Energy-Efficient Cluster-based Routing Protocol for Solving Data Route Selection Problem in Wireless Sensor Networks

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***Abstract*—Wireless sensor networks (WSNs) consist of many sensor nodes (SNs) used in remote or critical environments. These nodes have restricted power resources; hence, power consumption is a critical issue for such networks. Cluster-based routing protocol plays a vital role in prolonging the WSNs lifetime. In a cluster-based structure, cluster heads (CHs) nodes can transmit their aggregated data toward the base station (BS) via a single-hop or multi-hop path that are called Inter-Cluster Single-Hop (ICSH) and Inter-Cluster Multi-Hop (ICMH) transmission, respectively. In ICSH, the energy hole problem arises as far away CHs nodes consume much more energy and die early. On the contrary, ICMH can prolong the network lifetime by balancing the energy consumption of these far nodes using relay transmission. This paper proposes an Energy-Efficient Cluster-based Routing Protocol based on the Dijkstra Algorithm (EEPDA), which groups SNs into clusters and establishes an optimal path to route data with the lowest energy consumption and save the lifetime of the SNs. The simulation results of various scenarios show that EEPDA outperforms other protocols from the prospective of energy consumption, throughput and network lifetime.**

Keywords— WSNs, ICSH, ICMH, optimal path, the network lifetime

I. Introduction

Currently, the development of technology, computing, communication, sensing, and the necessity for monitoring the environmental and physical phenomena in real-time led to the outgrowth of wireless sensor networks (WSNs). These networks gain high interest in many applications such as environmental monitoring, disaster, industrial, target tracking, intelligent home furnishing, military surveillance, safety applications, Patient monitoring, and cardiovascular diseases [1, 2]. The main aim of patient monitoring is to improve patient's health. The WSNs allows the doctors to respond promptly from remote location. In the modern era, wireless sensors are embedded in the Human body to monitor pivotal signs like temperature, body pressure, glucose monitoring and heart rates [3]. WSNs are composed of an unlimited power source node called Sink or Base Station (BS) and a hundred to thousands of limited resources sensing nodes. These nodes can sense the surrounding environment, process the collected data, and wireless communication. The sensor nodes (SNs) send the collected data to BS. BS has high abilities and acts as a gateway between SNs and the user [4, 5]. Mainly, WSNs applications are employed in remote places or in inimical environments. Thus, the published SNs have to be battery-powered devices. From a practical and economical point of view, these batteries are merged into SNs during the fabrication process where recharging or replacing batteries is not an available option. Hence, these nodes must fulfil the optimum energy use to stay a long time without any external charging [6].

Efficiently routing data among SNs can play a pivotal role in prolonging the network lifetime. Designing an efficient energy routing protocol and achieving the efficient utilization of the nodes energy through the routing data process is a vital research issue. Many routing protocols have been developed in WSNs [7, 8]. In terms of the participation style of nodes, these routing protocols can be classified into three types: a single-hop transmission, multi-hop transmission, and clustering technique. In single-hop transmission, each node transmits its detected data directly to its BS. The transmission energy cost is directly proportional to distance. Hence, it is not preferable for large-scale networks [9]. The multi-hop technique is applied to overcome this problem, where the SNs work cooperatively to relay their data to their BS. Consequently, multi-hop is convenient for far nodes because the consumed energy is partition into small parts between nodes on the path. During the network operation, the nodes closest to BS work as relays for far nodes data. This causes a faster drain of these nodes energy and resulting hot spot problem. In [10] Low Energy Adaptive Clustering Hierarchy (LEACH) protocol was introduced to solve the energy and delay problems of single-hop and multi-hop techniques. In LEACH, some nodes selected as leaders, other nodes act as member nodes (MNs) and these nodes are grouped around their leaders. Hence, many separate clusters are formed, and each one has a master node called a cluster head (CH). The sensed data by MNs are delivered into CH. CH is responsible for aggregating and fusing data in a single Block before transmitting it to BS. Only CH is allowed to communicate with BS. Thus, the number of forwarded packets to BS is decreased, and the stability period is increased.

Generally, the cluster heads (CHs) communicate to their BS using the single-hop technique [11]. Recently, Inter-Cluster Multi-Hop (ICMH) technique is employed when CHs are far away from BS or have a limited communication range [12]. Hence, CHs within the same network collaborate to relay the data to BS. This is suitable for large-scale network and fixed BS. ICMH paths are evaluated through two metrics: the hop count and energy cost along the path. From the point of view of hop count, ICMH technique are classified into two styles: long-hops routing, the data is routed over a few numbers of hops , and short-hops routing, at which data is routed through a large numbers of hops . Authors in [13] referred several causes favoring the first style, such as the overhead cost, the total energy dissipation [14], reliability, and delay. From above, the distances and hops between CHs and their related BS have a significant effect on the energy dissipation within each network. Hence determining the optimal path with fewer hops will balance energy consumption. To this end, Energy-Efficient Cluster-based Routing Protocol based on Dijkstra Algorithm (EEPDA) is proposed. EEPDA uses the Dijkstra algorithm to search for the least cost path efficiently and solve the route selection problem. Finally, a few long hops and a minimum cost path are obtained. This paper organized as follows: Previous works are introduced in section 2. In section 3, the Network model and problem statement are introduced. Our proposal EEPDA is illustrated in details in section 4. Then, in section 5, Energy Consumption Analysis are indicated. Simulation and results are displayed in section 6, the conclusions of this paper are presented in section 7.

II. PREVIOUS WORKS

In LEACH, SNs organize themselves as master nodes and MNs through a specific time called round. Each round has two phases, named the setup phase and the steady-state phase. The setup phase is interested in CHs selection and cluster formation based on the probabilistic model. At starting of each round, every node generates a random number between 0 and 1 and compares it with the threshold value; TH (i), which is specified by [10],

$$TH(i) = \begin{cases} \dfrac{p}{1 - p(r \bmod 1/p)} & , if \ \ i \in G \\ 0 & , otherwise \end{cases} \qquad (1)$$

Where p is the probability of CHs, r is the round number, if a node i ∈ G, this means that it has not been selected as a CH in the recent rounds. This guarantees the rotation role of CH periodically among all nodes. If the generated number is less than a threshold value TH (i), the node becomes CH in the current round. The CH role rotated between the nodes in every group of rounds (GOR) to distribute energy costs equally. Non-CH nodes can determine their cluster with least communication energy cost dependent on the received signal strength of CHs. The steady-state phase is concerned with data transmission between SNs and BS. It is done by Time Division Multiple Access to avoid collision between data .

LEACH protocol used a radio propagation model [15] to estimate the energy dissipation between two nodes, energy dissipation from a sender to receiver nodes denoted by.

$$E_{TX}(k,d) = \underbrace{K * E_{elec-cir}}_{\substack{\text{Dissipated power} \\ \text{in electronic circuit}}} + \underbrace{K * \varepsilon_{amp} * d^{n}}_{\substack{\text{Dissipated energy} \\ \text{in the amplifier}}} \qquad (2)$$

$$E_{TX}(k,d) = \begin{cases} \underbrace{K * E_{elec-cir}}_{\substack{\text{Dissipated power} \\ \text{in electronic circuit}}} + \underbrace{K * \varepsilon_{fs} * d^{2}}_{\substack{\text{Free space dissipated} \\ \text{energy in the amplifier}}} & , if \ d \le d_0 \\ \underbrace{K * E_{elec-cir}}_{\substack{\text{Dissipated power} \\ \text{in electronic circuit}}} + \underbrace{K * \varepsilon_{mp} * d^{4}}_{\substack{\text{Multipath dissipated} \\ \text{energy in the amplifier}}} & , if \ d > d_0 \end{cases}$$

$$E_{RX}(k) = \underbrace{K * E_{elec-cir}}_{\substack{\text{Dissipated power} \\ \text{in electronic circuit}}} + \underbrace{K * E_{DA}}_{\text{Aggregration Cost}} \qquad (3)$$

Where E_{TX} and E_{RX} are the energy cost in both transmitter and receiver. K is bits per signal, $E_{elec-cir}$ is the dissipated energy to operate the electronic circuit per *k-bit* data, d is the actual distance and $d_0 = \sqrt{\varepsilon_{fs} / \varepsilon_{amp}}$ is the threshold distance. ε_{amp} is consumed energy in amplifier, ε_{fs} and ε_{mp} are transmit amplifier factors for free space and multipath fading modes. If the receiving CH executes processing tasks on the data, it will consume an extra amount of energy equals $K * E_{DA}$

LEACH protocol neglected the amplification cost compared with the component cost ($E_{elec-cir}$). CHs of LEACH based on ICSH to transmit their data; Hence, they used high amplification cost during transmitting data to BS and reduce the energy dissipation of CHs circuitry through the transmitting and receiving process. However, the protocol that uses ICSH consumes minimum energy, but it is not appropriate for large-scale networks.

In [16], an energy efficient cluster-based multi-hop (ECMR) is proposed to improve the data transmission. ECMR is combining the Dijkstra algorithm with ICMH to find the shortest path between CHs to reach BS. The energy cost of both transmitter and amplifier is used as the weight factor of edges. Thus, ECMR neglected the energy cost of the receiver compared with the transmitter and amplifier costs. The amplification cost is mainly dependent on the distance of transmission, and it dominates the energy dissipation. As a result, a greedy algorithm had been generated where each CH transmits data to the closest CH to reach its destination. Hence, a large number of hops were obtained. Like this case was obvious in low-density and small-scale networks. Certainly, when the weight factors increase, such as receiving cost, the number of hops on the path becomes limited and more efficient than the previous approaches. Finally, ECMR based on the radio energy dissipation model used in the LEACH protocol. The energy consumption for transmitting and receiving data expressed as equations (2,3) above. If the CH node used as a relay for another CH data node, the radio consumption is denoted by

$$E_{Relay}(k,d)=E_{RX}(k)+E_{TX}(k,d) \tag{4}$$

$$=\begin{cases} 2*K*E_{elec-cir}+K*E_{DA}+K*\varepsilon_{fs}*d^2 & ,if\ d\le d_o \\ 2*K*E_{elec-cir}+K*E_{DA}+K*\varepsilon_{mp}*d^4 & ,if\ d>d_o \end{cases}$$

III. Network Model and Problem Statement

A. Network Model

The SNs are randomly distributed within the intended area (m*m). At first, all nodes have a similar capability, homogeneous, unique ID, stationery, and play an equal role. Then, some nodes become CHs, and their capacities differ from MNs. The energy used for sensing and transmitting is almost small for MNs. Thus, we are given less attention in comparison with the receiving and the transmitting cost for CHs nodes. As a result, the Dijkstra algorithm only takes into account the CHs nodes. Therefore, it directly influences the transmission policy of CHs nodes, and it reduces the running complexity of the EEPDA protocol. The WSNs of our proposal has been modelled as a weighted directed graph G (A, E), A represents the set of apexes or CHs, and E represent set of edge. Two CHs nodes a_i and a_j can communicate with each other, weight of the edge $e_{i,j}$ $\in$ E.

B. Problem Statement

In our network, lets us consider several numbers of CHs nodes that have already aggregated data and need to send them to BS. The many questions will be proposed:

- Whether CH sends fused data directly (ICSH) or it use other CHs as a relay (ICMH) ? a threshold distance (d0) is applied for solving this question.
- If CH has applied the ICMH technique, on which hops does CH depend? Short-hops (a large number of hops) or long-hops (a few numbers of hops)? impact of the various hops demands to be analyzed.

IV. Energy-Efficient Cluster-based Routing Protocol based on Dijkstra Algorithm (EEPDA)

The target of EEPDA is to improve the lifetime and the stability period of the network by using the energy cost of transmitter, amplifier and receiver as weights of the Dijkstra algorithm. Therefore, ICMH with few numbers of hops transmission will be constructed as recommended in [13,17]. The operation of EEPDA is split into three phases: initialization, setup, and steady-state. The initialization phase is done in the first network operation; both setup and steady-state phases are executed the death of all SNs. The EEPDA flowchart is illustrated in Fig. 1.

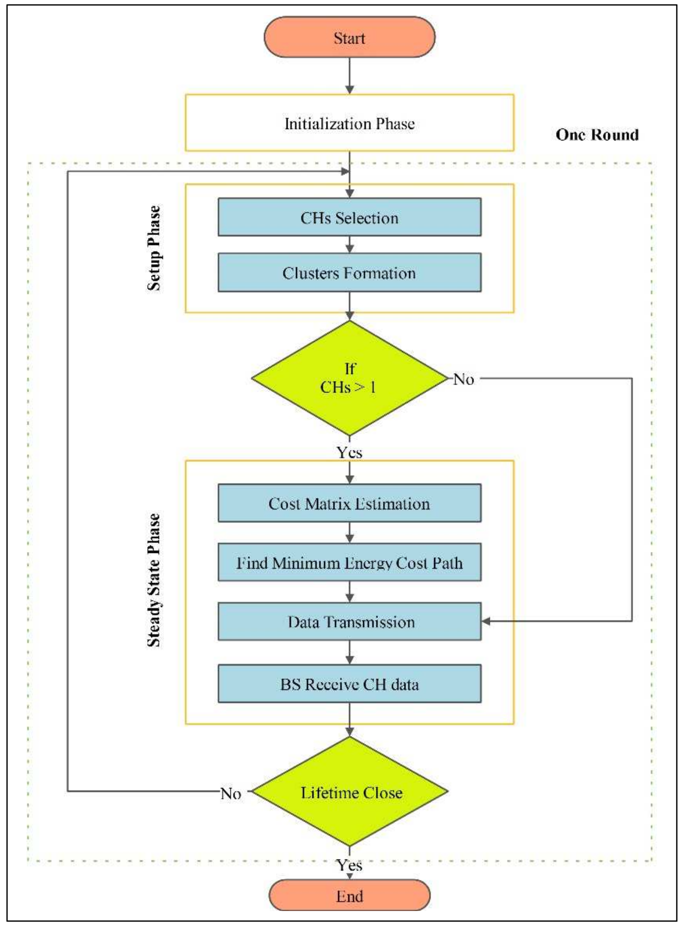

Fig. 1. Flowchart of proposed EEPDA

The initialization phase and setup phase of EEPDA are similar to LEACH protocol in many ways, while the steady-state phase totally differs from it. In the steady-state, the energy costs between CHs reach BS are estimated to be weights for edges. All the edges are categorized into transmitter energy cost, amplifier energy cost, and receiver energy cost. The total edge weight is considered for efficient path selection.

The Dijkstra algorithm starts to determine the least energy consumed path depending on the edges. Hence, it assigns initial energy cost and gradually improves them until reaching to BS with the best route, which achieves the least cost. Accordingly, CHs route packets via the optimal path found. The energy of

CHs of the path is updated in each round until the death of all nodes. The pseudo-code for the steady-state phase is as follows:

ALGORITHM (1) FINDING THE LEAST ENERGY COST PATH BASED ON DIJKSTRA ALGORITHM

```
Input: CHs, BS, E, Energy Cost, Dead_threshold.
Output: Optimal path.
Process:
while CHs greater than 1
for CH i = 1 : CHs   // i = Source node
%% Initialization:
for CH j = 1 : CHs + BS   // j = Destination node
if j = i
CH j Energy Cost = 0   // CH j Energy Cost = Tentative energy cost
end if
if (E_j > Dead_ threshold)
CH j Energy Cost = ∞   // Tentative energy cost is unknown to reach CH j from CH i
Previous = [ ]   // The optimal path is empty
CH j ∈ Q   // All nodes (CH j) added to a queue (Q) and defined as un-visited nodes except source node
end if
end for
%%Main loop:
while Q is not empty
z = min (Q, Energy Cost) // z ∈ Q, and has least energy cost to arrive it from CH i
Remove z from Q   // Node z as a visited node
if (z = BS)
break   // Out from the loop
end if
for all CH j ∈ Q and adjust by z
if (z Energy Cost + Energy Cost (z , CH j) < CH j Energy Cost)   // New least-cost path from a current node to CH j has been found
CH j Energy Cost = z Energy Cost + Energy Cost (z , CH j)   // Removing the tentative cost and replace it with the modern minimum cost path
Previous = z   // Set z as the previous step
end if
end for
end while
return Previous [ ]   // We get the previous steps (optimal path) in reverse order from BS → source node
end while
```

V. ENERGY CONSUMPTION ANALYSIS

In this section, the energy consumed by CHs is illustrated. The energy cost of the initial and setup phases is neglected. Thus, we are interested in the steady-state phase .

The proposed protocol specifies which transmission manner ICSH or ICMH will achieve minimum consumed energy based on the energy model mentioned previously [15]. Fig. 2 shown a linear network with several CHs. N number of inter-cluster hops among the source node and the destination node, CH 1 is the source node, N is BS (final destination), CH 2 to CH N-1 are intermediate CHs nodes among them, d is the distance. d/N is the distance among intermediate CHs.

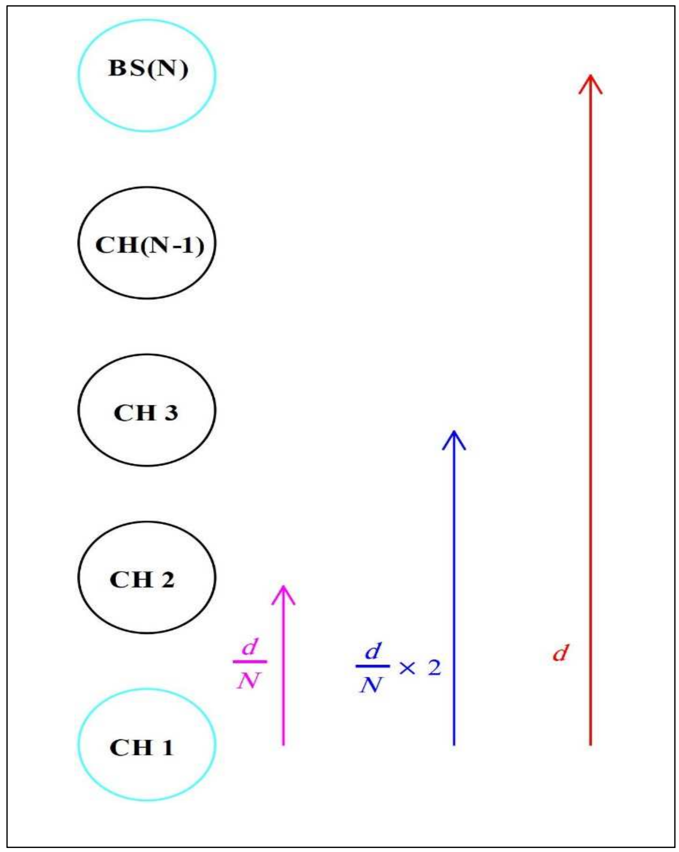

Fig. 2. Relay nodes network model

CH 1 can communicate with BS via ICSH or ICMH with short-hops or ICMH with long-hops. The consumed energy by ICSH manner is given by:

$$E_{CH\_ICSH}(i,k,d) = \begin{cases} K.E_{elec-cir}.n_i + K.E_{DA}.(n_i+1) + K.E_{elec-cir} + K.\varepsilon_{fs}.d^2 & ,if\ d \le d_0 \\ \underbrace{K.E_{elec-cir}.n_i}_{\text{Receiving Data from Member Nodes}} + \underbrace{K.E_{DA}.(n_i+1)}_{\text{Aggregating Data}} + \underbrace{K.E_{elec-cir} + K.\varepsilon_{mp}.d^4}_{\text{Transmitting Aggregated Data to BS}} & ,if\ d > d_0 \end{cases} \quad (5)$$

The consumed energy by ICMH manner with short -hops is given by:

$$E_{CH\_ICMH(short-hops)}(i,k,d)$$
$$=\begin{cases} K.E_{elec-cir}.n_i + K.E_{DA}.(n_i+1) + K.E_{elec-cir} + K.\varepsilon_{fs}.(d/N)^2 \\ +(CH\,N-1).(2.(K.E_{elec-cir}) + K.\varepsilon_{fs}.(d/N)^2) \qquad , \quad if\,(d/N) \le d_0 \\ \\ \underbrace{K.E_{elec-cir}.n_i}_{\text{Receiving Data from Member Nodes}} + \underbrace{K.E_{DA}.(n_i+1)}_{\text{Aggregating Data}} + \underbrace{K.E_{elec-cir} + K.\varepsilon_{mp}.(d/N)^4}_{\text{Source CH Transmission Energy}} \\ + \underbrace{(CH\,N-1)}_{\text{Number of intermediates CHs on path}} . \underbrace{(2.(K.E_{elec-cir}) + K.\varepsilon_{mp}.(d/N)^4)}_{\text{Consumed Energy by The intermediate CHs}} \quad , \quad if\,(d/N) > d_0 \end{cases} \tag{6}$$

The consumed energy by ICMH manner with long-hops is given by:

$$E_{CH\_ICMH(long-hops)}(i,k,d)$$
$$=\begin{cases} K.E_{elec-cir}.n_i + K.E_{DA}.(n_i+1) + K.E_{elec-cir} + K.\varepsilon_{fs}.((d/N).2)^2 \\ +(CHN-1).(2(K.E_{elec-cir}) + K.\varepsilon_{fs}.((d/N).2)^2) \qquad , \quad if\,(d/N).2 \le d_0 \\ \\ \underbrace{K.E_{elec-cir}.n_i}_{\text{Receiving Data from Member Nodes}} + \underbrace{K.E_{DA}.(n_i+1)}_{\text{Aggregating Data}} + \underbrace{K.E_{elec-cir} + K.\varepsilon_{mp}.((d/N).2)^4}_{\text{Source CH Transmission Energy}} \\ + \underbrace{(CHN-1)}_{\text{Number of intermediates CHs on path}} . \underbrace{(2.(K.E_{elec-cir}) + K.\varepsilon_{mp}.((d/N).2)^4)}_{\text{Consumed Energy by The intermediate CHs}} \quad , \quad if\,(d/N).2 > d_0 \end{cases} \tag{7}$$

Where n_i is the number of cluster nodes or MNs, and E_{DA} is data aggregation cost.

ICSH is more efficient than ICMH manner with short -hops if:

$$\Delta E = E_{CH\_\mathrm{ICSH}} - E_{CH\_\mathrm{ICMH\,(short-hops)}} \le 0 \tag{8}$$

ICMH manner with short -hops is more efficient than ICMH manner with long-hops if:

$$\Delta E = E_{CH\_ICMH(short-hops)} - E_{CH\_ICMH(long-hops)} \le 0 \tag{9}$$

Based on the Figure above, CH 1 can transmit sensed data directly to BS via ICSH or ICMH transmission. We proposed three possible paths to transmit data. The path distance hops number and path cost of each possible path are summarized as shown in table 1

TABLE 1. ROUTING METRICS OF POSSIBLE PATHS

Path	Path distance	Hops number	Path consumed energy
{CH1, BS}	160	1	3,607,872 *nj*
{CH1, CH2, CH3, CH N-1, BS}	160	4	1,656,000 *nj*
{CH1, CH2, BS}	160	2	1,112,000 *nj*

Great interest is given to the consumed energy cost as the main metric to determine the best route. The third path is considered the optimal path with the least path cost (1,112,000 nj). Of course, the path distance is the same for all because we are taking a linear network. For this reason, the energy cost is considered instead of the distance in finding the optimal path depending on the Dijkstra algorithm. Lastly, the proposed protocol can determine the optimal transmission manner between CHs to reach BS, either ICSH or ICMH depending on the energy cost of CHs

VI. SIMULATION AND RESULTS

Matlab 2016a is used as a simulation platform to estimate the performance of EEPDA. The network model consists of a number of homogeneous SNs in a fixed size network. Hence, the nodes have the same initial energy. Our proposal interests in either large-scale networks or long-distance transmission cases, thus BS located at the border. All simulation parameters are mentioned below in table 2 and presented in [18]

TABLE 2. SIMULATION PARAMETERS

Parameters	Scenario
Sensing field dimensions	225*225 $m2$
Number of nodes	90
BS location	(225, 225)
Initial energy $(\boldsymbol{E_o})$	0.5 J
$\boldsymbol{p}$	0.1
$E_{elec\ -\ cir}$	50 nJ/bit
E_{DA}	5 nJ/bit
ε_{fs}	10 pJ/bit/$m2$
ε_{mp}	0.0013 pJ/bit/$m4$
Data packet size (K)	4000 bits
Number of rounds	1500

To achieve a fair comparison between protocols, all SNs are published randomly, and these SNs have the same position for all protocols. Furthermore, BS in our scenario located at a border of the network.

A. Network lifetime

The network lifetime refers to the number of SNs that have not yet consumed their energies. Fig. 3 shows the total number of SNs alive versus 1500 rounds. ECMR is more stable than LEACH because it depends on the MH while transmitting data. Hence, the stability period of ECMR is relatively larger than LEACH. EEPDA achieves the best number of rounds compared with LEACH and ECMR protocols. EEPDA is dependent on ICMH transmission and uses long-hops to transmit data with the least cost path. Moreover, it considers the energy cost of the transmitter, amplifier, and receiver. Definitely, this will balance the inter-cluster transmission energy cost between CHs. Hence, the transmission distance and communication cost are optimized

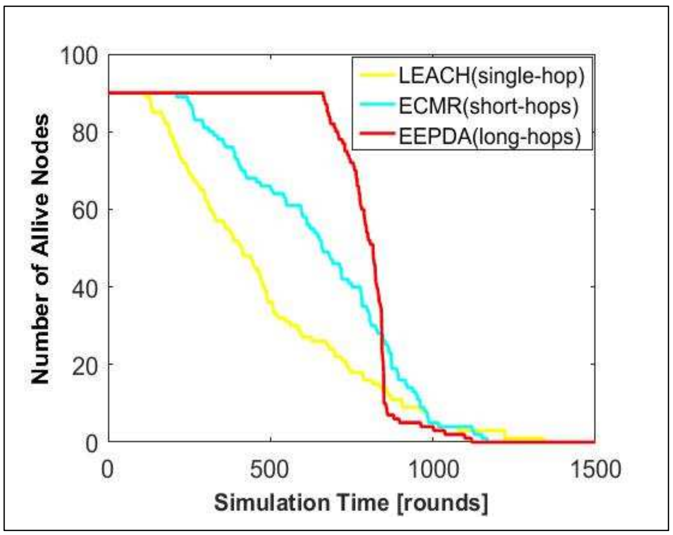

Fig. 3. Network lifetime

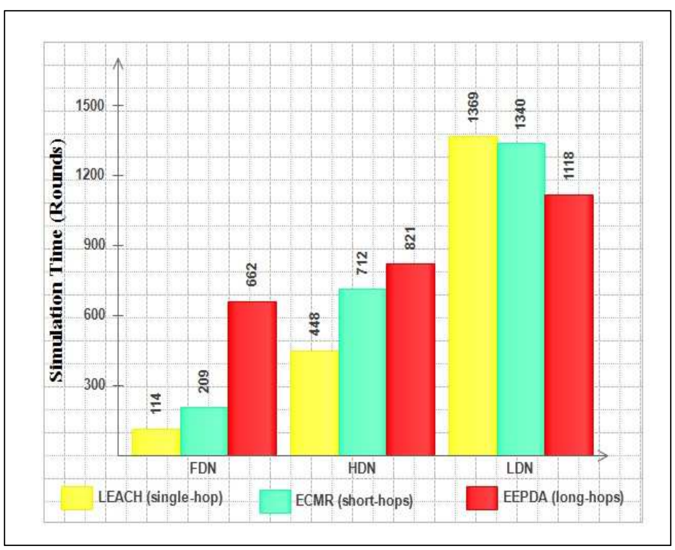

Fig. 4. FDN, HDN, and LDN

Fig. 4 shows FDN, HDN, and LDN for LEACH, ECMR and EEPDA, respectively. EEPDA achieved the highest number of FDN (stability period) and HDN in comparison with others protocols. In terms of FDN, EEPDA is more efficient than LEACH and ECMR by 480.7% and 216.7%, respectively. LEACH performance is the worst one regarding FDN because the far away CHs consumed much more energy in sending their data directly to BS; hence they die early. Either concerning HDN, EEPDA also outperforms LEACH and ECMR by 83.2% and 15.3%, respectively. It chooses the least cost path; therefore, the CHs conserve their energy for a longer period. Although the LDN of LEACH and ECMR is longer than that of EEPDA, it implies that the energy consumption of these protocols is not so well balanced. Thus some CHs have more residual energy to live longer

B. Throughput

The throughput comparison of proposed EEPDA and other protocols obtained in performance analysis is shown in Fig. 5. By applying the Dijkstra algorithm, efficient hops are selected, which is used to increase the network lifetime and energy efficiency. It concludes that our proposal has the highest throughput compare to LEACH and ECMR

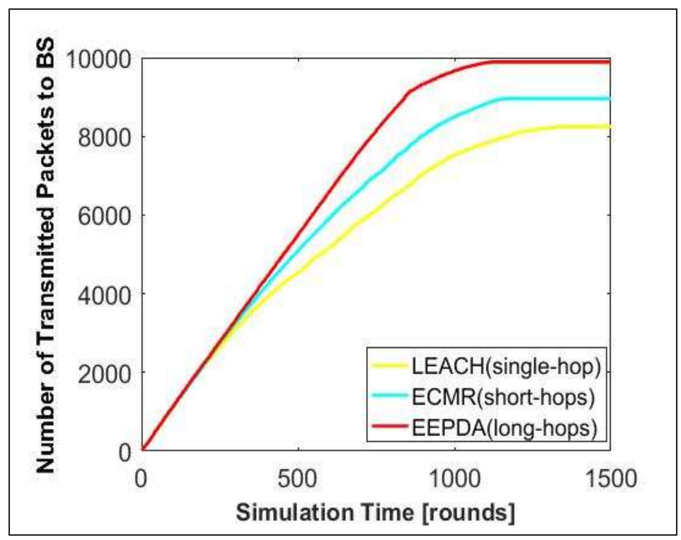

Fig. 5. Total number of received packets

C. Residual energy

The residual energy of SNs over the rounds are shown in Fig. 6 . LEACH, protocol uses ICSH to send data to BS. Hence, CHs require more power to transmit their data, especially in large-scale networks. The slope of the LEACH curve is significantly below. ECMR depends on ICMH to send data instead of using ICSH. Therefore, the slope of the ECMR curve is higher than LEACH. EEPDA depend on ICMH with long-hops and always looked for the least-cost path. Hence, its curve is higher than LEACH and ECMR

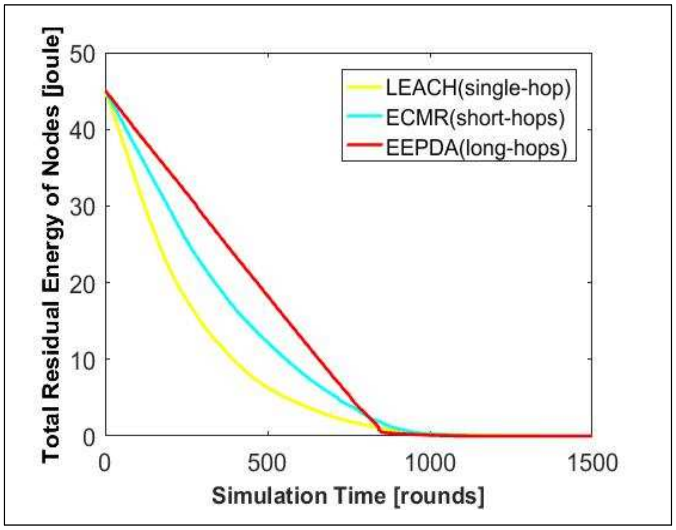

Fig. 6. Total residual energy

VII. CONCLUSION

In this paper, we have proposed an EEPDA protocol for selecting an efficient path to transmit data and improve network lifetime in WSNs. The optimal path selection is depended on three factors; transmitter cost, amplifier cost, and receiver cost. We have proved the effectiveness of energy cost instead of distance for selection optimal path. The Dijkstra algorithm applied to overcome Data Route Selection Problem based on the factors above. Finally, in the steady-state phase, we use three models to transmit data to BS; ICSH, ICMH with short-hops, and ICMH with long-hops. Through the energy analysis and simulation, we have shown our proposed protocol with long-hops achieves best performance in terms of network lifetime, Throughput, and residual energy.

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