7, no. 4, pp. 529-539, Nov. 2011.

[8] Z. Lu and Y. Wen, "Distributed algorithm for tree-structured data aggregation service placement in smart grid," *IEEE Syst. J.*, vol. 8, no. 2, pp. 553-561, 2013.

[9] R. Kr. Tripathi, S. Dhuli, Y. N. Singh, and N. K. Verma, "Analysis of weights for optimal positioning of base station in a wireless sensor network," in *IEEE 2014 Twentieth National Conference*, 2014.

[10] Y. Shi and Y. T. Hou, "Optimal base station placement in wireless sensor networks," *ACM Trans. Sens. Netw.*, vol. 5, no. 4, pp. 1-24, 2009.

[11] G. Rolim, D. Passos, I. Moraes, and C. Albuquerque, "Modeling the data aggregator positioning problem in smart grids," in *Proc. IEEE CIT*, Liverpool, UK, 2015, pp. 632-639.

[12] F. Aalamifer, G. N. Shirazi, M. Noori, and L. Lampe, "Cost-efficient data aggregation point placement for advanced metering infrastructure," in *Proc. IEEE SmartGridComm*, Venice, Italy, 2014, pp. 344-349.

[13] G. Souza, F. Vieira, C. Lima, G. Junior, M. Castro, S. Araujo, and T. Vasques, "Developing smart grids based on GPRS and ZigBee technologies using queuing modeling-based optimization algorithm," *ETRI Journal*, vol. 38, no. 1, pp. 41–51, 2016.

[14] G. Wang, Y. Zhao, Y. Ying, J. Huang, and R. M. Winter, "Data aggregation point placement problem in neighborhood area networks of smart grid," *Journal of Mobile Networks and Applications*, vol. 23, no. 4, pp. 696-708, Jan. 2018.

[15] F. Aalamifar and L. Lampe, "Optimized data acquisition point placement for an advanced metering infrastructure based on power line communication technology," in *IEEE Access*, vol. 6, pp. 45347-45358, 2018.

[16] Y. Li, T. Wang, and S. Wang, "Cost-efficient approximation algorithm for aggregation points planning in smart grid communications," *Wireless Netw*, vol. 26, pp. 521–530, 2020.

[17] S. Tanakornpintong, N. Tangsunantham, T. Sangsuwan, and C. Pirak, "Location optimization for data concentrator unit in IEEE 802.15.4 smart grid networks," *2017 17th International Symposium on Communications and Information Technologies (ISCIT)*, Cairns, QLD, 2017, pp. 1-6.

[18] Z. Hanzálek and P. Jurˇcík, "Energy efficient scheduling for cluster-tree wireless sensor networks with time-bounded data flows: Application to IEEE 802.15.4/ZigBee," *IEEE Transaction on Industrial Informatic*, vol. 6, no. 3, pp. 438-450, Aug. 2010.

[19] T. Liu and W. Liao, "Location-dependent throughput and delay in wireless mesh networks," *IEEE Trans. Veh. Tech.*, vol. 57, no. 2, pp. 1188-1198, 2008.

[20] *IEEE 802.15 WPAN, Task Group 4g (TG4g) Smart Utility Networks*, Piscataway, NJ, USA, 2011.

[21] D. J. C. MacKay, *Information Theory, Inference, and Learning Algorithms*. Cambridge, UK: Cambridge Univ. Press, 2013.

[22] M. Zuniga and B. Krishnamachari, "Analyzing the transitional region in low power wireless links," in *First IEEE International Conference on Sensor and Adhoc Communications and Networks (SECON)*, Santa Clara, CA, October 2004.

[23] N. T. Le, S. W. Choi, and Y. M. Jang, "Approximate queueing analysis of IEEE 802.15.4 sensor networks," in *IEEE ICUFN2010*, 2010, pp.193-198.

[24] A. Goldsmith, *Wireless Communications*. Cambridge, UK: Cambridge Univ. Press, 2005.

[25] L. Kleinrock, *Queueing Systems Vol. 1 Theory*. John Wiley & Sons, 1975.

[26] J. Shortle, J. Thomson, D. Gross, and C. Harris, *Fundamentals of Queueing Theory*, 5th ed. Hoboken, NJ: Wiley, 2018.

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