Applying Queuing Theory to Evaluate Performance of Cluster Wireless Sensor Networks

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***Abstract*— Enhancement of Wireless Sensor Networks (WSNs) by improving the network performance has been researched in recent years. This paper presents the application of queuing theory to evaluate performance of WSNs using queuing network models. The analysis of performance parameters consider both kinds of data and routing packets. Moreover, the optimal values of parameters such as service rate and queue length of each sensor node are also investigated under the consideration of lossy WSNs with the coverage of signal transmission and packet loss ratio. The results of the proposed analytical model is compared with the simulation results in various scenarios for validation.**

Keywords—Wireless Sensor Networks; queuing theory; network performance

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have tremendous strides in recent years and have been widely applied successfully in the military, manufacturing, and everyday life. A WSN consists of a large number of sensor nodes which have small volume, low cost, limited computation, and constraint power capacity. They require longer lifetime, as well as higher network performance. Wireless sensor nodes not only inherit limitations of wireless networks in general (e.g. broadcast medium, collision) but also have additional restrictions such as power, dimension, bandwidth, processing speed (in addition to communication, nodes have to perform ambient sensor data), memory and buffer size [4]. Efficient buffer size of each sensor node is a key factor to reduce the production cost. If a node is congested, supposedly because the buffer size is too small, it will affect the overall network performance [1]. Especially for WSNs, retransmission of lost packets due to buffer overflow will significantly impact battery life of a node. Therefore, the determination of the optimal value of buffer size in order to minimize packet loss attracts various recent studies [1]. The applications of WSNs are often developed for a specific purpose to optimize hardware and target the lowest production cost. One of the requirements is the optimum service rate of sensor nodes to target the lowest cost (depends on the specific application) and achieve the highest performance throughout the network. In addition to the development of network, applications for WSNs increasingly require higher performance, so the evaluation of specific performance parameters (e.g. throughput, node utilization, response time, waiting time, number of packets) for WSNs has attracted a lot of recent studies [3,4,5,7]. These studies only evaluate a specific parameter in a simple network model WSNs and examine only the data information in WSNs, but they have not taken into account the routing traffic and not considered the lossy WSNs.

The contributions of this paper not only estimate the performance parameters in WSNs before deployment but also guide to design sensor hardware. The investigated optimal values can be used to enhance performance of WSNs. Moreover, this paper also applies the analysis to different WSNs model with combination of routing information and data traffic under the consideration of packet loss models.

This paper is structured in 5 sections: section 1 is the introduction to the scope of this paper, section 2 describes the background of queuing models. In section 3, the analytical models are proposed to evaluate the WSNs performance. Section 4 presents the numerical calculation and simulation of the proposal analytical models in three different scenarios. The optimal value of service rates and buffer sizes of sensor nodes, and the coverage of signal transmission in WSNs are also presented in section 4. Final conclusions are given at the end of this paper.

II. BACKGROUND OF QUEUING THEORY

WSNs consist of many sensor nodes monitoring the habitat, processing data and transmitting to the sink node or to the base station. Usually, the sensor node senses the environment with data rate λ packets/s with Poisson distribution, and the central processing unit of node processes these data with ability μ packets/s with exponential process. This behavior is similar to the model of queuing network with the external arrival rate λ packets/s and service rate μ packets/s. Hence, the queuing model is suitable for the WSNs to examine the performance parameters.

In WSNs, the probability distribution of arrival rate of sensing data and service rate of a sensor node are appropriately complied with the Poisson and exponential distribution [16]. Therefore, M/M/1 queuing model can be used to analyze the performance of WSNs. In practice, buffer size of a sensor node is also limited; hence applying model M/M/1/K to WSNs help to estimate the performance parameters of the real WSNs. The evaluation of WSNs will be analyzed by using M/M/1 and M/M/1/K models in different scenarios in section II.

Usually, the traffic in WSNs basically categorized into three following types:

- *Originated traffic*: is the data which senses the habitat and is sent to neighbor sensor nodes or to the sink node.

- *Forwarding traffic*: is the data information traffic which is transferred from neighbor nodes.
- *Routing traffic*: is introduced by routing protocol.

The data information (originated traffic and forwarding traffic) is modelled by open queuing network. Data packets are either originated packets containing collected from sensors or forwarded packets from neighbor nodes. These packets can be transmitted to the sink directly if the connection between sensor and the sink is good; or they can be forwarded to a neighbor node as intermediate node to reach the sink node using multi-hop communication. Finally collected data packets at sink node are transmitted to target base station. The data information is generated by sensing applications from outside of network and eventually leave the system, so the open queuing network model are suitable for this kind of data information network.

Popular proactive routing protocols of WSNs (e.g. CTP) usually use beacon packets containing the most important routing information of sensor nodes to find the next-hop for packet forwarding. These beacons are generated by the sink node and traverse inside the network to update the routing status of sensor nodes to the neighbors. Hence, the routing information network can be modelled by the closed queuing network.

In order to facilitate the analysis of queuing network model for WSNs, some popular symbols are defined in the following table.

TABLE 1. DEFINITION OF SYMBOLS

Symbol	**Description**
μ_i	Service rate of the jobs at the *ith* node
$1/\mu_i$	The mean service time of the jobs at the *ith* node
p_{ij}	Routing probability, the probability that a job is transferred to the *jth* node after service completion at the *ith* node.
λ_i^e	The arrival rate of jobs from outside to the *ith* node
λ_i	The overall arrival rate of jobs at the *ith* node
e_i	Visit ratio of the *ith* node in the closed networks
K_i	Number of packets at the *ith* node
W_i	Waiting queue time at the *ith* node
T_i	Response time at the *ith* node
U_i	Utilization at the *ith* node
C_Σ	Total cost for WSNs
K	Total number of packets in the closed networks

A. Model M/M/1

Model M/M/1 has the following attributes: the arrival process is Poisson process, the service times are exponentially distributed; and there are an input queue and a single server. The system can be modeled as a birth-death process with birth rate (arrival rate) λ and a constant death rate (service rate) μ. We assume that $\lambda<\mu$, so the queue is ergodic in steady state. Hence, the queuing system is stable. In model M/M/1, the performance parameters are given as following formulae:

- Average number of customers at each node:

$$E[K_i] = \sum_{k=1}^{\infty} k.\pi_i(k) = \frac{\rho_i}{(1-\rho_i)} = \frac{\lambda_i}{\mu_i - \lambda_i} \tag{1}$$

- Average waiting queue time at each node:

$$E[W_i] = E[T_i] - \frac{1}{\mu_i} = \frac{\rho_i}{\mu_i(1-\rho_i)} \tag{2}$$

- Average response time at each node, using Little's law:

$$E[K_i] = \lambda_i E[T_i] \tag{3}$$

- Utilization of each node

$$E(U_i) = \sum_{k=1}^{\infty} \pi_i(k) = 1 - \pi_i(0) = \rho_i \tag{4}$$

- Average throughput at each node:

$$E[X_i] = \mu_i \sum_{j=1}^{\infty} \pi_i(j) = \mu_i(1-\pi_i(0)) = \rho_i\mu_i = \lambda_i \tag{5}$$

B. Model M/M/1/K

Similarly, the model M/M/1/K can be modelled in birth-death process with the buffer size K. In this model, the performance parameters are given as following formulae:

$$E[K_i] = \sum_{j=0}^{K} j\pi_i(j) = \frac{\rho_i}{1-\rho_i^{K+1}}\left(\frac{1-\rho_i^K}{1-\rho_i} - K\rho_i^K\right) \tag{6}$$

$$E[T_i] = \frac{E[K_i]}{\lambda_i} = \frac{1}{\mu_i\left(1-\rho_i^{K+1}\right)}\left(\frac{1-\rho_i^K}{1-\rho_i} - K\rho_i^K\right) \tag{7}$$

$$E[W_i] = E[T_i] - \frac{1}{\mu_i} \tag{8}$$

$$E[U_i] = 1 - \pi_{i,0} = \frac{\rho_i(1-\rho_i^K)}{1-\rho_i^{K+1}} \tag{9}$$

$$E[X_i] = \mu_i \sum_{j=1}^{K} \pi_i(j) = \lambda_i \frac{1-\rho_i^K}{1-\rho_i^{K+1}} < \lambda_i \tag{10}$$

Due to limited queue length, when the queue is full (having *K* packets), a new arriving packet will be dropped. The probability of packet loss is given in the following formulae [14]:

$$P_{B,i} = \pi_i(K) = \frac{(1-\rho_i)\rho_i^K}{1-\rho_i^{K+1}} \tag{11}$$

With a given packet loss probability $P_{B,i} = \pi_i(K) = \varepsilon$, a closed-form expression for the buffer size which is the largest integer is as follows [14]:

$$K_i = \left\lceil \frac{\ln\left(\dfrac{\pi_i(K)}{1-\rho_i+\pi_i(K).\rho_i}\right)}{\ln(\rho_i)} \right\rceil \tag{12}$$

III. PROPOSED ANALYTICAL MODELS

A. Coverage of signal transmission

Because WSNs are lossy networks, packet loss probability of node *i* to node *j* in the monitoring region can be described as below [15]:

$$p_{ij,loss} = \begin{cases} 0 & , \quad d(i,j) \le R_1 \\ 1-e^{-\beta(d(i,j)-R_1)}, & R_1 < d(i,j) \le R_2 \\ 1 & , \quad d(i,j) > R_2 \end{cases} \tag{13}$$

where R_1, R_2 are parameters which are adjustable and related to the sensor physical properties, e denotes the natural logarithm, and $d(i,j)$ represents the distance between node i and node j.

Hence, the transition probability between node i and node j with consideration coverage of signal transmission is given as below:

$$p_{ij}^{*} = p_{ij} - p_{ij,loss} \tag{14}$$

B. *Queuing Networks*

1) Open Queuing Networks

The arrival rate λ_i for node $i = 1...N$ of an open queuing network is calculated by adding the arrival rate from outside and the arrival rates from all other nodes. In statistical equilibrium, the rate of departure from a node is equal to the rate of arrival. Based on the equilibrium equation, overall arrival rate of each node is calculated by an iterative method. Firstly, initial values are set to the network status, and then gradually revised the last time arrival rate by our iterative method. Finally, a system was approached to reach equilibrium. The reduction algorithm is as algorithm 1.

ALGORITHM 1

Step 1: According to transition probability, each node connection in the queuing network model is obtained. External arrival rate λ_j^e is determined.

Step 2: Initialize N nodes with the total arrival rate λ_j^0 $(1 \le j \le N)$

Step 3: Calculate the arrival rate λ_j node j:

$$\lambda_j = \lambda_j^e + \sum_{i=1}^{N} \lambda_i (p_{ij} - p_{ij,loss}) = \lambda_j^e + \sum_{i=1}^{N} \lambda_i p_{ij}^{*}$$

Step 4: Go to Step 3, until the difference of the internal arrival rate for two computing (before and after) is less than a certain value (error limit of our calculations is 10^{-4}).

Step 5. Return the total arrival rate λ_j^n of each node.

The famous model of open queuing networks is Jackson's model [2]. According to Jackson's Theorem, steady-state probability of the network can be expressed as the product of the state probabilities of the individual nodes, that is:

$$\pi(k_1, k_2, ..., k_N) = \pi_1(k_1)\pi_2(k_2)...\pi_N(k_N) \tag{15}$$

with $\pi_i(k_i) = \pi_i(0)\rho_i^{k_i} = (1-\rho_i)\rho_i^{k_i}$, for $i = 1...N$. (16)

Using algorithm 1, the total arrival rate of each node can be calculated. Using the Lagrange multiplier method [13], the optimal value of service rate with a given total cost $-C_\Sigma$ can be determined for the WSNs. In this paper, the total cost is the number which the total arrival rates of all node of network is around 90% of the cost C_Σ. The optimal value of service rate is given below:

$$\Rightarrow \mu_i^{*} = \lambda_i + \sqrt{\frac{\lambda_i}{c_i}} \cdot \frac{C_\Sigma - \sum_{i=1}^{N} c_i \lambda_i}{\sum_{i=1}^{N} \sqrt{c_i \lambda_i}} \tag{17}$$

After having the total arrival rate and optimal value of service rate of each node, the performance parameters in WSNs by applying of formulae in the model Jackson.

2) Closed Queuing Networks

The well-known model of closed queuing networks is Gordon/Newell's model. In this model, no job can enter or leave the system ($\lambda_{0i}=0$; $\lambda_{i0}=0$). This restriction means that the number of jobs – K in the system is always constant:

$$K = \sum_{i=1}^{N} k_i \tag{18}$$

The number of possible states is finite, and it is given by the binomial coefficient C_{N+K-1}^{N-1}. The following algorithm is introduced to compute the state probability as Gordon/Newell's method. After calculating the visit ratio with the equilibrium equation by applying the algorithm 1, the optimal value of service rate μ_i as (21) is also applied into this algorithm.

ALGORITHM 2

Step 1: Compute the visit ratios e_i for all nodes $i = 1,..., N$ of the closed network using:

$$e_i = \sum_{j=1}^{N} e_j (p_{ij} - p_{ij,loss}) = \sum_{j=1}^{N} e_j p_{ij}^{*}, \text{ for } i=1 \text{ ... } N$$

Step 2: Compute the functions $F_i(k_i)$ for all nodes using:

$$F_i(k_i) = \left(\frac{e_i}{\mu_i}\right)^{k_i} \cdot \frac{1}{\beta_i(k_i)}, \text{ for } i=1...N$$

Step 3: Compute the normalization constant G(K) using:

$$G(K) = \sum_{\sum_{i=1}^{N} k_i = K} \prod_{i=1}^{N} F_i(k_i)$$

Step 4: Compute the state probabilities of the network using

$$\pi(k_1, ..., k_N) = \frac{1}{G(K)} \prod_{i=1}^{N} F_i(k_i)$$

From the marginal probabilities, which can be determined from the state probabilities using the following formulae, all other required performance measures can be determined.

$$\pi_i(k) = \sum_{\substack{\sum_{j=1}^{N} k_j = K \\ k_i = k}} \pi(k_1, ..., k_N)$$

After finding the state probabilities in closed queuing networks, performance parameters are computed by definition. For example, mean number of packets at a node is given as the below formula:

$$E[K_i] = \sum_{k=1}^{\infty} k.\pi_i(k) \tag{19}$$

Similar to open queuing networks, the optimal values of service rates are driven by using the Lagrange multiplier method. With a given total cost for WSNs is equivalent to the total service rate $C(\mu) = \sum_{i=1}^{N} c_i \mu_i = C_\Sigma$. The result of optimal values is obtained:

$$\lambda^* = \frac{C_\Sigma .K}{\left(\sum_{i=1}^{N} \sqrt{c_i e_i}\right)^2 + K\sum c_i e_i}, \qquad (20)$$

$$\mu_i^* = \lambda^* e_i \left(\frac{\sum_{i=1}^{N} \sqrt{c_i e_i}}{K\sum c_i e_i} + 1 \right) \qquad (21)$$

IV. NUMERICAL CALCULATION AND SIMULATION

In this section, the analysis results are applied into section III to a typical scenario of WSNs – cluster WSNs. Both data information network and the routing information are investigated using queuing network models M/M/1 and M/M/1/K models. In addition, the service rate used in these scenario is the optimal value and the queue length in model M/M/1/K is also complied the packet loss probability around 1%. The result analysis of this topology is examined by simulation in Java Modelling Tool (JMT) [9] for comparison.

A. Scenario – Cluster Wireless Sensor Networks

The topology of cluster WSNs is composed from 4 different subnets of WSNs, which include 6 sensor nodes and one sink node at the center. In each subnet, sensor nodes transfer packets to a sink node. Then the sink node forwards these packets to other sink nodes or sends directly to the target base station [17]. In the sink node, the data packet transmission is divided into two parts: the internal part handles internal communication within the subnet while the external one handles communication between Cluster Heads (CH) in cluster WSNs. For simplicity, the data information network and the routing information network are investigated separately.

1) Data Information Networks

The data information network for cluster WSNs has topology [17] and transition probabilities as Fig. 1. In this topology, four subnets in cluster WSNs are the same. In each subnet, all node from 1 to 6 are sensor nodes, node 7 is the sink node. The external arrival rate for each node is 5 packets/s (as the experiment in a live WSN [1]). After applying algorithm 1, the total arrival rate of each node can be determined. Then the total cost for this subnet is defined as *Total Arrival Rate = 90%* C_Σ . Applying (17), it can be easy to obtain the optimal value of service rates of sensor node: $\mu_{sensors}=26.06$ (packets/s), $\mu_{sink}=93.64$ (packets/s). These optimal values are used to calculate performance parameters as section III. The numerical calculation results from each subnet WSNs are used as input for network between four CHs. Transition probabilities between four CHs are also shown in Fig. 1. Two left-hand-side CHs transmit their packets to two right-hand-side CHs to reach to the destination.

This topology is also deployed in the simulator software JMT. Result between analysis and simulation in this scenario are compared in the following figures. In these figures, node 1 to node 6 are sensor nodes in each subnet while sink1, sink2, sink3, sink4 are part of sink nodes to communicate internally of each subnet; CH1, CH2, CH3, CH4 are the cluster heads part of sink nodes to communicate externally. Basically, results are matched between analysis and simulation in both models M/M/1 and M/M/1/K. In the model M/M/1/K, performance parameters are slightly smaller than in the model M/M/1 with an acceptable gap.

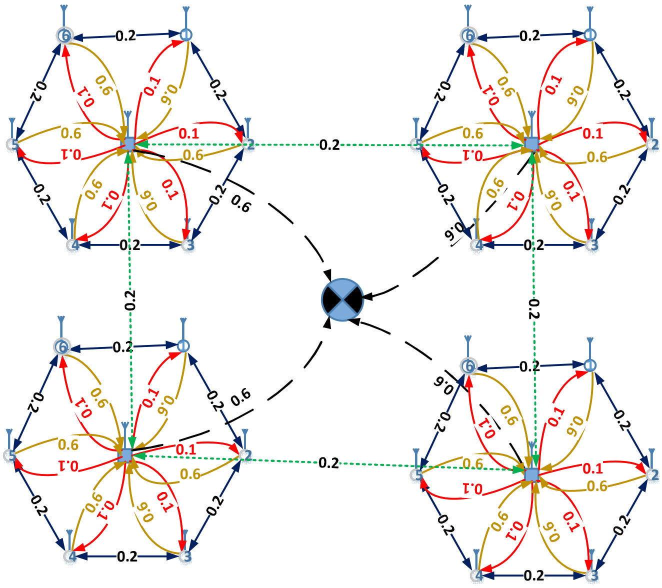

Fig. 1.Topology of data information networks in Cluster WSNs

Average numbers of packets at each sensor node are shown in Fig. 2. Because sensor nodes are symmetry in each subnet, average number of packets at sensor nodes are closely and around 7 packets/s. In the model M/M/1/K, because of the limitation of queue length, average number of packets at each node is smaller than model M/M/1. Sink node has to handle forwarding traffic from all sensor nodes, therefore the average number of packets is bigger, although the service rate of sink node is faster than sensor node. Mean number of packets in CH at subnet 1 and subnet 4 is slightly lower than at subnet 2 and subnet 3 as in 2.

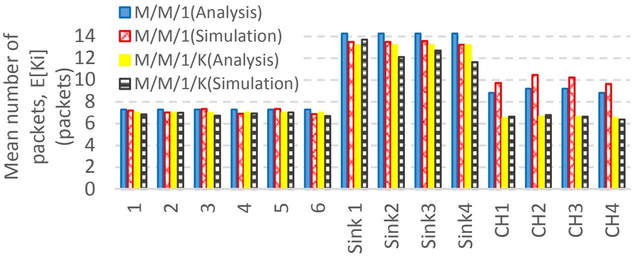

Fig. 2. Mean number of packets at each node for data information networks

In Fig. 3, the mean response times at each node are depicted. Results of analysis and simulation are nearly the same for both models M/M/1 and M/M/1/K. In model M/M/1 with infinite queue length, packet has to wait in longer queue before processing. This causes the longer response time in the model M/M/1 than in the model M/M/1/K. Mean response time at sensor nodes are higher than at sink part, and mean response time at sink part are higher than at cluster head part as shown in Fig. 3. This is because the service rate at sink part is faster than that of sensor nodes, and service rate at CH part is higher than sink part as well.

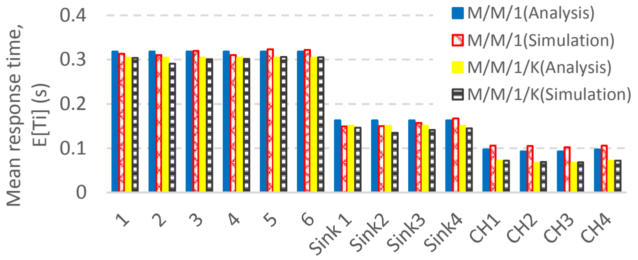

Fig. 3. Mean response time at each node for data information networks

Besides, Fig. 4 illustrates the mean throughput at each sensor node. Analysis and simulation results are similarly. Mean throughput at sink node is significant higher than sensor nodes because the traffic from all nodes is drawn toward the sink node. Mean throughputs at CH1 and CH4 are slightly smaller than CH2 and CH3 because traffic from CH1 and CH4 has to go through CH2 and CH3 as in Fig. 4.

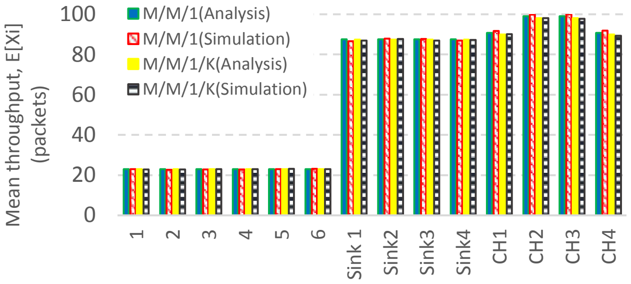

Fig. 4. Mean throughput at each node for the data information network.

2) *Routing Information Networks*

Routing information networks in cluster WSNs have a topology between subnets. The routing information in cluster WSNs is modeled by closed queuing network and divided into levels as hierarchical structure. Each subnet communicates routing information packets internally for updating the status, finding the best route (e.g., shortest-path based) to reach to sink node. At higher level, the routing information networks between four CHs are established to find the route to the target base station as well. The routing information network between four CHs is investigated with total number of packets in this network is a constant number $K=4\text{-}1=3$ packets. Assume that each CH transmits routing information packets to three other CHs with equal probability.

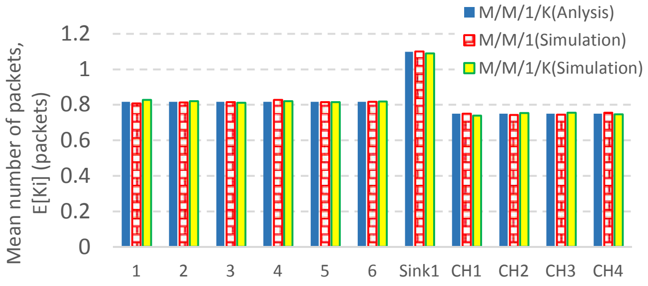

Fig. 5. Mean number of packets at each node for the routing information network.

Applying algorithm 2, state probabilities of each node are found and then performance measures are determined in closed queuing network. Results between analysis and simulation in this scenario are shown in the following figures. Mean number of packets in the sink node is around 1 packet and a little bit higher than in sensor nodes as shown in Fig. 5.

In the meanwhile, the mean response times at sensor node are slightly higher than at sink node and CH part of sink node as in Fig. 6 because the service rate of sensor nodes are lower than sink part and CH part of sink node.

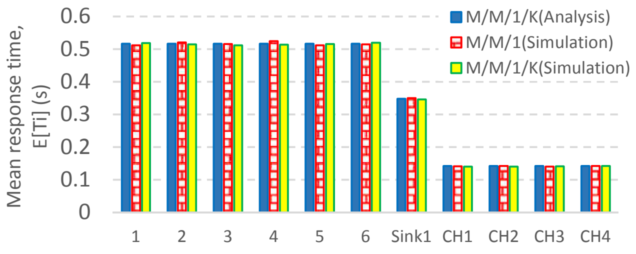

Fig. 6. Mean response time at each node for the routing information network.

Moreover, the mean throughput of sink part and CH part are higher than sensor node because all sensor nodes are connected to sink node. Especially in CH part of sink node, their service rate is high to ensure that the routing information at subnet level is always updated. Therefore, the throughput at CHs is higher than sink part and sensor node as in Fig. 7.

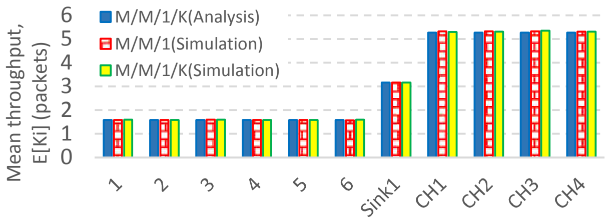

Fig. 7. Mean throughput at each node for the routing information network.

B. *Optimal Value of Service Rates and Buffer Sizes*

In this section, the service rates and buffer sizes are investigated to find the optimum values. After that, these optimums are validated by simulation in simple one layer WSN (a subnet of cluster WSN).

1) *Optimal Value of Service Rates*

Optimal values of service rates are found in analysis in section III. In this section, the JMT tool is used to simulate with a range of service rates. Results of simulation will indicate which values are the optimal for performance parameters (mean number of packets, mean response time, and throughput). When service rate of sink node changes, the average number of packets at node 1 are simulated and the optimal value of average service time of sink node is around 0.011s, it is equivalent to the service rate is 1/0.011s = 90.91 (packets/s). The result is similar to analyzed value 93.64 (packets/s). Similar to the sink node, optimal value of service rate of sensor nodes is validated by changing the service rate at the observed node. Because all sensor nodes play the same role, node 1 is selected to simulate and examine. When the service rate at node 1 changes, the average number of packets at node 4 is changed. In this simulation, the optimal value of service rate of node 1 is 1/0.039s = 25.64 (packets/s). This value is similar to the analyzed value (= 26.06 packets/s).

Therefore, the results of simulation for both sensor nodes and sink node prove the optimization process in the proposed analytical model.

2) *Optimal Value of Buffer Size*

In the same examined scenario simulation, the optimal queue length is investigated such that the probability of packet loss is estimated to be 1%. In this section, we verify the value of the calculated optimal queue length by changing queue length of sensor node 1 around the analytical optimum value.

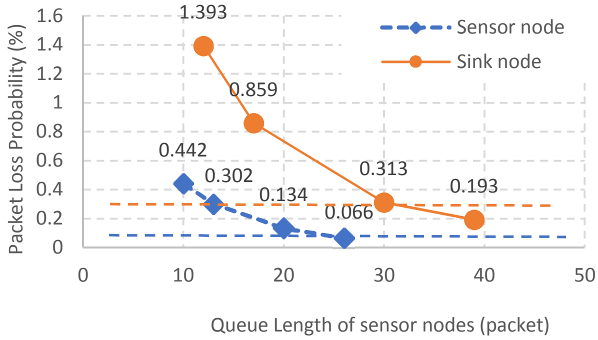

Fig. 8. Probability of packet loss at nodes

It can be seen clearly that the probability of packet loss in sensor nodes and sink nodes decrease when the queue length increases as in Fig. 8. However, it cannot be optimal to produce the node with very large queue length because it increases cost and inefficiencies in the management of nodes causing unnecessary battery drain. Within the scope of this paper, probability of packet loss is desired about 0.1% at sensor nodes and 0.3% at sink node. Based on the analysis and simulation, the calculated values in data information network in one layer WSNs are optimal. According to the simulation, the optimal queue length of the sink node and the sensor node are 30 and 20 packets respectively.

V. CONCLUSIONS AND OUTLOOKS

In this paper, performance of WSNs are analyzed by applying queuing theory in different models (M/M/1 and M/M/1/K) in the typical cluster WSNs scenario. The optimal values of service rates are given with total cost suitable for external arrival rate of specific application. Queue length of sensor node in model M/M/1/K is provided to node's design of the guidance number of buffer size. This paper also examines the effect of coverage of signal transmission in lossy WSNs. All results are analyzed and simulated for comparison in many practical scenarios.

In the future, the proposed analytical model will be extended to investigate the network performance of WSNs with mobility support. Another improvement of the model is support many queuing classes for different kinds of application traffic.

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