A Hierarchical Routing Protocol for Smart Grid

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***Abstract*—Nowadays, power grids have many variations and each day we see more development. Meanwhile power grids have a significant importance and their structure are developing and improving. Due to more efficiency and increasing the performance of traditional power grid, smart grid is appeared. In view of the traditional electric grid network infrastructure and integration with wireless sensor networks, new services ability is added to the total structure of traditional electrical grid. One of the smart grid infrastructure requirement is wireless sensor networks that is perfect solution for data acquisition from environment and equipment in the smart grid and transmission of information. Routing in wireless sensor networks due to its particular application in smart grid have gained significant attention. In this paper, we provide a hierarchical routing protocol for both HAN and NAN level by considering low power consumption and delay. Our proposed protocol is compared with two energy-aware and shortest path protocol, in addition to achieving energy efficiency and lower latency, higher data delivery rate and less data loss is achieved.**

***Index Terms*—delay, remaining energy, hierarchical infrastructure, wireless sensor network, smart grid, routing**

I. Introduction

According to the research conducted, it is predicted that by 2050, demand will triple the current consumption that this is implies the need for an urgent and vital to today's power grids to change its structure [1]. Rapid developments in the fields of communication and information management systems in recent years, led to administrative and economic solutions as new features electric grid utilities are facing [2]. Moving toward modern electricity grid, the smart grid, is inevitable. Therefore detailed studies for this intelligence in smart grid should be done. Part of these studies is related to communication technology in smart grid and have important role in smart grid [3], [4].

The purpose of this paper is to present a model for hierarchical routing structure's definition of smart grid according to the energy and delay factors that will be examined in more detail in the next section. In this model, by considering communication technologies and smart grid range, a hierarchical infrastructure to better monitor and management is proposed. This model, by considering routing challenges in hierarchical structure of smart grid and open look to the requirements and future application of this network is presented. In the second section of the proposed protocol is compared and evaluated with energy aware routing and shortest path protocol and in the third section will describe the evaluation results of this study. Then results of the hierarchical routing will be briefly presented [5], [6].

II. Proposed Protocol

In this structure for choosing the next hop, we have been considered parameters, which respect to these parameters, the best nodes can be selected with regard to the requirements of each level. Overall, chose the best path to reach the sink. These parameters are: the distance from the sink node, distance from the sender node to the next node, the remaining energy in the receiving node, link usage, a delay for the nodes and the channel error that each of them will be examined in details.

Given to this structure, we have proposed two requirements of energy consumption and delay for smart grid that each of the requirements according to the hierarchical structure of the smart grid have been considered. In HAN, according to its application in smart grid, we have chosen smaller energy consumption requirements due to our proposed routing algorithm, routing energy consumption will be lower. For NAN, due to the aggregation data of each HAN is routing and transmitting to the distribution center and based on it important decision is made, we consider smaller delay requirements. This data often contains important information such as network failures or technical failures and amount of required or consumption load of network. To this end should be transferred to the decision and distributed center with minimum delay. At this level, we sacrifice the energy consumption to the aggregation data with minimum delay to transfer aggregation and important data to the sink, rapidly.

A. Implementation of the Proposed Method

First, note that without considering location of neighbor nodes and decision to choose one of the candidate node as a next hop, it will be lead to create a loop in routing; therefore, it is necessary that only a particular number of nodes as the candidate nodes for the

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next hop is to consider and they are the nodes that are closed to the sink [7].

In Fig. 1, the network is intended to be location-aware, i.e. each node is aware of its location. We assume that each node can be in control of its transmission power. The nodes are shown in adjacent with v_s is their neighbors. According to the neighbors' node of v_s, we define the nodes that bring positive progress that forward data to the sink. These nodes are set of v_s neighbors' nodes that are closer than v_s to the sink. Fig. 1 shows both neighbor nodes and selected nodes that are closer to the sink.

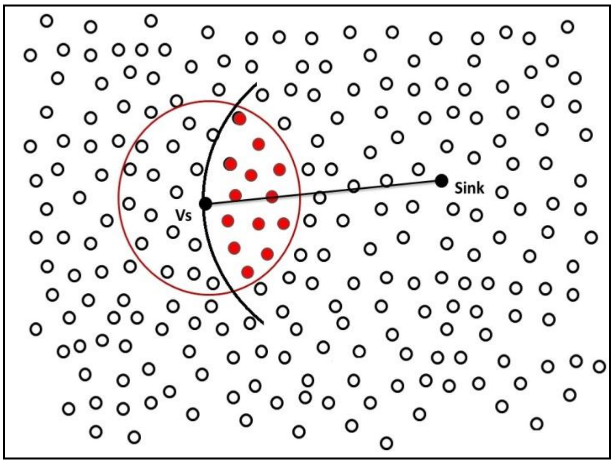

Figure 1. Neighboring nodes of v_s and those that are closer to the sink.

Like all geographic routing protocols, each node requires to be aware of location of its neighbor nodes and location of sink node. Also for effective location routing, nodes are considered to be fixed. Density of nodes is considered in a way that nodes for send data to the sink have at least a node closer to the sink. With this, the routing loop problem goes away.

- Distance from the sender node to the sink

One of route selection criteria is to find a path that is both directly and with the minimum distance to the Sink i.e. the greater route deviation from the sink we have more energy consumption and latency. We write distance equation from the sink node, as follows:

$$d_s = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \quad (1)$$

where x_1 is the location of candidate node and x_2 is the location of sink node, y_1 is the location of candidate node and y_2 is the location of node sink respect to the x and y axis, respectively. This is shown in Fig. 2, graphically.

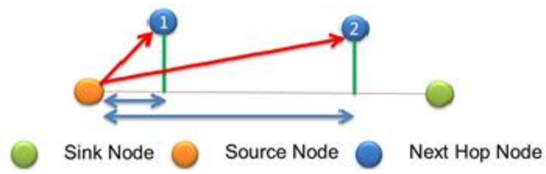

Figure 2. Select node based on node distance from the sink or the transmitter.

Now to sum up various parameters on the routing function we have to normalize them. We normalize candidate recipient node distance to sink as follows:

$$d_{s_n} = \frac{d_{s_{max}} - d_s}{d_{s_{max}}} \quad (2)$$

According to the (2), parameter d_s represents the direct distance of candidate receiver node the candidate from the sink, $d_{s_{max}}$ is Distance from the sender node to the sink and d_{s_n} is normalize value of d_{s_n} that is without dimension. Each node that has more normalized value, its probability to select as a next hop is more.

- Distance from the transmitting node to the receiving node

Another criteria for selecting the next route hop is to use short and numerous hops. Since energy consumption is proportional to the square of the distance between the transmitter and the receiver node, therefore; short hops consume less energy than single hop and high range data transmission. According to Fig. 3 and (3), the distance between the sender node and the receiver node candidates can be calculated as follows.

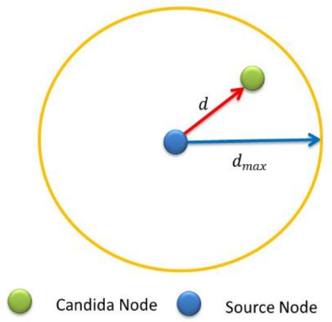

Figure 3. Position the candidate node to calculate the distance to the transmitting node.

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \quad (3)$$

Like pervious parameter this parameter should be normalize. We have:

$$d_n = \frac{d_{max} - d}{d_{max}} \quad (4)$$

According to the (4), d represent sender node direct distance to the candidate receiver node, d_{max} represents the node transmission radius and d_n is normalized value that is without dimension.

- Remaining energy of candidate node

Whatever nodal remaining energy of the candidate nodes is more, if the conditions are almost identical, the chance of select that node as the next hop will be higher and thus will increase the network lifetime. According to (5), we normalize the value of receiver node remaining energy.

$$E_n = \frac{E}{E_{max}} \quad (5)$$

In the above equation, E represents the remaining energy of the candidate node, E_{max} is the initial energy of

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node and E_n is the normalized remaining energy. Our radio model is the same as [8]. In this radio model, the consumed energy in sending and receiving data formulated as follows:

$$R_x = \varepsilon_{elec} \times k \quad (6)$$

According to (6), the energy consumption model of wireless sensor nodes in this study is the first order radio model. In this model, the amount of energy consumed to receive a k-bit package is equal to R_x, where ε_{elec} have constant value equal to $50\frac{nj}{bit}$. So if packets containing information have the same size, can be easily concluded that the received information to the nodes, has the same energy; this energy is not related to the distance between the transmitter and the receiver node.

$$T_x = \varepsilon_{elec} \times k + \varepsilon_{amp} \times d^2 \times k \quad (7)$$

According to above equation, the amount of energy consumption for transmitting a k-bit packet that the distance of transmitter to receiver node is d meter, is equal to T_x. ε_{elec} and ε_{amp} have the value of $50\frac{nj}{bit}$ and $100\frac{pj}{bit \times m^2}$, respectively.

- Link usage

In the case of repeated applications of a direct route from source to destination nodes, after a while, the nodes energy is depleted and the nodes are destroyed; resulting in lower network lifetime and even causes the loss of network nodes may suffer from fragmentation. Therefore, selected route should be safe from repeated and frequent selection and this selection balance is done by link usage. The normalized equation of this parameter is as follows:

$$Lu_n = \frac{Lu_{\max} - Lu}{Lu_{\max}} \quad (8)$$

In this equation Lu is the pervious number of used communication link from sender node to receiver candidate node, $Lu_{\max}$ is equal to total number of sent packets to that moment of transmitter node that for calculation of all candidate nodes of Lu_n on that hop, they have the same value of $Lu_{\max}$. Lu_n is the normalized value of Lu.

- Channel error rate

Each link of the route has an error rate. There are different data for the measurement of channel error rate that most of them need to support MAC layer in order to determine the quality of those links. Due to channel error, the packet is discarded will be notified by the link layer. We assume that the link layer is normal and gives us all the information and in network layer we only do retransmission, whatever this link error is lower we have lower retransmission and energy consumption and thus the network lifetime increases. It is worth mentioning that in the HAN, due to the closed environment we have high error rate that is caused to broken link goes up [9].

- Speed (delay)

In the calculation of delay we act like as speed protocol [10], according to (9), we have:

$$S_{off} = \frac{d_{ist}(v_i, \text{sink}) - d_{ist}(v_j, \text{sink})}{\omega_t(v_i) + \text{d}_{tr}(v_j) + \omega_t(v_j)} \quad (9)$$

where the parameters are as follows: $d_{ist}(v_i, \text{sink})$ is the distance to sink transmitting node v_i, $d_{ist}(v_j, \text{sink})$ is the distance to sink transmitting node v_j, $\omega_t(v_i)$ and $\omega_t(v_j)$ are estimated waiting time in the queue node of V_i and V_j, respectively. Finally, $d_{tr}(v_j)$ is the estimated time of packet transmitting from the moment that the queue node is v_i to moment that in node V_j is received. For estimation value of $\omega_t(v_i)$, $d_{tr}(v_j)$ and $\omega_t(v_j)$ we used floating average method. The amount of moment delay is obtained from the following equation and then using the averaged value is updated after each send.

$$\omega = t_{Ack} - size(Ack)/bw - t_0 \quad (10)$$

t_{Ack} is the moment of Ack receiving message a packet, t_0 is the moment that is ready to send packet in the queue, bw is the bandwidth and finally $size(Ack)$ is the size of Ack message. To normalize this parameter we needed a maximum value, to this end we run network once and we have compared obtained S_{off} values and used maximum value for normalization. We have:

$$S_{off_n} = \frac{S_{off}}{S_{off_{\max}}} \quad (11)$$

Now the routing function can be calculated as follows and according to level that simulation is running, validate coefficients. Here the coefficients C_1 to C_6 in the sum is equal to one, and the quantities of each, depending on the importance of the relevant factors are weighted.

$$P_{win} = c_1 d_{s_n} + c_2 d_n + c_3 E_n + c_4 Lu + c_5 CER_n + c_6 S_{off_n} \quad (12)$$

III. Evaluation

In this section we examine the performance of the proposed routing protocol compared with two power-aware routing and shortest path protocols with Opnet software. Fig. 4 illustrates the overall structure of a hierarchical smart grid in this simulation. Routing function coefficients on both HAN and NAN have been considered as follows: for HAN we have:

$$c_1 = 0.15, c_2 = 0.1, c_3 = 0.3, c_4 = 0.05, c_5 = 0.35, c_6 = 0.05$$

And for NAN we have:

$$c_1 = 0.2, c_2 = 0.05, c_3 = 0.2, c_4 = 0.1, c_5 = 0.25, c_6 = 0.25$$

In Table I we represent the network parameters of simulation.

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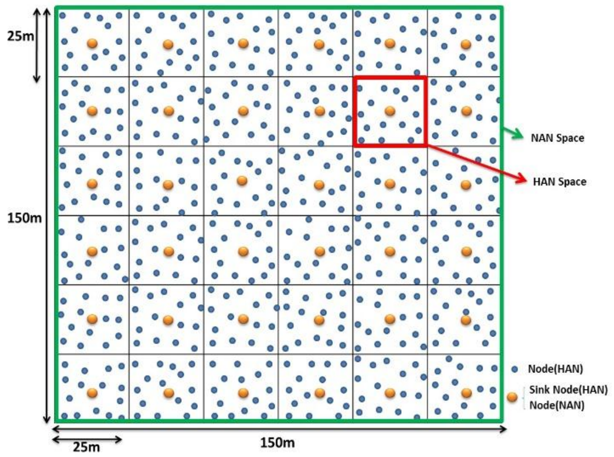

Figure 4. Smart grid hierarchical structure used in simulation.

TABLE I. SIMULATION PARAMETERS

Parameters of the simulation	HAN	NAN
simulation Space	25m×25m	150m×150m
Radio range	10 m	40 m
Number of nodes	15 nodes	35 nodes
nodes Order	Random	grid
Buffer sizes	5 packets	5 packets
Data packet size	100 bits	200 bits
Control packet size	50 bits	50 bits
Initial energy of node	25 J	50 J
Service rate of nodes	700 packets	150 packets
The average generation rate of packet	10 packets per sec	10 packets per sec

IV. DATA AND DIAGRAM ANALYSIS

With the implementation of simulation in OPNET environment to compare the data obtained are as follows. Fig. 5 shows a diagram of the average energy consumption in HAN level. Given the choice of the next node in the proposed protocol to reduce energy consumption by factors such as distance to the sink node, distance from neighbor nodes, remaining energy and channel errors are considered. In the SP protocol which in data sends based on the closest node to the sink, due to long hop the energy consumption goes up. In the EAR protocol in which data send based on the remaining energy of next hop, have more energy consumption compared to our proposed protocol. For this reason that we consider short hop and another factors for selecting next hop. Also, consider the channel error in our proposed protocol makes routs that have high channel error not select, so it will prevent retransmission. In energy aware mode, due to node just consider the remaining energy for selecting the next hop caused packet data have longer routes than proposed protocol, this results an increase in energy consumption.

Fig. 6 shows the average end-to-end delay in the HAN. Our priority at HAN is achieving lower energy consumption and it has also been obtained. In this regard, the routing function coefficients were chosen so that we neglect delay for next hop selection, so as to achieve lower power consumption. However, in addition to achieving the appropriate level of energy consumption compared to the previous scenarios, the delay could be achieved by the relative improvement compared to these cases.

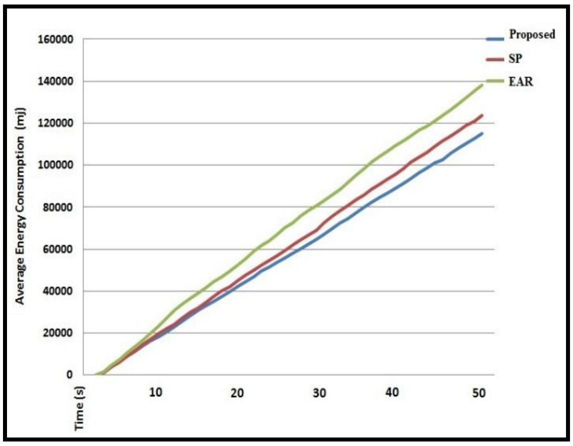

Figure 5. Average energy consumption in the HAN.

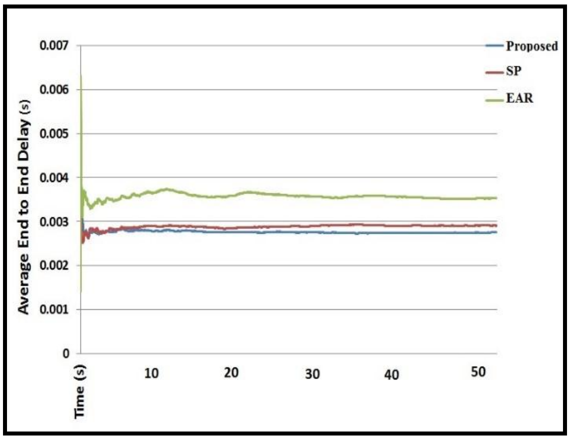

Figure 6. Average end-to-end delay in the HAN.

Fig. 7 shows the data delivery ratio. As you can see, our proposed protocol has increased the delivery ratio. One of the main reasons that lead to better delivery ratio is that in our proposed method, routes that have high channel error rate have the less chance to assign as the next hop. Therefore, the probability of packet loss due to channel error is reduced thereby increasing the rate of packet delivery in proposed protocol.

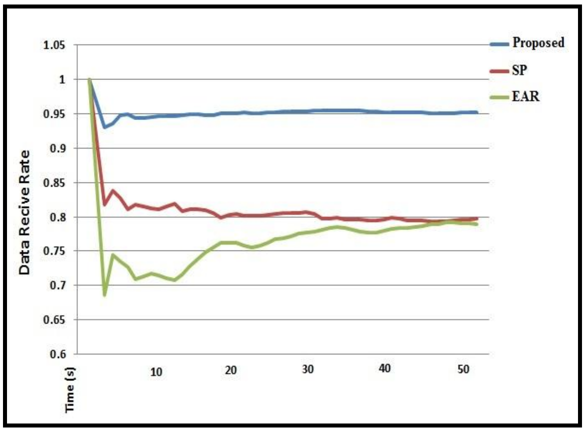

Figure 7. Delivery ratio at HAN.

Fig. 8 shows the comparison of packet loss due to channel error. As can be seen, the proposed method becomes better than two other scenarios. Because in proposed method, we consider the channel error rate. That way, if in a route channel error rate was high, based on the coefficient of route function, we have given it less chance to select, so number of lost packets become less. Note that in proposed method, by increasing control coefficient of channel error achieved less packet lost.

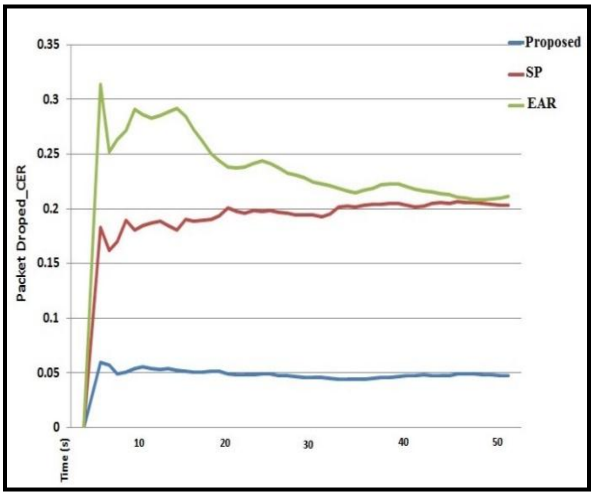

Figure 8. Packet loss due to channel error in HAN.

Now we examine and analyze the results of simulation in NAN level in detail. It should be noted that the nodes that forming this level are meters or sinks in HAN level. Fig. 9 shows the average energy consumption of the proposed protocol, EAR and GFR protocols in NAN. Route function coefficients were chosen so that the energy level has less importance in order to achieve lower latency priorities. Our proposed scheme in terms of energy consumption of the two other scenarios, shows a better performance. One of the factor of realization this scheme is that the network have grid structure in this level and the routes have the same structure.

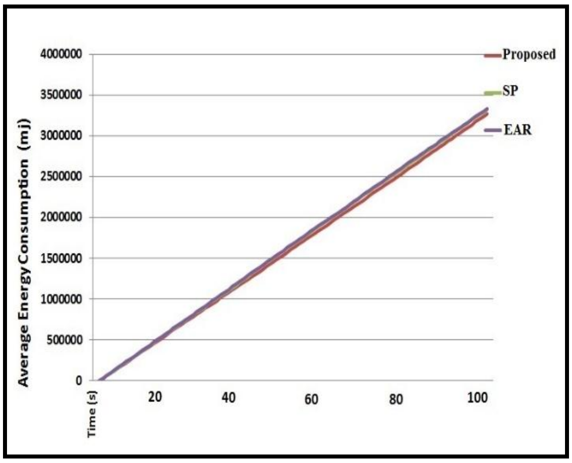

Figure 9. Average energy consumption in NAN.

Fig. 10 compares the average end-to-end delay of the proposed protocol with two other scenarios that our proposed methods have better remaining energy than two others and have better value, but in compare with SP method with a neglect difference becomes inferior. In fact, we can say that our protocol by not considering this difference with SP method have the same delay. Shortest path scenario, due to the fact that the nearest node to the sink node in radio range of the sender chooses is the fastest way to send data. Therefore, it was expected that the lowest possible latency achieved. In energy aware method, when a node wants to choose next hop, examine the next node energy level. So transmit packets quicker is not important in this scenario, it cause more delay.

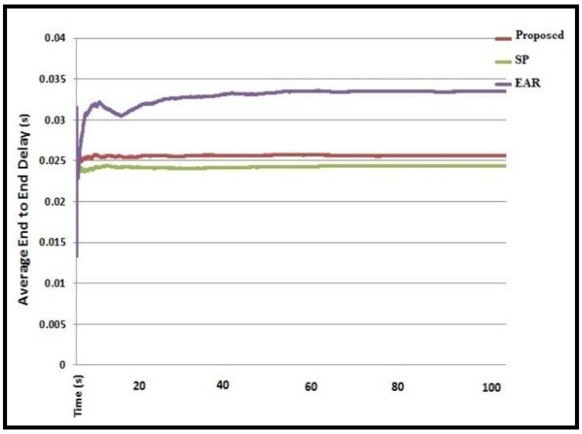

Figure 10. Average end to end delay in NAN.

Fig. 11 shows the comparison between the data delivery rate of the proposed protocol with two other methods in NAN. Our proposed method by a little different than the shortest path scenario and minimal difference of energy aware of remaining energy is better. The reason for this improvement is that in the proposed scheme, we tried to manage the buffers of next hop and not using of a good communication link which causes fast filling of the buffer, prevent throughout the packets and delivered more packets and thereby increase the rate of delivery of the proposed scenario.

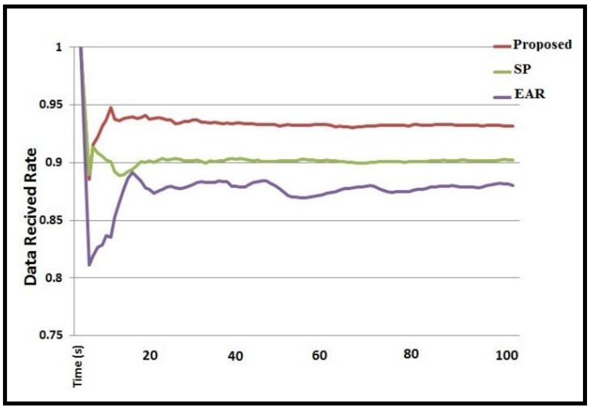

Figure 11. Delivered rates at NAN.

Fig. 12 shows the comparison of packet loss due to channel error in the NAN. In this comparison diagram of our proposed scheme has much better than two other scenarios, these obtained results were not unexpected. As the comparison of these parameters is explained in HAN, in the proposed scenario, channel errors are parameters that are used to select the next hop. Therefore we withdraw the node that its channel error is high between

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transmitter and candidate node and we decrease the packet loss due to the link error.

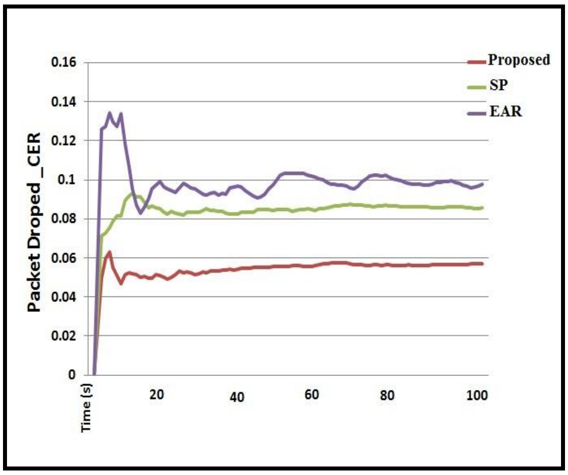

Figure 12. Packet loss due to channel error, in NAN.

V. CONCLUSIONS

Our proposed protocol is consists of a hierarchical structure of HAN and NAN and by introduced routing function route and transmit data. As shown in the previous diagram obtained from simulation our proposed protocol given to priority of energy consumption could achieve to lower energy consumption compared to both energy aware and shortest path protocol in the HAN level. Also this proposed protocol has lower delay compared with two other protocols and achieve lower power consumption. In the NAN level of hierarchical structure of proposed protocol compared with energy aware protocol achieved less delay but compared with the shortest path protocol failed to improve but this small difference compared with the shortest path delays can be ignored and supposed both protocol to be identical in delay, with this difference that our proposed protocol is able to consume less energy than two others protocol. Therefore, our proposed protocols in a hierarchical structure could achieve much lower power consumption and the amount of received packets goes up in main base. With these interpretations, the proposed protocol can be useful for a hierarchical structure of the Smart Grid application.

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