Modeling and Evaluating Reliable Real-time Degree in Multi-hop Wireless Sensor Networks

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***Abstract*- Wireless Sensor Network (WSN) should be capable of fulfilling its mission, in a timely manner and without loss of important information. In this paper, we propose a new analytical model for calculating RRT (Reliable Real-Time) degree in multihop WSNs, where RRT degree describes the percentage of real-time data that the network can reliably deliver on time from any source to its destination. Also, packet loss probability is modeled as a function of the probability of link failure when the buffer is full and the probability of node failure when node's energy is depleted. Most of network properties are considered as random variables and a queuing-theory based model is derived. In this model, the effect of network load on the packets delay, RRT degree, and nodes energy depletion rate is considered. Simulation results are used to validate the proposed model. The simulation results agree very well with the model.**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are self-organized ad-hoc networks, which are equipped with limited computing and radio communication capabilities [1]. Nodes are capable of sensing, gathering, processing and communicating data, especially the data pertaining to the physical medium in which they are embedded. It is envisioned that a typical WSN consist of a large number of nodes [1], [2], [3]. A typical network configuration consists of sensors working unattended and transmitting their observed or sensed values to some processing or control center, the so-called sink or base-station node, which serves as a user interface. Due to the limited transmission range, sensors that are far away from the sink deliver their data through *multi-hop* communications, i.e. using intermediate nodes as relays. In this case, a sensor may be both a data source and a data router.

Although energy efficiency is usually the primary concern in WSNs, the requirement of low latency communication is getting more and more important in emerging applications. Out-of-date information will be irrelevant and even leads to negative effects to the system monitoring and control. Real-time (RT) sensor systems have many applications especially in intruder tracking, medical care, fire monitoring and structural health diagnosis.

WSN differs dramatically from the traditional RT systems due to its wireless nature, limited resources (power, processing and memory), low node reliability and dynamic network topology. Thus, developing real-time applications over WSN should consider not only resource constraints, but also the node and communication reliability and the globally time varying network performance.

This paper establishes a probabilistic fundamental quantitative notion for performance-critical applications on real-time information transfer in multi-hop wireless networks. However, bounded delay latency is extremely impressed in path reliability when any lost packet must be retransmitted and it can cause to additional delivery delay. Here, the packet loss probability is the probability of one path's link failure when node's buffer in the end point of the link is full and there is no space for new packets or the probability of one path's node failure when node's energy is depleted and the node does not have any energy for taking more transmissions.

Application areas for sensor networks might be production surveillance, traffic management, medical care or military applications. In these areas it is crucial to ensure that the sensor network is functioning even in a worst case scenario. It must be clear that the sensor network can support all possible communication patterns that might occur in the network without being overloaded. If a sensor network is used for example for production surveillance it must be ensured that messages indicating a dangerous condition are not dropped. If functionality in worst case scenarios cannot be proven, people might be in danger and the production system might not be certified by authorities.

We propose a new probabilistic analytical model for calculating RRT (Reliable Real-Time) degree in multi-hop WSNs, where RRT degree describes the percentage of real-time data that the network can reliably deliver on time from any source to its destination. Analytical expressions for reliable real-time degree facilitate the process of designing a WSN that is guaranteed to meet specified throughput and delay requirements. These expressions describe values of a set of variables that will enable the network to meet anticipated real-time requirements. In other words, they define the feasibility region in the space of such variables. In the event of dynamically changing network, which is expected of WSN, besides planning and designing, the feasibility region allows optimization of the operation of the network.

Thus, the purpose of this paper is to perform a probabilistic analysis of Reliable Real-time Degree in wireless sensor network, which considering the packet loss and packet delay as real-time measures, and node failure and link failure as reliability measures.

The rest of this paper is organized as follows: in Section II a literature survey is presented. In Section III the preliminaries and assumption of the problem are clarified. In Section IV a model for evaluating the reliable real-time degree is derived.

Section V presents the simulation results and Section VI provides some conclusions and future work.

II. RELATED WORK

A large amount of research on sensor networks has been recently reported, ranging from studies on network capacity and signal processing techniques, to algorithms for traffic routing, topology management and channel access control.

Some researchers have looked at latency issues from different perspectives. For instance, the approach of Intanagonwiwat et al. [4] exploits latency and credibility trade-off in order to propose a solution to the problem of "How long a node should wait before aggregating and sending its data to its parent?", where a parent denotes the next hop. Another in-network data aggregation scheme that aims at minimizing the end-to-end delay is proposed in[5]. This scheme does not consider any latency bound but tries to minimize the average end-to-end delay by concatenating multiple packets into one at the MAC layer. The idea is to limit the medium access contention so that the packet queuing delay will be reduced. Moreover, they use a feedback mechanism at each sensor node to adjust the number of concatenated packets based on the current traffic conditions. In [6] Abdelzaher et al. a sufficient condition for schedulability under fixed-priority scheduling which allows capacity planning to be employed prior to deployment such that real-time requirements are met at run-time. The bound is derived for load balanced networks, as well as networks where all traffic congregates at a number of sinks. The approach of Chiasserini et al. [7] exploits several performance metrics, among which is the distributions of the data delivery delay. They consider that the information sensed by a network node is organized into data units of fixed size, and can be stored at the sensor in a buffer of infinite capacity. They assume that wireless channel is error-free. In [8] we proposed a quantitative real-time model for WSNs and we described real-time degree by considering the packet loss and packet delay as real-time measures. However, this model does not consider the probability of node failure due to node energy depletion and its effect on path reliability and real-timeliness in WSNs.

III. PRELIMINARIES

For evaluating the reliable real-time degree of wireless sensor networks, we suppose that each node of sensor network has the structure depicted in Fig. 1, i.e. each sensor can receive and transmit, also generates data units according to a Poisson process [7], so we can model it as an M/M/1/k queue.

Moreover, suppose that the network is a set of such nodes, so that its topology is unknown. A sample network is shown in Fig. 2.

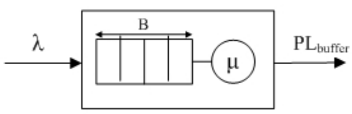

Fig. 1. Structure of sensor network nodes

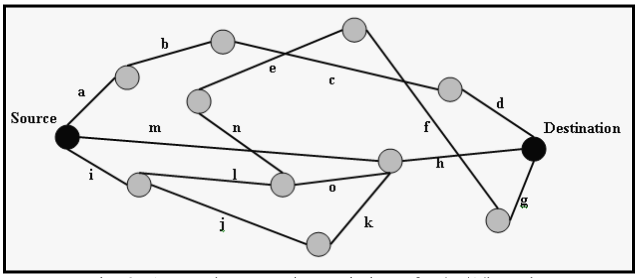

Fig. 2. A sample network consisting of m/m/1/k nodes

For example, there are several potential paths between the source and the destination nodes. Suppose that the path {a, b, c, d} is established. If for some reason, this path is disconnected, another path can be used as a replacement. For instance, if link c fails, the paths {m, h} or {i, l, o, h} can be used.

Consider a transmission over one hop and let nodes i and j ($1 \le i \le N$, and $0 \le j \le N$ with 0 indicating the sink) be the transmitter and the receiver, respectively. The transmission is successful if [9]:

1) the distance between i and j is not greater than tr (Transmission Range),

$$d_{i,j} \le tr \tag{1}$$

2) for every other node, k, simultaneously receiving,

$$d_{i,k} > tr \tag{2}$$

3) for every other node, l, simultaneously transmitting,

$$d_{l,j} > tr. \tag{3}$$

In this work we consider a sensor network whose nodes have already performed the initialization procedures necessary to self configure the system. Therefore sensors have the knowledge of their neighboring nodes, as well as of the possible routes to the sink. (for instance, through a routing algorithm such as the one proposed in [10]). Since we consider a network of stationary nodes performing, for instance, environmental monitoring and surveillance, the routes and their conditions can be assumed to be either static or slowly changing.

An important consideration is that generally in wireless sensor networks, the network topology is unknown. That is, we have to consider anything as statistical. For performing mathematical operations, most of network parameters must be treated as random variables. The following assumptions about nodes and the network itself are made:

1. Network nodes have the same statistical properties.
2. The routing algorithm selects each of alternative paths with equal probability.
3. Initially, there are R paths.
4. The network links and nodes fail independently from each other.
5. If at least one of the path's nodes fails, we consider that path as failed (disconnected).
6. The network paths have the same statistical properties.
7. The number of nodes of a path is a random variable called N with average of $E[N]$.
8. The buffer size of each node is b byte or B packets.
9. Packet arrival to each node has the Poisson distribution with parameter λ (it includes the packets generated by the

node plus packets arrived at the node from other nodes in the network).

10. The service rate of packet is μ .
11. The network load is *r*.

IV. EVALUATING THE RELIABLE REAL-TIME DEGREE

With the above assumptions, we begin the modeling process.

In this paper we define reliable real-time degree by considering node failure and link failure as reliability measures. In this paper we model energy depletion of a node as the node failure too.

Step 1: We calculate the packet loss of a typical path. The packet loss probability of a path, PL_{path}, is modeled as a function of the probability of link failure when the buffer is full and the probability of node failure when node's energy is depleted.

$$PL_{path} = 1 - \left(\left(1 - PL_{buffer}\right)^{E[N]} \times R_{path} \right) \tag{4}$$

where R_{path} is the probability that none of the path's nodes fails during the deadline and it is calculated by (20).

Now, we have to calculate the mean value of packet loss in each node. The packet loss probability (link failure probability) is the probability that the node's buffer is full and there is no space for new packets. From queuing theory it is equal to PL_{buffer} [11]:

$$PL_{buffer} = P_{B+1} = \frac{(r)^{B+1}(1-r)}{1-(r)^{B+2}} \tag{5}$$

where *r* is the average network load at a sensor node and you can find it by (7).

Now, assuming that S, the sensing rate, is the new traffic rate emerged in the source node of each source-destination pair, and assuming a retransmission in the event of packet loss. Thus, under the premise that G is the total traffic rate (i.e. the sum of new emerged traffic and the retransmitted traffic), we have the following relation between G and S:

$$S = G\left(1 - PL_{path}\right) \tag{6}$$

Now we have to calculate the value of r. To compute the network load at a sensor node, we note that, because of packet loss probability at the sensor node, the load will be reduced at each successive node from source to a destination. For example, in the i^{th} node, i = 0, 1, 2, … E[N]-1, this traffic exists in the case of traversing all previous i-1 nodes without packet loss. Therefore the probability of traffic existence is equal to $\left(1 - PL_{buffer}\right)^i$ and because of similarities between nodes and paths statistical properties, we have:

$$r = \left(\frac{G}{E[N]}\right) \sum_{i=0}^{E[N]-1} \left(1 - PL_{buffer}\right)^i = \frac{G[1 - \left(1 - PL_{buffer}\right)^{E[N]}]}{PL_{buffer} \times E[N]} \tag{7}$$

Comparing these two relationships, (5) and (7), we find out that for calculating the value of PL_{buffer}, we need to know the value of r, and vice versa. Similar problems often occur in the computation of blocking probabilities in circuit-switched networks with fixed routing, in which the well known Erlang fixed-point method can be applied [12], [13]. For this type of problem, an iterative method is known to have efficient computation time. The iteration is carried out until convergence is achieved.

Step 2: We calculate the mean value of a typical path's delay, or actually the time duration that it takes for a packet to successfully be delivered to the base station.

A packet traversing from source to destination waits a time equal to W in each node where W includes queuing time plus transmission delay, then enters a link and has a propagation delay equal to t_p. Therefore, as there are N nodes and N-1 links, the path's delay is:

$$\begin{aligned} Delay_{path} &= \sum_{i=1}^{E[N]} W + \left(E[N]-1\right) E\left[t_p\right] \\ &= \sum_{i=1}^{E[N]} W + \frac{E\left[Len_{path}\right]}{C} \end{aligned} \tag{8}$$

And, as we proved in our paper [8] W is:

$$W = \frac{r'\left[1 + (B+1) r'^{B+2} - (B+2) r'^{B+1}\right]}{\lambda\left(1 - r'\right)\left(1 - r'^{B+1}\right)} \tag{9}$$

Where r' as an effective traffic rate, is:

$$r' = \frac{r}{\beta} \tag{10}$$

Len_{path} is a random variable and represents the cumulative distribution of links' length. C is the radio speed or more precisely, the propagation speed of radio waves in the space. β is the probability to transmit a data unit in a time slot given that the buffer is not empty.

Step 3: We calculate the probability that a data unit is transmitted in a time slot. It accounts for the channel contention, i.e., it would be equal to 1 if there were no contention on the wireless medium.

We define β as the probability to transmit a data unit in a time slot given that the buffer is not empty. As described in Section 3, a node transmission attempt is successful if the conditions expressed in (1)–(3) are satisfied. Thus the computation of β requires a careful investigation of the interference produced by other sensors trying to transmit in proximity of the node for which we want to estimate β. In order to explain our approach, consider the set of nodes shown in Fig. 3.

The transmission range of three nodes, {A,F,H}, is represented by a circle. Assume that we want to estimate the parameter β of node A, which has two next-hops, B and C. We need to find all transmissions that could potentially interfere with the transmission of A to its next-hops. Let (X,Y) denote the transmission from the generic node X to the generic node Y. We notice that transmissions like (D,E) and (H,C) violate condition (2) since the receivers are within the radio range of A; a special case is given by the transmissions whose receiver is A itself (e.g., (E,A)). Instead, transmissions like (F,G) and (H,I) meet condition (2) and violate condition (3) since the transmitters interfere with A's next-hops. In addition, we

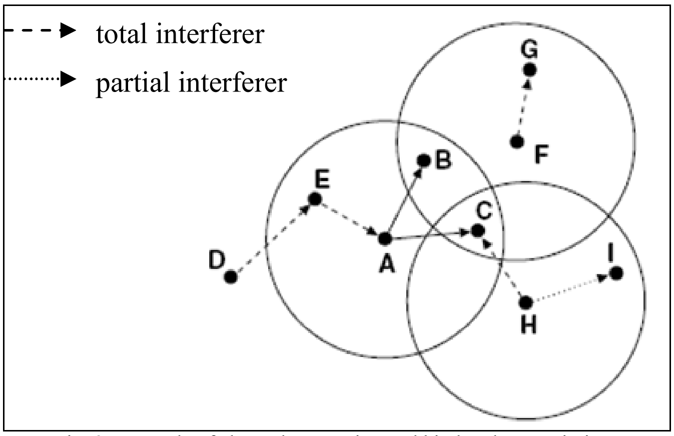

Fig. 3. Example of channel contention and hindered transmissions

observe that transmissions as (D,E), (E,A), (H,C) and (F,G) totally inhibit *A*'s transmission, thus we call them *total interferers* [7]. Instead, transmissions like (H,I) do not necessarily prevent A from sending data (e.g., (A,B) could take place), thus we call them *partial interferers* [7]. To estimate β for the generic sensor i we proceed as follows. First we compute for each node n ($1 \le n \le N$) the probability $I^i(n)$ that a transmission in which n is involved as either transmitter or receiver, totally inhibits i's transmission (*total interferer*). Our approach is based on the knowledge of the average transmission rates $r_{n,m}$ between n and its generic receiver m. So based on [7]:

$$I^i(n) = \sum_{m=1}^{N} r_{m,n}\, 1_{\{d_{(n,i)} \le tr\}} + \sum_{m=0}^{N} r_{n,m}\, 1_{\{d_{(m,i)} > tr\}}\, V^i(n) \qquad (11)$$

where $m = 0$ denotes the sink and $1_{\{.\}}$ is the indicator function. The first summation on the right hand side accounts for the transmissions violating (2) or destined to i, while the second summation accounts for the transmissions that meet (2) but violate (3). The term $V^i(n)$ is equal to 1 if there exists at least one next-hop of i within the transmission range of n, with n being different from i:

$$\mathrm{V}^i(n) = \begin{cases} 1 & \exists k \in H^i : d_{(n,k)} \le tr \text{ , } n \ne i \\ 0 & \text{otherwise} \end{cases} \qquad (12)$$

where H^i is the set of next-hops of i. Then, β^i is estimated as follows [7]:

$$\beta^i = \prod_{n=1}^{N} \left[1 - I^i(n)\right]. \qquad (13)$$

$$\beta = \frac{\sum_{i=1}^{E[N]} \beta^i}{E[N]} \qquad (14)$$

Now, for evaluating the reliable real-time degree of a path, we employ the following reasoning:

If the path does not fail, as long as the values of packet loss and packets' delay do not exceed a specific threshold, the reliable real-time degree is equal to one. When these values exceed their thresholds, the value of reliable real-time degree has inverse relation with the packet loss and delay to their threshold. Now, if this path fails, with some probability, a spare path is chosen, and then the reliable real-time degree of this new path determines the reliable real-time degree of the previous one.

However, packet loss and delay have different units of measurement and we can not apply mathematical operation on both of them simultaneously. Therefore we embed the effect of packet loss into the notion of delay: when a packet loss occurs and the source receives a NACK, or does not receive an ACK and a timeout occurs, a random interval between 1 and K elapses and then the packet is retransmitted. We consider the time of transmitting of a packet of average length as the unit of this interval. So a value equal to $T\left(2\left(E[N]-1\right)E\left[t_p\right]+\frac{K+1}{2}\right)$ is added to path delay, where $T = \frac{(G-S)}{S}$ indicates the ratio of retransmitted packets to the new generated packets. Considering packet loss and retransmission, the total delay of the path is:

$$Delay_{path} = \sum_{i=1}^{E[N]} W + \frac{E\left[Len_{path}\right]}{C} + T\left(\frac{2E\left[Len_{path}\right]}{C} + \frac{K+1}{2}\right) \qquad (15)$$

$$Delay_{path} = \sum_{i=1}^{E[N]} W + \frac{(2T+1)E\left[Len_{path}\right]}{C} + \frac{(K+1)T}{2} \qquad (16)$$

However, finding *RRT degree* is the ultimate goal of this section and it describes the percentage of real-time data that the network can reliably deliver on time from any source to its destination. Having the above relations in the mind and the similarity of the statistical properties of the paths help us to obtain *RRT degree* as the following equation:

$$RRT\_degree = (1 - PL_{buffer})^{E[N]} \times (1 - MissRatio) \times (1 - P_{failure}) \qquad (17)$$

As we assume that packet arrival to each node has the Poisson distribution with parameter λ, so we can assume that time interval between packets has the exponential distribution, so *Miss Ratio* is calculated as:

$$MissRatio = e^{-\frac{1}{Delay_{Path}} \times T_{Delay}} \qquad (18)$$

where T_{Delay} is the threshold values for packets' delay. So, if $Delay_{path}$ exceeds the thresholds, miss ratio begins to increase and reliable real-time degree begins to decrease with inverse relation.

Considering the fact that initially there are R non-failed paths. If a path fails, it can be substituted by another path and this continues until there are not any paths for data transmission. $P_{failure}$ is equal to the probability that R paths fail and there are not any spare paths for data transmission that you can find it on (19):

$$R_{Total} = 1 - P_{failure} = 1 - (1 - R_{path})^R \qquad (19)$$

Step 4: We calculate the reliability of a typical path. The path reliability, R_{path}, is equal to the probability that none of the path's nodes fails during the deadline (T_{Delay}). Therefore:

$$R_{path} = e^{-(\frac{1}{Path\,Lifetime}) \times T_{Delay}} \qquad (20)$$

where failure rate, $\frac{1}{Path\ Lifetime}$, is the expected number of failures during the path lifetime.

Now, we have to calculate the mean value of lifetime for a typical path. The energy cost of a node is computed as follows.

$$E_{i,j} = E_{i,j}^{(tx)} + E_{j}^{(rx)} \qquad (21)$$

Where $E_{i,j}$ is the energy cost for transferring a data unit from node i to its next-hop in path, node j. It is equal to the sum of the transmission energy spent by i $(E_{i,j}^{(tx)})$ and the reception energy consumed by j $(E_{j}^{(rx)})$. In the transmitting mode, energy is spent in the front-end amplifier, which supplies the power for the actual RF transmission, in the transceiver electronics and in the node processor implementing signal generation and processing functions. In the receiving mode, energy is consumed entirely by the transceiver electronics and by processing functions, such as demodulation and decoding. Therefore, $E_{j}^{(rx)}$ is due to the transceiver electronics $(E^{(ele)})$ and to processing functions $(E^{(proc)})$; while $E_{i,j}^{(tx)}$ has to account for $E^{(ele)}$, $E^{(proc)}$ as well as for the energy consumption due to the amplifier, that is assumed to be proportional to the squared distance between transmitter and receiver [14].

$$E_{i,j} = \left[2\left(E^{(ele)} + E^{(proc)}\right) + d_{i,j}^{2} E^{(amp)} \right] \qquad (22)$$

where $E^{(amp)}$ is a constant value and $d_{i,j}$ is the distance between i and j in the disk of unit radius.

So, the energy consumption ratio for a typical path is computed as follows.

$$e(path) = \sum_{i=0}^{E[N]-1} (\lambda \times E_{i,i+1}) \qquad (23)$$

So, the mean value of node's energy consumption ratio is:

$$e(node) = \frac{e(path)}{E[N]} \qquad (24)$$

The network lifetime is defined as the smallest time that it takes for at least one node in the network to drain its energy beyond the point where it can function normally.

$$Path\ Lifetime = \frac{\min \{B_i,\ i \in (0, E[N]-1)\}}{e(node)} \qquad (25)$$

where B_i is the residual energy of node i on the path in the moment of new packet transmission.

V. SIMULATION RESULTS

In this section we use GloMoSim [15] to study the reliable real-time degree of wireless sensor networks.

GloMoSim is a scalable discrete-event simulator developed by UCLA. This software provides a high fidelity simulation for wireless communication with detailed propagation, radio and MAC layers. Table I describes the detailed setup for our simulator. The communication parameters are mostly chosen in reference to the Berkeley Mote [16] specification.

TABLE I
SIMULATION SETTINGS

MAC Layer	MACA [17]
Routing Layer	DSR [10]
Propagation Model	TWO-RAY
Bandwidth	200Kb/s
Payload Size	32 Byte
Terrain	(200m, 200m)
Node Number	100
Node Placement	Uniform
Radio Range	40m
R	2
Transmit Power Consumption	26.7 mw
Receive Power Consumption	22.6 mw

In our evaluation, we use a base station scenario, where 6 nodes, randomly chosen from the left side of the terrain, send data to the base station at the middle of the right side of the terrain. The average hop count between the node and base station is about 8~9 hops. Each node generates flow with a rate of 1 packet/second. In order to evaluate the end-to-end delay we increase the rate of this flow step by step from 1 to 100 packets/second over several simulations.

Fig. 4 plot shows the end-to-end delay. As you can see in Fig. 4, by increasing the packet transmission rate, end to end delay increases as well. Because when the rate increases, the buffer full probability increases as well and the lost packets must be retransmitted until they are successfully delivered to the sink.

Fig. 5 shows the miss ratio. We assume that T_{Delay} is 150 ms, and as you can see in Fig. 5, by increasing the packet transmission rate, miss ratio increases as well. Because when the rate increases, then the average end-to-end delays will be increases too.

The reliable real-time degree is a metric in soft real-time systems. We set the buffer size to 50 packets. In the simulation, some packets are lost due to buffer is full. We also consider this situation as a deadline misses. Fig. 6 shows that, when the packet rate increases, the buffer full probability and node failure probability increases as well. Hence the packet loss increases too. Another consequence of the rate increase is the end-to-end delay augmentation. So the packet rate increscent, yielding to a decrease of reliable real-time degree (percentage of on time successfully delivered data).

Fig. 7 plot shows the node energy consumption rate versus data rate. When the packet transmission rate increases, the node energy consumption rate increases as well.

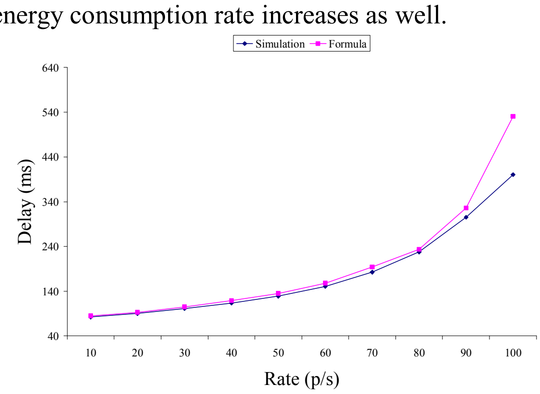

Fig. 4. End-to-End delay under different network loads

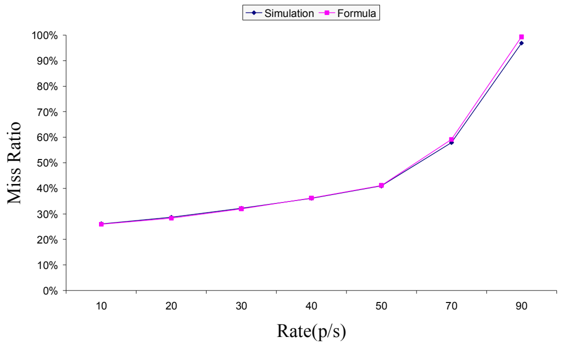

Fig. 5. Miss Ratio under different network loads

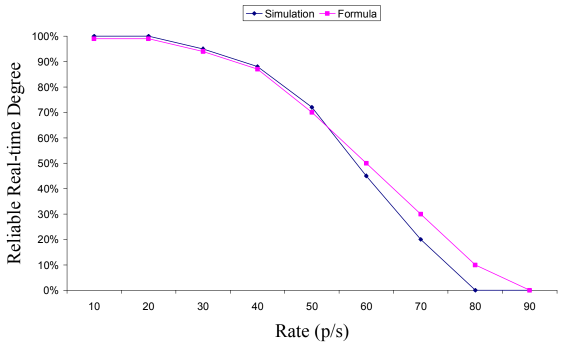

Fig. 6. Reliable real-time degree under different network loads

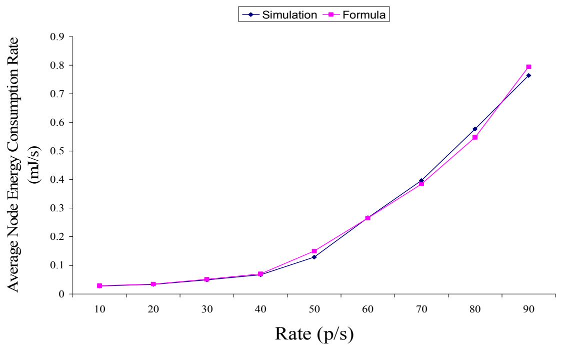

Fig. 7. Node energy cost under different network loads

VI. Conclusions And Future Work

We introduced in this paper a metric, reliable real-time degree, based on a queuing-theory model for general-case wireless sensor network in which the nodes are M/M/1/k queues. Parameters such as packet loss, packet delay and path lifetime were considered as important factor in determining the reliable real-time degree of such network. We have analyzed a semi-qualitative phenomenon, so that we can predict the real-time behavior of network in the case of stochastic events. Simulation results are in accordance with the model.

The model could be modified to take into account some aspects that have not been addressed in this work and that can be interesting subject of future research. For instance, a model of other queuing policy or firm real-time can be included and some of the assumptions that we made while developing the analytical model, such as those on all the nodes are active and none of them in sleep mode, can be modified. Furthermore, we point out that the model can be extended to describe various aspects in the design of sensor networks, such as data aggregation or backpressure traffic mechanisms. Finally, cluster-based network architectures as well as the case where the network topology varies could be studied.

Acknowledgment

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