International Journal of Electrical and Computer Engineering (IJECE)
Vol. 12, No. 6, December 2022, pp. 6440∼6448
ISSN: 2088-8708, DOI: 10.11591/ijece.v12i6.pp6440-6448

Novel reliable and dynamic energy-aware routing protocol for large scale wireless sensor networks

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Article Info

Article history:

Received Oct 6, 2021
Revised Jun 6, 2022
Accepted Jul 1, 2022

Keywords:

Energy efficiency
Life-time
Multi-hop
Reliabilty
Wireless sensor networks

ABSTRACT

Wireless sensor networks (WSN) are made up of an important number of sensors, called nodes, distributed in random way in a concerned monitoring area. All sensor nodes in the network are mounted with limited energy sources, which makes energy harvesting on top of the list of issues in WSN. A poor communication architecture can result in excessive consumption, reducing the network lifetime and throughput. Centralizing data collection and the introduction of gateways (GTs), to help cluster heads (CHs), improved WSN life time significantly. However, in vast regions, misplacement and poor distribution of GTs wastes a huge amount of energy and decreases network's performances. In this work, we describe a reliable and dynamic with energy-awareness routing (RDEAR) protocol that provides a new GT's election approach taking into consideration CHs density, transmission distance and energy. Applied on 20 different networks, RDEAR reduced the overall energy consumption, increased stability zone and network life time as well as other compared metrics. Our proposed approach increased network's throughput up to 75.92% , 67.7% and 9.78% compared to the low energy adaptive clustering hierarchy (LEACH), distributed energy efficient clustering (DEEC) and static multihop routing (SMR), protocols, respectively.

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1. INTRODUCTION

Wireless sensor networks (WSN) is a set of hundreds or thousands of sensor nodes, distributed in random way, to collect and send data from the monitored area [1]. WSN have been adopted by a lot of domains like defense, pollution monitoring, medical field and different industry domains [2]–[4]. This kind of networks can provide many advantages compared to traditional communications adopted in electrical power systems [5]. Each node in the network is equipped with a limited source of power [6]. Although, WSNs are usually used for unreachable fields and areas, node's batteries cannot be replaced. So, network's energy should be consumed in an optimal way [7], [8]. Various researches have been designed for WSN to improve energy awareness, data transfer and routing paradigms [9]. The insufficient power sources of the sensor nodes are to be considered as a key issue in WSN [10]. Consequently, the failure in network arises because of node failure [11]–[14].

The issue of energy management in WSNs have been the major concern of researchers in recent years. The excessive node's energy consumption is caused by the direct data transmission and direct links with the base station (BS) [15]. Consequently, more energy efficiency is required in WSN to achieve longer lifetime and improve its performances [16]. To handle the problem of energy efficiency in the network, many researches have adopted clustering, which refers to group sensors into clusters mastered by a cluster head (CH). This later is gathers cluster members data, aggregate it and route it to the sink [17]–[19]. Meanwhile, when it comes to vast monitored fields, the risk of data loss increases, adopting direct transmissions to the sink. Which may create isolated CHs which cannot reach the sink because it is out of range, resulting excessive energy consumption and data loss [20].

The main purpose of this work is to decrease energy consumption and improve reliability by minimizing the distance of transmission either for intra-cluster communication, by using nodes of the same cluster as relays, and for inter-cluster communication by electing reliable gateways (GTs) to maintain CHs routing data with less energy consumption and with more reliable links and resistance to data loss. The remainder of the paper is organized as follow: section 1 is the introductory to the main problem in WSN, section 2 reveals and disscusses some related works, motivated by to create the developed method. In section 3, the propagation radio model adopted in this paper is described, while section 4 outlines our reliable and dynamic with energy-awareness routing (RDEAR) protocol. Our proposed protocol performances are evaluated in regards to some recent works in section 5, and section 6 is the conclusion.

2. RELATED WORK

A variety of protocols have been developed in order to balance energy resources utilization in WSNs. Low energy adaptive clustering hierarchy (LEACH) [21] is a hierarchical protocol that drains energy uniformly by role rotation, selecting a predefined number of CHs periodically based on a probability. These CHs are meant to receive packets from cluster members and route them directly towards the BS. Distributed energy efficient clustering (DEEC) [22], uses a new threshold value for CHs election, taking into consideration nodes residual energy. This way nodes with big residual energy are prioritized to be CH than minor energy nodes, which preserves links during transmission. The main inconvenient of [21], [22] is that each CH creates a direct link to the BS, which results a huge energy consumption and arises the probability of data loss especially in large monitored areas, where far CHs will not be in the range of communication of the BS, making the reliability impossible. To handle this problem, multi-hop LEACH (MH-LEACH) [23] saves CHs energy using nodes that lies on the way to the BS for data routing for data routing the BS. Hybrid, energy-efficient, distributed clustering approach (HEED) [24] considers nodes residual energies and communication cost while choosing a CH. it uses multi-hop communication between CHs and guaranties coverage in contrast with LEACH. The study [25] presents a multi-hop technique for LEACH (MHT-LEACH) which adopts leveling by classifying CHs into two groups. First level CHs which create direct single hop links with the sink and second level CHs which uses multi-hop communication relaying on first level CHs to communicate with the BS. But still in vast areas some CHs of second level will not be able to reach other CHs in the first level which creates the same problem as in LEACH. To handle this problem, an enhanced dynamic multi-hop technique for LEACH (EDMHT-LEACH) [26] aimed to minimize the distance of transmission by proceeding to network leveling. The study [26] balances the intra-cluster load by limiting the number of cluster members in each cluster. This process results the appearance of some nodes not belonging to any cluster and used them as relays to help CHs in inter-cluster routing process. Static multihop routing (SMR) [27], is an improvement of [26]. It uses an improved CHs election threshold value and introduces intra-cluster communication to preserve cluster members energy. However, since the deployment, CHs election and clustering processes are based on a probability. The main problem of [26], [27] is that independent nodes (relays) may be distributed in upper levels and may be misplaced to other CHs, so they will not be able to participate in routing process, resulting an exceed of energy consumption and decreasing coverage in the network.

To handle this problem, this paper proposes a novel RDEAR to balance energy consumption and warranty reliability between CHs and the BS. The protocol introduces a new dynamic approach to select reliable gateways (GTs) taking into consideration the location of CHs in upper levels, energy and other probable GTs density. This technique led us to have more efficiency by selecting well positioned GTs to help CHs and preserve energy and decreases the probability of data loss during the routing process.

3. RADIO MODEL

Many wireless communication radio propagation models anticipate signal strength degradation with distance d. In this paper we will use both free space propagation model and multipath propagation model depending on transmission distance as described in [28]. The energy consumed for transmission E_{tx} and for reception E_{rx} are expressed in (1) and (2) [28], [29]:

$$E_{tx} = LE_{ele} + \begin{cases} L\varepsilon_{fs}d^2 & \text{si} \quad d < d_0 \\ L\varepsilon_{amp}d^4 & \text{si} \quad d \geq d_0 \end{cases} \tag{1}$$

$$E_{rx} = LE_{ele} \tag{2}$$

where ε_{fs} and ε_{amp} are respectively the transmission powers in the free space and multi-path propagations models separated by a threshold distance value d_0.

4. PROPOSED ROUTING PROTOCOL

In this work we present our proposed protocol RDEAR. Our proposed protocol consists of two major phases: setup phase and communication phase. In the setup phase the infrastructure of the network is constructed while routes and real communication is maintained in the communication phase.

4.1. Set-up phase

As a departure, we consider that the network is divided into k levels. Each level k have a radius of $k * \frac{do}{2}$ from the BS [30] as shown in Figure 1. After leveling we proceed to CHs election and GTs selection to maintain cluster-heads to transmit collected information to the base station.

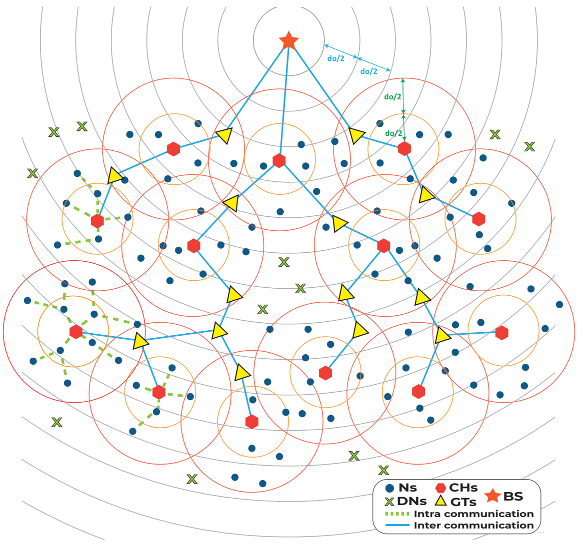

Figure 1. Clustering, intra and inter-cluster communications with leveling to the BS

4.1.1. CHs election process

In this stage, CHs are elected based on the same process used on LEACH where each node will decide being a CH or not based on a random number compared with a threshold value $T(s)$, expressed, as in [27], [30], in (3), the node became a CH if the number chosen is less than $T(s)$.

$$T(s) = \begin{cases} max\left(\frac{p_s}{1-p_s\cdot(rmod\frac{1}{p_s})} \times \frac{E_{res}}{E_0}, T_{min}\right) & \text{si } \{s\} \in G \\ 0 & \text{Otherwise.} \end{cases} \tag{3}$$

where, E_{res} and E_0 are respectively residual and initial energies of each node. T_{min} represents election threshold value in case E_{res} is very low [27], [30]. Once CHs are elected, each CH advertises itself in the network with a CH advertisement (CH-ADV) message containing CH identifier (CH-ID), level and position. Based on CH-ADV messages, the number of CHs in range of each node $CH\_range_r(s)$, the distance to each CH and the average distance to all CHs in range $Avg\_DCH^k_r(s)$ are calculated. Based on these messages each

CH creates an initial routing table (RT), containing other CHs withing the range of transmission. After the election of Gateways, all RTs will be updated.

4.1.2. Gateways election

To balance energy consumption and enhance data transmission, the proposed protocol introduces a new dynamic GTs election process, selecting from the rest of normal nodes taking into consideration the residual energy of candidate nodes, the density of CHs and the average distance to other probable GTs for each level in the network. To guaranty having enough GTs for routing process, the number of GTs in each level $NGT^k(r)$ is mainly related on the number of CHs in upper level $NCH^{k+1}(r)$, as expressed in (4).

$$NGT^k(r) = \alpha NCH^{k+1}(r) \quad (4)$$

First of all, only nodes with enough residual energy are legitimate to be GTs. For a level k, $LGT^k(r)$ represents the set of legitimate nodes to be gateways for the current round r and expressed in (5).

$$\{s \in LGT^k(r)/E_{res}(s) \geq Avg\_E^k(r)\} \quad (5)$$

With $Avg\_E^k(r)$ denotes the average energy of all nodes in the level k. Each legitimate node broadcast a legitimate advertisement message (LGT-ADV) to declare itself to other legitimate nodes in the same level. To have an efficient communication, a node is more practical to be a GT if it covers an important number of CHs with small average distance and more residual energy. Based on LGT-ADV messages, all legitimate nodes are aware the number of other legitimate nodes in the same level k : $GT\_range_r(s)$. To well distribute GTs in each level, we need to consider the density of other legitimate nodes as a selection factor.

Finally, our new dynamic cost function for electing optimal and well distributed GTs in each level is expressed in (6):

$$Cost(s) = c_1 * \left(\frac{Avg\_DCH_r^k(s)}{CH\_range_r(s)} * \frac{Avg\_E^k(r)}{E_r(s)}\right) + c_2 * \left(\frac{GT\_range_r(s)}{CH\_range_r(s)}\right) \quad (6)$$

with c_1 and c_2 are random numbers: $\{c_1, c_2 \in [0,1]/c_1 + c_2 = 1\}$. For each level, all first $NGT^k(r)$ legitimate nodes with the minimum $Cost$ value are selected to be GTs in the level k for the current round r. All selected GTs broadcast a GT-ADV message containing GTs identifier (GT-ID), level and position to inform other GTs and CHs. Based on these messages CH's RT are updated and GT's RT are created. Each CH/GT will send data to the closest CH/GT in the updates RTs and withing the path to the BS as demonstrated in Figure 1 .

4.1.3. Clustering

To well distribute load over all CHs, we restricted the number of nodes by cluster to N_o which is equal to the ratio of the number of remaining nodes $Nbr\_NA(r)$ by the number of CHs elected $Nbr\_CH_t(r)$ as expressed in (7).

$$N_o = \frac{Nbr\_NA(r)}{Nbr\_CH_t(r)} \quad (7)$$

Relaying on CH-ADV messages, normal node locates all CHs in range, and joins the closest based on Euclidean distance, sending a Join-Req to the first closet CH but withing a distance less or equal to d_o. Selected CH, in turn, checks if there is a place in the cluster. If so, the CH send an acceptance message, with a time-division multiple access (TDMA) slot schedule, to the normal node. Otherwise, the request is declined by sending a refusal message. In the other hand if the request is rejected, the normal node sends to the second closest CH in range and so on until it is accepted. In case no CH approved the Join-Req, the node is considered as dormant node (DNs) and will not participate at all in the processes of sensing and communication. For each cluster, nodes distant by more than $do/2$ from the CH are considered as nodes of the second level, moreover, nodes with a distance less or equal to $do/2$ are considered as nodes of the first level, theses nodes besides their own collected data, will route second level node's data to the CH.

4.2. Communication process

To avoid collision and packet loss, scheduling is necessary. Each node in the network used to route data creates a TDMA schedule to well distribute sending time between considered nodes as shown in Figure 2. In each cluster, nodes of the first level broadcasts a first-level advertisement message (FL-ADV) to inform second level nodes of their location and ID. Nodes of the second level calculates the distance to each first level node and respond with a Route-REQ message to the closest node of the same cluster. In the other hand based on the number of requests, each first node level creates a TDMA schedule as shown in 2 and sent it back to all concerned nodes. For inter-cluster communication process, each CH/GT communicate their data to the closest GT/CH from the same or lower levels but with a distance to the BS lesser than the sender. To avoid data collision, each CH/GT create and send a TDMA schedule to other GTs and CHs using the route to send data to the BS as illustrated in Figure 2.

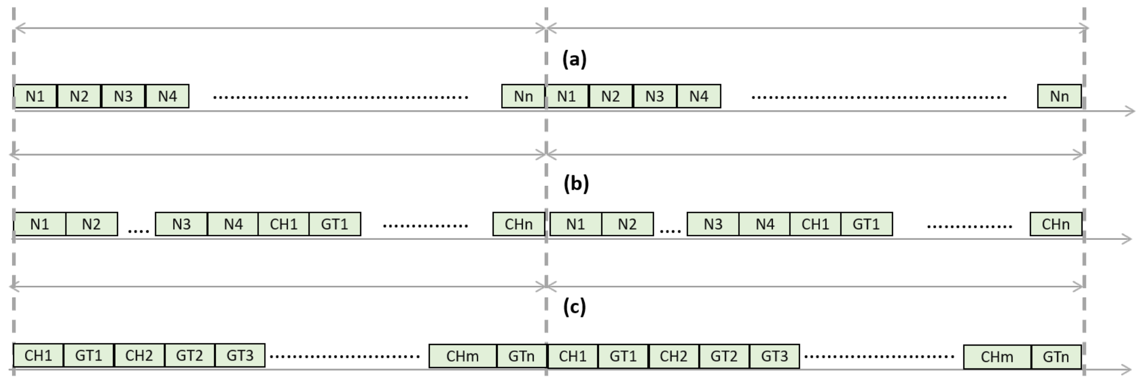

Figure 2. TDMA schedule of (a) first level node, (b) cluster heads, and (c) GTs

5. SIMULATION RESULTS

To evaluate the performance of RDEAR, a MATLAB program is used on a network containing 200 nodes randomly deployed in an area of 500×500 m with the BS is located far from the network at 250 m and 550 m. Since the deployment and election processes are random, the performance of any routing protocol may change from a network sample to another. To evaluate well our proposed protocol, we consider 20 different networks. Based on these simulations, we will compare means, calculate confidence intervals (CIs) and extract statistical analysis, for different compared metrics. Main parameters adopted in simulations, are mentioned in Table 1.

Table 1. Simulation parameters

Parameters	Value
L	6400 bit
E_0	0.5J
E_{fs}	10 pJ/bit/m^2
p_s	0.2%
E_{elec}	50 nJ/bit
E_{data}	5 nJ/bit
T_{min}	0.03
E_{amp}	0.0013 pJ/bit/m^4
α	0.8

5.1. Results

Analyzing results, the first thing that stands out is that our suggested protocol has increased network life-time and stabilized the network compared to other protocols as illustrated in Figure 3(a). As an evidence of this improvement, the total number of packets delivered to the sink increases, as in Figure 3(b), while the total energy consumption is decreases Figure 3(c). All significant rounds of death of the First node, half nodes and All nodes respectively are improved Figure 3(d), when compared to LEACH, DEEC and SMR. Highlighted graphs represent 95% T-distribution confidence intervals of each protocol calculated based on results obtained from the 20 simulations.

To know more about the performances of our proposed protocol, we have done a statistical study for the significant rounds including the round of the death of the first node (FND), the round where the half number of nodes in the network are dead (HND) and the round of death of all nodes in the network (AND). Also, in Table 2 we resume the throughput improvement (THI) of our proposed protocol compared to other protocols. All these statistics are extracted from the 20 simulation cases and justified with confidence intervals. We can easily denote that all significant rounds are improved using RDEAR compared to all other protocols. Also, the THI is by a means of 75.92%, 67.7%, and 9.78% in regards to LEACH, DEEC and SMR respectively.

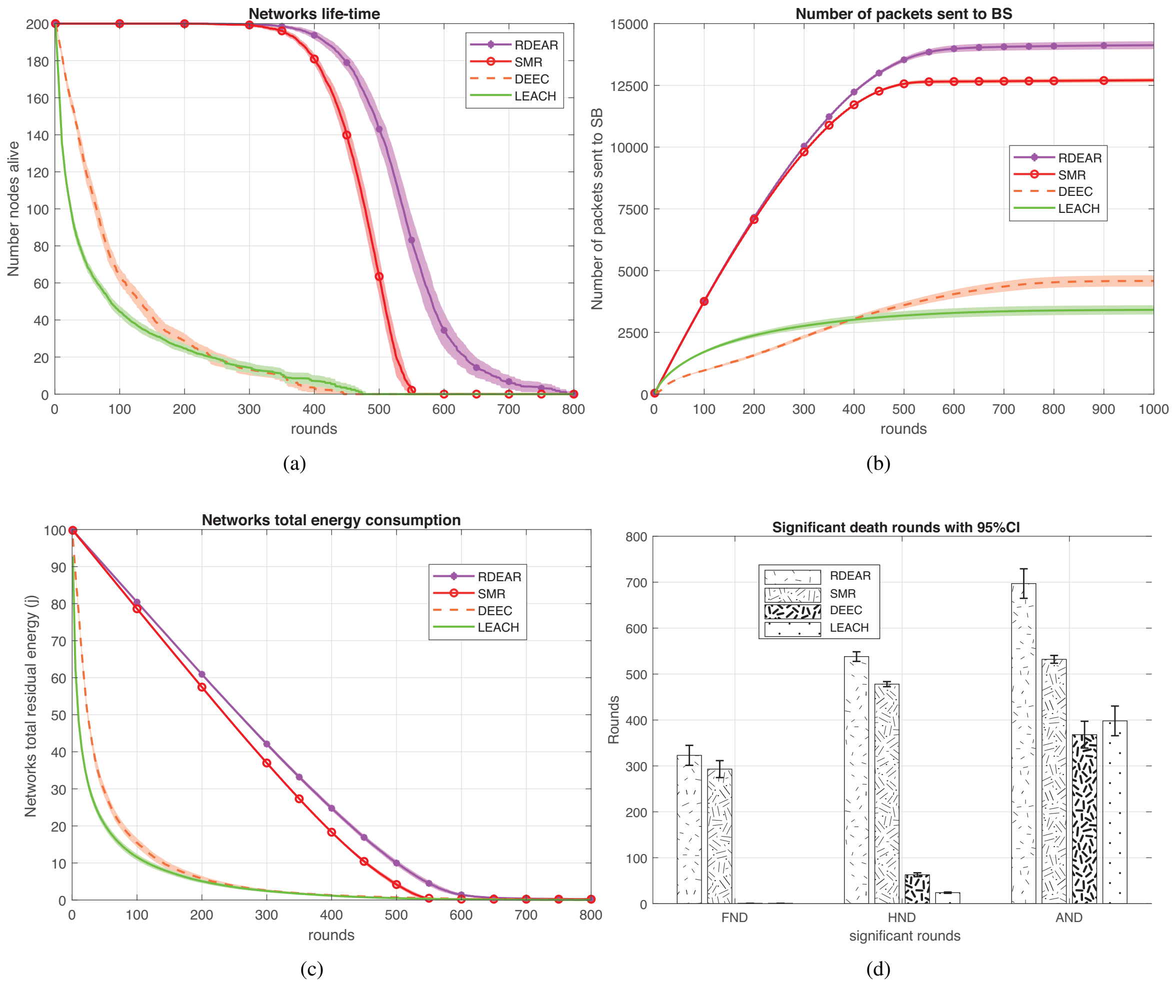

Figure 3. Comparing means and CIs performed on 20 network samples of (a) life-time, (b) packets sent to the BS, (c) energy consumption, and (d) significant death roundsproaches

Table 2. Means and 95% CI of first, half and all node death rounds and THI

Technique	Value	FND	HND	AND	THI
RDEAR	Mean	323	538	968	***
	95%CI	[301, 344]	[528, 548]	[883, 1053]	***
SMR	Mean	293	478	537	9.78%
	95% CI	[275, 312]	[472, 484]	[529, 546]	[9.09, 10.48]%
DEEC	Mean	1	63	624	67.70%
	95% CI	[1, 2]	[59, 68]	[579, 669]	[66.31, 69.09]%
LEACH	Mean	1	24	621	75.92%
	95% CI	[1, 1]	[23, 26]	[591, 651]	[74.73, 77.1]%

5.2. Results discussion

The analysis of obtained results revealed a significant improvement of RDEAR in network's performances, in all simulated situations. When compared to LEACH, DEEC and SMR, network's life time is improved, network stability is prolonged, energy harvesting is reduced and throughput is increased. This improvement was achieved due to two main factors. The first one is minimizing the overall transmission distances using leveling inside and outside clusters. The second factor is our suggested method for electing reliable and well-placed GTs which takes into consideration the residual energy, the number of CHs, average distance to CHs and density of probable GTs in the same level. This process helped to minimize communication distance and reduced energy consumption on CHs making transmissions with minimal energy cost. Introduction of DNs helped also in preserving the energy of non-participating nodes rather than consume it without a purpose.

6. CONCLUSION

The fundamental idea behind RDEAR is to provide an energy efficient communication architecture by introducing a dynamic process for selecting GTs in the network taking into consideration the number of CHs and the density of other possible GTs in communication range. Simulation results have shown that the proposed method has stabilized and increased the network's lifetime, reduced energy consumption and improved the throughput by a mean of 9.78%, 67.7% and 75.92% respectively compared to SMR, DEEC and LEACH. Finally, this improvement demonstrates the efficiency of our proposed new dynamic GTs election process, and communication schemes elaborated. Placing GTs in the right place in regards to CHs reduces the distance of transmission and reduces the energy consumption. This improvement affects all rated performance metrics compared to all presented protocols. For further works we intend to use evolutionary algorithm for the routing problem.

ACKNOWLEDGEMENT

This work was partially funded by the CNRST Morocco.

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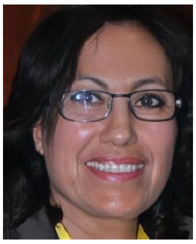

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