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EESRA: Energy Efficient Scalable Routing Algorithm for Wireless Sensor Networks

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ABSTRACT Many recent wireless sensor network (WSN) routing protocols are enhancements to address specific issues with the ''low-energy adaptive clustering hierarchy'' (LEACH) protocol. Since the performance of LEACH deteriorates sharply with increasing network size, the challenge for new WSN protocols is to extend the network lifespan while maintaining high scalability. This paper introduces an energy-efficient clustering and hierarchical routing algorithm named energy-efficient scalable routing algorithm (EESRA). The goal of the proposed algorithm is to extend the network lifespan despite an increase in network size. The algorithm adopts a three-layer hierarchy to minimize the cluster heads' load and randomize the selection of cluster heads. Moreover, EESRA uses multi-hop transmissions for intra-cluster communications to implement a hybrid WSN MAC protocol. This paper compares EESRA against other WSN routing protocols in terms of network performance with respect to changes in the network size. The simulation results show that EESRA outperforms the benchmarked protocols in terms of load balancing and energy efficiency on large-scale WSNs.

INDEX TERMS Energy efficiency, LEACH, load balancing, scalability, wireless sensor networks.

I. INTRODUCTION

A wireless sensor network (WSN) is a massive collection of low-power, intelligent and multifunctional sensor nodes connected to base stations (BS) [1], [2]. The enormous number of nodes, low available data rates, and various resource constraints have limited the usability of generic ad-hoc routing protocols in WSN. To maximize the network lifespan and overcome limited battery capacity, WSN routing protocols tend to support resource-awareness and adaptivity [3]–[5].

Based on the network structure, WSN routing protocols are categorized into two classes: flat and hierarchical routing protocols. A flat routing architecture allows sensor nodes to perform identical roles in the routing process. Hence, all sensor nodes are set to forward the sensed packets directly to base stations. In contrast, a hierarchal routing architecture segments the sensor nodes into clusters. Within a cluster, nodes are differentiated according to the tasks performed. In a typical two-layer hierarchy structure, low-level nodes (i.e. cluster members (CM)) are responsible for sensing data from the environment and forwarding the data to their respective cluster head (CH), while high-level nodes (i.e. cluster heads) are responsible for compressing and transmitting the gathered data to the base stations [6].

Heinzelman *et al.* [7] proposed a dual-layer, low energy adaptive clustering hierarchy protocol commonly known as (LEACH), which formed the basis for various WSN routing protocol in use today. LEACH uses a two- layer hierarchal structure with task randomization to equally balance the load among nodes. Network operations are divided into steps for cluster formulation, environment sensing and data transmission. The timespan for iterating through these steps is referred to as a round. Each round takes place in two phases: set-up and steady-state phase. In the set-up phase, the clusters for the current round are established, while in the steady-state phase, cluster members transmit the sensed data to their respective cluster-heads according to pre-allocated TDMA schedules. Thus, cluster members are responsible for sensing the data from particular phenomena, while cluster-heads are responsible for compressing and transmitting the sensed data to the base station.

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TABLE 1. LEACH-variant protocols.

Protocol	Merits			
	MAC	Communication method		Aggregation process
		Intra-cluster	Inter-cluster	
LEACH [7]	TDMA	Single hop	Single hop	CH
Cell-LEACH [15]	TDMA	Multi-hop	Multi-hop	CH
Multi-LEACH [13]	TDMA	Single hop	Multi-hop	CH
FLLEACH [18]	TDMA	Single hop	Multi-hop	CH
LEACH-WM [17]	TDMA	Single hop	Multi-hop	CH
MMR-LEACH [27]	TDMA	Single hop	Multi-hop	CH

It is well known that LEACH is vulnerable to the hot-spot (i.e. unbalanced network load distribution) problem [8]. Thus, CHs consume their energy more rapidly due to their extra duties [9]–[13]. Moreover, the increase in network size increases limit the ability of the LEACH protocol to sufficiently compensate for further energy exhaustion in hot-spot nodes while performing the CH role [6], [8].

By using the LEACH protocol as a foundation, many mechanisms have been proposed to boost the network lifespan and reduce the energy consumption [12], [14]–[18]. For example, better network lifespans were achieved by adopting methods to enhance the physical capabilities of the hot-spot nodes, by maximizing the amount of transmitted information during communications, and by rotating the active cluster-heads to balance the overall energy consumption and to accommodate continuous changes in network topology. These mechanisms enabled the WSN research community to focus on optimizing energy consumption and on addressing network scalability as the most critical challenges [19]–[21]. Consequently, some enhanced LEACH protocols have modified their intra- or inter-cluster communication approaches to improve network scalability (refer to Table 1) [22].

The rotation of the cluster head role achieves a minimum level of load balancing [10], [15], [23]–[25]. However, such an arrangement does not address the issue of energy exhaustion while performing the cluster head role. Thus, cluster heads consume more energy due to their roles in aggregating, processing and routing data. In addition, LEACH allocates TDMA slots for each node to transmit their sensed data, even though the node might not have data to transmit [26].

To reduce the energy consumption, Cell-LEACH further divides the clusters into smaller cells [15]. The cluster and cell formation occur once during the setup phase and is maintained throughout the network lifespan, while the cell and cluster heads are selected and updated dynamically. The cell members transmit their sensed data to the respective cluster heads via their cell heads. Similarly, FLLEACH [18] applies a super cluster-head (SCH) concept, where the SCH acts as an intermediate node between the CHs and the BS. MMR-LEACH utilizes an adaptive hierarchy with one node within a cluster acting as a vice cluster head [27]. In contrast, Multi-LEACH utilizes a multi-hop strategy by considering the signal to noise ratio of different links, as well as by modifying the CHs selection process to account for the residual energy of the nodes [13]. LEACH-WM [17] replaced the single-hop inter- and intra-cluster communications with a multi-hop strategy.

This paper proposes a scalable, low energy and adaptive clustering hierarchy routing algorithm named Energy-Efficient Scalable Routing Algorithm (EESRA) to maintain the network lifespan in spite of increases in the network size. EESRA adopts a three-layer hierarchy structure to reduce the load on cluster heads and uses multi-hop transmission for intra-cluster communication while randomizing the clusters head selection. This paper evaluates EESRA against other WSN routing protocols in terms of network performance with respect to changes in the network size. Simulation results show that EESRA outperforms benchmarking protocols in term of load balancing and energy efficiency for large scale WSNs.

The rest of the paper is organized as follows: Section 2 demonstrates modeling of the network environment. Section 3 describes the proposed protocol, while Section 4 presents the results. Section 5 carries out the discussion. Finally, the conclusion is presented in Section 6.

II. MODELING THE WSN ENVIRONMENT

Deploying an actual WSN with a large number of devices for protocol development and testing incurs significant costs; therefore simulation and modeling approaches were adopted by the majority of protocol enhancement studies [4], [28]–[30]. Thus, simulation testbeds were developed and used for evaluating and analyzing the performance of the proposed WSN protocols.

In this paper, the network and energy models define the behavior of the WSN environment is needed for EESRA design and performance analysis. These models are derived from the network profile and energy dissipation model used by the original LEACH routing protocol. Table 2 provides a list of variable definitions and notations used in the manuscript. The modeling and simulation of the network environment as well as the various WSN scenarios were carried out using the MATLAB 2015 simulation software.

A. NETWORK MODEL

The network model assumes that all sensor nodes are homogeneous and deployed randomly in a square two-dimensional space. The space is assumed to be free of obstacles which may obstruct the signal transmission. Moreover, sensor nodes are categorized into clusters and the cluster's activities and the inter-cluster communications is managed by a cluster-head (CH). On the other hand, low-level cluster members (CM) are responsible for sensing and collecting the data about a particular phenomenon. The network environment used throughout the study is based on the following assumptions:

TABLE 2. Table of variable definitions and notations.

Notation	Description
E_{ele}	Energy consumed to run the transmitter or the receiver circuit per bit.
ε_{fs}	Free space factor.
E_{CT}	Total energy drawn by a cluster- head
E_{ChS}	Energy consumed at CH selection step
E_{CsA}	Energy consumed to broadcast a CH advertisement
E_{CrJ}	Energy consumed to receive joint request from non-CH nodes
E_{CS}	Energy consumed to transmit aggregated data from CH to BS
E_{CR}	Energy consumed to receive sensed data from CM
N	Total number of nodes in network
s_c	The size of the control packet.
α	Throughput of non-persistent CSMA
d	Distance to base station
z	Maximum number of CH/rounds;
β	Ratio of reception and idle listening
N_M	Number of cluster members
k	Number of data frames per round
N_G	Number of congregation nodes who must send the data in current round
s_d	The size of the data packet.
E_{MT}	Total energy consumption by a cluster- member
E_{MsJ}	Energy consumed to send joint message to CH
E_{MS}	Energy consumed to transmit sensed data from CM to CH.
E_{MR}	The energy consumed to receive cluster heads' advertisements
E_{ni}	Node energy
m_{cor}	Number of correlated data-frame
E_{GR}	Energy consumed to receive sensed data from CG-group members
E_{GaT}	Energy consumed to aggregate and compress the receiving data by CG
E_{GsP}	The energy consumed to broadcast a CG advertisement
E_{GT}	The energy drawn by CG
E_{GaP}	Energy consumed by data aggregation process.
N_{gm}	Number of nodes per group
m	Number of CH per round
N_{cg}	Number of congregation nodes

- All sensor nodes and the BS are stationary.
- All sensor nodes have the same resources and capabilities.
- Each node has a unique identifier (ID).
- The communication link between any two nodes is symmetrical.

The stated assumptions ensure an application-oriented consistency and set the scope of the network model in terms of node distribution, initial battery store, and mobility status. Moreover, the assumptions are in line with the assumptions adopted by related works, which enable us to evaluate the proposed routing algorithm against other protocols using common network topologies and simulation scenarios.

B. ENERGY MODEL

This study adopts an energy model similar to the one used in LEACH protocol. Accordingly, the cost of transmitting a s-bit message over a distance d, will be calculated as a summation of the energy costs incurred by the digital and analog components (the total energy per bit expended for data transmission). Based on whether the distance is larger or smaller than a predefined threshold, the cost computation will either uses a free space factor (ε_{fs}) or a multi-path factor (ε_{mp}). These factors assume that the WSN transmitter operates at a bit rate of 1 Mb/s with a central frequency of 914 MHz. Similarly, the cost of receiving a s-bit message, will be calculated as the combined energy costs of the digital and analog components (the total energy per bit expended for data reception). Therefore, the WSN energy model can be described as the energy consumed by individual network component as follows:

1) Energy consumed by a cluster head (E_{CT})

The energy consumed by a cluster head consists of the energy consumed in the cluster creation as well as the energy consumed for performing all tasks assigned to the CH role. These tasks include CH selection, CH advertisement, as well as transmission and reception of various control/data packets.

2) Energy consumed by a cluster member (E_{MT})

The CMs are responsible for data sensing, as well as sending and receiving of various control/data packets. Thus, the aggregate total of the energy dissipated by a cluster member will be calculated based on the cost of the node setup and transmission procedures.

III. THE PROPOSED ALGORITHM (EESRA)

As a LEACH variant routing algorithm, EESRA is designed to serve static nodes and base stations. The non-mobile setup supports clustering as well as the subsequent data sensing and communication tasks. Figure 1 shows the topology of the EESRA routing algorithm. Accordingly, each cluster is composed of a cluster head and one or more cluster congregations, each with a set of cluster members. The three-layer hierarchy topology is introduced to reduce the CH load. Figure 2 demonstrates the steps for EESRA operations that take place in a round-based sequence, where each round is composed of two phases: a set-up and a steady-state phase.

A. SET-UP PHASE

The set-up phase applies a stochastic rotation scheme adopted from LEACH protocol to select cluster-heads [7]. Following the cluster-head selection, the clusters of the current round are established. Moreover, each CH selects one or more eligible nodes to act as cluster congregation (CG) nodes. The CGs are responsible for receiving and aggregating sensed data from the CMs and passing their data to the CHs using a hybrid MAC protocol. The CM nodes access the channel in

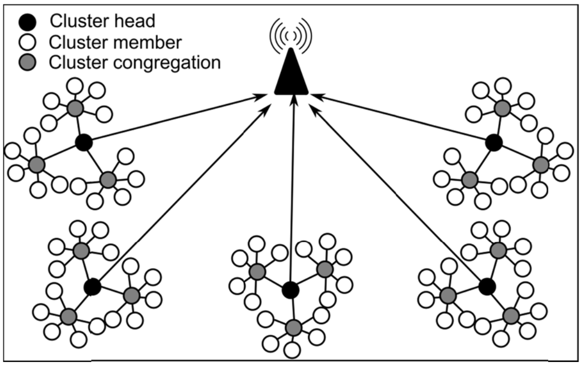

FIGURE 1. **EESRA topology.**

```
For each round
  Select the optimal number of CHs
  Establish the clusters
  For each CH
    Select the respective CG based on residual energy
    For each CG
      Aggregate and transmit data to CH
    End for
    CH transmit to BS
  End for
End for
```

FIGURE 2. **EESRA operations.**

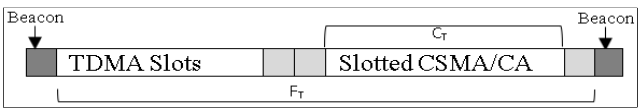

FIGURE 3. **Structure of the hybrid MAC frame.**

a CSMA/CA fashion to send sensed data to their CG (low-level MAC). In contrast, each CG transmits the collected data to its CH within its allotted TDMA slot (high-level MAC). Figure 3 shows structure of the hybrid MAC frame. Where F_T is hybrid MAC frame length, beacon is followed by TDMA period, which is divided into a number of time slots. The CSMA/CA period, which immediately follows the TDMA period. If there is no TDMA slots available F_T is used as the CSMA/CA period (C_T).

B. STEADY-STATE PHASE

In the steady-state phase, each CM turns on its radio communication modules to send the sensed data to the respective CG. Hence, the nodes will be active only during their operation time and sleep otherwise. The CGs aggregate, compress and forward the data to their respective CHs. Thus, multi-hopping is used as intra-cluster transmission scheme. Furthermore, each CH transmits the received data to the BS. After the BS receives all the data, the CHs send END round messages to the members. Eq. 1 shows the total energy drawn by a CH in each round (E_{CT}).

$$E_{CT} = E_{ChS} + E_{CsA} + E_{CrJ} + E_{CR} + E_{CS} \quad (1)$$

where:

$$E_{ChS}(s,d) = \left(\left(\frac{s_c}{\alpha}\right) * \left(E_{ele} + \varepsilon_{fs} d_{toBS}^2\right)\right) + \left(\frac{z * N - 1}{\alpha} * (s_c * E_{ele} * \beta)\right) \quad (2)$$

$$E_{CsA}(s,d) = s_c * E_{ele} \quad (3)$$

$$E_{CrJ}(s) = N_{cm} * s_c * E_{ele} \quad (4)$$

$$E_{CR}(s) = k * \left(N_{cgs} * s_d * E_{ele}\right) \quad (5)$$

$$E_{CS}(s,d) = \left(\frac{s_d}{\alpha}\right) * \left(E_{ele} + \varepsilon_{fs} d_{toBS}^2\right) + \frac{z * N - 1}{\alpha}(s_d * E_{ele} * \beta) \quad (6)$$

On the other hand, the total energy consumed by a cluster member in each round (E_{MT}) can be calculated as follows:

$$E_{MT} = E_{MrA} + E_{MsJ} + E_{MS} \quad (7)$$

Given that:

$$E_{MrA}(s) = m * s_c * E_{ele} \quad (8)$$

$$E_{MsJ}(s,d) = \left(\left(\frac{s_c}{\alpha}\right) * \left(E_{ele} + \varepsilon_{fs} d_{toCH}^2\right)\right) + \left(\frac{N_{cm} - 1}{\alpha} * (s_c * E_{ele} * \beta)\right) \quad (9)$$

$$E_{MS}(s,d) = k * \left(N_{cgs} * s_d * E_{ele}\right) + \left(N_{cg} - N_{cgs}\right) * \beta * s_d * E_{ele} + s_d * \left(E_{ele} + \varepsilon_{fs} d^2\right) \quad (10)$$

Moreover, the total energy consumed by a cluster congregation in each round (E_{GT}) can be computed as:

$$E_{GT} = E_{GsP} + E_{GR} + E_{\mathbf{GaP}} + E_{GS} \quad (11)$$

Given that:

$$E_{GsP}(s) = N_{gm} * s_c * E_{ele} \quad (12)$$

$$E_{GR} = k * \left(N_{cgs} * s_d * E_{ele}\right) \quad (13)$$

$$E_{GaP} = m_{cor} * (s_d * E_{DA}) \quad (14)$$

$$E_{GS}(s,d) = k * s_d \left(E_{ele} + \varepsilon_{fs} d^2\right) \quad (15)$$

To further describe the node's behavior based on the energy consumption in EESRA, we propose the following lemmas.

Lemma 1: Suppose E_{ni} is the energy consumed by a node n_i, then the amount of energy consumed in a particular round by the node can be computed based on the role of node n_i in the routing procedure.

Proof: In each round, the node n_i must take one role out of three available roles: CH, CG or CM. Thus, the computation of the energy consumption E for node n_i, is based on its role during the round r. Accordingly, if the energy consumed by CH, CG, or CM node during its entire cluster-head, congregation or member service is (E_{CT}), (E_{GT}), (E_{MT}), then the vector $E_{vec} = [E_{CT} E_{GT} E_{MT}]$ represents the energy consumed by a node n_i based on its role in the routing procedure.

$$E_{ni} = E_{vec} * I_C \quad (16)$$

subject to:

$$I_C = \begin{cases} 1 \quad 0 \quad 0 \quad \text{if node } i \text{ acts as CH} \\ 0 \quad 1 \quad 0 \quad \text{if node } i \text{ acts as CG} \\ 0 \quad 0 \quad 1 \quad \text{if node } i \text{ acts as CM} \end{cases} \tag{17}$$

where I is a 3×3 identity matrix and the value of C determines the column to be used to activate the corresponding node function.

Lemma 2: Suppose E_{ni} could be calculated by Lemma. 1, then the total energy over rounds during the node lifespan can be calculated via the following equation:

$$E_{ni-total} = \sum_{r=1}^{r=R_i} (E_{ni,r}, r) = \sum_{r=1}^{r=R_i} (E_{vec}, r) * I_C \tag{18}$$

Proof: Given E_{ni} is the energy consumed by node n_i during round r, then the energy consumed by node n_i during rounds R_i within the operational lifespan of node n_i is the totality of E_{ni} during R_i.

Lemma 3: Suppose the initial energy of the node n_i is $E_{ni-initial}$, and the energy consumed is $E_{ni-total}$, then the residual energy of this node E_{ni-res} could be calculated by the following equation:

$$E_{ni-res} = E_{initial} - E_{ni-total} \tag{19}$$

Proof: If $E_{initial}$ is initial energy of node n_i when the network starts and $E_{ni-total}$ is the total energy consumed during the node lifespan, then the residual energy of node at round r is the difference between the total consumed energy and initial energy. Thus, when a node fully consumes its initial energy $E_{initial}$, which occurs when $E_{ni-total} = E_{initial}$, and hence, $E_{ni-res} = 0$, it is no longer in operation. Accordingly, when all the nodes have depleted their energies (i.e. $E_{ni-res} = 0 \rightarrow n_i$) in round R_i, then the WSN lifespan will be equal to R_i.

IV. SIMULATION RESULTS

In order to evaluate EESRA performance, the algorithm was benchmarked against LEACH, Cell-LEACH and Multi-LEACH. We focused on assessing the energy efficiency considering four scalability case studies (100, 200, 300, and 400 nodes). To evaluate the energy efficiency of the EESRA algorithm, we employed network lifespan and the load balancing principles. Thus, the timespan from the start of network operation to when first node dies (*FND*), the timespan to reach the All Nodes Depleted (*AND*) condition, the average residual energy per round and the energy consumption rate for all active sensor nodes are considered to reflect the EESRA performance [4], [18], [30], [31]. Moreover, to illustrate the impact of EESRA algorithm on network scalability, the network lifespan and the number of delivered packets criteria are reported over 10 simulation runs for four scalability case studies. The redundant simulation runs were carried out to improve the reliability of the simulation results. In each run, the initial location of the sensor nodes was randomized, and the assessment metrics were measured. Table 3 shows the simulation parameters which are based on the network model proposed in [7].

TABLE 3. Simulation parameters.

Network parameter	Value
Network size	100 m x 100 m
Number of base stations	1
Number of nodes	100,200,300,400
Data size of packet	2000 bits
control packet size	25 bits
Initial energy of node	2J
E_{ele}	50nJ/bit
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
E_{DA}	5 nJ/bit/signal
Number of rounds	1500

A. ENERGY EFFICIENCY

From an energy efficiency perspective, the performance of EESRA was evaluated via the following parameters: 1) number of alive nodes per round, 2) average residual energy per round, and 3) node energy consumption rate per round. Figures 4 show the number of alive nodes per round for four scalability case studies. In first case study (100 nodes) shown in Figure 4 (a), EESRA algorithm maintains the network operational in maximum capacity (evaluated by the time from start to first node dead *FDN*) respectively 363 compared to 42 and 129 and 107 rounds of LEACH, Cell-LEACH and Multi-LEACH protocols. These values are 330 compared to 41, 122, and 123 in second case study; 322 compared to 41, 122 and 122 in third case study; and 312 compared to 41, 121 and 121 in fourth case study as shown in Figure. 4 (b), (c) and (d). In the same context, network performance is determined by the All Nodes Depleted (*AND*) condition. In the first case study, EESRA extended the network to 206, 318, and 222 rounds more than LEACH, Cell-LEACH and Multi-LEACH protocols. Furthermore, these values are 256, 336, and 267 in second case study; 287, 367, 286 in third case study; and 302, 376, and 294 in fourth case study.

As mentioned previously, the initial energy for each node was set to 2 Joules (refer to Table 3). Intuitively, the residual energy will keep decreasing over time due to the need to perform various communication tasks, until it reaches zero (i.e. the residual energy for all nodes drop to zero). The depleted residual energy condition indicates the end of the simulation. In that context, the average residual energy per round is measured via the total of the residual energies of all alive nodes divided by the number of alive nodes in a particular round. Figures 5 depicts the outcomes of the average residual energy per round for the four protocols obtained for four scalability case studies. As can be seen from Figure. 5 (a), (b), (c) and (d), LEACH, Cell-LEACH and Multi-LEACH exhibit steeper drops in the average residual energy as compared to the proposed EESRA algorithm, where the steeper drops indicate faster energy depletion.

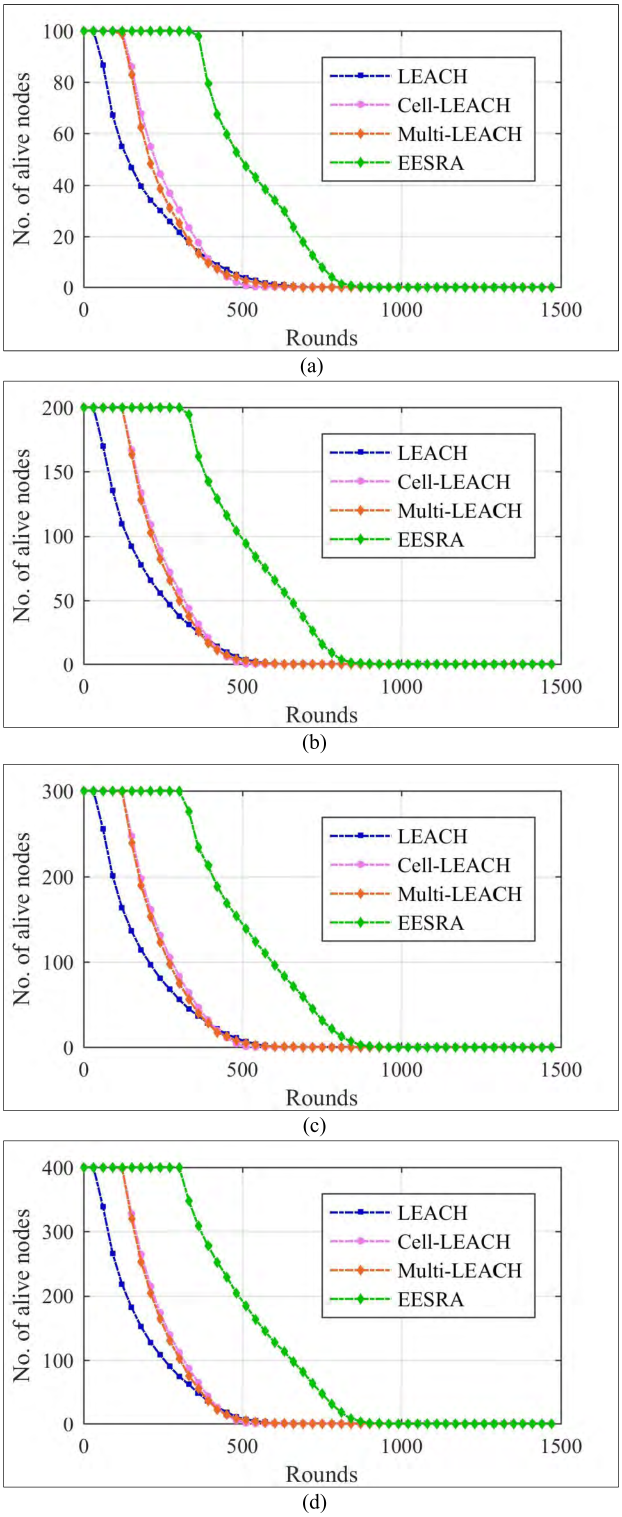

FIGURE 4. Number of alive nodes per round for: (a) 100 nodes, (b) 200 nodes, (c) 300 nodes, (d) 400 nodes.

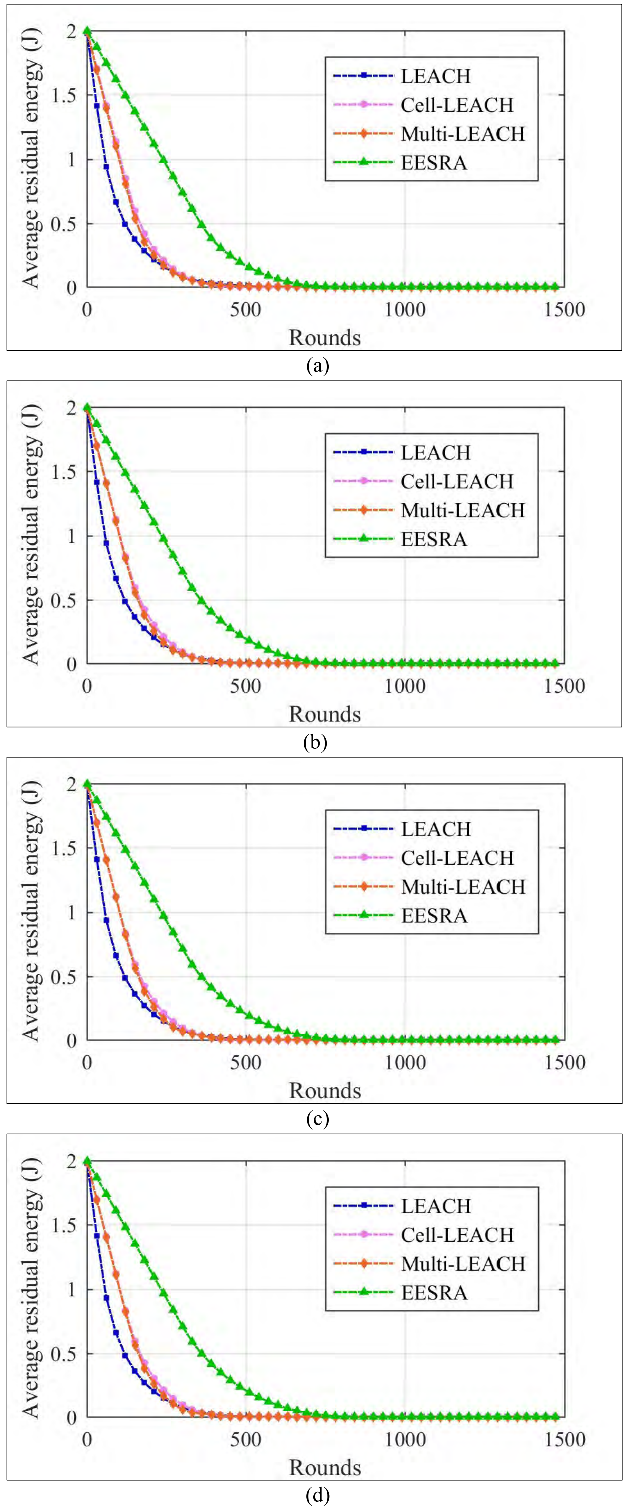

FIGURE 5. Average residual energy per round for: (a) 100 nodes, (b) 200 nodes, (c) 300 nodes, (d) 400 nodes.

Figure 6 depicts the energy consumption rate for all active sensor nodes per routing protocol. This measurement was taken over a sample of ten rounds using the 100-nodes scenario, where Figures 6 (a), (b), (c) and (d) show the nodes' energy consumption for LEACH, Cell-LEACH, Multi-LEACH and EESRA protocols respectively. The high energy consumption variance for LEACH, Cell-LEACH and Multi-LEACH shown in Figures 6 (a), (b) and (c) indicate that there were unbalanced load distributions among the CHs and CMs. In contrast, Figure 6 (d) exhibits much lower variance and a gradual increase in the energy consumption rate as

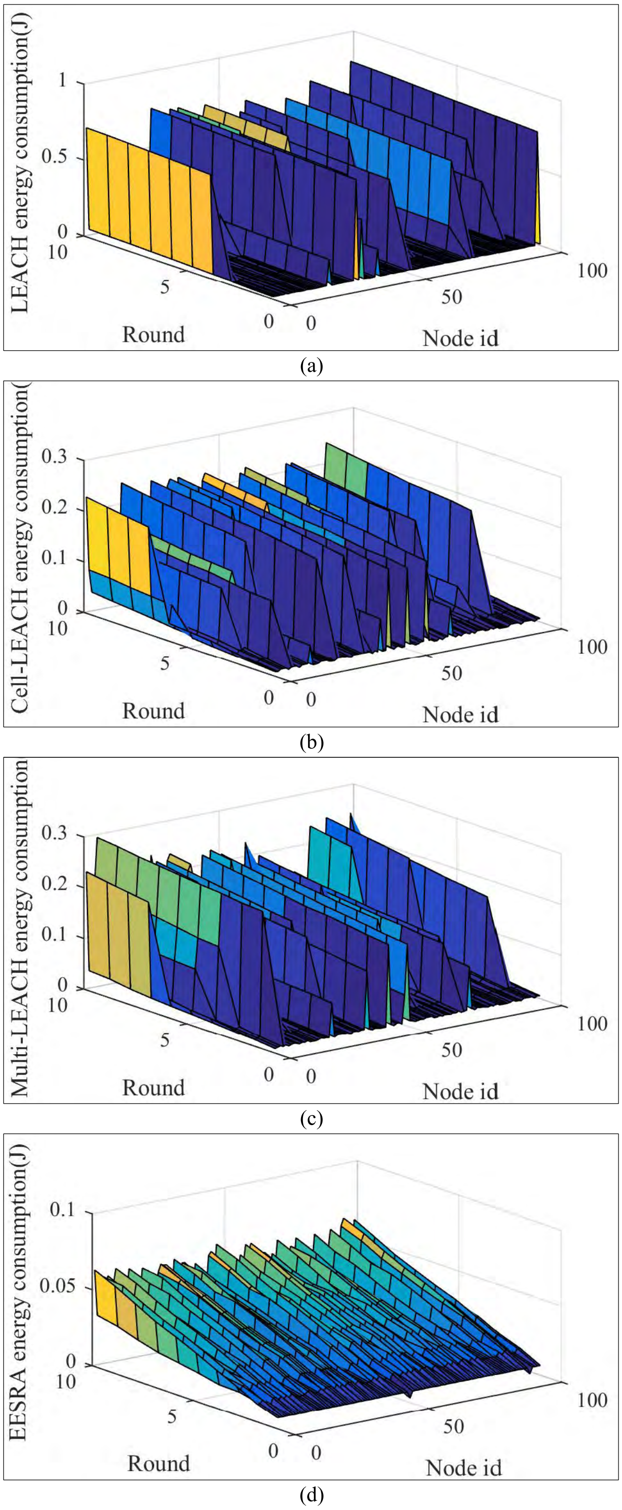

FIGURE 6. Energy consumption of each node versus rounds: (a) LEACH, (b) Cell-LEACH, (c) Multi-LEACH (d) EESRA.

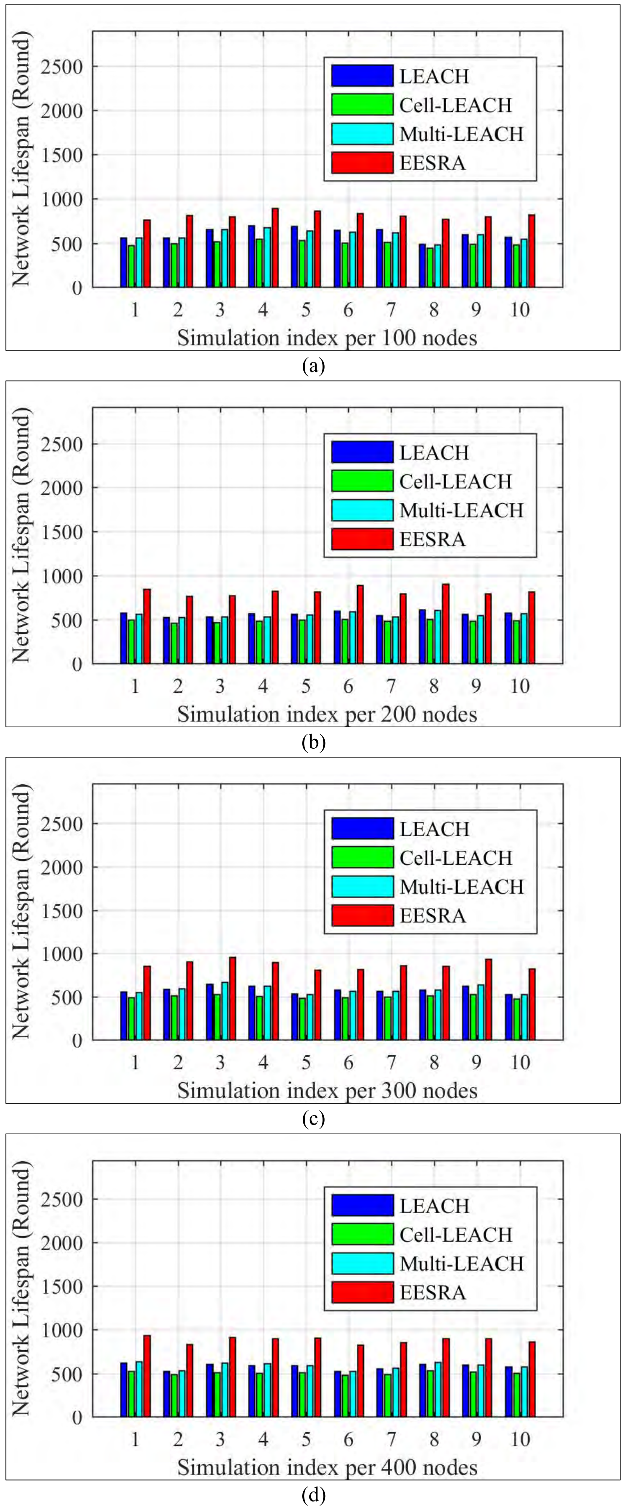

FIGURE 7. Network lifespan per: (a) 100 nodes, (b) 200 nodes, (c) 300 nodes, (d) 400 nodes.

the simulation progressed, which indicate that CHs, CGs and CMs have balanced energy consumption rates.

B. SCALABILITY

To demonstrate the impact of applying EESRA algorithm on network scalability, the network lifespan (i.e. the time interval starting from the first network transmission to the depleted of all nodes) as well as the number of delivered packets criteria are reported per 10 iterations with different initial starting positions for the sensor nodes for four scalability case studies. The lifespan is used to validate that the proposed EESRA algorithm is capable of maintaining

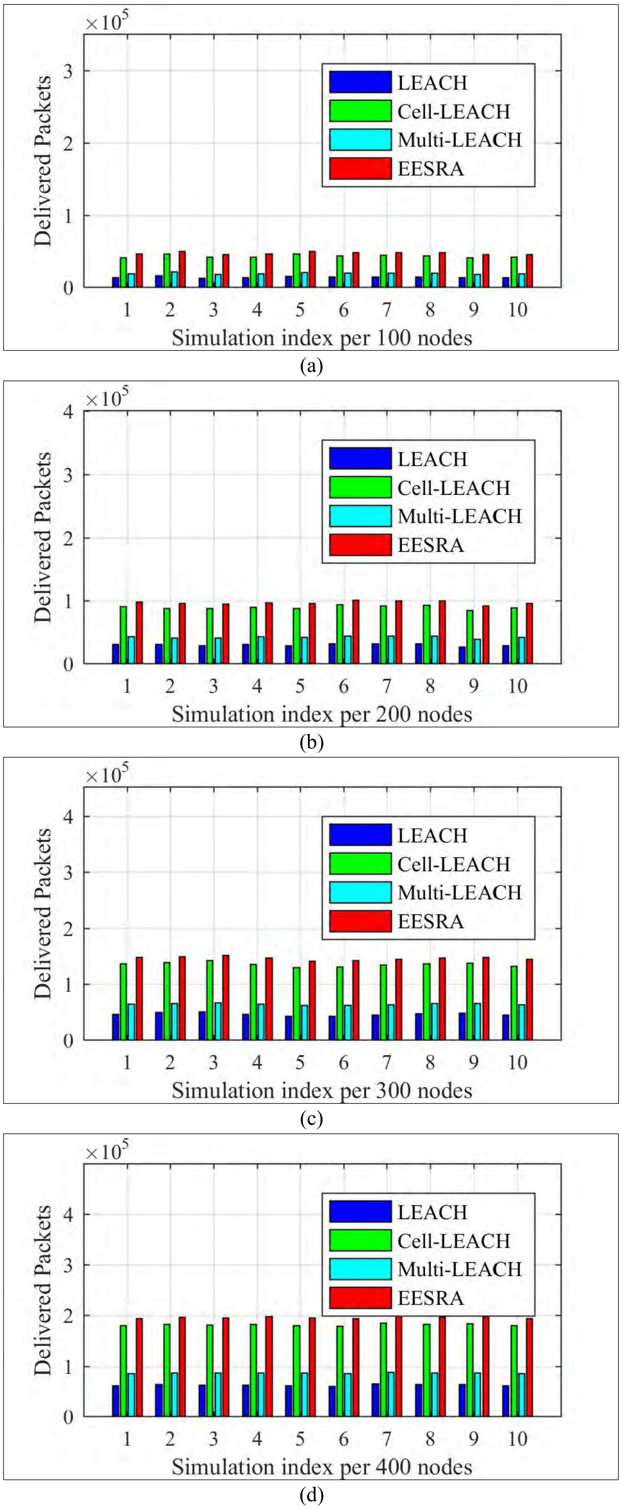

FIGURE 8. Packets delivery ratio per: (a) 100 nodes, (b) 200 nodes, (c) 300 nodes, (d) 400 nodes.

the network functioning given the increase of the number of nodes. In contrast, the number of delivered data packets indicate the high network connectivity.

Figure 7 shows the network lifespan and Figure 8 shows the number of delivered packets per simulation iterations, where Figures 7 and 8 (a), (b), (c) and (d) shows the obtained results based on the first, second, third and fourth scenarios respectively. The performance of EESRA for each case study outperforms LEACH Cell-LEACH and Multi-LEACH in terms of network lifespan as well as the number of delivered packets.

TABLE 4. Comparison of leach, Cell-LEACH and EESRA protocols.

No. of nodes	Protocol	FDN	FDN ratio	AND	AND ratio
100	LEACH	42	1	613	1
	Cell-LEACH	129	3.14	501	0.82
	Multi-LEACH	107	2.6	597	0.97
	EESRA	363	8.85	819	1.33
200	LEACH	41	1	570	1
	Cell-LEACH	122	2.97	490	0.86
	Multi-LEACH	123	3	559	0.98
	EESRA	330	8.05	826	1.45
300	LEACH	41	1	585	1
	Cell-LEACH	122	2.97	505	0.86
	Multi-LEACH	122	2.97	586	1
	EESRA	322	7.85	872	1.49
400	LEACH	41	1	581	1
	Cell-LEACH	121	2.95	507	0.87
	Multi-LEACH	121	2.95	589	1.01
	EESRA	312	7.61	883	1.52

V. DISCUSSION

Table 4 elaborates on the results presented in Figure 4, where the First Dead Node (*FDN*), FDN ratio (FDN of a given protocol divided by the LEACH FDN), All Nodes Depleted (*AND*), and the AND ratio (i.e. the AND of a given protocol divided by the LEACH AND), were shown. The FND and AND ratios are used to measure the network's full operational capacity as well as the network lifespan performance. The proposed EESRA routing algorithm maintained the network in full operational capacity for 312, 289, 282 and 281 more rounds as compared to LEACH, 234, 208, 200 and 191 more rounds as compared to Cell-LEACH and 256, 207, 200 and 191 more rounds as compared to Multi-LEACH protocol for the first, second, third and fourth case studies respectively.

As can be seen from Figures 7, 8, and Table 4, EESRA algorithm extended the network lifespan compared to LEACH, Cell-LEACH and Multi-LEACH, which leads to an increase in overall network connectivity. Due to that, the number of delivered data packets is increased as well [29], [30]. That is, EESRA algorithm is more reliable for large-scale wireless sensor networks. Moreover, the use of a multi-hop intra-cluster communication in place of a direct communication strategy boosted the ability of EESRA to reduce overall energy consumption. The EESRA capability of balancing the load between nodes is due to the adoption of a three-layer hierarchy (i.e. layer-one sensor nodes, layer-two CGs, and layer-three CHs) which results in a more even load distribution. Finally, the use of a CSMA/CA channel access mechanism between CMs and CGs increases the network scalability and further extends the network lifespan. Therefore, these enhancements allow EESRA to maintain its performance as the network size increases.

VI. CONCLUSION

This paper proposed a new three-layer WSN routing algorithm named Energy Efficient Scalable Routing Algorithm (EESRA) based on the LEACH protocol. The goal of developing EESRA is to maintain the network lifespan with increasing network size. A hybrid MAC protocol incorporating sleep and collision avoidance mechanisms for data sensing, in addition to TDMA slots for data forwarding in each round was adopted. Moreover, congregations (CGs) were utilized to receive sensed data from CMs for more load balancing.

The simulation results proof that the strategy presented by EESRA algorithm is applicable in both small and large networks and the results demonstrated that the network lifespan using EESRA algorithm has been extended by 33.61%, 63.47% and 37.19%; 44.91%, 68.57% and 47.76%; 49.06%, 72.67% and 48.81%; 51.98%, 74.16% and 49.92% compared to LEACH, Cell-LEACH, Multi-LEACH protocols for 100-, 200-, 300- and 400-node scenarios respectively. Further, the three-layer hierarchy enabled the EESRA algorithm to decrease node energy consumption and achieved better load balancing among the nodes.

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