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DISTRIBUTED ENERGY-EFFICIENT AND POSITION-AWARE ROUTING PROTOCOL FOR HETEROGENEOUS WIRELESS SENSOR NETWORK

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Abstract

A Wireless sensor network is a group of small sensors having limited computation, memory, communication and sensing capabilities. One of the fundamental challenges in their design is to maximize their network lifetime. In this regard, many routing protocols have been proposed to optimize energy efficiency in wireless sensor networks. Clustering is an effective approach that improve the network lifetime, reduce energy consumption and increase the scalability in the sensor network. In this paper, we propose and analyse a distributed energy-efficient and position-aware routing protocol for heterogeneous wireless sensor networks. In this protocol, cluster heads are elected using a probability based on the ratio between residual energy of each node and the total energy of the network. Moreover, it uses an extra hierarchical level by selecting the most powerful cluster head in an appropriate position to act as a gateway for data transmission to the base station. Simulation results using different evaluation metrics show that our proposed protocol outperforms other current existing protocols.

Keywords: Clustering algorithm, Energy efficiency, Heterogeneous environment, Network lifetime, Routing protocols, Wireless sensor networks.

1. Introduction

Recent advances in MEMS (Micro-Electromechanical Systems) have enabled the development of tiny, low-cost, low power and multifunctional sensors able to communicate in short distances. A Wireless Sensor Networks (WSN) are made of a large number of micro-sensors spatially dispersed over a geographical area in order to sense, measure and monitor physical parameters such as temperature, humidity and pressure, in order to monitor and react to phenomena in the environment. WSN are widely used in several applications [1-5] such as precision agriculture, environmental monitoring, security and health care. In WSN, the sensors are usually randomly scattered in a sensor field. Each of these sensor nodes has the ability to collect data and route it back to the sink than to the end-users. Nayak and Stojmenovic [6] explained that data is routed back to the end-user by multi-hop communication through the sink as shown in Fig. 1.

The energy of sensors is usually limited since they are generally powered by batteries. Furthermore, harsh conditions and remote applications area make it quite impossible to recharge or replace their batteries. The energy of sensor nodes is consumed by sensing, processing and communicating data and also by other operations performed by nodes. Based on studies by Akyildiz and Vuran [7] and Estrin [8], radio communication is the greediest part, in fact, it consumes the largest amount of energy as illustrated in Fig. 2.

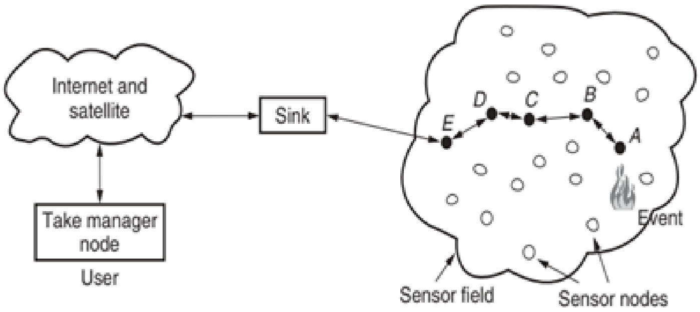

Fig. 1. Overview of WSN architecture.

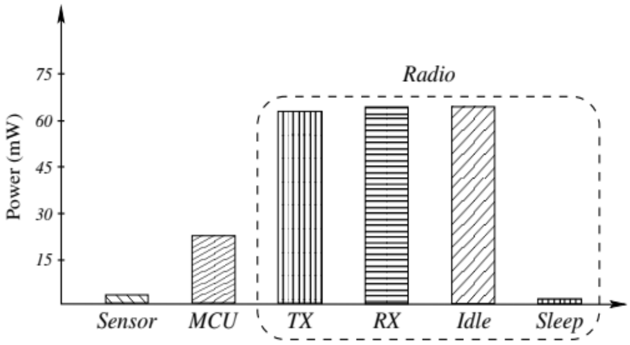

Fig. 2. Energy consumption of a sensor node.

As energy is the major constraint in WSN, we have the real need to develop energy efficient routing algorithms [9-13] that optimize energy consumption and increase the WSN lifetime. In this context, clustering algorithm [14-21] is one of the most used technique that optimize energy consumption in WSN. It consists of classifying sensor nodes in two or more groups, the normal nodes and the cluster heads (CHs). Normal nodes send collected data to their respective CHs, and then the CHs send the collected data to the BS after aggregation and compression.

Since only CHs transmit data over a long distance to the BS, a large amount of energy is saved and the overall network lifespan is increased. We recognize two kinds of wireless sensor networks. The homogeneous WSN in which all sensor nodes have the same amount of energy such as LEACH [22], HEED [23], PEGASIS [24], FCBA [25] and PRRP [26]. The heterogeneous WSN where all the sensor nodes have different amount of energy, such as SEP [27], LEACH-E [28], DEEC [29], EDDEEC [30], BEENISH [31], EEHC [32] and modified BEENISH [33].

Based on LEACH-E protocol, we develop and validate a Distributed Energy-Efficient and Position-Aware (DEEP) routing protocol for heterogeneous wireless sensor networks. DEEP aims to improve the overall network lifetime of heterogeneous WSN by adding an extra hierarchical layer for data transmission to the Base Station (BS) taking into account the position and the energy level of the sensor node. The use of an extra-hierarchical layer for data transmission to the BS promotes multi-hop and small distance transmissions and therefore reduce greatly energy consumption.

In our proposition, the most powerful CH having the optimal position acts as gateway node between the CHs and the BS. This allows a better energy utilization through the sensor network and increases the network lifetime accordingly. The remainder of this paper is organised as follows. Section 2 presents the heterogeneous WSN model. Section 3 exhibits the details and analyses the properties of DEEP. Section 4 evaluates the performance of DEEP trough simulations and comparison with LEACH-E, EEHC and DEEC protocols. Finally, Section 5 gives a conclusion and perspectives.

2. Heterogeneous Network Model

The main goal of cluster-based routing protocol is to efficiently maintain the energy consumption of sensor nodes by involving them into multi-hop communication and by performing data aggregation and fusion in order to decrease the number of transmitted messages to the BS.

In this section, we introduce the network and energy model used in this work. In this study, we suppose that there are N sensor nodes, which are consistently dispersed over an M×M square area as illustrated in Fig. 3. These sensors have always information to transmit to the BS, which is located far from the sensing area. This kind of WSN setting can be used in various fields such as space exploration, environmental monitoring, agriculture and military applications.

Normally, CHs transmit collected data directly to the BS. We suppose that sensor nodes are stationary. We assume that the WSN has the following properties:

- Nodes are randomly distributed in the monitoring area and they can communicate with the base station directly.

- The position of the BS and the nodes are fixed.
- All nodes have equal status and similar processing and communication capabilities.
- The nodes can judge the distance from the signal source through the strength of the signal and adjust the transmission power.

Nodes use data fusion and aggregation to reduce the amount of data transmission.

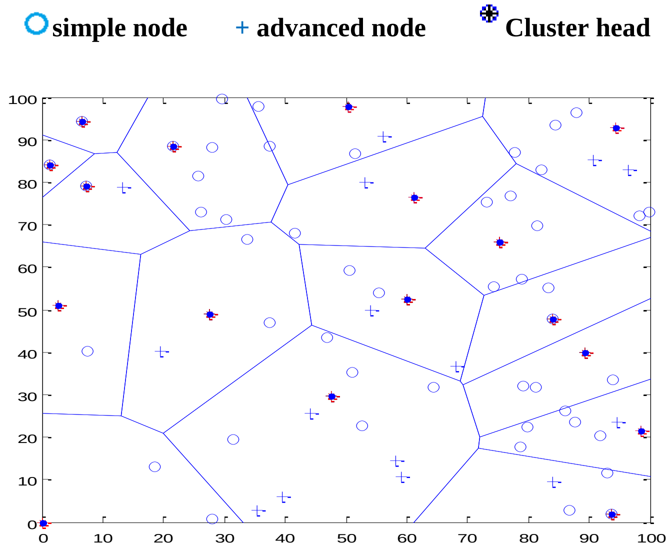

Fig. 3. Random deployment of heterogeneous nodes.

In heterogenous WSN, there are two kinds of sensor nodes, the advanced nodes and normal nodes. E_0 is the initial energy of normal nodes, and (m) is the fraction of advanced nodes, having a factor of (a) times more energy than the normal nodes $(a\ x\ E_0)$. There are $(N\ x\ m)$ advanced nodes fit out with $E_0(1+a)$ initial energy, and $N(1-m)$ normal nodes fit out with same initial the energy E_0. The total initial energy of the two-level heterogeneous network is given by Eq. (1):

$$E_{total} = N(1-m)E_0 + NmE_0(1+a) = NE_0(1+am) \qquad (1)$$

We use the radio energy dissipation model illustrated in Fig. 4.

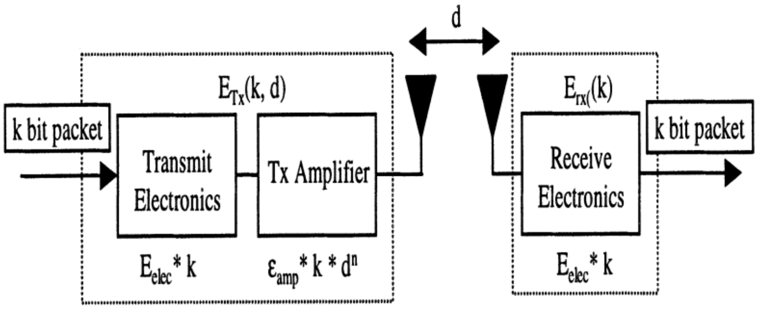

Fig. 4. Radio and energy dissipation model.

In order to transmit an L-bit message over a distance d, the dissipated energy by the radio transmission is given by Eq. (2):

$$E_{Tx}(L,d) = \begin{cases} LE_{elec} + L\epsilon_{fs}d^2\,, & d < d_0 \\ LE_{elec} + L\epsilon_{mp}d^4, & d \geq d_0 \end{cases} \tag{2}$$

where E_{elec} is the energy dissipated per bit to run the transmitter E_{Tx} or the receiver E_{Rx} circuit, and the amplifier energy $\epsilon_{fs}d^2$ *or* $\epsilon_{mp}d^4$ depends on the distance to the receiver and the acceptable bit-error rate. We have fixed the value of d_0 at 87.7 meters. In most WSN, sensor nodes have limited power supply since they are usually powered by batteries. Thus, energy is a key factor to consider in the design of WSN.

One of the drawbacks of LEACH-E is that all CHs communicate directly to the BS as shown in Fig. 5, this can lead to high energy dissipation in the sensor network. In addition, all CHs send data to the BS, which can cause redundant and unnecessary data transmitted to the BS. Therefore, this can consume a large amount of energy and decrease the lifetime of the sensor network.

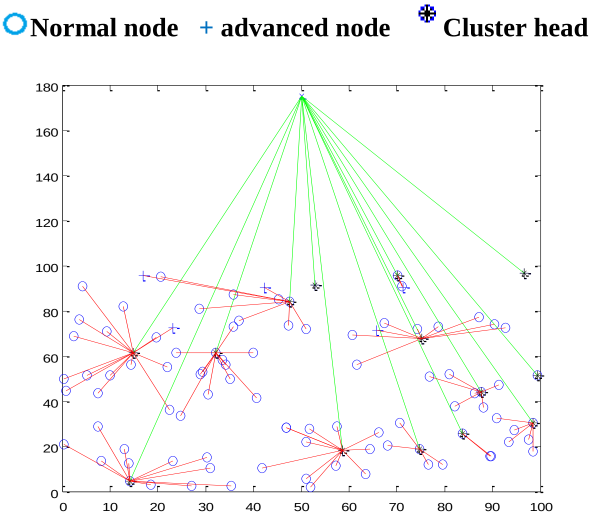

Fig. 5. Communication process in LEACH-E.

In this perspective, we develop a Distributed Energy-Efficient and Position-aware (DEEP) routing protocol for heterogeneous wireless sensor networks. DEEP achieves a large reduction in energy consumption and increases the WSN lifespan. In next section, we describe DEEP protocol in more details.

3. DEEP protocol

In DEEP we used the same probability formula presented by Heinzelman et al. [28] stated after in Eq. (3). In order to optimize energy consumption, we add a second hierarchical layer for data transmission to the BS. Moreover, we set a condition about the position of the CH, which will act as a relay between all CHs and the BS. For this, we select the most powerful CH, which we call Master Cluster Head

(MCH) to act as a relay node between CHs and the BS. The algorithm of DEEP uses the same strategy in CHs selection, however, it uses a new strategy for data transmission. The algorithm for data transmitting to the BS is described by the flowchart displayed in Fig. 6.

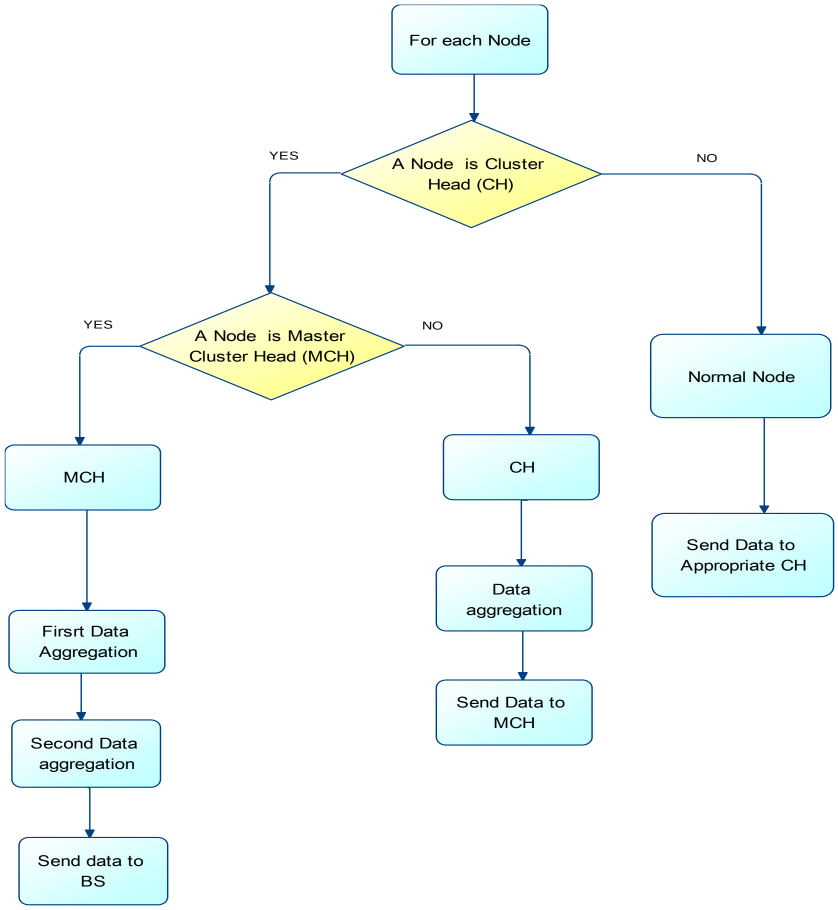

Fig. 6. Flowchart of DEEP.

The MCH is chosen based on its residual energy and its position relative to the BS. In fact, by implementing this algorithm we reduce the number of far distance transmissions since the CHs make short distance transmissions and only the MCH will perform transmissions to the BS. The main characteristics of the DEEP protocol are:

- All nodes in the network are heterogeneous and have limited energy.
- All nodes are able to communicate with the CH.
- CHs perform data compression and aggregation.
- CHs communicate to BS through the MCH.
- The MCH is chosen among all CHs.
- The MCH is the CH having the highest energy level and optimal position close to BS.

- The BS is immobile and located far from the sensing area.

We assume that there are N = 100 nodes distributed over the M×M square zone and the network topology stay the same over time, the BS is situated in the position of (x = 50, y = 175) as shown in Fig. 7.

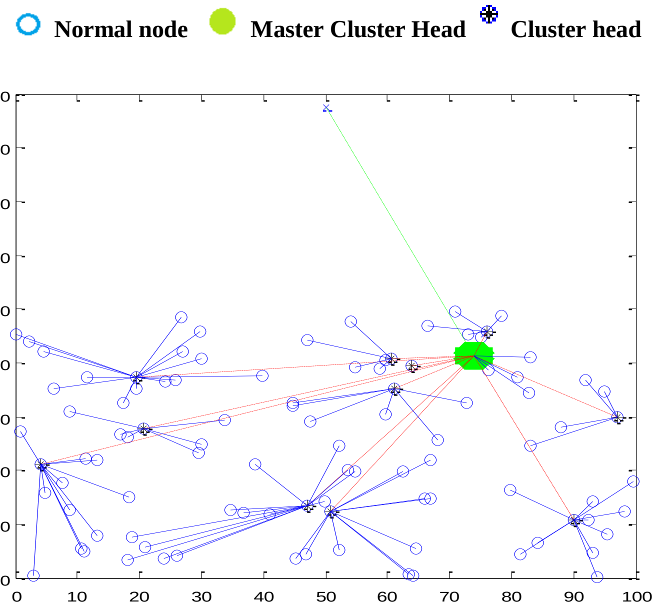

Fig. 7. Communication with BS in DEEP.

In DEEP, we calculate the threshold that each node s$_i$ uses to determine his eligibility to become a CH, as illustrated in Eq. (3):

$$T(s_i) = \begin{cases} \frac{p_i}{1 - p_i\left(r \bmod \frac{1}{p_i}\right)} & if \quad s_i \in G \\ 0 & otherwise \end{cases} \tag{3}$$

where G is the set of nodes that are eligible to be cluster heads at round r. Also, we define the average probability p$_i$ as follow in Eq. (4):

$$p_i\,(r) = min\left\{\frac{E_i\,(r)}{E_{total}\,(r)}k, 1\right\} \tag{4}$$

where $E_i\,(r)$ is the current energy of node s_i, k is the desired number of cluster, and $E_{total}\,(r)$ is the total remaining energy of the network per round r, which can be given by Eq. (5):

$$E_{total}(r) = \sum_{i=1}^{N} E_i(r) \tag{5}$$

To calculate $E_{total}(r)$ by Eq. (5), each node needs to know the total energy of all sensor nodes in the network. An estimation of $E_{total}(r)$ is given by Eq. (6):

$$E_{total}(r) = E_{initial}\left(1 - \frac{r}{R}\right) \tag{6}$$

where R is the total number of rounds of the entire network. All sensor nodes use the same amount of energy in each round. The value of R is given by Eq. (7):

$$R = \frac{E_{initial}}{E_{Round}} \tag{7}$$

And E_{Round} is the total energy dissipated by round in the network given by Eq. (8):

$$E_{Round} = L\left[2NE_{elec} + NE_{DA} + (k-1)\epsilon_{mp}d^4_{toMCH} + N\epsilon_{fs}d^2_{toCH} + \epsilon_{mp}d^4_{toBS}\right] \tag{8}$$

And k is the number of clusters, E_{DA} is the energy dissipated by data aggregation functions, $\mathrm{d}_{\mathrm{toBS}}$ is the average distance from the MCH to the BS, d_{toMCH} is the distance between the CH and the MCH and d_{toCH} is the average distance between the cluster members and the cluster head. Assuming that these nodes are uniformly distributed, we can get the equations as follow:

$$d_{toCH} = \frac{M}{\sqrt{2k\pi}} \tag{9}$$

$$d_{toMCH} = \frac{1}{M^2}\iint \sqrt{(x_i + x_j)^2 + (y_i + y_j)^2}\, dxdy \approx \frac{M}{2} \tag{10}$$

$$d_{toBS} = \sqrt{2\pi}\,\frac{M}{2} \tag{11}$$

$$k_{opt} = \frac{\sqrt{E_{fs}}}{\sqrt{E_{amp}}}\,\frac{\sqrt{N}}{\sqrt{2\pi}}\,\frac{M}{d^2_{toMCH}} \tag{12}$$

Based on the position of coordinates and the broadcasted message, the CH elected can select the MCH. Consequently, the CH with the highest energy level and close to the BS will be chosen as MCH in this round. The MCH gather all data coming from all CHs, aggregate and compress it into a single signal and then send it to the BS. This strategy will reduce considerably the amount of energy consumption.

4. Simulation: Results and Discussion

In our simulation, we use MATLAB to evaluate the performance of our proposed protocol DEEP and compare it with LEACH-E and EEHC protocols. Then, we run our simulations to examine several metrics such as number of nodes alive over time, number of messages received at the BS over time. We assume that energy is reduced whenever a node transmits or receives data or performs data aggregation. First, we examine the stability period of our DEEP protocol and compare it to that of LEACH-E and EEHC. For that, we consider a WSN of N = 100 nodes randomly distributed over an area of 100 m × 100 m, the simulation parameters are listed in Table 1.

Firstly, we calculate the number of nodes alive over time. Figure 8 shows the results in the case of m = 0.1 and a = 5. This metric is very important because it gives the end-user reliable information of the sensing area. We can clearly see that the stability period of DEEP exceeds considerably that of LEACH-E and EEHC. It means that DEEP performs better than LEACH-E and EEHC in terms of network lifetime, all nodes remain alive until 1740 rounds for DEEP, while the corresponding number for LEACH-E and EEHC are 906 and 938 rounds respectively. Furthermore, we observe that more than 50% of nodes remain alive at 3000 rounds in DEEP while it's less than 4% for LEACH-E and EEHC. This result is especially interesting for non-critical applications such as in smart agriculture.

Table 1. Simulation parameters.

	Values	Units
Energy dissipated/bit E_{elec}	50	nJ/bit
Free space factor ϵ_{fs}	10	pJ/bit/m^2
Multi-path factor ϵ_{mp}	0.0013	pJ/bit/m^4
Initial energy of sensor E_0	0.5	J
Energy of data aggregation E_{DA}	5	nJ/bit/message
Threshold distance d_0	87.7	m
Message size	4000	bits
Number of nodes N	100	-

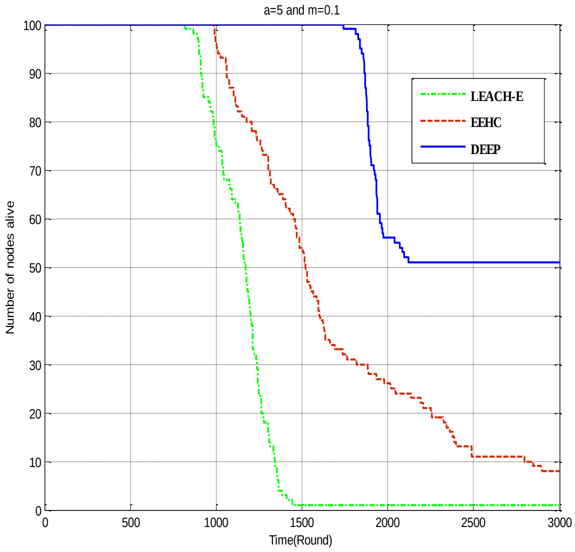

Fig. 8. Number of nodes alive over time.

Secondly, we compute the number of messages received at the BS over time for DEEP, LEACH-E and EEHC. The results in Fig. 9 shows that the messages delivered to the BS by DEEP are much higher than those of LEACH-E and EEHC. This means that DEEP can offer better performance and is a more efficient protocol in terms of reliability.

Thirdly, we compute the number of messages received at the BS over the energy dissipation. It is clearly illustrated in Fig. 10 that the number of messages received at the BS for DEEP is much greater than those of LEACH-E and EEHC.

Lastly, we calculate the First Node Died (FND) and the Half Node Died (HND) for DEEP, LEACH-E and EEHC and compare them with the results in the literature of DEEC presented by Qing et al. [29]. In fact, half of nodes remain alive until 3000 rounds for DEEP while it is only 4 nodes for DEEC as shown in Table 2.

The results are summarised in Fig. 11. We can clearly state that DEEP is a more efficient protocol and offer better stability and reliability than other protocols.

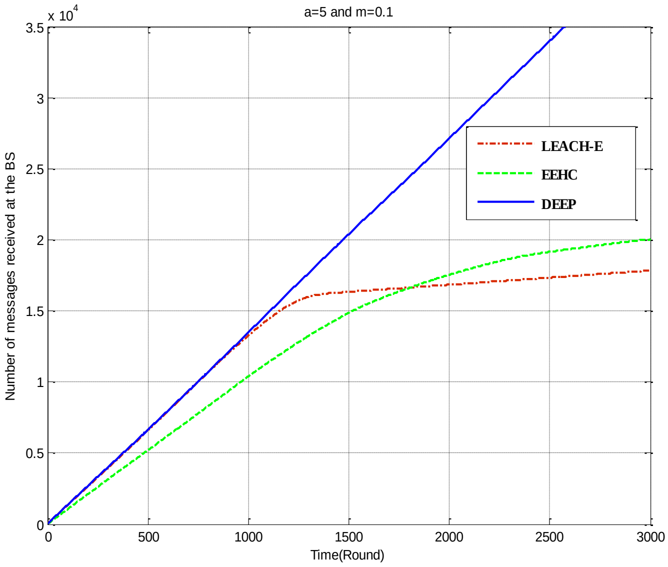

Fig. 9. Number of messages received at the BS.

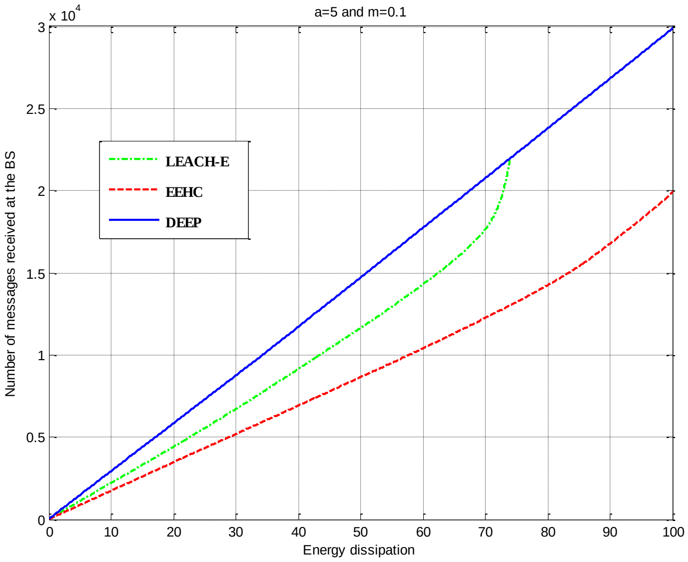

Fig. 10. Number of message received at the BS over energy dissipation.

Table 2. DEEP and LEACH-E in terms of FND, HND and number of nodes alive at 3000 rounds.

	DEEP	DEEC	EEHC	LEACH-E
FND in rounds	1740	1480	938	906
HND in rounds	3000	1730	1490	1140
Nodes Alive at 3000 rounds	50	4	8	1

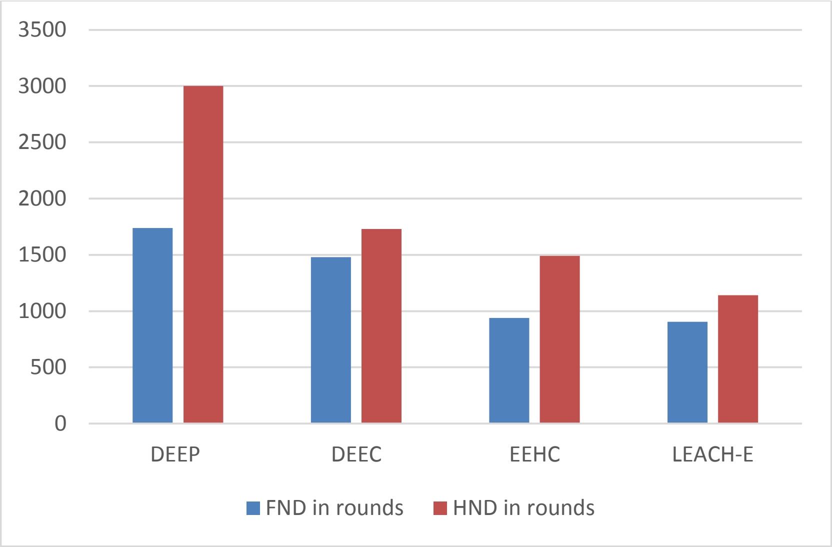

Fig. 11. Comparison of DEEP other routing protocols

5. Conclusion

Most of the existing hierarchical routing protocols aim to maximize the lifetime of wireless sensor networks. In this paper, we propose a Distributed Energy-Efficient and Position-aware (DEEP) protocol for heterogeneous wireless sensor networks. In DEEP, we select the most powerful CH in an optimal position to act as gateway node between the cluster heads and the base station. The simulation results show that DEEP outperforms LEACH-E, EEHC and DEEC in terms of network lifetime and number of message received at the BS. Furthermore, we notice that 50% of nodes remain alive after 3000 rounds in DEEP, which offer more stability and durability. In perspective, we aim to extend our approach by using software defined network paradigm in order to optimise energy consumption and improve network management.

Nomenclatures

d	Distance between sender and receiver, m
d_o	Threshold distance, m
d_{toBS}	Distance to base station, m
d_{toCH}	Distance to cluster head, m
d_{toMCH}	Distance to master cluster head, m
E_{DA}	Energy of data aggregation, nJ/bit/message
E_{elec}	Eenergy dissipated per bit by transmitter, nJ/bit
E_o	Initial energy of sensor nodes, J(Joule)
E_{TX}	Energy dissipated by transmission, J
E_{total}	Total energy of network, J
K_{opt}	Optimal number of cluster heads
k	Number of clusters
L	Number of bits in message
m	Fraction of advanced nodes

N	Number of nodes
R	Total number of rounds
Greek Symbols	
ϵ_{fs}	Free space factor, pJ/bit/m^2
ϵ_{mp}	Multi-patch factor, pJ/bit/m^2

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