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Load Propagation Balancing Strategy for Wireless Sensor Networks

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Abstract: In this paper, we present a simplistic approach for many-to-one energy hole issue in Wireless Sensor Network (WSN) by load factoring sensor nodes. Load factor is a measure of link count i.e. the number of nodes a recipient node receives data from. We consider a strip-like distribution of nodes where leaf nodes have a load factor of zero as they only sense the surroundings while the factor count grows steadily as the data progress towards the root of the tree (base station). We present an "early load sharing" intervention strategy where a node spawns child process (in upward direction towards sink) for load balancing. Under network saturation, the node switches to advanced mode and transmit directly to Base Station/sink (BS) with residual energy. Extensive simulations demonstrate the effectiveness of proposed strategy.

Keywords: advanced mode; load balancing; load factor; load propagation; wireless sensor networks

1 INTRODUCTION

WSNs are networks that are made up of a large number of sensors spread out across a large region in order to collect data about the region of interest. Sensors sense the surrounding, processing the acquired data as per the application, and transfer the processed field information to the centralized base station (BS) [1]. Because sensors are powered by a limited number of battery units, power management becomes a major issue. The larger the strain a sensor must bear and the higher its power consumption, the more messages it must send. In most circumstances, the sensor nodes battery units are not changeable, and the sensors are deemed throwaway after they die. The network may fail prematurely if the load imposed on these sensor nodes is not adequately balanced. To improve network efficiency, solutions must be designed that address the challenges of energy, network longevity, and scalability all at the same time. Scalability, fault tolerance, data aggregation, and energy efficiency are some of the key objectives of clustering, hence it plays a significant role. Clustering saves energy by designating energy-efficient nodes as Cluster Heads (CHs), which collect, consolidate, and transmit data from other nodes. As a CH, an optimal node based on various factors can be chosen, and when the energy of CHs falls below a threshold value [2, 3]. Additionally, the emergence of an energy hole near the sink has been a major concern. In a multi-hop network, data transmission follows a many-to-one pattern, resulting in a higher traffic burden for nodes near the sink. This is due to relaying of additional task of data aggregation and relaying which increases rapidly as the data progresses towards the sink/BS. As a result, these nodes quickly run out of energy, resulting in an energy vacuum and network failure [4, 5]. Many related works have attempted to balance energy consumption using extra nodes/advanced nodes near the sink, but none have succeeded in achieving perfectly balanced energy consumption or avoiding energy hotspots far away from the sink. The following is the summary of the main contributions of the proposed methodology:

- Load factor is an early network-wide indication of all under-utilized nodes in the WSN.
- Second, it serves as an implicit request for not only transferring data load but also the amount of data that should be redirected.
- Third, it also acts as a minimum hop count path for directing the spawned tasks.
- Finally, under network saturation when the load factor of all nodes (in upward region towards sink) has reached its threshold value, nodes switch to advanced power mode and transmit directly to sink.

The rest of the paper is organized as follows: A review of related work in is included in Section 2. The terminologies and energy model used in the proposed algorithm are discussed in Sect. 3. Sect. 4 describes the proposed work. Simulation is carried out in Sect. 5, and Sect. 6 draws a conclusion based on the findings.

2 RELATED WORK

A node deployment approach based on Gaussian node distributions was reported by Halder and Ghosal [6]. The number of sensor nodes was shown to be an effective metric in determining the lifetime of a network. They discovered that the Gaussian distribution could be effective in balancing energy. In corona-based networks, Wei Kuang Lai et al. [7] presented two deployment strategies to maximize network lifetime and achieve load balancing in corona based networks. They discovered that by adhering to a few basic assumptions, nearly balanced load may be obtained. Liu et al in [8] have proposed a model based on super links for off-loading data from overcrowded places to less crowded locations. Determining the optimal position of such nodes is done based on traffic and distance from the sink. Khan et al. [9] have proposed a robust model that takes routing decisions on a hop basis for realizing load balancing. Using a slice-based model, Liu et al. [10] came up with the idea of balancing energy usage in all nodes in the network. The authors used a mixed transmission technique that was divided into two halves (i.e. intra-slice and inter-slice). Their proposed solution could provide certain benefits in terms of load balancing, delay reduction, and lifetime extension. Arya et al. [11] established the necessary circumstances for bandwidth usage that allow for a routing path as well as connection bandwidth evaluation and energy optimization using the ant colony optimization technique. Khabiri et al. in [12] proposed a clustering routing strategy based on the cuckoo algorithm for optimizing CH (cluster head) selection. Significant improvement in network lifetime has been achieved. Li et al. [13] have proposed a method that is based on high energy efficiency called EBCNC (Enhanced-Balanced Compressed Network Coding) in which the amount of data collected is greatly reduced using the data compression technique, while the efficiency of data collection is maintained using the transmission mechanism. Mahdi et al. [14] suggested a routing method for balancing energy in multi-hop networks. Their scheme could boost energy efficiency by improving the quality of the link between the source and the destination. Lipare et al. [15] suggested the idea of energy-efficient routing using one-to-one connection method. With the goal of preventing energy holes, easing heavy traffic, and balancing network load, the multiple layer method was utilized in the routing structure. Smaragdakis et al. [16] have proposed SEP (stable election protocol) to extend the time interval before the first node dies (called as stability period), which is critical for many applications where the sensor network's feedback must be trustworthy. SEP is based on the weighted election probabilities of each node to become cluster head depending on its remaining energy. Qing et al. [17] have proposed distributed energy-efficient clustering algorithm for heterogeneous wireless sensor networks (DEEC) wherein cluster-heads are elected by a probability based on the ratio between residual energy of each node and the average energy of the network. Shah et al. [18] have proposed a novel fuzzy logic clustering routing protocol that handles the rotation of cluster heads (CHs) using fuzzy logic with metrics as residual energy, base station distance and neighbour nodes in a cluster. By utilizing the softmax function for CH election and introducing novel procedures based on graph theory concepts, Osamy et al. [19] have propounded a clustering technique for IoT based wireless sensor networks the algorithm that achieves efficient resource allocation and management. Authors in [20] proposed a routing protocol energy-saving called Bacterial foraging optimization routing protocol (BFORP). It decreases the routing of excessive messages that may result in severe energy waste by recycling the information that frequents the source node into the sink. The preferable node in the sending routes is chosen by prioritizing the lowest traffic load, the highest residual energy, and the shortest path to the sink.

3 ENERGY MODEL

We adopt the radio model as given in [21]. We assume that the radio hardware loses energy in two main ways: first, the transmitter, which powers the power amplifier and radio electronics, and second, the receiver, which also powers the radio electronics. The power loss model for the free space channel and the multipath fading model for the receiver were utilised in the tests detailed here, with the choice made based on the distance between the two devices [22]. To counteract this loss, power control can adjust the power amplifier such that it uses the free space (*fs*) model if the distance is below a certain threshold or the multipath (*mp*) model otherwise. Therefore, in order to send a message that is l bits long over distance d, energy dissipated is given by Eq. (1) and (2).

$$E_{T_x}(l,d) = E_{T_x} - elec(l) + E_{T_x} - mp(ld) = \\ = \begin{Bmatrix} l \cdot E_{elec} + l \cdot \varepsilon_{fs} \cdot d^2 \text{ if } d < d_0 \\ l \ldots E_{elec}^{T_x} + l \cdot \varepsilon_{mp} \cdot d^4 \text{ if } d \geq d_0 \end{Bmatrix} \tag{1}$$

To receive message, radio expends

$$E_{R_x}(l) = E_{R_x} - elec(l) = l \cdot E_{elec} \tag{2}$$

The electronics energy, E_{elec}, depends on factors such as the digital coding, modulation, filtering, and spreading of the signal, whereas the amplifier energy, $\varepsilon_{fs} \cdot d^2$ or $\varepsilon_{mp} \cdot d^4$ depends on the distance to the receiver and the acceptable bit-error rate.

We make following assumptions:

- Sensors are randomly and unevenly deployed in a region as shown in Fig. 1.
- Sensors are homogeneous in nature.
- BS has unlimited battery supply.
- Sensors can directly reach BS at higher power cost.
- Every sensor and BS have knowledge about the topology of the network.

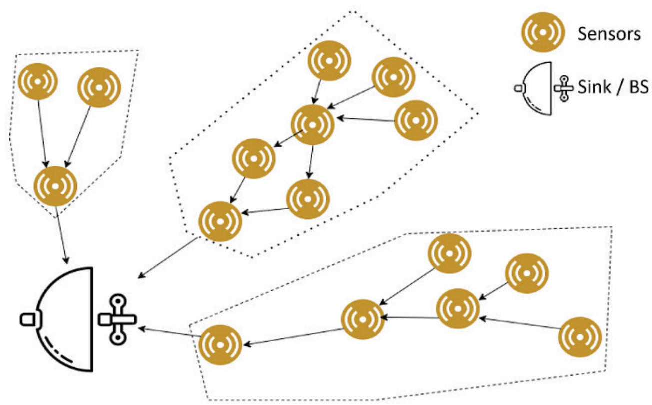

Figure 1 Network model

4 LOAD FACTOR MODEL

The load factor model is a type of localized load balancing in which each sensor only interacts with its neighbours towards the sink direction. Propagation is used to achieve global balancing and the subsequent refinement of local load data. The load balancing is achieved by spawning workload from a node with high load factor towards a low load factor node. Load factor is a measure of link count i.e. the number of nodes a recipient node receives data from.

4.1 Load Propagation

A two-tiered load balancing mechanism is used. The first step is to allow each sensor to determine it load factor. A sensor load status can be defined using fuzzy values light, average, or heavy over time depending on their load factor. In common parlance, if a sensor is light, it wishes to be loaded more. It wants to get rid of some of its current burden if it is heavy. It is average if neither of these conditions are met.

Definition: The length of the shortest path between two sensors m and n in a wireless sensor network is referred to as d and the maximum distance between any two nodes of the network N is called its range.

$$range(N) = \max\{d_{m,n}\, for\ all\ m, n\ \varepsilon\ N\}$$

Definition: If the node is lightly loaded, then its state is open. It is otherwise closed.

$\boldsymbol{if}\ Sensor = Light$ ***THEN***
$STATE = 1(OPEN)$ ***ELSE***
$STATE = w_{\max}$ (OFF) ***WHERE***
$w_{\max} = range(N) + 1$

A sensor with light load factor allows the influx of fresh workloads. The second stage is to create a system-wide load factor propagation to make task migrations easier. Load factor propagation is represented by set of all *affinities.*

Definition: The least distance between a sensor i and a light loaded node in the system (in upstream region towards sink) is the defined as *affinity* w_i. If a system has no light nodes, w_i is equal to $w_{\max}$. This implies that

$w_i = \min\ \{ d_{m,n}\ over\ k\ where\ STATE_k = 1\}$
$\boldsymbol{if}\ \ a\ light\ node\ exists\ towards\ sink$
$\boldsymbol{else}$
$w_i = w_{max}\ \ if\ no\ light\ node\ exists\ in\ the\ network$

The affinity of a lightly loaded node is zero. The affinity of average or heavy sensor node is computed by adding one to the minimum affinity of neighbors. A system with no light nodes can be compared to one having a light node at a distance greater than the network's range.

Definition: A network's load propagation (LP) is the collection of all sensors affinities defined as:

$$LP = [w_1, w_2\ \dots \dots w_n]$$

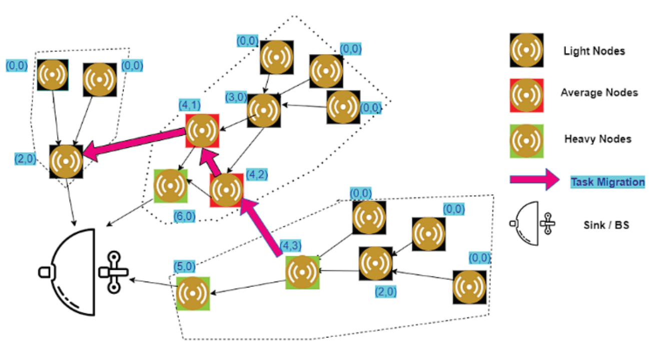

Figure 2 Load propagation model

Fig. 2 shows a WSN with BS at the corner along with load factor (*lf*) and the affinity (a) of each node as shown as (*lf* , a). Affinity values comprise the load propagation.

The load propagation has several characteristics. First, it is a network-wide indicator of all underutilized sensor nodes. Second, it contains an implicit work load request. Third, it directs unprocessed jobs using a minimum distance hops. However, knowing all affinities is a key requirement to formulate the load propagation model.

A load migration method will continue until one of the following requirements is met: The task arrives at the light node, or other tasks arrive at the light node and change sensor state to OFF. A new load propagation is reshaped if there is another underutilized node in the system. The task is then redirected to the new light sensor closest to it.

4.2 Saturation

There is no need to balance the load when all sensors are heavily loaded. During this time, any load balancing activities will just add to the system's overhead and impair performance.

Definition: If none of the sensors are lightly loaded the system is saturated. In other words, if all affinities are equal to $w_{\max}$, the system is saturated.

When the network is saturated, any task movement is futile as it will further drain the nodes and cause energy hole issues. Under such scenario, nodes switch to advanced mode and transmit directly to BS with their leftover energy. When node death occurs due to any reason, its neighbors can set the affinity of the dead sensor to $w_{\max}$, which prevents fresh jobs from being moved to the node.

4.3 Algorithm

Based on the load propagation model, a distributed and asynchronous load balancing mechanism can be designed for each node as:

$\boldsymbol{LOOP}\ Sensor\ i\ determines\ its\ loading\ state$
$(Light, Average\ or\ Heavy)\ as\ per\ its\ load\ factor$
$\boldsymbol{CASE\ Load\ State} =$
$\boldsymbol{light}$:
$Set\ \ affinity\, w_i = 0$
$Ignore\ load\ \ information\, from$ *neighbors*
$\boldsymbol{Average}$:
$w_i\ = 1 + \min\{w_j\} for\ all\ neighbors\ j$
$if\ w_i >\ w_{\max}\ then\ w_i =\ w_{\max}$
$(\boldsymbol{Saturation}\ )\ Node\ i\ switches\ to\ advanced\ mode\ and$
$transmit\ directly\ to\ BS$
with $residual\ energy$
$\boldsymbol{Heavy}$:
$w_i\ = 1 + min\{w_j\}\ for\ all\ neighbors\ j$
$if\ w_i >\ w_{\max}\ then\ w_i =\ w_{\max}$
$(\boldsymbol{Saturation}\ )\ Node\ i\ switches\ to\ advanced\ mode\ and$
$transmit\ directly\ to\ BS$ with $residual\ energy$
$ELSE\ if\ \min\{w_j\} <\ w_i\ \boldsymbol{THEN}$
$Perform\ task\ migration\ to\ node\ j\ where\ w_j\ is\ minimum$
$\boldsymbol{END\ CASE}$
$Broadcast\ w_i$
$to\ all\ neighbors\ if\ modified\ since\ last\ update$
$\boldsymbol{END\ LOOP}$

5 PERFORMANCE EVALUATION

The simulations are performed for a network scenario with 100 sensor nodes randomly distributed over 100 × 100 m^2 area. Comparative analysis of the proposed model is carried out with SEP, DEEC, Fuzzy model as proposed in [18] protocols considering uneven node distribution. Residual energy threshold are set as ≤ 30 % (light), ≤ 50 % (average) and up to 70 % (heavy) of the initial energy. Detailed parameters of simulation are listed in Tab. 1.

Table 1 Simulation parameters

Parameter	Value
Area Size	100 × 100 m^2
No of sensor nodes	100
Initial Energy	1J
E_{elec}	50 nJ/bit
Data Packet Size	400 bytes
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4

The performance of all algorithms has been evaluated by considering following metrics.

5.1 Number of Alive Nodes

Fig. 3 shows the comparison of DEEC, SEP, Fuzzy and proposed algorithm in terms of number of alive nodes. Proposed model performs better as the rounds increase than its counterparts. Fuzzy version initially performs better but as the network progresses it can be seen that proposed algorithm has a better network longevity. This shows that task migration has a positive impact on node balancing load, and that some of the data traffic owned by heavy-burden nodes is shifted to nodes with lower data traffic.

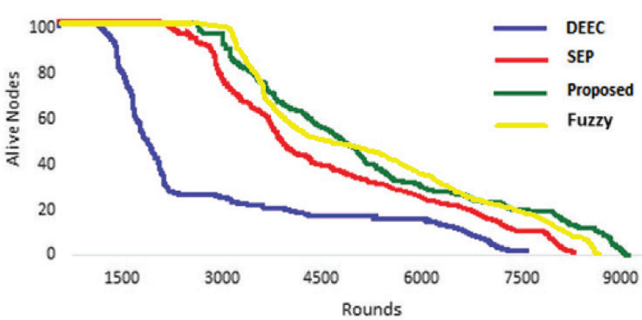

Figure 3 Number of alive nodes

5.2 Number of Dead Nodes

The proposed model has a better dead node ratio as compared to DEEC, SEP as shown in Fig. 4 owing to the fact that it's an early intervention strategy that spawns task migration as the load reaches the threshold value thereby relieving the heavily loaded nodes and increasing its lifetime. In comparison to fuzzy version, both algorithms perform good in patches with proposed slightly having a better node death ratio in the end.

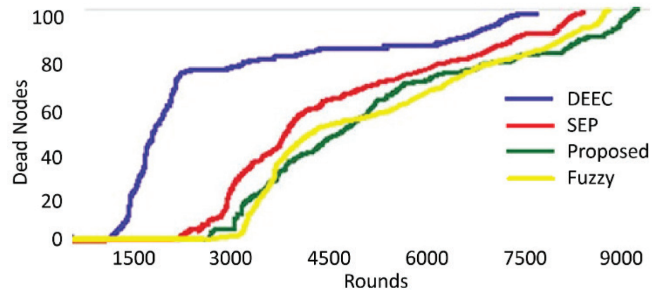

Figure 4 Number of dead nodes

5.3 Throughput

Fig. 5 compares these algorithms in terms of throughput, that is the total number of packets delivered to sink. The proposed model outperforms the other two algorithms (DEEC and SEP) as it's a active strategy rather than a late remedy approach and also owing to the fact that each node transmits directly to BS with leftover residual energy rather than transmitting on a hop by hop basis wherein packet loss due to energy hole issues in upstream region would take place. Comparing to fuzzy version, it performs better towards the end.

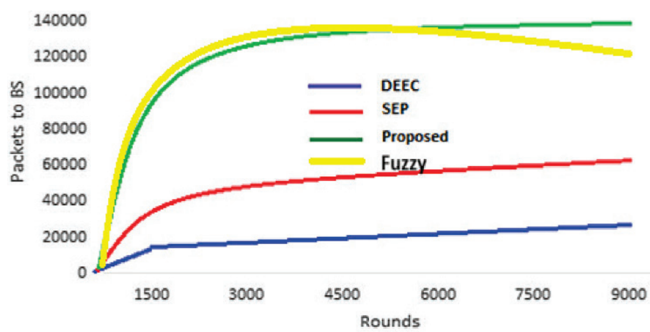

Figure 5 Throughput

5.4 First Node Death (FND), Half Node Death (HND) and Last Node Death (LND)

These statistics calculate the number of rounds until the network's first, half and last node dies. FND, HND is an indicator of overall network stability. LND is a measure of network lifetime. Fig. 6 draws the analysis. It can be seen that the suggested algorithm performs better overall.

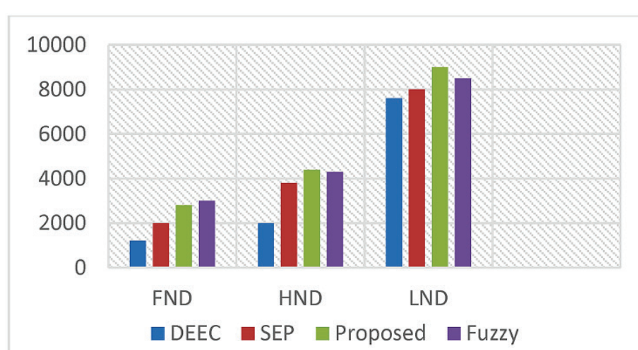

Figure 6 FND, HND and LND analysis

Finally, we summarize the advantages and disadvantages of our work as under:

- This early intervention strategy triggers task migration when the load reaches a threshold value, alleviating heavily loaded nodes and extending their lifespan.
- It is an active strategy instead of a late remedy approach, and because each node transmits directly to BS with leftover residual energy instead of transmitting hop by hop, this mitigates packet loss due to energy hole issues that may occur in the upstream region.
- The proposed model will suffer overhead when it comes to mobile wireless sensor networks wherein constantly changing network topology will affect the process of finding the best route and thereby the task migration scheduling.

6 CONCLUSION

In this paper, distributed load balancing system is proposed. The methodology is built on a demand-driven principle, in which underutilized nodes dynamically initiate load balancing requests. As a result of these requests, a system-wide load propagation model is created. Task migration takes place from overloaded sensors towards lightly loaded ones.

A global balance state is computed by approximating multiple localized balances in a series of steps. When the system is completely occupied, the idea of saturation is introduced to discourage pointless load migration whereby the node switched to advanced mode and transmit directly to BS with leftover residual energy. It is a proactive strategy which is more pragmatic in large scale WSNs. The efficacy of our model is mirrored through metrics viz. dead nodes, alive nodes and throughput.

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