A novel Tunable Opportunistic Routing Protocol for WSN Applications

Mohammadreza Soltani

Amirkabir University of Technology, Tehran, Iran

Abstract*— *The application of Wireless Sensor Networks (WSN) technologies in various engineering and scientific areas has seen a rapid growth in recent years. WSNs have been applied to monitoring, measuring, control and coordination in different areas like military applications, industrial environments, agriculture and more. Many WSN applications such as industrial applications require real-time communication between WSN nodes and demand reliable packet delivery. In addition, the energy consumption aspects of wireless nodes need to be carefully considered. In this paper we introduce a novel routing protocol for WSNs in real-time. Our protocol uses geographic information of sensor nodes and a tunable cost function for selecting intermediate relay nodes. This allows it to adapt to various network designs and application requirements. Our results show that the presented routing algorithm achieves highly reliable, near real-time delivery of data packets at improved energy efficiency.

Keywords—Reliability; Void-Avoidance; Real-Time; Routing Protocols; Energy Consumption; Wireless Sensor Networks

I. INTRODUCTION

Wireless technology is becoming increasingly prevalent in our everyday lives. With applications spanning virtually the entire spectrum, it has become one of the most influential accelerators in research and development in our generation. Wireless technologies, in particular Wireless Sensor Networks (WSN), have seen tremendous growth and research efforts in a variety of areas. Leveraging the small size, mobility, longevity, and capabilities of WSN nodes they enable real-time monitoring, process control and automation applications, and more. WSN protocols enable seamless communication between information source devices, relay nodes and destination devices which are responsible for gathering information produced by source sensors and analyze them in order to provide appropriate outputs or to issue proper commands. These advances, however, do not come without their own significant challenges. These include the need for energy efficient operation, overcoming the inherently error-prone wireless channel to accomplish reliable data communication, as well as effective ad-hoc routing methods, all of which are necessary for real-time and reliable applications [1].

Of particular focus in our work is the reliability of data delivery to the destination, which is necessary because of the presence of noise in wireless channels – and in particular in harsh environments – which adversely affects the wireless link and thus impairs reliability in data delivery. Another key concern related to WSNs is energy efficiency of WSN nodes, since the lifetime of wireless sensor nodes using battery is limited. Thus, suitable routing protocols for communication operations need to include considerations of energy consumption and remaining energy reserves in the routing decision process.

The support of mobility in WSN applications is a key benefit [2-4], but also requires significant research to enable high reliability and low latency in route discovery and data delivery. Finally, the confidentiality and security of related information is another key challenge in these networks [5].

In this paper, we focus on introducing a novel tunable opportunistic WSN routing protocol for situations in which the amount of channel noise is high. Of particular interests to us for the design of this protocol are

1. the real-time delivery of data packets,
2. high data delivery reliability, and
3. minimizing the energy consumption of sensor nodes throughout the routing process.

In our previous work [6], we proposed a geographic routing protocol that selects the next candidate node based on a cost function that considers both energy and real-time criteria. In this paper, in addition to these concerns the reliability of wireless links has also been included in the route determination process to address the needs of reliable applications. We have incorporated the consideration for high reliability into this routing protocol at two levels: The first level is related to the delivery of information over reliable links and in the second level the protocol deals with predicted or discovered voids along the path from source to destination and route recovery, if necessary.

Our results show significantly better performance of this proposed routing protocol compared to other greedy routing strategies, with or without the ability of estimating the link status in terms of remaining energy in nodes, lifetime of the network and reliability of end-to-end paths in the network. Also, because of the use of geographic and proactive routing methods for our algorithm, near real-time delivery of data at low network latencies has been achieved.

The remainder of this paper is organized as follows: Section II reviews related works and provides some information about other routing protocols. In Section III, we describe the proposed routing protocol and its features. The simulation results are presented in Section IV, and finally the paper is concluded in Section V.

II. Related Work

In [6] a geographic routing protocol has been proposed for optimizing energy consumption of wireless sensor nodes that also handles encountered voids during the routing of data packets to the destination. To accomplish this, a cost function is used for selecting the next candidate node in the routing process based on gathering information about neighborhood nodes and creating a neighborhood table in each node. As a result, the cost function in this method includes only the remaining energy of neighboring nodes and their Euclidean distance to the sink node. Results in this paper show the increase in network life time and traffic load balancing among different nodes. The algorithm for handling of voids is based on right-hand rule that was proposed in [7]. But in this paper, the reliability issue is not considered especially for wireless links as a key requirement in applications which need the reliability of delivering packets to destination.

The authors of the routing method in [8] consider the real-time delivery of data packets, the reliability and the energy usage parameters in sensor nodes in an approach similar to [9]. Both of these algorithms can be categorized as reactive routing protocols and the process of routing is started from the sink node backwards to the source nodes. Because of this methodology, a process called route discovery phase is necessary and introduces additional delay to the data delivery. Hence, it does not present a suitable routing candidate for real-time applications.

In [10], a proactive routing protocol that uses geographic routing has been presented. In this protocol, the selection of the next node in the route path is determined using an optimizing function that selects one of the neighbor nodes based on the remaining energy parameter and geographic distance to destination. Furthermore, the presented method uses energy harvesting in the sensor nodes to compensate for some of the energy consumed over time. But in this work, there is no solution for handling encountered voids as a common problem in geographic routing protocols. The authors of [11] present a routing protocol developed using a cross-layer approach. In this protocol, the reliability of data delivery to the sink node, congestion control as well as the handling of probable voids is considered. This routing protocol selects the next candidate node based on a competition between candidate nodes at the receiver side, and hence imposes extra delay during this phase that can be a challenge in real-time scenarios.

The work presented in [12] introduces a routing protocol which considers energy consumption of nodes and their reliability. In this protocol, topology information about the network is periodically exchanged among sensor nodes in order for nodes to be able to estimate the quality of the links. This adds significant overhead that is detrimental to the overall lifetime of the network.

An energy-based MAC and routing protocol which uses a TDMA method for communicating between sensor nodes in body sensor applications is described in [13]. The routing is accomplished using an asymmetric downlink and uplink architecture in which a coordinator node sends data packets directly to sensor nodes, whereas sensor nodes send their information in a multi-hop scheme to the coordinator. In this work while the energy consumption of sensor nodes is addressed, the reliability and real-time delivery of data packets are not considered. In addition, use of TDMA-based methods imposes more delay in real-time applications.

While all of these protocols partially address the requirements imposed by real-time and reliable WSN applications, none of them address all of them, nor in a satisfactory fashion.

III. Proposed Routing Protocols

In this section, our new routing protocol for WSN applications need low latency and ensuring the delivered reliable data packets is described in detail. This protocol is based on geographic routing, which is tunable to the specific application needs, and consists of two modes. The first mode called Optimized Forwarding Mode (OFM) manages the routing process for environments where the void problem, in which all available neighbor nodes are farther away from the destination, does not exist for network paths between sources and sink nodes. The second mode is called Perimeter Forwarding Mode (PFM), and considers the presence of voids between source nodes and destination nodes. The primary assumption of this algorithm is explained as follows:

- Every node has its own geographic position information using a GPS device or other localization methods. This assumption is valid since every sensor node is located in a certain location suitable for collecting or relaying data packets to destination nodes.
- Every node has the geographic information of the destination node. This premise is reasonable inasmuch as the location of destination or sink node is related to the management section of the application center. Therefore, it should be accessible for every sensor node.
- In this algorithm we assume that the WSN nodes may be portable, and that the velocity of nodes is not a major concern, such that their mobility does not interfere with the procedure of our routing protocols.

Based on the above assumptions, we describe the two modes of this routing algorithm in the following sections.

A. Optimized Forwarding Mode

All of the geographic routing protocols introduced by the research community over the years are in some fashion derived from the Greedy algorithm. In the Greedy method the closest node to the destination shall always be selected. This protocol does, however, not cope with voids or dead zones in progressing to the sink nodes. In addition the mentioned problem which will be addressed in our PFM approach, utilizing greedy methods can cause the depletion of some nodes and result in the partitioning of networks. In our proposed protocol, sensor nodes use "Hello" packets to send their information to their neighbor nodes. Sending these Hello

Energy remaining at Sender	Sequence Number of Hello Msg	Time Stamp of Hello Msg	Node Location: y-Coordinate	Node Location: x-Coordinate

Fig. 1. Fields of Hello packets

packets is conducted in periodic intervals and are considered as control overhead of the protocol. The different fields of a Hello packet are shown below.

1) Routing Mechanism

For each transmission of Hello packets, the node will first update all fields to their current values. After receiving a Hello packet, the receiver node verifies whether or not it has a neighbor node closer than itself to its destination, based on the X and Y coordinate fields. If there is no such node, the routing protocol is switched to PFM mode. Otherwise, the indicated remaining energy of the neighbor node is compared to the energy threshold value. This threshold is determined by the energy model for this protocol. According to this model, the consumption of energy for wireless nodes is exclusively at the time of receiving and sending control or data packets. Therefore, it is assumed that the energy consumption for data processing tasks is negligible. Furthermore, we suppose that there is no limitation in amount of energy for sink nodes, so the threshold value can be calculated as:

$$Threshold_{EN} = P_{tx}T_{tx} + P_{rx}T_{rx} \quad (1)$$

Where P_{tx} and P_{rx} are transmitting and receiving power, respectively. Similarly, T_{tx} and T_{rx} represent the duration for transmitting one message and the receiving duration, respectively. In addition, the link between nodes – having satisfied distance and energy conditions – and the sending node should have a Packet Delivery Rate (PDR) higher than a threshold in order to be considered a link with good status.

After this process a node may have several candidate neighbors in its neighbor table. Therefore, when the node wants to transmit data to the destination it will use stored values from the last received Hello packet from each neighbor and calculate the result of a Cost Function for each candidate. It will select the candidate with the lowest resulting cost value as the next-hop destination for this data packet. After receiving the data packet this next-hop node will perform the same procedure in order to continue the data delivery process towards the sink node.

For our protocol we provide the possibility of two distinct cost functions, similar to [10]. The first function is the Linear Cost Function (LCF) and the second is the Exponential Cost Function (ECF). The performance of these two functions is evaluated and discussed in section IV. The use of LCF or ECF, as well as their parameters, allows the adaptation of our routing protocol to the specific application needs. These two cost functions are defined below:

$$LCF = \frac{1}{\alpha \times Norm\big(PD(i,N,D)\big) \times PDR_{N,i} + (1-\alpha) \times Norm(E_{res})} \quad (2)$$

$$ECF = \frac{1}{\eta^{\lambda_i} \times PD(i,N,D) \times PDR_{N,i}} \quad (3)$$

Where α , η are tunable parameters and λ_i is the fraction of remaining energy in node *i*. The term $Norm\big(PD(i,N,D)\big)$ represents the normalized progressive distance from node *i* to node *N* with *D* as the distance between them, $PDR_{N,i}$ is the Packet Delivery Rate of the wireless link between nodes *i* and *N*, which is calculated from the Sequence Number and transmit time of "Hello" packets and a link quality estimation algorithm called EWMA. This algorithm is explained in the next subsection and is derived from the algorithm in [14]. $Norm(E_{res})$ is defined as the normalized remaining energy among candidate neighbor nodes of a sender. It is important to note that the normalization operations in equations (2) and (3) are performed with respect to the biggest value of progressive distance and remaining energy among all neighboring candidate nodes for $PD(i,N,D)$ and E_{res}, respectively.

2) Exponential Weighted Moving Average (EWMA) Algorithm

In addition to the void avoidance mechanism we developed in [6], the algorithm presented in this paper also utilizes a network-level reliability mechanism based on the Exponential Weighted Moving Average (EWMA) for estimating the wireless link state between a sending node and its candidate neighboring nodes. Before we explain this algorithm, we have to mention that a wireless link is considered symmetric for reliability estimation, which means that the estimation result for the link direction from node i to node j is the same as the one from node *j* to node *i*. The pseudo code of this algorithm is as follows:

When a Hello packet is received, or when timer expiration indicates the loss of a Hello packet:

$$\begin{aligned}
& if\ Ne_{time} < Curr_{time}\ \{ \\
& \quad Ne_{pdr} = Ne_{pdr} - \theta \\
& \} \\
& N_m = Curr_{seq} - Last_{seq} - 1 \\
& Last_{seq} = Curr_{seq} \\
& L_c = Max(N_m, 0) \\
& Ne_{pdr} = \gamma\big(Ne_{pdr} \times \gamma^{L_c}\big) + (1-\gamma)
\end{aligned}$$

Fig 2. Pseudo code of EWMA Calculation

The EWMA calculation in our routing algorithm is executed every time a sensor node receives a Hello packet from one of its neighbors, or if a timeout indicates that a Hello packet was lost due to adverse channel conditions. The algorithm begins by looking up the values stored in the corresponding neighbor table entry and proceeds with the EWMA calculation outlined above. If it determines the loss of a Hello packet the if-statement will evaluate to true and a penalty will be applied to the neighbor's link PDR, Ne_{pdr}, by subtracting the value of the tunable parameter θ from it. The algorithm continues by calculating the number of missed Hello packets based on the current and previous sequence numbers, if available, given by the parameters $Curr_{seq}$ and $Last_{seq}$, respectively. This value L_c, is used in the update of the neighbor's link PDR based on the exponential weighted moving average by applying equation (4).

$$Ne_{pdr} = \gamma\big(Ne_{pdr} \times \gamma^{L_c}\big) + (1-\gamma) \quad (4)$$

In equation (4), the parameter γ is limited to the range (0,1), in order to achieve a stable and agile estimation for wireless link status [15]. In the simulation and results section the values for γ and θ and their impact are further evaluated.

The reduction of Ne_{pdr} when a Hello packet is lost represents the update in current link status and ranking among the neighbors as part of the determination of the neighbor that is the next hop towards the sink node.

In this fashion, the routing process of data packets based on the cost function and neighbor selection continues towards the destination, unless a void in the network is encountered along the path towards the sink node, at which point the routing mode switches to the Perimeter Forwarding Mode (PFM).

B. Perimeter Forwarding Mode

When data packets are routed to their appropriate destination, it is possible for them to encounter a situation where none of the available neighbors at the current forwarding node can contribute towards a distance reduction between the current node and the destination, i.e. all available neighbor nodes are farther away from the destination A network configuration such as this is called a void or dead zone, and the routing protocol should provide a strategy to recover from this situation in the hope that the routing of data packets can continue to sink nodes. In our proposed routing algorithm an approach similar to our previous work in [6] is utilized, called Right-Hand rule [7]. In this algorithm the distance between the destination node and the point where we first encounter the void and switch to the PFM Mode is called Reference Distance (RD). We kindly refer the reader to the detailed description of the PFM operation in the referenced work.

In our proposed protocol, a data packet will be received when the Signal to Noise Ratio (SNR) in the receiver node is higher than a given threshold. This assumption is valid for all the receiving packets that use either OFM or PFM. Otherwise, receiving date packet is ignored or considered as a background noise. The flowchart of this routing protocol is illustrated in Fig.3.

IV. SIMULATION AND RESULTS

In this section, we have presented the simulation results for variant scenarios. To simulate the performance of our routing protocol, we implemented it in NS 2.34 [15]. The different

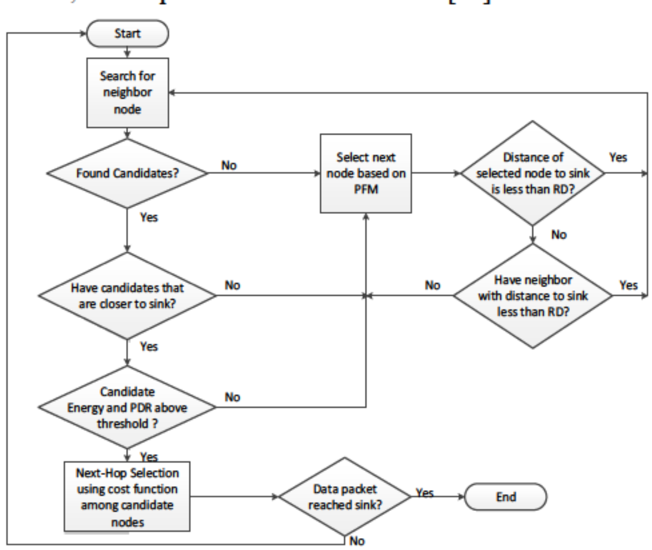

Fig. 3. Flowchart of the routing Protocol

TABLE I. Parameters for Simulation

Parameter Name	Value
MAC layer	IEEE 802.11 (CSMA/CA)
Propagation Model	Two-Ray Ground
SNR Threshold	13.5 db
Bandwidth (Mb/s)	2
Payload Of Packets (Bytes)	32
Terrain (m × m)	200 × 200
Number of Nodes	50, 75, 100, 125
Nodes Deployment	Uniform random
Sink Node Location	(200 , 100)
Effective Radio Range (m)	40
Initial Energy Per Node (Joule)	6, 1.5
Simulation Duration (seconds)	250, 450
Data Packet Traffic Generator (pkt/sec)	CBR (0.5, 0.75, 1, 2)
Hello Packets Interval (seconds)	50

parameter values and assumptions used in our various scenarios are presented in Table 1.

In addition to the parameters in table 1, the EWMA algorithm's parameters θ and γ have been set to 0.1 and 0.9, respectively. The value of α in LCF is set to 0.25, 0.5, 0.75 and 1. Finally, η in ECF is chosen as 100000. We consider a large value for η because we want to make sure that ECF is enough sensitive to the decreasing of the energy of sensor nodes.

In the first scenario, similar to those we evaluated in [6], we want to study the performance of our proposed routing protocol in terms of energy consumption. The average remaining energy as well as standard deviation of remaining energy per node are shown in figures 4 and 5, for LCF with all selected values of α, including $\alpha = 1$ (similar to GPSR [7]), as well as for ECF. In this scenario, there is no error model in the network and PDR for both cost function is set to 1. Simulation time is 250 seconds, the initial energy of sensor nodes is 6 J, and the number of simulation runs for statistical reliability is 50.

As we can see in Fig. 4, the average remaining energy for both cost functions are similar for higher node density levels. At lower density levels, ECF achieves significantly higher values of average remaining energy than GPSR and LCF. This results from the fact that at lower density, the probability of encountering a void is higher. Hence, the routing protocol is forced to function in PFM for longer time intervals. It is important to realize that ECF is more sensitive with respect to energy levels in sensor nodes. When a node is repeatedly selected which results in encountering a void, ECF has a faster reaction time to avoiding this node in future routing decisions. Thus, with ECF we have a higher probability of avoiding the dead zone and thus a lower rate of utilizing PFM and its higher energy consumption. When the routing process is based on LCF, however, it requires more time until the route changes due to the energy depletion in the node at the void. Thus, PFM is active more often and more sensor nodes participate in the routing process. Consequently, the average remaining energy for GPSR and LCF (α≠1) will be less than ECF for lower density of nodes.

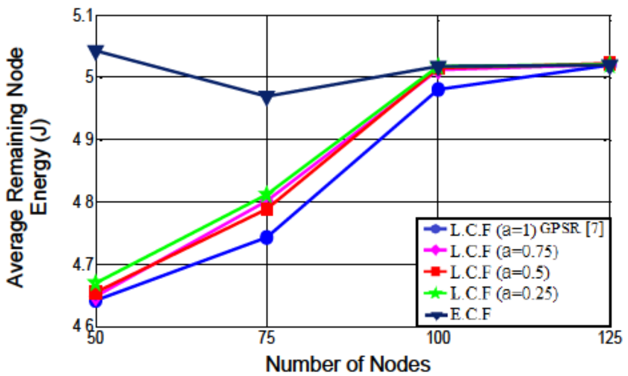

Fig. 4. Comparison average remaining energy between LCF and ECF

In Fig. 5, ECF also shows better results than GPSR and LCF (α≠1) because of the same reason as shown above. In fact, when more nodes participate in the routing process, the decrease in energy will be more uniformly distributed, and thus the standard deviation of remaining energy is better and all nodes will have somewhat similar remaining energy levels. Moreover, from the decrease in standard deviation we can imply that the traffic load is distributed among different nodes, and thus we can control congestion and load balancing at bottleneck sensor nodes in the network.

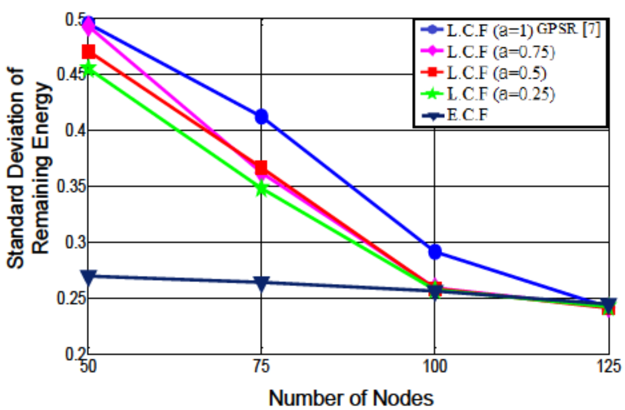

Fig. 5. Standard deviation of remaining energy between LCF and ECF

It should be noted that for denser deployment scenarios, all curves converge to a specific level. In other words, when the number of nodes increases, the Progressive Distance $PD(i, N, D)$ in equations (2) and (3) will be same for all candidate nodes. Hence, only the energy contributes to selecting neighboring nodes and the standard deviation of nodes will converge.

Fig. 6 shows the node deployment topology for our second simulation scenario. In this scenario the number of nodes is 50. There is no error model in this scenario (PDR = 1). The initial energy of each node is 1.5J and the initial energy for the sink node is considered 6J since we want to ensure that the sink node never fails due to energy depletion. The simulation time is 450 seconds. Finally, the traffic generated is CBR with 0.25, 0.5, 0.75, and 1 seconds per packet as the interval time for generating packets.

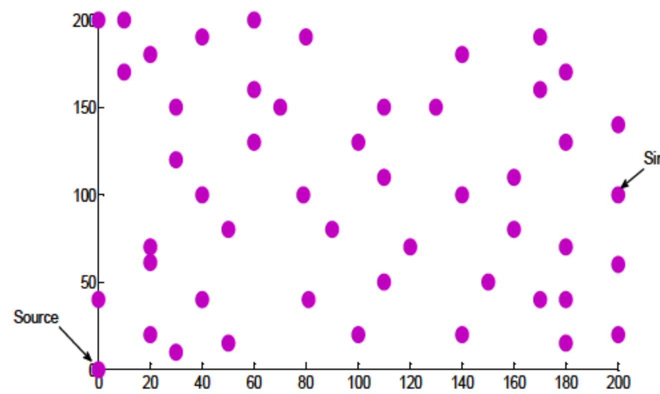

Fig. 6. Deployments of nodes in second scenario on a 200x200m grid

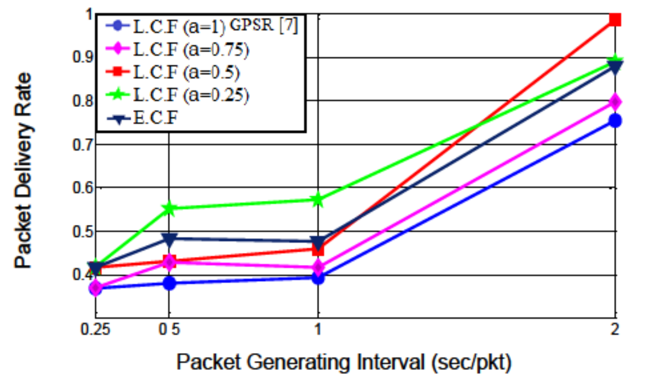

Fig. 7. Packet Delivery Rate to Destination

In Fig. 7, the Packet Delivery Rate from the source node to the destination has been illustrated for the second scenario. The PDR for ECF and LCF with α = 0.25, which are more sensitive to the variation in energy consumption, demonstrate better results than GPSR as the depletion of energy in the sensor nodes requires more time.

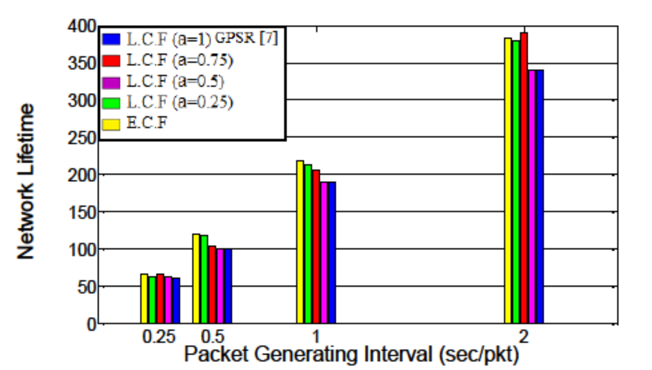

Fig. 8. Lifetime of the network using with LCF and ECF

In Fig. 8, the lifetime of the network for our second scenario is shown. We have used the definition of lifetime as the time it takes from the start of the simulation until the first node dies in the network. ECF and LCF with lower α show longer lifetime in comparison with GPSR, and this is also because of the effect of the energy term in ECF and LCF with lower α compared to the other values of α.

Finally, for Figures 9 and 10 we are evaluating the scenario in which we are in fact introducing errors into the simulated network links. Therefore, our routing algorithm now also needs to consider the value for PDR in the ECF and LCF calculation for selecting the next candidate node. The parameter we utilize here is the product of all PDRs of links between the source and sink nodes. This corresponds to the reliability of a path from source to destination and is calculated as follows:

$$PDR_{src-to-sink} = \prod_{src \le i < j \le sink} PDR_{i,j} \qquad (5)$$

In the two following figures the ECF cost function algorithm achieved better results than the others.

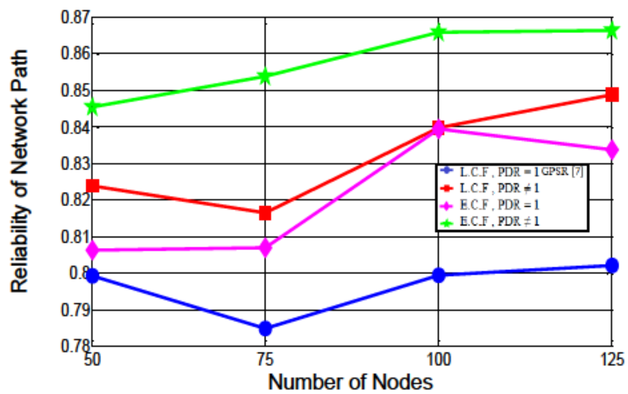

Fig. 9. Reliability percentage among data delivery paths between source nodes and destination for L.C.F (α = 1) and E.C.F

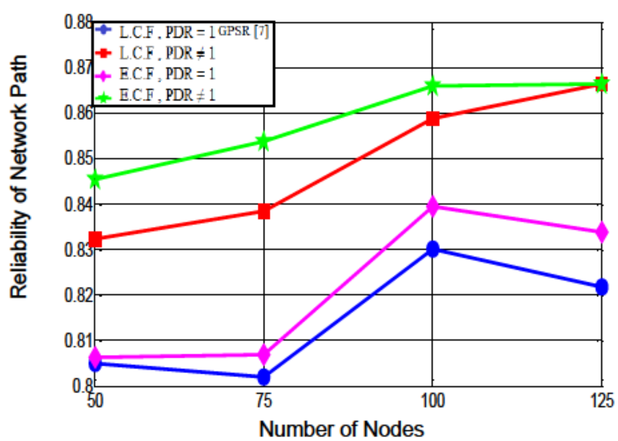

Fig. 10. Reliability percentage among data delivery paths between source nodes and destination for L.C.F (α = 0.25) and E.C.F

V. CONCLUSION

In this paper, we introduced an opportunistic routing protocol that can be tuned to specific application requirements for Wireless Sensor Networks, particularly for applications where reliability and energy efficiency are key requirements. We could show that it achieves both better data delivery reliability and longer network lifetime.

It also achieves low latency communication due to its proactive operation and the resulting lack of a distinct route discovery phase that is often found in reactive routing protocols. Our presented routing protocol is based on geographic routing, which uses information about location and other factors from neighboring nodes for selecting the next forwarding node when routing data packets. To avoid encountered voids along the network path an algorithm based on the Right-Hand Rule has been employed. The simulation results show better performance of our proposed routing protocol than Greedy Routing and other energy aware methods, both with and without packet error handling.

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