The IoT-Distributed Energy Efficient Clustering (IoT-DEEC) Routing Protocol for Wireless Sensor Networks

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ABSTRACT

Wireless Sensor Networks (WSNs) consist of many small devices that have a scarce amount of energy, and an efficient routing protocol is needed to prolong its lifetime. Although most cluster-based related protocols deal with energy heterogeneity, they tend to disregard two important values, the distance between the nodes and the Base Station (BS) and the average inter-node distance. The present paper proposes IoT-DEEC, a hierarchical, multi-radio, multi-channel protocol that tries to overcome these limitations. The selection of Cluster Head (CH) is done on the basis of residual energy, node-to-CH distance, and CH-to-BS distance while a sleep and wake-up mechanism is involved to save energy. Distant node management is a IoT-DEEC feature that implements a threshold energy model. The simulation results indicate that IoT-DEEC drastically enhances the performance of the network compared to TDEEC, with more alive nodes per round, less dead nodes, more packet transmissions to the BS, and less energy consumption.

Keywords-IoT-DEEC;CH; BS; WSNs

I. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of spatially distributed sensor nodes that monitor physical or environmental conditions, such as temperature, vibration, and motion [1, 2]. These nodes relay sensed data to a central Base Station (BS), but due to their limited battery power, energy efficiency remains a primary challenge in WSN design. Cluster-based routing protocols have emerged to address this issue, with protocols such as LEACH and DEEC demonstrating improved scalability and energy distribution [3-6]. In heterogeneous WSNs, where nodes have varying energy levels, protocols like DEEC prioritize nodes with higher residual energy as Cluster Heads (CHs) to prolong network lifetime [8]. Several enhancements of DEEC have been proposed to improve performance in heterogeneous networks. For example, DDEEC introduces adaptive CH selection based on residual energy and average network energy. TDEEC incorporates a threshold function for energy-aware CH selection, while EDEEC introduces three energy levels (normal, advanced, and super) to improve clustering in highly diverse networks [7]. SEP and its variants, such as G-SEP and eTSEP, incorporate probabilistic CH selection based on energy level and occasionally distance [8, 9].

Despite these improvements, many protocols still overlook critical spatial factors, such as the distance between nodes and the BS, or the average inter-node distance, during CH selection. This oversight leads to increased energy consumption in nodes located far from the BS and imbalanced energy depletion across the network.

In this study, we propose IoT-DEEC, a hierarchical, multi-radio, and multi-channel protocol that addresses both residual energy and node distance in CH selection. The protocol integrates a threshold-based energy model [10], a sleep–awake scheduling mechanism, and distance-aware optimization. Simulation results demonstrate that IoT-DEEC significantly improves energy efficiency, throughput, and network lifetime compared to TDEEC.

II. MATERIALS AND METHODS

A. *The Existing DEEC Protocol*

The Distributed Energy-Efficient Clustering (DEEC) protocol [4, 10] is a cluster-based routing protocol introduced to be used in multi-level or two-level energy-heterogeneous WSNs. In two-level heterogeneous networks, the nodes are classified as basic (normal) and high-energy (advanced). CHs are initially probabilistically selected with regard to the available energy of each individual node and the overall network energy. Nodes with relatively high initial and residual energy in each round is preferred by DEEC, and thus low-energy nodes save their energy, and hence the network lifetime and reliability are increased. The hierarchical clustering mechanism deployed by DEEC is designed in the configuration of the node deployment of the WSN. CHs have the role of gathering and relaying data to the BS as well as giving details of the network and the status of node residual energy. It is vital to adequately predict the number of nodes that are functioning within each round to ensure network operation. Nodes in high energy states are more likely to be elected as CHs, and thus more energy can be balanced between nodes in the network.

The control range of higher energy nodes in the network surpasses that of lower energy nodes, affecting the overall network energy distribution. Equation (1) [11-13] calculates a set of expenses $E(r)$, requiring each node to be aware of the total remaining energy in the network. Further details on maximizing this equation will be discussed below.

$$E(r) = \frac{1}{N}\sum_{i=1}^{N} E_i(r) \qquad (1)$$

Noise and interference affecting signals in the environment may lead to errors, making signals less efficient and increasing the network traffic while affecting the service efficiency, mainly due to the limited available bandwidth in the DEEC architecture.

A two-level energy heterogeneous network uses two types of nodes. The CHs are chosen probabilistically taking into consideration the remaining energy with respect to the mean node energy in the network. Equations (2) and (3) [14] present the two classes of nodes in the DEEC protocol:

$$Pi = \frac{Popt\ Ei(r)}{(1+a*m)E(r)} \qquad (2)$$

$$Pi = \frac{Popt\ (1+a)Ei(r)}{(1+a*m)E(r)} \qquad (3)$$

where *Popt* is the value for the average probability *Pi*, *a* is a constant, and *m* is the ratio of nodes considered as advanced. As in the homogeneous networks, all the nodes are initialized with equal initial energy and *Popt* is used as the reference energy for the probability *Pi*. But in the heterogeneous networks, the *Popt* is different and depends on the initial energy of each node. Equation (4) [15] gives the average energy of a network at any round *r*:

$$E(r) = \frac{1}{N} Etotal\ (1 - \frac{r}{R}) \qquad (4)$$

where *R* represents the total rounds of the network lifespan, which is determined by:

$$R = \frac{Etotal}{Eround} \qquad (5)$$

where E_{Total} represents the total energy consumption in the entire network while E_{round} represents the energy consumption in one round. Let us consider a probability p_i that a sensor node (s_i) has to be selected as a CH in a round. In each round, each of the sensor nodes is assigned a random decimal number between 0 and 1. If it is less than the threshold determined according to (6), the node will become the CH [16].

$$T(s_i) = \begin{cases} \dfrac{p_i}{1 - p_i (r \bmod \frac{1}{p_i})} & \text{if } s_i \in G \\ 0 & \text{otherwise} \end{cases} \qquad (6)$$

Procedure G, for CH addressing, considers sensor nodes [3, 17] as CH-capable candidates [18]. Figure 1 portrays a case of remaining node power exploration. However, no matter if the distant nodes (shown in green) are advanced or not, they must switch to the nearby CHs due to the better received signal strength. This mandatory packet-metering creates quite a burden for transmitting stop-over stations. The additional transmission lengths place a considerable strain on the nodes, resulting from the energy losses while transferring end reports to the distant BS unit.

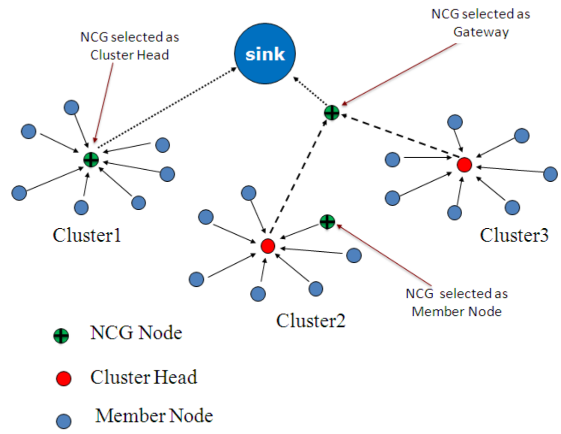

Fig. 1. The DEEC protocol.

B. DEEC Drawbacks

During the implementation of the majority of WSN systems, sensor nodes are placed randomly across the target space. As a result, a number of nodes are near the BS, whereas others are at significantly farther distances. The impact of this variation on energy consumption is very significant and must be put into consideration when choosing CHs. Nevertheless, most works in the DEEC protocol only consider residual energy as the major criterion to select CHs, without taking into consideration the spatial distance to the BS. This causes a number of inefficiencies:

- Increased energy consumption when the distant CHs relay data to the BS.
- Increased delay in data delivery as a result of the prolonged transmission path.
- Increased signal interference or data loss possibility in the course of transmission.
- There is a possibility that some of the nodes might be compelled to relay their information to a distant CH hence wasting energy.

All these factors decrease total throughput and network lifetime. Thus, it is important to include the node distance to the process of CH selection to enhance both energy efficiency and reliability of WSN communications.

Therefore, only the residual energy of the nodes is taken into account. For instance, if distant nodes are chosen as CHs, the other nodes have to transmit their data to these distant CHs only because they have very high RSS. This action significantly decreases the energy in the nodes. The selected CHs, despite their ability to transmit data over long distances, consume a significant amount of energy when sending to the distant BS.

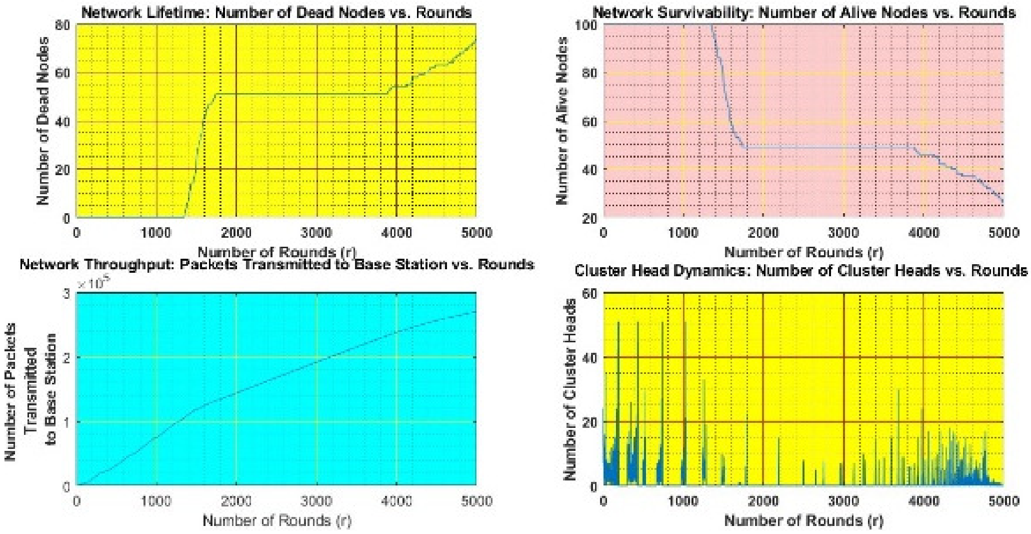

Fig. 2. Simulation result.

III. INTERNET OF THINGS DEEC (IOT-DEEC) PROTOCOL

The DEEC protocol randomly selects one of the nodes in the network to act as the CH for each cycle. Clusters are created based on the advertising message that the selected CHs can pass on to the nodes. In the DEEC algorithm, if a CH is selected in a particular round, it does not change in the subsequent rounds until it exhausts its energy for the entire term, even if it has not a high energy level. To handle such a problem, the proposed IoT-DEEC has a threshold value. If a CH has more energy than the specified threshold it will act as a CH in the next round. This strategy saves energy within the round since the information is passed to the next concerned CH. It also allows controlling the additional amount of energy required for the formation of a new cluster due to the appearance of a new CH. This is done due to the fact that, if the distance between node *N* and the CH is smaller than d_0, the energy consumed during data transmission from *N* to the CH is:

$$E_N^{CH} = D_N^{CH}(E_{ele}) + D_N^{CH}(E_{fs})(d^2) \quad (7)$$

where $d_0 = \frac{4\Pi h_{tr} h_{rc}}{\lambda}$ and h_{tr} and h_{rc} denote the heights of the transmitting and receiving antennas, respectively. When the distance between a node and the CH is $d > d_0$ the energy expended by the CH to transmit data to (S) is:

$$E_N^{CH} = D_N^{CH}(E_{ele}) + D_N^{CH}(E_{amp})(d^4) \quad (8)$$

When $d < d_0$, the energy expended by the CH to transmit data to (*S*) is:

$$E_{CH}^{S} = D_{CH}^{S}(E_{ele}) + E_{DA} + D_N^{S}(E_{fs})(d^2) \quad (9)$$

The total energy consumed by the CH is:

$$E_{T\_CH} = E_{CH} + E_N \quad (10)$$

The average energy consumed by the CH is:

$$E_{av\_CH} = \frac{E_{T\_CH}}{N} \quad (11)$$

So, the saved energy for normal nodes in each round is:

$$E_{S\_N} = E_{ele} + E_{TX} + E_{amp} \quad (12)$$

The saved energy of the CH is:

$$E_{S\_CH} = E_{ele} + E_{DA} + E_{TX} + E_{RX} + E_{amp} \quad (13)$$

The saved energy for the sleeping nodes is:

$$E_{ST} = \sum_{i=0}^{n} Ei \quad (14)$$

The average saved energy for n sleeping nodes is:

$$E_{S\_AV} = \frac{E_{ST}}{n} \quad (15)$$

where Pi: Election probability of node i to become a cluster head, $Popt$: Reference value for the average election probability, a: Constant used in the election probability calculation, m: Proportion of advanced nodes in the network, $Ai(r)$: Residual energy of node i in round r, $A(r)$: Average energy of the network in round r, $E(r)$: Average energy of the network in round r, R: Total number of rounds in the network lifetime, $Etotal$: Total energy of the network, $Eround$: Energy consumed per round, ci: Distance of node i from the base station $cavg$: Average distance of all nodes from the base station, $ERX(k, d)$: Energy consumed by a non-cluster head node to receive k bits of data over a distance d, EAD: Energy consumed for data aggregation, $Eamp$: Energy consumed by the power amplifier, k: Number of bits in the data message, d: Distance between nodes, $d0$: Distance threshold, htr, hrc: Heights of the transmitting and receiving antennas, respectively and λ: Wavelength of the transmitted signal D-DEEC Protocol [10-19].

The IoT-DEEC algorithm follows:

```
- Set BS_position (base station position)
with X and Y coordinates
-> Main Loop (continues until network
lifetime ends)
- Count Alive and Dead Nodes
- Call count_alive_nodes(nodes) to
determine alive_nodes
- Calculate dead_nodes as N - alive_nodes
- Identify Sleep Nodes
- Create an empty list sleep_nodes
- Iterate through each node in nodes:
- If node.energy <= 0:
 - Set node.status = "Dead"
- Else if node.energy <= ETH (energy
threshold):
- Append node to sleep_nodes
- Set node.status = "Sleep"
- Count Packets Sent to Base Station
- Call count_packets_sent(nodes) to get
packets_sent
- Calculate Maximum Distance to Base
Station
- Call calculate_max_distance(nodes,
BS_position) to determine max_distance
- Enter Threshold Energy (ETH) (assumed
already defined)
- Select Cluster Heads
- Create an empty list cluster_heads
- Iterate through each node in nodes:
- If node.status == "Alive" and
node.energy > ETH:
- Append node to cluster_heads
- Set node.status = "ClusterHead"
- Handle Sleep Nodes
- Iterate through each node in
sleep_nodes:
- If node.energy > 0:
- Set node.status = "Normal"
- Else:
- Set node.status = "Dead"
- Cluster Head Operations
- Iterate through each node ch in
cluster_heads:
- Call ch.broadcast_cluster_formation()
- Set ch.power_level = "High"
- Check Cluster Head Energy
- Iterate through each node ch in
cluster_heads:
- If ch.energy <= ETH:
- Handle CH death
- Check for End of Network Lifetime
- If network_lifetime_ended():
- Break the loop (network is dead)
-> End (network loop exits)
```

IV. SIMULATION RESULTS

Performance analysis of TDEEC and the proposed IoT-DEEC on an heterogeneous WSN was carried out in MATLAB R2022b. In the experiment, 100 nodes were randomly scattered over a two-dimensional, 100 m × 100 m area while the BS lies at a distance from the centroid of the network. After deployment, only the source node continued to move. The energy lost due to interference between the signals transmitted by different nodes was not considered. The simulation parameters can be seen in Tables I and II.

TABLE I. SIMULATION PARAMETERS OF IOT- DEEC

Parameter	Description	Value
Xm	Distance at the X-axis	100 m
Xy	Distance at the Y-axis	100 m
-	BS position	50-50
N	Total number of sensor nodes	100
P_{opt}	Probability of CH	0.1
E_t	Total energy of the network	0.5 J
E_{mp}	Energy dissipation: Receiving (multipath loss)	0.0013/pJ/bit/m^4
E_{fs}	Energy dissipation: Free space model loss	10/pJ/bit/m^2
E_{DA}	Energy dissipation: Data Aggregation Energy	5/nJ/bit

TABLE II. SIMULATION PARAMETERS OF T-DEEC

Parameter	Description	Value
E_{elec}	Energy used due to running of radio electronics	5 nJ/bit
E_{fc}	Energy of free space	10 pJ/bit/m2
E_{mp}	Energy of multi path	0.0013 pJ/bit/m4
E_o	Normal energy	0.5 J
Message size, k	Probability of CH	4000 bits
N	Number of nodes	100
P_{opt}	Reference value of average probability	0.1
E_{DA}	Data aggregation cost expended in the cluster heads	5 nJ/bit/message

Figures 3-7 show the implementation results. It can be seen that the proposed IoT-DEEC surpassed TDEEC in every considered metric.

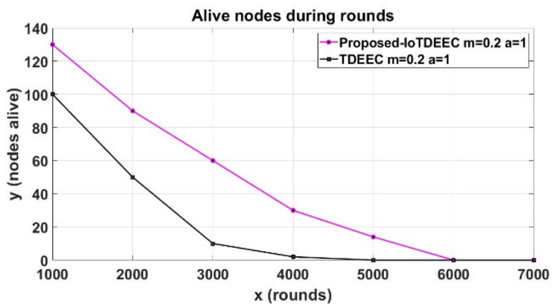

Fig. 3. Number of alive nodes per round.

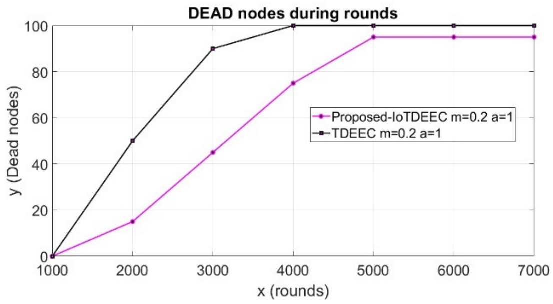

Fig. 4. Number of dead nodes per round.

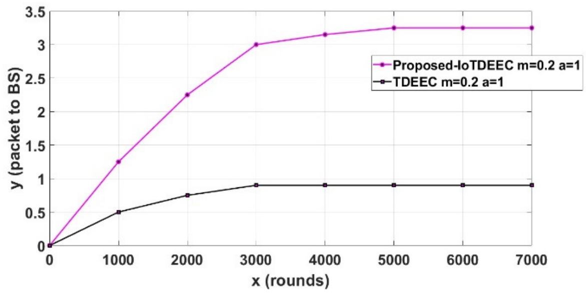

Fig. 5. Packets to the BS.

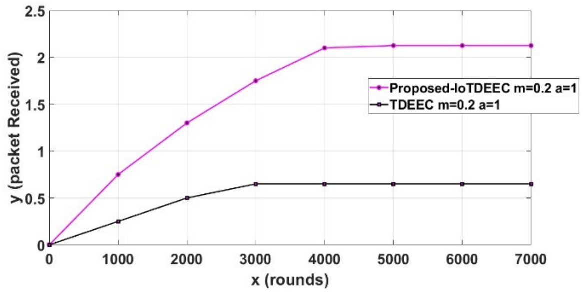

Fig. 6. Packets received by the BS.

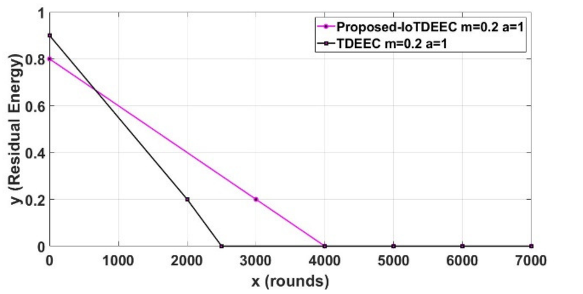

Fig. 7. Residual energy.

V. CONCLUSION

In this paper, IoT-DEEC protocol was presented and its performance was compared with that of the established TDEEC. TDEEC chooses Cluster Heads (CHs) considering the residual energy level and the distance to the Base Station (BS) whereas IoT-DEEC proposes a threshold-based energy model of CH selection. The simulation outcomes show that IoT-DEEC outperformed TDEEC in the considered metrics, i.e. alive nodes per round, dead nodes per round, packets transmitted to the BS, packets received by the BS, and residual node energy. These results show the capability of IoT-DEEC to provide higher efficiency and reliability to Wireless Sensor Networks (WSNs).

Future work can investigate the possibility of incorporating such energy-aware protocols into sensor hardware along with other power-saving mechanisms.

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