Technical paper on Relay Node Identification for Energy Efficient and Opportunistic Forwarding in Wireless Sensor Networks

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Abstract- *Energy savings optimization becomes one of the major concerns in the wireless sensor network (WSN) routing protocol design, due to the fact that most sensor nodes are equipped with the limited nonrechargeable battery power. In this paper, we focus on minimizing energy consumption and maximizing network lifetime for data relay in one-dimensional (1-D) queue network. Following the principle of opportunistic routing theory, multihop relay decision to optimize the network energy efficiency is made based on the differences among sensor nodes, in terms of both their distance to sink and the residual energy of each other. Specifically, an Energy Saving via Opportunistic Routing (ENS_OR) algorithm is designed to ensure minimum power cost during data relay and protect the nodes with relatively low residual energy. Extensive simulations and real test bed results show that the proposed solution ENS_OR can significantly improve the network performance on energy saving and wireless connectivity in comparison with other existing WSN routing schemes.*

Keywords- Energy efficiency, one-dimensional (1-D) queue network, opportunistic routing, relay node, wireless sensor network (WSN).

I. INTRODUCTION

WIRELESS sensor network (WSN) offers a wide range of applications in areas such as traffic monitoring, medical care, inhospitable terrain, robotic exploration, and agriculture surveillance. The advent of efficient wireless communications and advancement in electronics has enabled the development of low-power, low-cost, and multifunctional wireless sensor nodes that are characterized by miniaturization and integration.

In WSNs, thousands of physically embedded sensor nodes are distributed in possibly harsh terrain and in most applications, it is impossible to replenish energy via replacing batteries. In order to cooperatively monitor physical or environmental conditions, the main task of sensor nodes is to collect and transmit data. It is well known that transmitting data consumes much more energy than collecting data. To improve the energy efficiency for transmitting data, most of the existing energy-efficient routing protocols attempt to find the mini-mum energy path between a source and a sink to achieve optimal energy consumption.

However, the task of designing an energy-efficient routing protocol, in case of sensor networks, is multifold, since it involves not only finding the minimum energy path from a single sensor node to destination, but also balancing the distribution of residual energy of the whole network. Furthermore, the unreliable wireless links and network partition may cause packet loss and multiple retransmissions in a preselected good path. Retransmitting packet over the preselected good path inevitably induces significant energy cost. Therefore, it is necessary to make an appropriate tradeoff between minimum energy consumption and maximum network lifetime.

We focus on one-dimensional (1-D) queue network, which has been designed and developed for a wide variety of industrial and civilian applications, such as pipeline monitoring, electrical power line monitoring, and intelligent traffic. Fig. 1 shows an example, illustrating a pervasive traffic information acquisition system based on 1-D queue network platform, where the nodes are linearly deployed along the road. Most of the existing traditional traffic information acquisition systems are implemented without power-saving management.

With the demands of various sustainable developments in smart city, an energy saving optimization solution for smart traffic information acquisition should be taken into account. In our solution, when a motion sensor node detects a vehicle in its sensing range, it will acquire traffic information, such as traffic volume, vehicle velocity, and traffic density. Sensor nodes will send the collected data to relay sensor nodes, and then the relay sensor nodes forward traffic information along the energy-efficient path to the sink node that is one or more hops away. Finally, comprehensive traffic information will be established by the sink node and sent to the traffic management center. Meanwhile, traffic management center will select appropriate information and offer it to the clients via the network. This smart traffic information acquisition solution can be used to extend the lifetime of 1-D queue network in the need of energy saving in WSN-based Information Technology (IT) infrastructure.

In this paper, we propose an energy-efficient routing algorithm for above 1-D queue network, namely, Energy Saving via Opportunistic Routing (ENS_OR). ENS_OR adopts a new concept called energy equivalent node (EEN), which selecting relay nodes based on opportunistic routing theory, to virtually derive the optimal transmission distance for energy saving and maximizing the lifetime of whole network. Since sensor nodes are usually static, each sensor's unique information, such as the distance of the sensor node to the sink and the residual energy of each node, are crucial to determine the optimal transmission distance; thus, it is necessary to consider these factors together for opportunistic routing decision.

ENS_OR selects a forwarder set and prioritizes nodes in it, according to their virtual optimal transmission distance and residual energy level. Nodes in this forwarder set that are closer to EENs and have more residual energy than the sender can be selected as forwarder candidates. Our scheme is targeted for relatively dense 1-D queue networks, and can improve the energy efficiency and prolong the lifetime of the network.

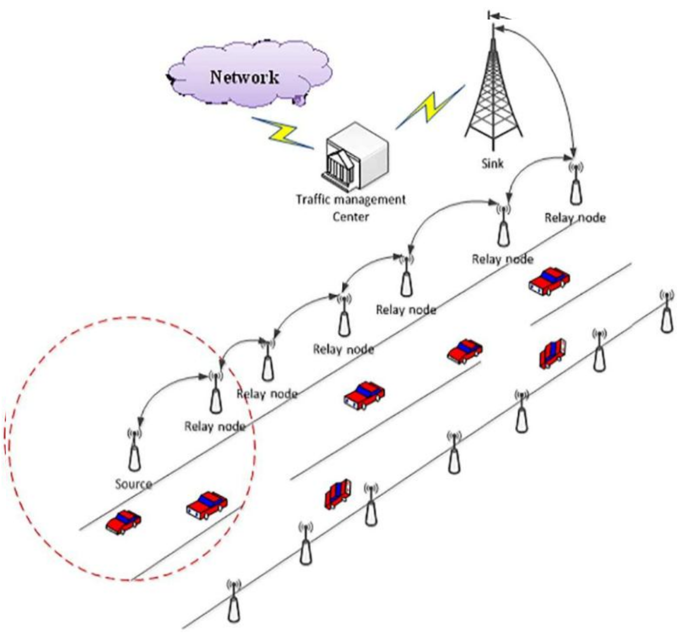

Fig. 1. Smart traffic information acquisition system.

The main contributions of this paper include the following.

1) We calculate the optimal transmission distance under the ideal scenarios and further modify the value based on the real conditions.
2) We define the concept of EEN to conduct energy optimal strategy at the position based on the optimal transmission distance.
3) We introduce the forwarder list based on the distances to EEN and the residual energy of each node into EEN for the selection of relay nodes.
4) We propose ENS_OR algorithm to maximize the energy efficiency and increase the network lifetime.

II. BASIC OPERATION OF OPPORTUNISTIC ROUTING IN WIRELESS NETWORKS

Opportunistic routing is based on the broadcast transmissions of the data packets. This type of transmission is used in order to increase the probability that at least one potential relaying node receives the packet. Next figure illustrates the advantage of broadcast transmissions. The source (S) needs to send packets to the destination (D). It knows that its neighbors N1, N2 and N3 provide different paths to the destination (path1, path2 and path3). It has also estimated the loss probability in each link (LLP) to its neighbor. Specifically, the link to N1 has a loss probability of 0.2 while to N2 and to N3 the loss probability is 0.3 and 0.4 respectively.

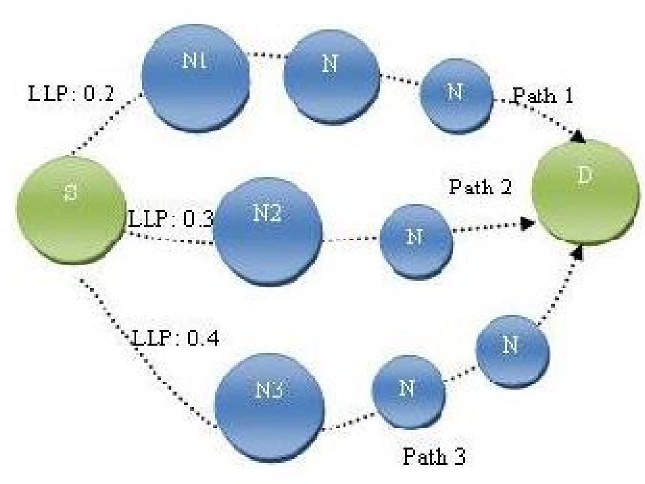

Fig 2.Connections in a wireless network to illustrate the benefits of opportunistic routing.

Using traditional routing, the Source S should select one of these potential forwarders as the next hop. Then, it will send the packet to this neighbor by a unicast transmission. Taking into account the loss probability, the source will select N1 as the next hop and the probability that the packet is not retransmitted is 0.2. Alternatively, opportunistic routing will emit the packet in broadcast so the three neighbors (and some others too) will be able to receive it and to retransmit it. The probability that the packet will not be retransmitted is equivalent to the probability that no neighbors will receive the packet. This probability is 0.2•0.3•0.4, that is, 0.024. As we can see, the loss probability obtained with the opportunistic strategy is much lower than the resulting from the traditional routing.

III. METRICS USED IN OPPORTUNISTIC ROUTING PROTOCOLS

The construction and ordering of the relay set highly impact on the network performance. The priority assignment of the nodes belonging to the relay set is performed according to their goodness to act as the next forwarding node. In this sense, most of the nodes in the relay set are at the same length (measured as the number of hops) to the destination. Thus, the number of hops may be employed to quantify the goodness of the nodes. In contrast, alternative metrics are used for this purpose. The metrics mainly depend on the specific implementation of the routing protocol. In this sense, the metrics can be classified as:

– Anycast Link Cost. In this case, the metric to order the candidates is based on the link properties (e.g the delivery rate on the link) or the neighbor characteristics (such as position). They are said to select the forwarding set hop-by-hop.

– Remaining Path Cost. They are also named end-to-end metrics as the properties of the remaining path (the nodes or the links in the path to the destination) constitute the metric. A simple end-to-end metric is the number of hops of the path.

IV. OPPORTUNISTIC ROUTING IN WSNS

Challenged networks where network contacts are intermittent or where link performance is highly variable and there is no complete path from source to destination for most of the time. The path can be highly unstable and may change or break quickly. To make communication possible intermediate nodes may take keeping of data during the blackout and forward it when the connectivity resumes. Opportunistic Routing used broadcast transmission to send packets through multiple relays. Opportunistic routing archives higher throughput than traditional routing.

First protocol was designed by Biswas and Morris in 2004. The main idea behind Opportunistic Routing is select a subset of the nodes between the source and the destination node and the node closest to the destination will first try to retransmit packets. The main two steps are-

1. Selection of the forwarder sets: Selecting only the potential nodes between the source and destination to increase the routing efficiency.

2. Prioritization among these forwarders: The highest priority forwarder should be the closest one to the destination.

4.1. Exclusive opportunistic routing (ExOR)

ExOR is an incorporated routing technique. ExOR broadcasts each packet, selecting a receiver to forward only after learning the set of sensor nodes which really received the packet. Delaying forwarding decisions pending after reception allows ExOR to try multiple long, but radio lossy links at the same time as, resulting in high estimated progress per transmission.

Unlike supportive diversity schemes, but a single ExOR sensor node forwards each packet, so that ExOR works with existing radios. The central challenge of realizing ExOR is ensuring that only the best receiver of each packet forwards it, in order to avoid redundancy. ExOR operates on sets of packets in order to cut the communication cost of the accord. The source node contains in each packet a list of candidates Forwarders prioritized by close to the destination. Receiving nodes buffer effectively received packets and wait for the end of the batch.

The maximum priority forwarder then broadcasts the packets in its buffer, as well as its copy of the “batch map" in each packet. The batch map includes the sender's excellent estimate of the highest priority node to have received each packet. The residual forwarders then send out in order, but only send packets which were not acknowledged in the batch maps of higher priority nodes. The forwarders maintain to cycle in the course of the priority list until the destination has 90% of the packets. The remaining packets are transferred with traditional routing. The advantage of this ExOR is the choice of forwarders to provide throughput gains of a factor of two to four. Another advantage of this ExOR improves performance

By taking advantage of long-distance, but lousy links which would otherwise have been avoided by traditional routing protocols. ExOR is likely to increase total network capacity as well as individual connection throughput

4.2. Energy Efficient Opportunistic Routing (EEOR)

EEOR is an algorithm which works on the basis of selecting forwarders’ list and prioritizing the nodes in it. Two scenarios have been presented in the paper for adjusting the power of the nodes during transmission. EEOR have been tested on TOSSIM simulator.

In first scenario it is assumed that the sensor nodes cannot adjust the power available with them. In other case the transmission power can be adjusted by the sensor node for each transmission.

When the forwarder list has been formed the expected cost of transmission has been recorded against each forwarder node entry. Initially the cost will be zero for all nodes. Distance vector routing has been used to decide the routes after the expected cost has been calculated. The advantage of this EEOR is the end-to-end delay is smaller than EXOR routing, As well as better in terms of the packet loss ratio, energy consumption, and the average delivery delay

4.3. Energy Aware Opportunistic Routing (EAOR)

Energy Aware Opportunistic Routing follows a same transmission method as the opportunistic routing. But, the main diversity of this approach is the next relay node selection criterion. The communicate node that will respond first to an RTS packet is different than that of opportunistic routing. In energy aware opportunistic routing, a sensor node checks its energy level. If the energy level is low, then it does not respond with CTS. In this manner, the lifespan of each client is increased. When a node has high power usage, the probability to get a DATA packet is more depressed. But, the sensor node can still involve you in some of the DATA packet transmissions. If a neighboring node has a high energy level, but it is not that close to the destination in comparison with other neighboring nodes, it will start participating in packet transmissions when some of the neighboring nodes consumed too much energy. Energy aware opportunistic routing tries to send the packets over nodes that are near to the destination and also accept a high energy level. In this manner, it can discover more routing paths compared to the opportunistic routing.

These paths do not always consist of a similar number of hops that the opportunistic paths, however, they consist of nodes that have not been used that much and have high energy levels. EOAR does not use beaconing mechanism, for that reason it avoids the disadvantages of beaconing and this is the advantage of this EOAR protocol.

4.4. Simple Opportunistic Adaptive Routing (SAOR)

SOAR is a proactive link state routing protocol. Each sensor node periodically calculates and distributes link quality in terms of ETX. According to this information, a sender chooses the default path and a list of next-hop that are suitable for forwarding the data. It then broadcasts a data packet together with this information. Upon consideration the transmission, the nodes was not present on forwarding list, just discard the packet. Nodes were present at the forwarding list store the packet and set forwarding timers based on their nearness to the destination. Smaller timer is set if the node is closer to the destination and forward the packet earlier. Upon examining this transmission, the other nodes will eliminate the resultant packet from their queues to avoid redundant transmissions.

Similar to all the existing opportunistic routing protocols, SOAR broadcast data packets at a fixed PHY data rate. The advantage of SOAR is promising to achieve effectively support multiple simultaneous flows and high efficiency.

4.5. EFFORT

EFFORT is another opportunistic routing protocol for WSNs. EFFORT based on the OEC (Opportunistic End-to-end Cost) metric, which represents the predictable end-to-end scarcity energy cost for each data transmission. Effort having three main components is:

- Method for OEC computation,
- Select Candidate and relay priorities
- Data forwarding and OEC is updating.

The first component enables each sensor node to calculate its optimal OEC in a dispersed manner. The second component lets every sensor node put its optimal forwarding set of its neighbors and verify the relay sequence. The third component tells how the chosen forwarders help with each other to relay data and update the OEC value consequently. Main advantage of this EFFORT routing, i.e., the improvement of transmission reliability and path diversity, to develop a distributed routing scheme for keeping up the network-lifetime of a WSN.

V. RELATED WORK

In recent years, there are several studies on routing-related parameters, like connectivity-related parameters and density of the distributed nodes, in 1-D queue networks. Previous works and studied the connectivity probability of two certain nodes versus the entire network. Other work in investigated on uniformly and independently distribution under the assumption that the transmission range is fixed among sensor nodes.

Some energy-efficient approaches have been explored in the literature. As transmitting data consumes much more energy than other tasks of sensor nodes, energy savings optimization is realized by finding the minimum energy path between the source and sink in WSNs. In, the theoretical analysis about the optimal power control and optimal forwarding distance of each single hop was discussed. There is a tradeoff between using high power and long hop lengths and using low power and shorter hop lengths. With this in mind, minimum energy consumption can be achieved when each sensor node locates with the optimal transmission distance away from others in dense multihop wireless network. The most forward within range (MFR) routing approach has also been considered in 1-D queue networks, which chooses the farthest away neighboring node as the next forwarder, and eventually results in less multihop delay, less power consumption. Another approach proposed in reduces the total consumed energy based on two optimization objectives, i.e., path selection and bit allocation. Packets with the optimum size are relayed to the fusion node from sensor nodes in the best intermediate hops.

Surprisingly, the benefit of optimal bit allocation among the sensor node has not been investigated in 1-D queue networks. The unreliable wireless links makes routing in wireless networks a challenging problem. In order to overcome this problem, the concept of opportunistic routing was proposed in. Compared with traditional best path routing, opportunistic routings, such as extremely opportunistic routing (ExOR), geographic random orwarding (GeRaF), and efficient QoS-aware geographic opportunistic routing (EQGOR), take advantage of the broadcast nature of the wireless medium, and allow multiple neighbors that can overhear the transmission to participate in forwarding packets. However, these routing protocols did not address exploiting OR for selecting the appropriate forwarding list to minimize the energy consumption, and optimize the design of an energy-efficient OR protocol for wireless networks. However, these routing protocols did not address exploiting OR for selecting the appropriate forwarding list to minimize the energy consumption, and optimize the design of an energy-efficient OR protocol for wireless networks. Mao et al. introduced an energy-efficient opportunistic routing strategy called energy-efficient opportunistic routing (EEOR), which selects a forwarder set and prioritizes them using energy savings optimization solution of forwarding data to the sink node in WSNs. While all of these routing methods to improve the energy efficiency of individual node or the whole network can minimize energy consumption, it is equally important to focus on other objectives such as network lifetime and residual energy of relay nodes. Therefore, it is reasonable to take residual energy of sensor nodes as a primary metric into consideration.

VI. OPPORTUNISTIC ROUTING ALGORITHM FOR RELAY NODE SELECTION

In this section, we further analyze the energy consumption of large-scale network under 1-D model.

6.1. Problem of Optimal Energy Strategy

In order to acquire the minimum energy consumption during data transmission in whole network, we introduce the concept of EEN to conduct energy optimal strategy at the position based on the optimal transmission distance *d*op. However, the optimal energy strategy does not explicitly takes care of the residual energy of relay nodes in the network. For instance, in the case of hop-by-hop transmissions toward the sink node, the relay nodes lying closer to the EENs tend to deplete their energy faster than the others, since *d*op is a constant. As a consequence, this uneven energy depletion dramatically reduces the network lifetime and quickly exhausts the energy of these relay nodes. Furthermore, such imbalance of energy consumption eventually results in a network partition, although there may be still significant amounts of energy left at the nodes farther away. Therefore, we should readdress the optimal energy strategy for large-scale network from Theorem 1. Inspired from the opportunity routing approach, EEN is formed by jointly considering the distribution of real nodes and their relay priority. The specific algorithm to choose EEN is described in the following section.

6.2 Forwarder Set Selection for Optimal Energy Strategy

We can achieve optimal energy strategy by choosing optimal hops *n*op to determine optimal transmission distance *d*op. In addition, factors such as energy-balanced of a network and the residual energy of nodes are also considered while selecting the available next-hop forwarder.

We assume that node h is sending a data packet to sink, and $h + i$ is one of neighbors of node h. If it is closer to the estimated result and has more residual energy, the neighboring node h + i can be a forwarding candidate, then the network can obtain better energy usage. Moreover, these eligible candidates rank themselves according to their distances from the EEN and the residual energy of each node as

$$P(h+i) = \begin{cases} (d_{h+i} - d_h)\left[\frac{1}{|d_{h\,|\,i} - d_{op}|} + (E_{h+i} - \zeta)\right] \\ (h \mid i) \subset F(h), \qquad R \le i \le R \end{cases}$$

where $d_{h+i} - d_h$ is the distance between node h and neighbor node h + i, E_{h+i} denotes the residual energy of node h + i, nd ζ denotes the value of energy threshold. F(h) (F(h) ⊆ (h)) is the selected forwarding candidate set of node h. The larger the value of P(h + i) is, the higher priority of the node will be. Only the forwarder candidate with the highest priority is selected as the next forwarder.

We use above forwarding candidate set to decide corresponding energy saving strategy, which is specifically achieved through the following opportunistic routing algorithm, called ENS_OR.

6.3 ENS_OR Algorithm

In this section, we will describe how to select and prioritize the forwarder set using optimal energy strategy on each node, and how to choose the optimal relay node among potential forwarders that respond in a priority order. In addition, the transmitted data can be naturally classified into two categories:

1) The former is the collected data of its own; and
2) The latter is the relay data from other nodes.

Obviously, we should distinguish incoming data (the data of second category) by tracing the ID of sender. Eventually, we introduce ENS_OR algorithm for energy saving to select the next relay node which has the highest priority in forwarder set to forward the incoming ENS_OR algorithm. Algorithm 1 depicts the pseudocode of ENS_OR algorithm.

Algorithm 1. ENS_OR Algorithm

Require: d_i, d_h, d_{op}, E_i, ζ, where $i \in F(h)$

Ensure: the position of next forwarder *dn*.

Event: Node *h* has a data packet to send to the sink node.

/ * Steps * /

1: start a retransmission timer

2: select the forwarder set *F*(*h*) from neighboring nodes *N* (*h*);

3: **for** each node $i \in N(h)$ **do**

4: **if** $((d(i, d_{op}) < d(h, d_{op})) \cup (E_i > \zeta))$ **then**

5: add *i* to *F*(*h*);

6: **end if**

7: **end for**

8: prioritize the forwarder set using Optimal Energy Strategy;

9: **for** each node $i \in F(h)$ **do**

10: $P(i) = (d_i - d_h)[1/|d_i - d_{op}| + (E_i - \zeta)]$;

11: **end for**

12: broadcast the data packet;

13: **for** each node $i \in F(h)$ **do**

14: receive the data packet;

15: checks the sender ID and start a timer and $time(i) = \frac{\alpha}{P(i)}$;

16: **end for**

17: **if** node *n* which has the highest-priority receives the data packet successfully **then**

18: reply an ACK to notify the sender;

19: **for** each node $i \in F(h)$ except *n* **do**

20: discard the data packet and close timer;

21: **end for**

22: **else**

23: **if** the priority timer expire **then**

24: set *n* = *n_*, node *n_* has the lower-priority;

25: goto 17;

26: **end if**

27: **end if**

28: **if** no forwarding candidate has successfully received the packet **then**

29: **if** the retransmission timer expire **then**

30: drop the data packet;

31: **else**

32: goto 2;

33: **end if**

34: **end if**

35: **return**

VII. PERFORMANCE EVALUATION IN DIFFERENT METRICS

We conduct the simulation experiments using MATLAB with 100 nodes uniformly and independently distributed over a line. Each node has the same frequency B = 1 Mbit/s, and firmware character E_{elec} and ε_{amp} in (1) is set as 50×10^{-9} J/bit and 100×10^{-12} J/bit/m2, respectively. Path-loss exponent of environment τ is 2. Hence, the value of optimal transmission distance d_{op} in (9) is approximately equal to 31.6 m. Since E_{elec} and ε_{amp}, τ are fixed, no matter how the distance between two nearest nodes changes, d_{op} still will be 31.6 m, without change. The longest transmission distance of a single hop is 50 m and the initial energy is 720 mJ. Other simulation parameters are listed in Table I. In this one-source-one-sink topology, a node can only act as a relaying node. In this paper, we ignore the interference among the generated signals of each node. To fully analyze the performance of ENS_OR, we compared it with the methods GeRaF and minimum transmission energy (MTE) which represent the transmission power strategy with minimum transmission power, to satisfy quality of service (QoS) requirement of reception.

1. Average energy in joules :it is calculated with the number of nodes in the 1-D queue hence the average energy consumed is minimal when compared to other algorithm.
2. PDR(Packet Delivery Ratio):it isncalculates to find the total number of packets that has reached thee destination with respect to the number of nodes.
3. Throughput:throughput of the algorithm is calculated to find the efficirncy of the algorithm.

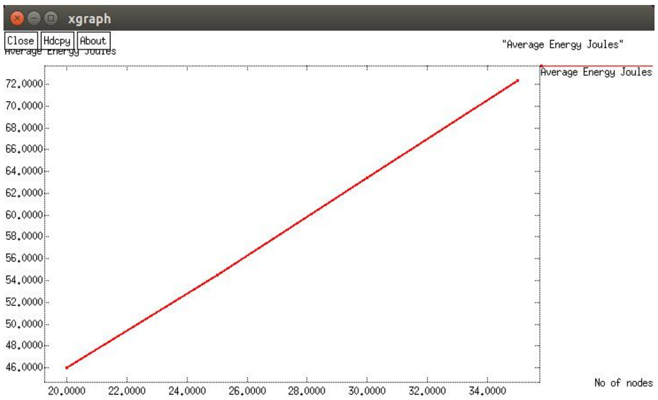

Fig.7.1. Graph showing the performance, average energy wrt no of nodes

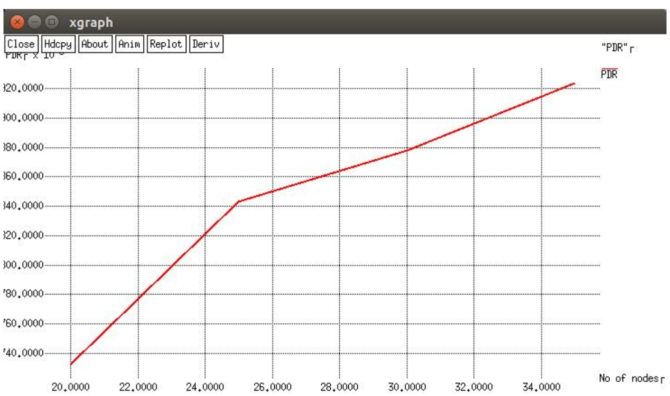

Fig.7.2. Graph showing the performance ,Packet Delivery Ratio(PDR) wrt no of Nodes

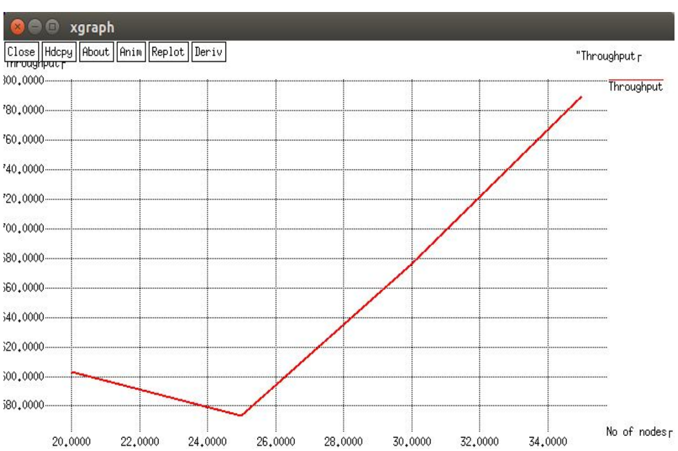

Fig.7.3. Graph showing the performance, Throughput wrt no of nodes.

VIII. CONCLUSION

WSN has been widely used for monitoring and control applications in our daily life due to its promising features, such as low cost, low power, easy implementation, and easy maintenance. However, most of sensor nodes are equipped with the limited nonrechargeable battery power. Energy savings optimization, therefore, becomes one of major concerns in the WSN routing protocol design.

In this paper, we reviewed the main routing protocols and focus on minimizing energy consumption and maximizing network lifetime of 1-D queue network where sensors' locations are predetermined and unchangeable. For this matter, we borrow the knowledge from opportunistic routing theory to optimize the network energy efficiency by considering the differences among sensor nodes in terms of both their distance to sink and residual energy of each other. We are trying to implement opportunistic routing theory to virtually realize the relay node when actual relay nodes are predetermined which cannot be moved to the place according to the optimal transmission distance. This will prolong the lifetime of the network. Hence, our objective is to design an energy-efficient opportunistic routing strategy that ensures minimum power is cost and protects the nodes with relatively low residual energy.

Numerous simulation results and real testbed results show that the proposed solution ENS_OR makes significant improvements in energy saving and network partition as compared with other existing routing algorithms.

In the future, the proposed routing algorithm will be extended to sleep mode and therefore a longer network lifetime can be achieved. Apart from that, an analytical investigation of the new energy model include sleep mode will be performed.

REFERENCES

[1] D. Bruckner, C. Picus, R. Velik,W. Herzner, and G. Zucker, "Hierarchical semantic processing architecture for smart sensors in surveillance networks," IEEE Trans. Ind. Informat., vol. 8, no. 2, pp. 291–301, May 2012.

[2] G. J. Pottie and W. J. Kaiser, "Wireless integrated network sensors," Commun. Assoc. Comput. Mach., vol. 43, no. 5, pp. 51–58, 2000.

[3] L. LoBello and E. Toscano, "An adaptive approach to topology management in large and dense real-time

wireless sensor networks," IEEE Trans. Ind. Informat., vol. 5, no. 3, pp. 314–324, Aug. 2009.

[4] D. Hoang, P. Yadav, R. Kumar, and S. Panda, "Real-time implementation of a harmony search algorithm-based clustering protocol for energy efficient wireless sensor networks," IEEE Trans. Ind. Informat., vol. 10, no. 1, pp. 774–783, Feb. 2014.

[5] D. Zhang, G. Li, K. Zheng, X. Ming, and Z.-H. Pan, "An energy-balanced routing method based on forward-aware factor for wireless sensor networks," IEEE Trans. Ind. Informat., vol. 10, no. 1, pp. 766–773, Feb. 2014.

[6] F. Ren, J. Zhang, T. He, C. Lin, and S. K. Ren, "EBRP: Energybalanced routing protocol for data gathering in wireless sensor networks," IEEE Trans. Parallel Distrib. Syst., vol. 22, no. 12, pp. 2108–2125, Dec. 2011.

[7] A. Behnad and S. Nader-Esfahani, "On the statistics of MFR routing in one-dimensional ad hoc networks," IEEE Trans. Veh. Technol., vol. 60, no. 7, pp. 3276–3289, Sep. 2011.

[8] A. Ghasemi and S. Nader-Esfahani, "Exact probability of connectivity one-dimensional ad hoc wireless networks," IEEE Commun. Lett., vol. 10, no. 4, pp. 251–253, Apr. 2006.

[9] A. Behnad and S. Nader-Esfahani, "Probability of node to base station connectivity in one-dimensional ad hoc networks," IEEE Commun. Lett., vol. 14, no. 7, pp. 650–652, Jul. 2010.

[10] P. Piret, "On the connectivity of radio networks," IEEE Trans. Inf. Theory, vol. 37, no. 5, pp. 1490–1492, Sep. 1991.

[11] P. Santi and D. M. Blough, "The critical transmitting range for connectivity in sparse wireless ad hoc networks," IEEE Trans. Mobile Comput., vol. 2, no. 1, pp. 25–39, Jan./Mar. 2003.

[12] V. Ramaiyan, A. Kumar, and E. Altman, "Optimal hop distance and power control for a single cell, dense, ad hoc wireless network," IEEE Trans. Mobile Comput., vol. 11, no. 11, pp. 1601–1612, Nov. 2012.

[13] S. Dulman, M. Rossi, P. Havinga, and M. Zorzi, "On the hop count statistics for randomly deployed wireless sensor networks," Int. J. Sensor Netw., vol. 1, no. 1, pp. 89–102, 2006.

[14] Y. Keshtkarjahromi, R. Ansari, and A. Khokhar, "Energy efficient decentralized detection based on bit-optimal multi-hop transmission in onedimensional wireless sensor networks," in Proc. Int. Fed. Inf. Process. Wireless Days (WD), 2013, pp. 1–8.

[15] H. Liu, B. Zhang, H. T. Mouftah, X. Shen, and J. Ma, "Opportunistic routing for wireless ad hoc and sensor networks: Present and future directions," IEEE Commun. Mag., vol. 47, no. 12, pp. 103–109, Dec. 2009.

[16] S. Biswas and R. Morris, "Exor: Opportunistic multi-hop routing for wireless networks," in Assoc. Comput. Mach. SIGCOMM Comput. Commun. Rev., 2005, vol. 35, no. 4, pp. 133–144.

[17] M. Zorzi and R. R. Rao, "Geographic random forwarding (geraf) for ad hoc and sensor networks: Multihop performance," IEEE Trans. Mobile Comput., vol. 2, no. 4, pp. 337–348, Oct./Dec. 2003.

[18] L. Cheng, J. Niu, J. Cao, S. Das, and Y. Gu, "Qos aware geographic opportunistic routing in wireless sensor networks," IEEE Trans. Parallel Distrib. Syst., vol. 25, no. 7, pp. 1864–1875, Jul. 2014.