A Packet Buffer Evaluation Method Exploiting Queueing Theory for Wireless Sensor Networks

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Abstract. In large-scale wireless sensor networks (WSNs), when the consumption of hardware is limited, how to maximize the performance has become the research focus for improving transmission quality of service (QoS) of WSNs in recent years. This paper presents a new evaluation method for packet buffer capacity of nodes using queueing network model, whose packet buffer capacity is analyzed for each type node, when it is in the best working condition. In order to evaluate congestion situation in the queueing network, and to get real effective arrival rates and transmission rates in the model, holding nodes were added in the queueing network model, and equivalent queueing network model is expanded. We establish an M/M/1/N type queueing network model with holding nodes for WSNs and design approximate iterative algorithms. Experimental results show that the model is consistent with the real data.

Keywords: wireless sensor networks, queueing network model, blocking, packet buffer capacity, node utilization.

1. Introduction

Wireless sensor networks (WSNs) are successfully applied in intelligent transportation, monitoring environment, location and other fields. They consist of tiny sensing devices that have limited possessing and computation capabilities, and can collaborate real-time monitoring, sensing, collecting network distribution of the various environments within the region or monitoring object information [1,2,3]. WSNs of distribution regions are composed of sink nodes [4,5,6], transmission nodes and boundary nodes [7]. The performance of each type node will affect the overall network performance in WSNs. Throughput and utilization [8,9,10] of the nodes in the lifetime [11,12] are the main evaluation performance indicators of WSNs. The

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packet buffer capacity of nodes is an important factor in utilization of network nodes [13]. If a node of WSNs is blocked, and packet buffer set too small, the entire network data transmission and processing efficiency is not high. Therefore, when the consumption of hardware is limited, how to optimize the node packet buffer size and maximize the performance for WSNs has become a research focus for improving the Quality of Service (QoS) of WSNs transmission in recent years.

In this paper, we consider that packet buffer capacity corresponds to the length of the waiting queue in the established limited capacity of the queueing network model. When the length of the waiting queue reaches the maximum, the node is blocked in the queueing network model. Therefore, a typical WSN is modeled by M/M/1/N type queueing network model. The method of modeling based on topology of nodes in WSNs and performance analysis of the packets buffer capacity have been proposed. According to the topology of WSNs and operational characteristics, arrival, transferring and leaving relationships of transmission nodes, boundary nodes and sink node are analyzed, and data flow balance equations are obtained. In order to evaluate the congestion situation in the queueing network, and get real effective arrival rates and transmission rates in the model, holding nodes were added in the queueing network model and equivalent queueing network model is expanded. By analyzing the queueing model with blocking probability, to obtain the performance index of system when it is in steady state, approximate iterative algorithms are designed. The performance parameters of nodes model in the WSNs are calculated using limited iteration times. The optimal values for packets buffer sizes settings are obtained for transmission nodes, boundary nodes and sink nodes.

The remainder of this paper is organized as follows. The related work and problem statement are introduced in Section 2 and Section 3. Section 4 describes the modeling of WSN and analysis. Section 4.1 describes the modeling method of using open queueing network model for WSNs; the balance equations of data flow are established. In Section 4.2, the equivalent queueing network model is obtained, that holding nodes are added in the may be blocking nodes. The model parameters of blocking probability of data packets, the arrival rate and node transfer rate, all are analyzed in Section 4.3 using the equivalent queueing model. Section 5 designs iterative approximation algorithms for total arrival rate of nodes and effective arrival rate and transfer rate of nodes with blocking probability. Section 6 gives the numerical calculation and analysis of experimental results. The performance parameters of WSN nodes are calculated using iterative algorithms given in Section 5. According to the relationship curves between utilization and buffer size, the packets size of the optimal buffer settings are obtained for transmission nodes, boundary nodes and sink node, respectively. The correctness of modeling and analysis method is verified by experimental data of the WSNs. Section 7 contains the conclusion and future work.

2.   Related Work

When the hardware has been implemented, it is difficult to adjust the node's hardware resources in accordance with specific needs. Therefore, researchers have proposed the need for large-scale WSN nodes modeling method [14]. Through performance evaluation of pre-setting nodes, optimal parameters of allocation for the hardware nodes are obtained. The current modeling method based on Petri nets [15,16,17] is suitable for macro-modeling, but it is not a specific modeling technique for large-scale WSNs. Queueing network is an effective system-level modeling method, which is widely used in the modeling and performance analysis of computing and communication systems [18,19]. It has many advantages that include a highly abstract and rich theory for modeling.

In recent years, researches have made some progress on analyzing and improving network performance in the application of finite capacity queueing networks. Bisnik et al. [20] modeled random access multi-hops wireless networks as open G/G/1 queueing networks and used diffusion approximation in order to evaluate closed form expressions for the average end-to-end delay. In [21,22], Kouvatsos and Awan described the priorities and blocking mechanisms with open-loop queueing network performance analysis, and queueing network parameters on the approximation and error estimates. Özdemira et al. [23] presented two Markov chain queueing models with M/G/1/K queues, which have been developed to obtain closed-form solutions for packets delay and packets throughput distributions in a real-time wireless communication environment using IEEE 802.11 DCF. Mann et al. [24] developed a queueing model for analyzing resource replication strategies in WSNs, which can be used to minimize either the total transmission rate of the network or to ensure that the proportion of query failures does not exceed a predetermined threshold. In [20], Liehr et al. introduced enhancements to the standard of extended queueing network models, which allow the modeling and the simulation of inter-process communication and highlight the benefits granted by their enhanced EQN approach. However, these researches don't address the packet buffer capacity of nodes and how to set the buffer size to derive the optimal performance of the nodes in WSNs.

3.   Problem Statement

Data packets are transmitted and processed in collaboration by the sink nodes, transmission nodes and boundary nodes. For a large scale WSN, a queueing network model can be used to analyze its performance [25, 26]. But how to configure resources to find the best value hardware using trends of changing the parameters of performance is an important reference for node design. The definition of the threshold of node buffer capacity is given below:

Definition 1. When the queueing network system is stable, node's hardware buffer capacity just accommodate the maximum length of the queue

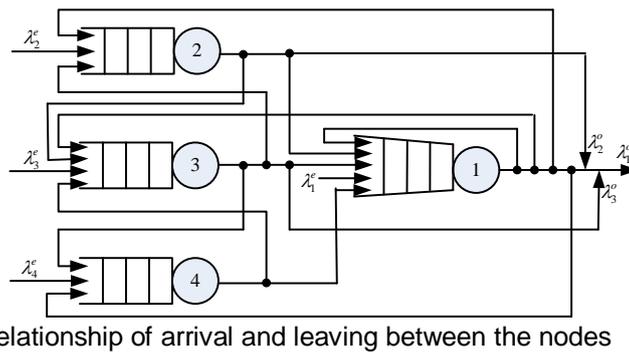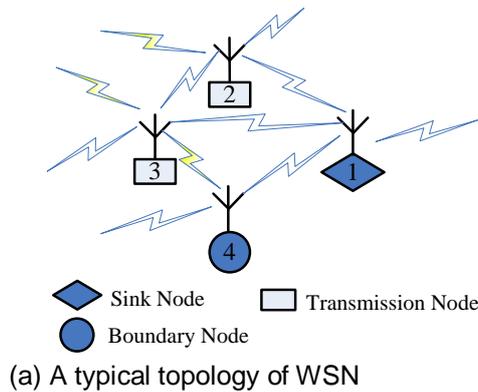to be processed. Buffer size value at the moment is called the node threshold, denoted by N_T.

(a) A typical topology of WSN

(b) Relationship of arrival and leaving between the nodes

Fig. 1. Topology and node transfer of the WSN.

In WSNs, for any node buffer size, we make the following discussion:

(i) If $N_i \geq N_T$, node queue length will never be processed over the buffer capacity when a system is in a steady state. Therefore, the packets that have not been timely processing data will be placed in the packet buffer. Newly arrived packets will not cause the blocking node server.

(ii) If $N_i < N_T$, when the packet buffer of node is full, the link paths that include the nodes are blocked, and lead to the processing efficiency of the whole WSN down. On the other hand, when the link path is blocked, all the nodes are in an active state in the link path. Therefore, energy consumption of the node is larger, and individual nodes are invalidated due to energy exhaustion.

Figure 1(a) shows a typical topology of WSN, which is composed of sink node 1, transmission nodes 2 and 3, and boundary node 4. According to the modeling method of open queueing network, it describes the transmission

relationship between the node queues as shown in Figure 1(b), where λ_i^e is the independent external Poisson arrival rate of node i and λ_i^o is the leaving rate after the completed service of node i. (Note: Boundary node does not include λ_i^o).

In practice, the task content of sink nodes, transmission nodes and boundary nodes is different. Therefore, its consumption of hardware resources will be different. For example, in Figure 1(b), the arrival rate of sink node 1 packets is the maximum. Therefore, finding a way to properly evaluate its performance becomes very important. That is, how to set the packet buffer capacity of wireless sensor nodes, in order that each node has the highest speed of data processing and throughput. Thus, the best parameters between the utilization of node and consumption of hardware buffer capacity will be found. In order to facilitate the analysis of queueing network model for WSNs, some symbols are defined in Table 1.

Table 1. Definition of symbols

Symbol	Description
i, j, k, d	Node No. in the queueing network.
M	Total number of paths in the queueing network.
N	Size of packet buffer capacity
λ_i	Arrival rate of node i.
μ_i	Service rate of node i.
ρ_i	Utilization of node i.
p_i	Steady-state probability of arrival node i.
p_i^o	Leaving probability from node i.
p_{ij}	Probability of from node i to node j.
S	State of node.
T_i	Monitoring cycle of i-th times in WSN.
A	Aggregate of all the holding nodes.
pb_{ij}	Blocking probability from node i to node j.
pb_i^e	Independent external Poisson arrival blocking probability of node i.
pb_i^a	Total arrival blocking probability of node i.

4. Open Queueing Network Analysis for WSN Model

In this section, we describe the modeling method of using open queueing network model for WSNs and the balance equations of data flow are established. In order to analyze blocking of the queueing network model, holding nodes were added in the may be blocking nodes, and the equivalent

queueing network model is obtained. Therefore, analysis of the blocking queueing network is possible.

4.1. Open Queueing Network

A typical open queueing network composed of WSN is consistent with a flow balance equation. According to the theorem for flow balance equation [25,27], we can give Corollary 1 and Corollary 2 for any WSN.

Corollary 1. For the transmission node, arrival node and leaving node in the queueing network of WSN, the number of all possible packets leaving the node i equals that of the arrival number in the state.

$$\lambda_i^e + \sum_{i=1}^{m-1} \lambda_k p_{ki} = \sum_{f=j}^{d} \lambda_i p_{if} + \lambda_i p_i^o \tag{1}$$

Proof: Using reductio ad absurdum, suppose the number of packets entering the node i is not equal to the number of packets leaving the node i, then according to the flow balance equation, there must be packets with probability $p_{ii} \neq 0$ in the self-loop. This is in contradiction with the fact that transfer node, arrival node and leaving node service is the order of one-way services in WSNs. Therefore, the Corollary 1 is established. □

Corollary 2. For the sink node in the queueing network of a WSN, the sum of the arrival packet and self-loop packet equals that of the sum of the leaving packet for node i in the state.

$$\lambda_i^e + \sum_{i=1}^{m-1} \lambda_k p_{ki} + \lambda_i p_{ii} = \sum_{f=j}^{d} \lambda_i p_{if} + \lambda_i p_i^o \tag{2}$$

Proof: For the sink node in the queueing network of a WSN, data transmission between nodes requires a very high accuracy. When the data packets validation is not correct, we should have re-transmission processed until the correct calibration data is received. Therefore, the phenomenon of self-loop appears in the node i. Increased the number of arriving packet is equivalent to $\lambda_i p_{ii}$. Therefore, we can get the sum of arrival packet as equation (3).

$$\lambda_i = \lambda_i^e + \sum_{i=1}^{m-1} \lambda_k p_{ki} + \lambda_i p_{ii} \tag{3}$$

According to flow balance equation [25,27], we can deduce that the flow balance equation (2) is established. □

The Nodes are used in environmental monitoring and control in WSNs, due to factors such as limited power consumption, which are not always in running state [28,29,30]. The states of nodes in WSNs are alternating between

monitoring and sleeping, as a premise in meeting the required monitoring conditions. Switching between states of nodes is shown in Figure 2.
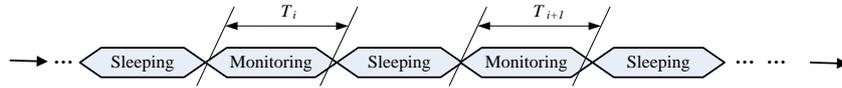

Fig. 2. Switching between states of nodes.

Next, we give the definition of the longest monitoring cycle of node i.

Definition 2. For all nodes in WSNs, the wake-up from a sleeping state into the monitoring state, and then entry into another sleep experienced by far the longest time is known as the longest monitoring cycle of WSN nodes.

$$T_i^m = \max\{T_1, T_2, \ ..., T_i \ , \ ..., T_N\} \tag{4}$$

In WSNs, each node has a packet capacity. If the packet buffer size is set too large, would be a waste of resources. Conversely, if the data packet buffer size is set too little, block of system will be increased. We give the theorems for packet queue length of sink nodes and transmission nodes.
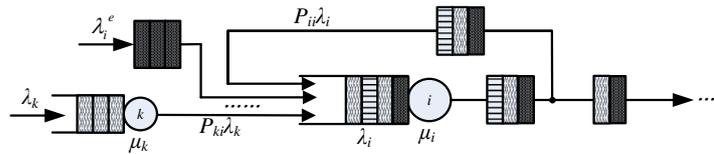

Fig. 3. Transmission relation of packet queue for sink node i.

Theorem 1. For any sink node i in WSNs, packet queue length of sink node is L_i^m, then the following relationship is obtained.

$$\lambda_i^e + \sum_{i=1}^{m-1} \lambda_k p_{ki} = \frac{L_i^m}{T_i^m} + (1 - p_{ii})\mu_i \tag{5}$$

Transmission relation of packet queue for sink node i in WSNs is shown in Figure 3. We give the proof of Theorem 1 below.

Proof: For sink node i in WSNs, according to Corollary 2, the data packets arrival rate is obtained by equation (6).

$$\lambda_i = \lambda_i^e + \sum_{i=1}^{m-1} \lambda_k p_{ki} + \lambda_i p_{ii} \tag{6}$$

In the time period, the arrival number is X_i given by equation (7).

$$X_i = T_i^m \lambda_i \tag{7}$$

At this time, the service rate is μ_i. The number of the data packets is Y_i given by Equation (8) after completion of the service.

$$Y_i = T_i^m \mu_i \qquad (8)$$

Therefore, packets queue length of node i is L_i^m, which is the difference between the number of effective arrival and leaving, and minus the number of packets being processed.

$$L_i^m = X_i - Y_i - 1 \qquad (9)$$

Putting Equations (6), (7), and (8) into Equation (9) will result in Equation (5). Therefore, Theorem 1 is proved. □

Theorem 2. For any transmission node i in WSNs, if packets queue length of transmission node is L_i^m, then the following relation is obtained.

$$\lambda_i^e + \sum_{i=1}^{m-1} \lambda_k p_{ki} = \frac{L_i^m}{T_i^m} + \mu_i \qquad (10)$$

Proof of Theorem 2 is relatively simple, using Corollary 1, and with reference to the proof of Theorem 1.

4.2.   Equivalent Queueing Network Model

The packet buffer size should be consistent with the length of the queue in the queueing model of WSNs. When the queue length reaches the maximum, the packet streams are stopped, resulting in queueing network being blocked [31,32]. When a data packet transfers from one queue to another queue and if the path is full, the packet will be blocked in by the just completed service in the queue. Then the blocked node cannot handle any other data packets until the destination node services, where there is a free packet buffer before they can lift the blocking. This situation is called Transfer Blocking.

Transfer blocking makes the internal arrival process and service process of node complicated. The blocking rule is that blocking should occur after service. Therefore, the queue will not be cached, only waiting on the link path. Some researchers [33,34,35,36] have discussed about thinking of adding holding nodes in the queueing networks, that adds the imaginary limitless capacity nodes, which may occur on the blocking path in the infinite queueing networks. The basic idea is to remove the blocking server, that is unblocked and save it in the holding nodes. As shown in Figure 1, the queueing network model for the topology of WSN is expanded to include holding nodes. Equivalent queueing network models are shown in Figure 4. M/M/1/∞-type queues are added holding nodes. (Note: When added to holding nodes, assuming that the original node does not exist, blocking is established.)

Intervals between the arrival time accord with the exponential distribution. Thus, we calculate the real effective arrival rate nodes, and its performance evaluation is possible.
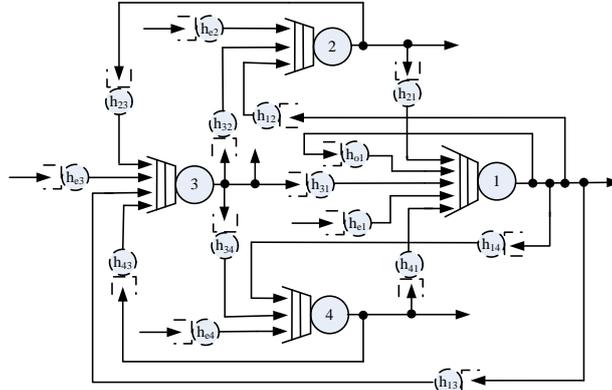

Fig. 4. Queueing network model with holding nodes.

4.3.   Queueing Model Analysis with Blocking Probability

When the holding nodes are added in queueing network, the packets that did not receive timely services are stored in the queue of holding nodes, as waiting for an empty target node. Total effective arrival rate is equal to the external arrival rate λ_j^e and the internal arrival rate of nodes $i^1, i^2, ..., i^A$ after considering blocking nodes. Then, the queueing network model with blocking probability is shown in Figure 5. Below we discuss flow balance of arrival and leaving data packets in the queueing network model.
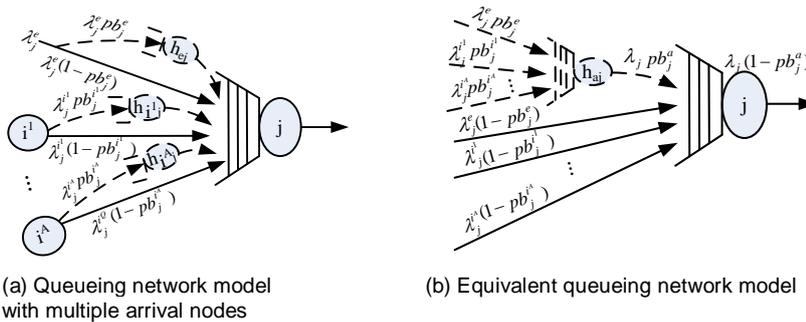

(a) Queueing network model with multiple arrival nodes

(b) Equivalent queueing network model

Fig. 5. Queueing network model with blocking probability.

Figure 5(a) shows that multiple arrival nodes are blocked in node j, and Figure 5(b) shows an equivalent model of Figure 5(a).

Therefore, the external effective arrival rate $\overline{\lambda}_j^e$ of node j is obtained as in Equation (11).

$$\overline{\lambda}_j^e = \lambda_j^e (1 - pb_j^e) \tag{11}$$

The effective data packets stream from node i to node j as shown in Equation (12).

$$\lambda_{ij} = \lambda_i p_{ij} (1 - pb_{ij}) \tag{12}$$

Let $\overline{\overline{\lambda}}_j$ be the effective internal arrival rate of node j, which is equal to the sum of effective internal arrival rate from independent internal nodes $i^1, i^2, \dots, i^A$.

$$\overline{\overline{\lambda}}_j = \sum_{i \in A} \lambda_{ij} \tag{13}$$

Total effective arrival rate with probability pb_j^a of node is obtained by Equation (14).

$$\overline{\lambda}_j = \lambda_j (1 - pb_j^a) \tag{14}$$

According to Corollary 1 and Corollary 2, we can obtain a flow balance equation of queueing network with blocking.

$$\overline{\lambda}_j = \overline{\lambda}_j^e + \overline{\overline{\lambda}}_j \tag{15}$$

Equation (16) is derived from applying equations (11) (12) (13) (14) into Equation (15).

$$\lambda_j (1 - pb_j^a) = \lambda_j^e (1 - pb_j^e) + \sum_{i \in A} \lambda_i p_{ij} (1 - pb_j^i) \tag{16}$$

In order to obtain the effective arrival rate of node j, the calculations of blocking probability pb_{ij}, pb_j^a and pb_j^e are needed. The three blocking probabilities are calculated, the specific derivation is shown as in [37].

Now we can determine the performance parameters of each type node according to the connection between nodes. In this paper, we use the approximate calculation. First, the initial values of blocking probabilities are given, then the algorithm performs in a limited iteration times. When the effective arrival rate and departure rate tends to reach equilibrium, the iterative algorithm is finished.

5. Total Arrival Rate of Nodes and Approximate Algorithm

Blocked nodes are released by adding holding nodes of infinite capacity in the queueing network model. Processing time of blocked node is the blocked time, and thus we can describe arrival and service process of nodes in the equivalent queueing network model. In a lot of practical application and engineering experiments, we found that when WSN node communication enters into a stable state, the average arrival rate of node tends to be a constant value. We designed an iterative method, such as shown in Algorithm 1. We set initial values to the network status, and then gradually revised the last time arrival rate by our iterative method. In the end, a system was approaching to reach equilibrium. The reduction algorithm is as follows.

Algorithm 1

Begin

Step 1. According to transition probability, each node connection in the queueing network model is obtained. External arrival rate $\lambda_j^{\,e}$ (j is the number of nodes) is determined.

Step 2. Initialize n nodes with the total arrival rate $\lambda_j^{\,0}$ $(1 \le j \le m)$.

Step 3. For queue j in queueing network, calculate the arrival rate λ_j of node j:

Step 3.1. If node j is a transmission node or boundary node,

$$\lambda_j^1 = \lambda_j^{\,e} + \sum_{i=1}^{m} \lambda_i p_{ij} \qquad (17)$$

go to Step 3.3. Otherwise, it is executed orderly.

Step 3.2. node j is sink node,

$$\lambda_j^1 = \lambda_j^{\,e} + \sum_{i=1}^{m-1} \lambda_k p_{ki} + \lambda_i p_{ii} \qquad (18)$$

Step 3.3. The outputting rate of node j is calculated by Corollary 1 and Corollary 2.

Go to Step 3.1, 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 4. After calculating the arrival rate of all nodes, if the difference of the internal arrival rate for two computing values is less than a value (10^{-4}), go to Step 5. Otherwise, use λ_j^1 instead $\lambda_j^{\,0}$, and go to Step 3.1, continue by

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iterative calculation.

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

End

The time complexity of Algorithm 1 is O(n*m), where m is the number of queueing network nodes and n is the number of iterative algorithms.

The total arrival rate of each node was obtained by Algorithm 1, but it is not the effective arrival rate, because the blocking probability of the nodes is not considered. Next we will have the numerical results of Algorithm 1 as the initial value of Algorithm 2, and then solve the blocking probability and system performance indicators. The reduction Algorithm 2 is as follows.

The calculation of Algorithm 2 mainly focused on the loop in Steps 3 to 6 of the cycle. The time complexity of Algorithm 2 is O(n*m*N), where N is the packet buffer size of node. When the iterative algorithm converges, the WSN performance parameters are outputted. According to that we can predict the actual operation of WSNs. Thus, the hardware design for the WSN node is guided by the performance parameters.

Algorithm 2

Begin

Step 1. The equivalent queueing network model is expanded by adding holding nodes in wireless sensor queueing networks. The total arrival rate of Algorithm 1 is the initial input value of Algorithm 2 for each node.

Step 2. Blocking probabilities of each node are initialized, and means and variances of internal arrival time are calculated.

Step 3. Calculate the utilization and steady-state probability of the nodes, where $n_i = \{1, 2, ..., N\}$, that means the number of data packet buffer of each node. When the system reaches a steady state, we assume that the probability of queue i in state n_i is $p_i(n_i)$, which is obtained by:

$$p_i(n_i) = \frac{\rho^{n_i}(1-\rho)}{1-\rho^{N+1}} \qquad (19)$$

where $\rho_i = \dfrac{\lambda_i}{\mu_i}$. Specific derivations of Equation (19) can be found in [38,39]. According to Jackson' theorem [30], the status of node i and the status of all other nodes are independent. Thus, we can get the steady-state probabilities of any node in the link path.

Step 4. Calculate the blocking probabilities.

Step 5. Correct means of the arrival time interval and variance of nodes

using blocking probabilities.

Step 6. If 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}), then go to Step 7. Otherwise go to Step 3 followed by iterative calculation.

Step 7. Return to the node utilizations with a blocking when system is stable.

End

6. Numerical Calculation and Experimental Results

According to the preceding analysis, we studied a WSN topology for temperature monitoring. The performance parameters of WSN nodes are calculated using the iterative algorithm proposed in Section 5. By setting different packet buffer capacity sizes of nodes, the relationship curves between utilization (ρ_i) and data packet buffer size (N_i) for transmission nodes, boundary nodes and sink node are obtained. In order to rationally allocate resources, the maximum utilizations of nodes are ensured within limited resources. According to the relationship curves between utilization (ρ_i) and data packet buffer size (N_i), the values of packet buffer capacity size for transmission nodes, boundary nodes and sink nodes are set.

6.1. A WSN Topology

We have designed the WSNs for temperature monitoring. Its typical topology is shown in Figure 6. It consists of many clusters, each of which comprises a mixed structure from the ring and star network topologies. Information between clusters is communicated by sink nodes.

From the WSN we can conclude that all the clusters can be divided into two categories. (i) Boundary cluster: It is located in the boundaries of the network by the cluster nodes, transfer nodes and boundary nodes; Cluster 1 is shown in Figure 6. (ii) Internal cluster: it is located within the network only by the sink nodes and transfer nodes. Cluster 2 is shown in Figure 6. According to the packets statistics in the engineering practice, amount of tasks for transmission node is the same in the boundary and internal clusters. Therefore, we studied Cluster 1, in which performance of internal nodes will be analyzed. Cluster 1 is comprised of sink node 1, transmission nodes 1–4, and boundary nodes 5–6. Ring structure is comprised of nodes 1–6, and node 7 is in the center of the other six nodules that shows a similar star, which is with 6 nodes to communicate. In practical engineering in applications, how to set the buffer

size to obtain the optimal performance of the nodes for hardware design of WSNs is a practical application problem that needs to be solved.
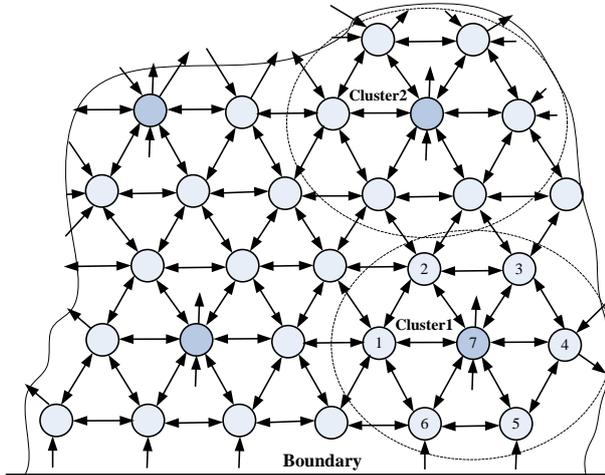

Fig. 6. A WSN topology for temperature monitoring.

6.2. Node Transition Probabilities and Total Arrival Rate

The node transition probabilities for the topology of Figure 6 are obtained from packet statistics in the engineering practice of WSNs for temperature monitoring. Thus the transition probability matrix is as follows.

$$P = \begin{bmatrix} 0 & 0.2 & 0 & 0 & 0 & 0.2 & 0.5 \\ 0.2 & 0 & 0.2 & 0 & 0 & 0 & 0.5 \\ 0 & 0.2 & 0 & 0.2 & 0 & 0 & 0.5 \\ 0 & 0 & 0.2 & 0 & 0.2 & 0 & 0.5 \\ 0 & 0 & 0 & 0.2 & 0 & 0.2 & 0.6 \\ 0.2 & 0 & 0 & 0 & 0.2 & 0 & 0.6 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0 \end{bmatrix} \tag{20}$$

In the distributed temperature acquisition process, for each sensor node placed in different positions, the amount of transmitted data is different. For example, node 1, node 2, node 3 and node 4 are transmission nodes within the WSN. Thus, the external arrival rates of the nodes are same. Node 5 and node 6 are the boundary nodes (do not allow other nodes from outside). Node 7 is the sink node. The external arrival rates of these nodes are different.

Table 2. Arrival rate for each node in the time T_i^m

Node number	External arrival rates λ_i^e (p/s)	Total arrival Rates λ_i (p/s)
1	10	29.6577
2	10	31.1161
3	10	31.1161
4	10	29.6577
5	3	22.3661
6	3	22.3661
7	2	89.6131

According to the input of the external arrival rates, the total arrival rate of node i can be calculated using Algorithm 1, as shown in Table 2.

6.3. Evaluation for Packet Buffer Capacity of Nodes

In WSNs, packet buffer capacity of nodes settings that affects the efficiency of the whole network system is an important factor. If packet buffer capacity is too small it will cause serious blocking to some link paths of the system, and lead to a low efficiency of data processing and transmission. If packet buffer capacity is too large, it will take up too much of the hardware resources, resulting in an increased cost of the hardware node. And the energy consumption will increase, causing a link failure to individual nodes due to energy depletion. Therefore, we design hardware nodes that make the data packet buffer capacity to reach the optimal settings.

Other input parameters of queueing network model for wireless sensor are shown in Table 3, where CA_i^e is the independent external Poisson arrival Variance of node i, μ_i is the service rate of node i, CS_i is the service variance of node i and N_i is the size of packet buffer capacity which ranges from 1 to 30.

Table 3. Input parameters for model

i	CA_i^e	μ_i	CS_i	N_i
1	10	40	14	1~30
2	12	40	16	1~30
3	12	40	16	1~30
4	10	40	14	1~30
5	7	30	10	1~30
6	7	30	10	1~30
7	16	100	30	1~30

According to of the approximate iterative Algorithm 2 in Section 5, packet buffer size (N_i) and node utilization (ρ_i) are calculated.
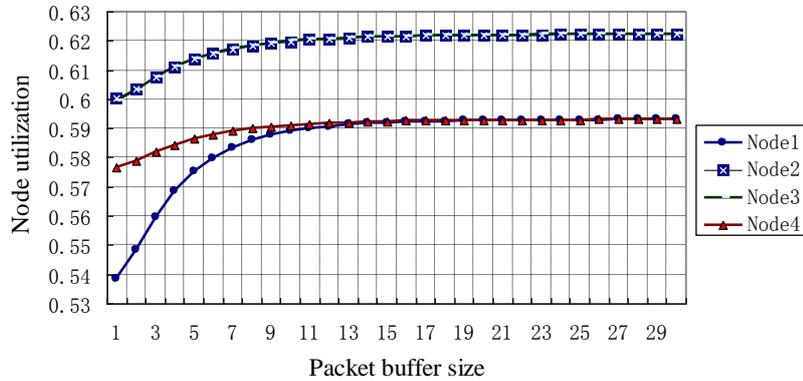

Fig. 7. Relationship curves between utilization and buffer size for transmission nodes.

The relationship curves between utilization and packet buffer size for transmission nodes are shown in Figure 7. In WSNs for temperature monitoring, node 1, node 2, node 3 and node 4 are the transmission nodes, in which the main function of the network is to collect data and transfer it to other nodes. With the increase of packet buffer size, increased speed of node 1 is the fastest, increased speed of node 4 has slowed down compares to other three nodes. When the packet buffer sizes are increased to $N_1 = N_4 = 14$, curves for nodes 1 and 4 coincide. Next, with the increase of packet buffer size, the curves in almost horizontal axis tend to become parallel. At this time, if we increase the packet buffer sizes, utilization for nodes will not have any impact. This point can be set as the value of packet buffer size then the node utilization is optimal. From point of view for the layout of the WSNs, nodes 1 and 4 are adjacent to the boundary nodes, transmission rates of data packets are almost the same. Therefore, when the system reaches equilibrium, packet buffer sizes in use become the same.

The curves between utilization and packet buffer size for nodes 2 and 3 are in coincidence in figure 8. When the packet buffer sizes are increased to $N_2 = N_3 = 11$, the curves in almost horizontal axis tend to become parallel. At this time, if we increase the packet buffer sizes, utilization for nodes will not have any impact. This point can be set as the value of packet buffer size then the node utilization is optimal. From the point of view of the layout of the WSNs, nodes 2 and 3 are internal nodes of the WSN, transmission rates of data packets are almost the same. Therefore, the relationship curves between utilization and buffer size for boundary nodes are the same.
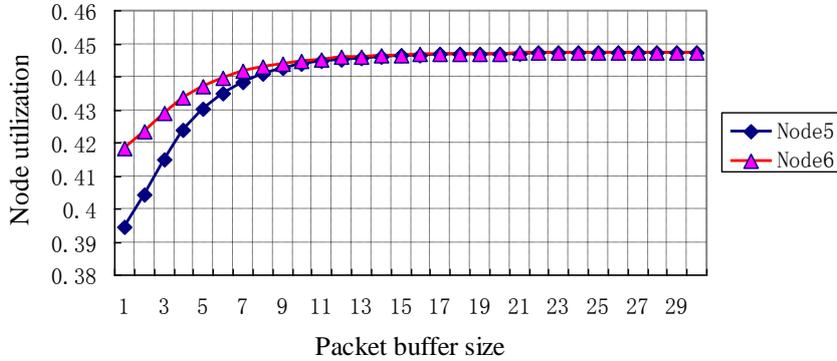
Fig. 8. Relationship curves between utilization and buffer size for boundary nodes.

The relationship curves between utilization and packet buffer size for boundary nodes are shown in Figure 8. With the increase of packet buffer size, beginning curves are relatively steep. The increased speed of curve for node 5 is the fastest; the increased speed of curve for node 6 has slowed down compared to curve for node 5. According to this situation, we can speculate that, when node 5 is set to a smaller packet buffer size, a more serious blocking occurred in the link paths for the node, resulting in relatively low node utilization. When the packet buffer sizes increased to $N_5 = N_6 = 13$, curves for nodes 5 and 6 are coincidence. And following the increase of packet buffer size, the curves in almost horizontal axis tend to become parallel. At this time, if we increase the packet buffer sizes, utilization for nodes will not have any impact. If this point can be set as the value of packet buffer size, then the node utilization is optimal. From the point of view of the layout of the WSNs, nodes 5 and 6 are located on the outside of the WSN, and they are boundary nodes. The transmission rates of data packets are almost the same. Therefore, when the system reaches equilibrium, the packet buffer sizes in use are the same.
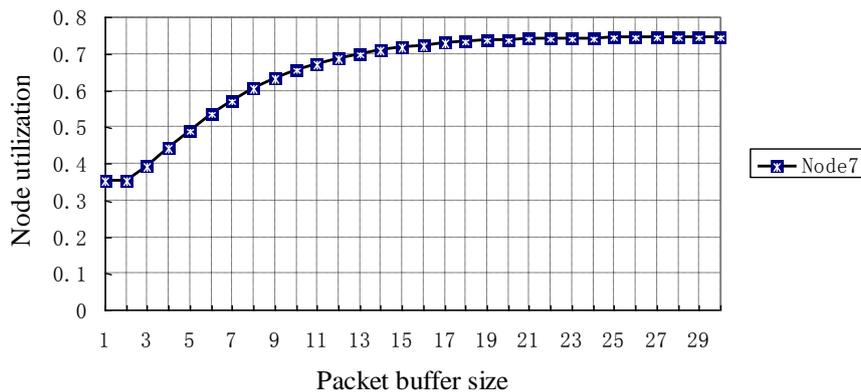

Fig. 9. Relationship curves between utilization and buffer size for sink node.

For sink node 7, on the one hand, it is responsible for collecting the date packets of adjacent transmission nodes and boundary nodes. On the other hand, information between clusters is communicated, and a partial data processing is completed by sink node. The relationship curves between utilization and packet buffer size for sink node are shown in Figure 9.

With the increase of packet buffer size, beginning curves are relatively steep. As per this situation, we can speculate that, when sink node 7 is set to a smaller packet buffer size, its utilization is relatively low. After the packet buffer sizes are increased to $N_7 = 19$, and following this, the curves in almost horizontal axis tend towards parallel. At this time, if we increase the packet buffer sizes, utilization for nodes will not have any impact. If this point can be set as the value of packet buffer size, then the node utilization is optimal.

6.4. Comparison of Experimental Data and Model Calculation Data

According to the size of the nodes through the analysis of packet buffer size in Section 6.3, the experimental environment was designed. The packet buffer sizes for transmission nodes are set as $N_1 = N_4 = 14$, $N_2 = N_3 = 11$, respectively. The packet buffer sizes for boundary nodes are set as $N_5 = N_6 = 13$, respectively. The packet buffer size for sink node is set as $N_7 = 19$. The simulation environment using NS2 software combined with random arrival derived the algorithm [39]. The experimental simulation for arrival rate of node with holding nodes was carried out. Figure 10 shows the comparison of nodes between the effective arrival rates.
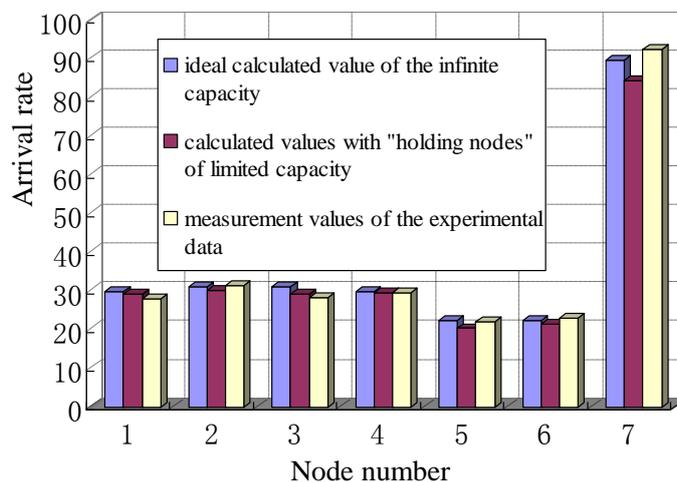

Fig. 10. Comparison of the data results.

In Figure 10, the arrival rates of the three situations are described: (i) Assuming queueing network model for wireless sensor works in an ideal state, the blocking probabilities { pb_{ij} , pb_j^a , pb_j^e } always equal 0, which is called the ideal calculated value of the infinite capacity nodes. (ii) Queueing network model for wireless sensor maintained by adding a finite number of nodes (based on the values obtained in Section 6.3), considering the given blocking probabilities { pb_{ij} , pb_j^a , pb_j^e }, the values of the effective arrival rate are calculated, these are called the calculated values with holding nodes of limited capacity. (iii) Experimental environment is created and random function for arrival rate is designed. Therefore, the actual arrival rates are obtained by statistical calculation, these are called the measurement values of the experimental data. Figure 10 clearly describes the comparison of data among the three situations. We can see that errors between the ideal calculated value of the infinite capacity nodes and the calculated values with holding nodes of limited capacity are very small, the maximum error being 6.12%. This proves that by adding finite holding nodes to a queueing network model, and obtained equivalent queueing network model can replace the infinite capacity model for performance analysis. The maximum error between the measurement values of the experimental data and the calculated values with holding nodes of limited capacity is 9.56%. As in the model calculation error is less than 10%, almost consistent indicators for equivalent queueing network model can be obtained with the actual operation of the WSN.

7.   Conclusions

In allusion to differ transmission nodes, boundary nodes and the sink node in WSNs, their processing data and the task capacity are different. And thus, before designing the hardware for nodes, an evaluation of packet buffer sizes is critical for the best performance. Based on this problem, we proposed an open queueing network mode with M/M/1/N queues for modeling WSNs. In order to evaluate congestion situation in the queueing network, and get real effective arrival rates and transfer rates in the model, holding nodes were added in the queueing network model and an equivalent queueing network model is expanded. The arrival rates when system reaches a steady state in WSNs are obtained using approximate iterative algorithm. The obtained steady-state parameters will be entered into with the blocking queueing network model. Blocking probability and system performance indicators of each node are calculated using approximate iterative algorithm for blocking probability. The ideal calculated value of the infinite capacity nodes, the calculated values with holding nodes of limited capacity and the measurement values of the experimental data are compared. The consistency is verified for calculated results of model and experimental data in WSNs. The results show that the method, which is used to analyze node performance and ensure that packet buffer sizes are of reasonable configuration using queueing network

model, provides a theoretical basis for design of high cost-effective hardware nodes for modeling large-scale WSNs. This work has important guiding significance for hardware design and performance evaluation of WSNs system.

This paper presents a modeling for only a single-server model in WSN and a method for calculating the packet buffer capacity size of nodes. However, the sink node requires a higher performance. Recently, there has been convergence of multiple processor nodes that can be used for M/M/m/N queues, which are also multi-server queues. In addition, for large-scale WSNs, if the clusters are set to be the priority, it will effectively improve the performance of WSNs. This will be our follow-up research.

8. References

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