Long Lifetime Real-time Routing in Unreliable Wireless Sensor Networks

Naser Alinaghipour*, Hamed Yousefi†, Mohammad Hossein Yeganeh*, and Ali Movaghar†
*Department of Computer Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
{n.alinaghipour, m.yeganeh}@srbiau.ac.ir
†Department of Computer Engineering, Sharif University of Technology, Tehran, Iran
hyousefi@ce.sharif.edu, movaghar@sharif.edu

***Abstract*—Lifetime is the most important concern in Wireless Sensor Networks (WSNs) due to limited battery power of sensor nodes. Moreover, a WSN should be capable of timely fulfilling its mission without losing important information in event-critical applications. In this paper, we focus on designing an energy-efficient and energy-aware real-time routing algorithm aiming to explore the long lifetime routing schemes in which delay constraint is satisfied in the presence of lossy communication links. To achieve this goal, our energy-aware forwarding protocol utilizes an optimum distance real-time routing algorithm to minimize energy consumption in unreliable WSNs. Simulation results reveal that the proposed algorithm outperforms other existing schemes in terms of energy consumption, network lifetime, and miss ratio.**

***Index Terms*—Wireless Sensor Networks; Real-time Routing; Network Lifetime.**

I. Introduction

The tendency to use high performance low cost products in wireless communications technology has led to the rapid development of wireless sensor networks [1]. Considering that communication costs (transmission power) are usually more than computing costs, energy efficient routing algorithms are very important in multi-hop WSNs where the constituent nodes have batteries with limited energy. Several energy-aware routing protocols (e.g. [2][3]) define the link cost based on the power required to transmit a packet on it, and accordingly employ minimum cost routing algorithms to determine the "minimum total transmission energy" route from source to destination.

However, in most scenarios, the metric of actual interest is the operational network lifetime [4][5][6], not the transmission energy of individual packets. Through the energy-aware routing mechanisms, the residual energy on each node is the basis of the routing decisions. The main objective of these algorithms is to avoid the extinction of nodes due to exhaustion of their battery power.

Although energy efficiency is usually the primary concern in WSNs, the requirement of real-time communication is becoming more and more important in emerging applications. Here, out-of-date information would be irrelevant and even lead to negative effects on the system monitoring and control. A real-time sensor system has many applications, especially in intruder tracking, medical care, fire monitoring, and structural health diagnosis. However, its wireless nature, limited resources (power, processing, and memory), low node reliability, and dynamic network topology dramatically make it different from the traditional real-time systems. Thus, in addition to the resource constraints, the globally time-varying network performance and the node-communication reliability should be considered in developing real-time applications over WSNs.

However, the previous works on real-time routing often assume the wireless links to be reliable. This is clearly too optimistic since even under benign conditions, wireless communication links are unreliable and often unpredictable due to various factors like fading, interference, multi-path effects, and collisions [7]. Besides, end-to-end delay is extremely impressed in path reliability. If a poor path is chosen for data delivery, the loss rate will be heavy and retransmissions will cause extra energy consumption and shorter network lifetime. Furthermore, more traffic also yields a higher collision probability and delivery delay. In [8], it has been shown why energy spent in potential retransmissions is a proper metric for reliable energy-efficient communications.

In this paper, we propose a Long Lifetime Real-time Routing protocol, LLRR, which is designed to achieve the aforementioned requirements in WSNs. It provides real-time data delivery in unreliable WSNs, while considering energy awareness. The primary contribution of this paper is to provide an optimum distance routing. It can be used to prevent packet loss in real-time communications and to guarantee significant improvement in terms of energy consumption and network lifetime.

To achieve these objectives, each neighboring node is assigned a probability of being selected to forward a packet provided it satisfies the real-time requirement. This probability is a function of three parameters: the residual node energy, the distance to the straight path between the current node and the sink, and the effective transmission energy cost which includes the energy spent in potential retransmissions. Finally, from a set of eligible neighboring nodes satisfying the real-time requirement, a node with a higher probability is more likely to be selected.

The remainder of the paper is organized as follows. Section II summarizes the related work. Section III explains the proposed scheme and presents the specifications of LLRR. Simulation results are presented and discussed in Section IV. Finally, Section V concludes our work and discusses some

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future directions.

II. Related Work

Many routing algorithms have been developed with the aim of providing timeliness in WSNs. Here, we briefly review some of the previous works in the field. SPEED [9] implements the end-to-end transmission delay control. It finds out the neighbors' information using a beaconing mechanism and chooses the next hop based on transmission velocity and local geographical information. Moreover, it utilizes a back pressure rerouting mechanism to avoid routing traps. RAP [10] prioritizes real-time traffic using velocity monotonic scheduling through a differentiated MAC layer. In [11], Akkaya et al. propose a routing protocol that finds a delay-constrained, least-cost path for real-time packets. They assume that every node knows the total network topology. The protocol finds the path by executing the Dijkstra's shortest path algorithm. However, the routing protocol does not support the scalability of WSNs. RPAR [12] tries to optimize power consumption by regulating the transmission power in real-time applications. This approach is, however, affected by anomalous behavior in heavy traffic conditions, which tends to favor network congestion. Hence, RPAR increases the transmission power that worsens the situation. ARP [13] considers not only the real-time requirement but also the energy index synthetically. It computes the required transmission velocity of data packets in each hop and chooses the next node according to both transmission velocity and residual node energy. In THVR [14], routing decisions are made based on two-hop neighborhood velocity integrated with the residual energy awareness mechanism. However, it might lead to high computing complexity and heavy message exchange overhead to enhance the service quality of real-time packet delivery in WSNs. Furthermore, in WSNs, it is necessary to consider reliable communication as an important QoS requirement. MMSPEED [15], an extended version of SPEED, can provide different deadlines and packet reliabilities. Moreover, R2TP [16] is a real-time routing protocol, which utilizes multi-path forwarding in such a distributed way to accomplish reliable transmission in WSNs. However, MMSPEED and R2TP are similar to SPEED in that they do not consider energy expenditure in data forwarding. This issue results in quick energy exhausting of some nodes and makes the real-time characteristic and the network lifetime worse and worse. Recently, EARQ [17] scheme has been proposed as a real-time and reliable routing which considers both residual node energy and link cost. However, it does not consider the link error effect in increasing the number of imposed retransmissions. As it is evident, to achieve reliability, all these proposed methods may send redundant packets via multi-path routing. Here, our goal is to find the optimum routes that provide not only real-time data transmission services but also the maximum network lifetime via an energy-efficient energy-aware optimum distance single-path routing. To the best of our knowledge there is no well-explored scheme to include these multi requirements together.

III. Protocol Overview and Properties

LLRR is a distributed on-demand algorithm that provides a robust transmission environment based on an energy-efficient and energy-aware real-time routing at the network layer. It is assumed that each node learns its own location and the geographic position of the sink. Moreover, the sensors exchange information with one-hop neighbor nodes to get the state information. We calculate the optimum hop length to route traffic through the energy-efficient links in an unreliable network. Therefore, as the routing decision is made accordingly, we will first formally define how to calculate its value.

A. Channel and Radio Model

Several studies [7][18] have revealed the existence of three distinct reception regions in a wireless link: connected, transitional, and disconnected. Since they have shown that real deployments have a "transitional region" with unreliable links the idealized perfect-reception-within-range models can be very misleading. Therefore, due to the significant impact that nodes in the transitional region have on upper-layer protocols, there is an increased understanding of the need for realistic link layer models in WSNs [19]. Empirical studies [19][20] have shown that the log-normal shadowing model provides the most accurate multi-path channel model. This model is given by:

$$PL(d) \;=\; PL(d_0) \;+\; 10n\,\log_{10}(\frac{d}{d_0}) \;+\; X_\sigma \tag{1}$$

where d_0 is a reference distance, d the transmitter-receiver distance, X_σ a zero-mean Gaussian random variable with standard deviation σ (shadowing effects), and n the path loss exponent. Due to the space constraints, we focus the analysis of the model on non-coherent BPSK, which is the modulation implemented in NS2 simulator [21]. Based on [19], for non-coherent BPSK modulation, P_e is the probability of bit error and is calculated via:

$$P_e = Q\left(\sqrt{2\gamma(d)\,\frac{B_N}{R}}\right) = \frac{1}{2} - \frac{1}{2}Erf\left(\sqrt{\gamma(d)\,\frac{B_N}{R}}\right) \tag{2}$$

where SNR γ at a distance d is calculated via [19]:

$$\gamma(d)_{dB} = P_t - PL(d) - P_n \tag{3}$$

where P_t and P_n are the transmitting power and the noise floor, respectively. Moreover, Packet Reception Rate (PRR) in terms of the SNR γ at a distance d is given by:

$$PRR = (1 - P_e)^{8f} = \left(\frac{1}{2} + \frac{1}{2}Erf\left(\sqrt{\gamma(d)\,\frac{B_N}{R}}\right)\right)^{8f} \tag{4}$$

where f is the packet size in byte, R the data rate in bits, B_N the noise bandwidth. Based on the last equations, where BPSK modulation and NRZ encoding are applied, we conclude the PRR expression at a distance d in the form of:

TABLE I
BIT ERROR PROBABILITY FOR DIFFERENT MODULATIONS [19]

ASK	$noncoherent : \frac{1}{2}\left[\exp^{\frac{-\gamma(d)}{2}\frac{B_N}{R}} + Q(\sqrt{\gamma(d)\frac{B_N}{R}})\right]$ $coherent : Q(\sqrt{\frac{\gamma(d)}{2}\frac{B_N}{R}})$
FSK	$noncoherent : \frac{1}{2}\exp^{\frac{-\gamma(d)}{2}\frac{B_N}{R}}$ $coherent : Q(\sqrt{\gamma(d)\frac{B_N}{R}})$
PSK	$binary : Q(\sqrt{2\gamma(d)\frac{B_N}{R}})$ $deferential : \frac{1}{2}\exp^{-\gamma(d)\frac{B_N}{R}}$

$$PRR = \left(\frac{1}{2} + \frac{1}{2}Erf\left(\sqrt{\frac{P_t.B_N}{R.P_n.\left(X_\sigma.P_l\left(d_0\right).\left(\frac{d}{d_0}\right)^n\right)}}\right)\right)^{8f} \tag{5}$$

The derived expression shows how the transitional region is impacted by important radio parameters such as output power, receiver noise, modulation, and encoding as well as important environmental parameters.

Even though the simulations are based on radios using BPSK modulation and NRZ (Non-Return-to-Zero) encoding, the model can be easily extended to other radio characteristics. Table I presents the error probability for common modulation techniques and encoding schemes [19].

B. Energy Consumption Model

In this section, our focus is on improving the energy cost in an unreliable WSN using optimization techniques at the physical layer. We determine the optimum distance at which data is transmitted reliably, and the energy consumption is minimized. The energy cost, $E_{i,j}$, for transmitting a data unit from node i to the next forwarding node j is computed as follows:

$$E_{i,j} = E_{i,j}^{(tx)} + E_{i,j}^{(rx)} \tag{6}$$

where the first term, $E_{i,j}^{(tx)}$, is transmission energy spent by i and the second term, $E_{i,j}^{(rx)}$, is reception energy consumed by j. In both send and receive modes, energy is consumed entirely by the transceiver electronics, $E^{(ele)}$. Moreover, the transmitter supplies the energy $E^{(amp)}$ for the actual RF transmission in the front-end amplifier proportional to the squared distance, $d_{i,j}$ [22].

$$E_{i,j} = \left(2E^{(ele)} + d_{i,j}^2 E^{(amp)}\right) \tag{7}$$

Hence, the energy cost to transmit a packet is computed by:

$$E_{i,j} = \left(2E^{(ele)} + d_{i,j}^2 E^{(amp)}\right).8f \tag{8}$$

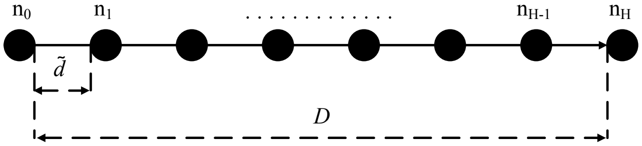

Fig. 1. Data forwarding in a multi-hop manner

However, effective total transmission energy, which includes the energy spent in potential retransmissions, is the proper metric for reliable, energy-efficient communications. In a link layer reliability (Hop-by-Hop Retransmission) manner, the expected number of transmissions (including retransmissions as necessary) to reliably forwarding a single packet through the link $(i, i+1)$ is calculated by $\frac{1}{PRR_{i,i+1}}$. Hence, the expected energy requirement is given by:

$$E_R\left(i, i+1\right) = \frac{E_{i,i+1}}{PRR_{i,i+1}} \tag{9}$$

where the numerator and the denominator are increasing and decreasing functions of distance, respectively. Therefore, $E_R(i, i+1)$ extremely increases with the distance. It may consume less energy when relaying data in a multi-hop manner as opposed to directly transmitting data. However, it may consume more energy if the data is relayed too many times. Moreover, the reliable routing algorithms must choose high quality paths including the minimum number of hop counts. Hence, determining an optimum distance is important for realizing energy efficient transmission in unreliable WSNs.

Figure 1 shows data forwarding between the source node n_0 and the sink node n_H. The optimized number of hops is calculated by:

$$H = \left\lfloor \frac{D}{\tilde{d}} \right\rfloor \tag{10}$$

where D and $\tilde{d}$ are the total path length and the average hop length, respectively. Therefore, the energy consumption through the path from n_0 to n_H is concluded in:

$$E\left(n_0, n_H\right) \approx \frac{D}{\tilde{d}} \times \frac{\left(2E^{(ele)} + \tilde{d}_{i,j}^2 E^{(amp)}\right).8f}{\left(\frac{1}{2} + \frac{1}{2}Erf\left(\sqrt{\frac{P_t.BN}{R.P_n.\left(X_\sigma.P_l(d_0).\left(\frac{\tilde{d}}{d_0}\right)^n\right)}}\right)\right)^{8f}} \tag{11}$$

However, as it is evident from (11), the first and the last terms are decreasing and increasing functions of average length $\tilde{d}$. The energy consumption is minimized when it has a local minimum value. To achieve this goal, we can calculate the optimum value of distance as follows:

$$\frac{\partial}{\partial \tilde{d}} E\left(P\left(n_0, n_H\right)\right) = 0 \tag{12}$$

The result, the optimum distance d_{op}, is included in the routing protocol to prevent packet loss in real-time communications, in unreliable WSNs. Hence, in addition to applying energy efficiency, our geographical optimum distance routing reduces the number of retransmissions caused by packet errors. Therefore, LLRR can guarantee retransmissions reduction and significant improvement in terms of reliability, energy consumption, and network lifetime.

C. Proposed Routing Protocol

LLRR will consider the optimum distance and the energy index provided that the real-time requirement has been satisfied. In real-time applications, packet's TTD (Time-To-Deadline) is used to indicate how much time it remains for the packet before its deadline and has an important role in making routing decisions. Hence, before node C forwards a packet, it computes the required velocity based on the progress made toward the sink node and the packet's TTD, as follows:

$$V_{req} = \frac{d(C,sink)}{TTD} \tag{13}$$

where $d(C, sink)$ is the Euclidean distance between the current node C and the sink node. It is important to note that the deadline is met if the required velocity is met at each hop [23]. Hence, the problem of meeting end-to-end deadlines is mapped to the local problem of meeting the required velocity at each hop. This policy considers the current network conditions to adapt the packet's required velocity. If a packet is late in its way to the sink node, then its required velocity increases so that it may catch up. Conversely, its required velocity decreases if the packet is early.

Based on the velocity requirement and the information provided for the estimated delay EHD, node N in the neighbor set is an eligible forwarding choice if it is closer to the destination and the velocity it provides $V_{relay}(C, N)$ is equal to or greater than the packet's required velocity V_{req} [23]. Relay velocity is calculated by dividing the advance in the distance to the next hop relay node by the estimated delay to forward the packet to that node:

$$V_{relay}(C, N) = \frac{d(C,sink) - d(N,sink)}{EHD} \tag{14}$$

where EHD, Estimated one-Hop Delay, is the time it takes to forward a packet from a current node to the next hop relay node including channel contentions, packet transmissions, and queuing delay.

Among the nodes in the eligible neighbor set, node i with a higher fitness value, Fit_i, has a higher priority than the others.

$$\begin{aligned} Fit_i = (w) \times &\left(\begin{array}{l} \left(p_1 = 1 - \left(\frac{\left|d_{(C,i)} - d_{op}\right|}{\sum_{\forall i}\left|d_{(C,i)} - d_{op}\right|}\right)\right) \times \\ \left(p_2 = 1 - \frac{\left(d_{(C,i)} + d_{(i,\sin k)} - d_{(C,\sin k)}\right)}{\sum_{\forall i}\left(d_{(C,i)} + d_{(i,\sin k)} - d_{(C,\sin k)}\right)}\right) \end{array} \right) \\ + (1 - w)&\left(p_3 = \frac{B_i}{\sum_{\forall i} B_i}\right) \end{aligned} \tag{15}$$

The terms p_1 and p_2 are the probabilities of choosing the next forwarding node as close as possible to d_{op} and to the straight path between the current node C and the sink, respectively (see Figure 1). Here, an eligible neighboring node on the straight path with a lower effective energy cost is more likely to be selected.

Moreover, B_i is the residual energy of node i. LLRR uses factor $(1 - w)$ to provide energy awareness in real-time routing as packets get closer to the sink based on the bottleneck Sphere theorem [24]. This bottleneck is placed near the sink node location where all nodes have the highest energy consumption. When all eligible nodes in the bottleneck sphere fail due to the depletion of energy, the sensing data outside this sphere will not reach the sink on time, which causes quality failure. Hence, we select the weight w, formally as:

$$w = \frac{TTD}{Deadline} \tag{16}$$

As packets get closer to the sink, the value of $(1 - w)$ increases, so the effect of residual node energy is more highlighted in routing decisions. Using this factor enables the even balance of traffic between the eligible nodes along the path to the sink node, and especially in the bottleneck sphere.

At last, a node will be picked out of the eligible neighbor set while its fitness value is the highest. However, if there is no eligible node in the neighbor set, the back pressure rerouting mechanism is aimed [9].

IV. Performance Evaluation

In this section, we evaluate the performance of our algorithm via simulation. We conducted our simulations using NS-2 [21]. The goal of the simulation is to show that LLRR can outperform other important real-time routing protocols by providing a high quality transmission environment in an error-prone network. The results are compared with SPEED [9] and ARP [13], two well-known real-time routing protocols for WSNs. SPEED is a real-time protocol designed to minimize the deadline miss ratio, while ARP considers synthetically the energy index as well as the real-time requirement. However, they do not consider effective link cost when they choose the next hop forwarding node. In contrast, LLRR build the routes not only based on the nodes specific parameter (e.g. residual battery energy), but also the links specific parameters (e.g. link error rate and the transmission energy for reliable communication across the links). It should be noted that the main approach of this paper is not to meet a predefined reliability constraint but to efficiently transmit data in a best effort real-time method via an optimum distance single-path routing. That is why we do not consider the previous reliable real-time routing protocols [15][16][17] for comparison here.

The simulation parameters for our model are mentioned in Table II. They are mostly chosen in reference to the MICAz mote specifications [25]. We ran the simulation with several parameters, including noise power and data rate, where 6 nodes randomly chosen from the left side of the terrain send periodic data to the sink placed at the middle of the right side of the terrain. We compare LLRR with existing protocols in terms of energy consumption, network lifetime, and miss ratio.

Figure 2 shows the average node energy consumption versus the noise power when the data rate is 2 pps (packet/s). Moreover, the simulation ends as soon as 2000 packets are received at the sink. When the noise power increases, the number of retransmissions increases as well, so more energy is required for successful data delivery. However, LLRR selects relay nodes by considering noise power condition. Hence, it imposes less retransmission than the others on data forwarding. It is actually the ability of LLRR to save energy via an

TABLE II
Simulation Parameters

Terrain	$500m \times 500m$
Node Number	200
Initial Node Energy	$1\ J$
Bandwidth	$250\ Kb/s$
Radio Range	$100m$
Modulation Scheme	BPSK
Payload Size	$50\ Bytes$
Deadline	$400\ ms$
$E^{(ele)}$	$50\ nJ/bit$
$E^{(amp)}$	$10\ pJ/bit/m^2$

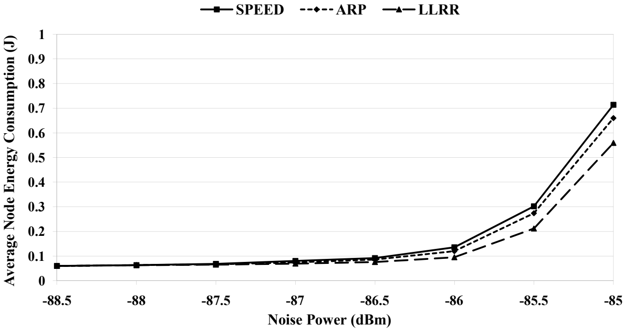

Fig. 2. Average node energy consumption under different noise power

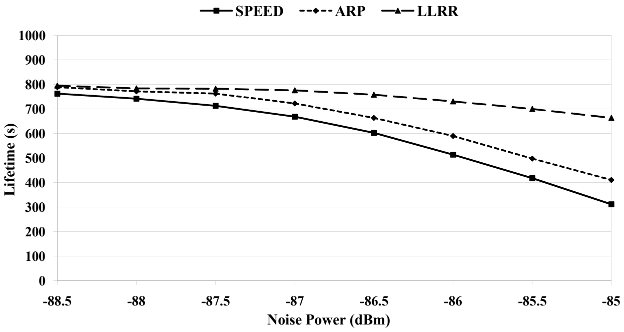

Fig. 3. Network lifetime under different noise power

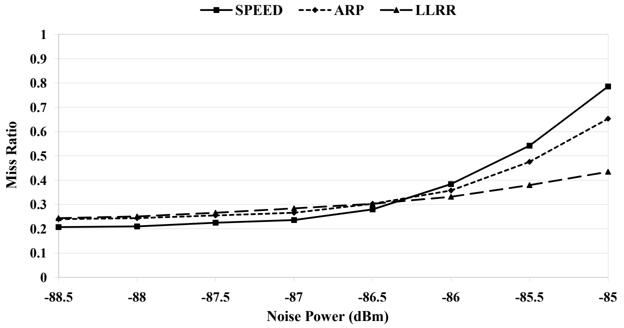

Fig. 4. Miss ratio under different noise power

optimum distance routing, even if the noise power is low enough. At the following, it can be seen how the LLRR energy saving mechanism can deal with the network lifetime to be considerably extended.

Network lifetime is defined as the time duration after which the QoS requirement (deadline constraint) cannot, in any way, be met due to the failure of some network nodes. Hence, the sensing data cannot reach the sink on time anymore, which causes quality failure. As it is evident from Figure 3, noise power increment causes the lifetime to shorten. However, our energy-efficient and energy-aware scheme holds the network functionality for a longer time in various noise power values. As already mentioned, this is mainly because battery drain is well balanced in our protocol. However, SPEED and ARP suffer from uncontrolled energy consumption, although ARP considers synthetically the node residual energy for routing, so they have undesirable lifetimes. In this scenario, on average, LLRR outperforms ARP and SPEED by 20% and 36% in terms of network lifetime, respectively.

Miss ratio, the most important metric in real-time systems, is defined as the percentage of packets that does not meet their end-to-end deadlines. Figure 4 shows packet miss ratio when the simulation duration is 100 seconds. In fact, the number of retransmissions increases with the noise power, so more packets will be lost due to the expiration of their deadline. Our scheme selects next hop nodes based on the closeness to the optimum distance. Therefore, sometimes the delay in this algorithm exceeds that of SPEED and RAP, so a higher miss ratio for LLRR is justifiable in low noise power. However, in higher noise power values, miss ratio will be significantly less than the others due to high quality path selection for data forwarding. Thus, LLRR can handle the number of retransmissions more effectively as the noise power increases. However, the SPEED protocol selects the node with the largest relay velocity and, in the highest probability, with a long distance from the current node. Therefore, it is severely affected by the noise power, especially in the higher values.

Figure 5 plots the network lifetime under various packet generation rates and median noise power level of -86 dBm. As demonstrated, LLRR efficiency will be considerable in terms of the network lifetime due to balancing the energy consumption. As the packet rate increases, the full buffer probability, the end-to-end delay, and the node failure rate increase too. It is the main reason behind the ascending form of miss ratio curves depicted in Figure 6 when the simulation duration is 100 seconds.

Simulation results reveal that the proposed algorithm improves energy consumption, lifetime, and miss ratio by selecting high quality paths for data forwarding in unreliable WSNs.

V. Conclusion

Reliable real-time data dissemination is a service of great interest to many sensor network applications. In this paper, we proposed LLRR to provide an optimum distance real-time routing in unreliable WSNs, while considering energy awareness. The simulation results demonstrate a significant performance improvement in terms of energy consumption, network lifetime, and miss ratio.

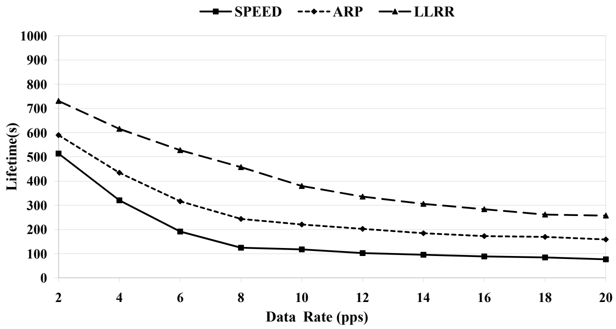

Fig. 5. Network lifetime under different network loads

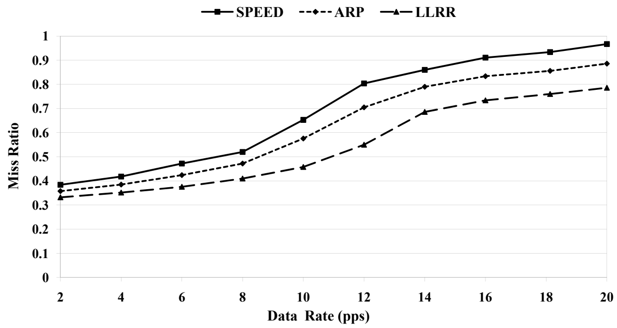

Fig. 6. Miss ratio under different network loads

The algorithm could be modified to take into account some aspects that have not been addressed in this work, which can be an interesting subject of future research. For instance, studying an aggregation-aware real-time routing protocol can be considered in future studies.

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