IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

SPECIAL SECTION ON GREEN COMMUNICATIONS ON WIRELESS NETWORKS

Received November 22, 2019, accepted December 27, 2019, date of publication January 9, 2020, date of current version January 21, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2965206

Heterogeneous Energy and Traffic Aware Sleep-Awake Cluster-Based Routing Protocol for Wireless Sensor Network

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This work is supported by University of Malaya IIRG Grant (IIRG003A-19IISSN), Ministry of Education FRGS and LRGS Grant [FP055-2019A, LR003-2019 (LRGS MRUN/F2/01/2019/001)].

ABSTRACT Sensor nodes heterogeneity if not properly utilized could lead to uneven energy consumption and load imbalanced across the network, which degrades the performance of the network. Routing algorithms should try to achieve energy-efficiency and load-balancing among the heterogeneous nodes to prolong network lifetime. One of the solutions is by using duty-cycling in cluster-based routing such as in Sleep-awake Energy Efficient Distributed (SEED) clustering algorithm to minimize redundant transmission to achieve energy efficiency. However, this scheme suffers from idle listening problem, which lead to energy wastage across the network. Moreover, SEED cannot cope with an environment with sensor nodes with heterogeneous traffic rate. To cope with energy and traffic heterogeneity issues among sensor nodes, a traffic and energy aware routing protocol (TEAR) is proposed. TEAR avoids selecting node with low energy and high traffic rate for cluster head role to achieve load balancing. However, TEAR does not avoid redundant transmission from the sensor nodes that are in close distances. In this paper, we proposed a hybrid method called energy and traffic aware sleep-awake (ETASA) mechanism to improve energy efficiency and enhanced load balancing in heterogeneous wireless sensor network scenario. Unlike prior methods, in ETASA, the paired nodes alternate into sleep and awake mode based on node's energy and traffic rate. Moreover, we revised the conventional TDMA scheduling in SEED by allocating one slot for group of pairs in a cluster. This is done to address idle listening problem to minimize energy consumption. The proposed method improves the cluster head selection technique that selects high energy, low traffic and nodes with high number of pairs to improve balanced energy consumption. The proposed approach is evaluated and compared against the state-of-the-art baseline protocols. The result shows that the proposed ETASA has 16% and 15% lifetime improvements against TEAR and SEED.

INDEX TERMS Energy-efficient, heterogeneous traffic, node pairing, routing protocol, sleep-awake, wireless sensor network.

I. INTRODUCTION

With the emergence of Internet of Things (IoT), interoperability among heterogeneous devices to achieve common objectives has become feasible. Wireless sensor networks (WSNs) is an important component of IoT spheres where interoperability among various heterogeneous elements is expected [1]. Node heterogeneity in WSNs can be expressed in terms of energy (energy level), computation (traffic), link connectivity, and other heterogeneities such as mobility scenarios and so on [2]. Wireless Sensor Network (WSN) is a network comprising of huge number of tiny nodes called sensor nodes. These sensor nodes collaborate together in sensing, processing and communication.

The associate editor coordinating the review of this manuscript and approving it for publication was Giovanni Pau.

As the sensors in WSN are getting better and more complex due to the recent advancement in microelectromechanical systems technology, makes it promising to implement them for sophisticated applications [3]. The sensor nodes are usually equipped with multimedia devices such as cameras that are capable of retrieving videos, images and audio streams [4], [5]. The multimedia data has excessive quality-of-service (QoS) requirements, whereas the sensor nodes in WSN are attributed with limited memory, low processing capacity, limited power and transmission bandwidth [2], [6]. Therefore, achieving the strict QoS demand of multimedia data translates to high energy consumption [7]. However, if the sensor nodes die quickly, all the desired QoS and other network performance will not be achieved. Thus, a cost-effective mechanism is needed to achieve the reasonable network duration, which lead to the realization of the desired QoS. WSN has numerous potential applications which include, battlefield surveillance, real-time water channel monitoring, target tracking, environmental monitoring, agricultural monitoring, inventory control, health monitoring, and ecological control [8], [9].

At the time of WSNs operation, the battery power of the sensor node is reduced proportionate to the amount of data it transmits [10]. This shows that communication activities consume large share of node's energy. Therefore, as the routing algorithms are connected with the communication activities among the sensor nodes, an effective data routing is needed to prolong the lifetime of WSNs. However, most of the early research work on routing protocol for WSN considered deployment of sensor nodes with homogeneous data rate. In practical settings, the sensor nodes in WSN are heterogeneous in their energy and data rate [11]. These heterogeneities among the sensor nodes if not properly utilized could lead to uneven energy consumption and load imbalanced across the network, which degrade the network performance.

Routing algorithms should try to achieve energy-efficiency and load-balancing among the heterogeneous sensor nodes to prolong the lifetime of the network. There are existing efforts to achieve energy efficiency in routing. One of the solutions is by employing duty-cycling in cluster-based routing to minimize redundant transmission in order to achieve energy efficiency. The Sleep-awake Energy Efficient Distributed (SEED) algorithm [12] is one of the state of the art routing scheme that utilizes duty-cycling to minimize redundant transmission from the sensor nodes that are in close proximity to achieve energy efficiency. However, SEED and other related routing schemes suffer from idle listening problem, which lead to unnecessary energy consumption across the network. The idle listening is the duration of time when sensor node's radio transceiver is active but no data is transmitted or received by sensor node [13]. The SEED algorithm uses conventional time division multiple access (TDMA) scheduling among cluster members (CMs), which leads to idle listening problem in the network [12]. With the conventional TDMA, each cluster member is allocated one slot. Therefore, the sensor node must be awaked and turn its radio "on" during its scheduled time slot even if the node has no data to report to cluster head (CH). Therefore, the node operates in idle state which consumes significant amount of energy. Likewise, the current CH operates in the idle state during this idle time slots and waste energy. Moreover, SEED cannot cope with an environment with sensor nodes with heterogeneous data rate [11]. In SEED, paired node alternate into sleep and awake mode in round-robin fashion without considering traffic heterogeneity among the sensor nodes. Accordingly, the sensor nodes with high data rate dissipates more energy in comparison to sensor nodes with low data transmission rate as such will die quickly [1]. Therefore, it is possible in SEED that the next node to be awaked do not have sufficient energy to transmit data at a given round.

To cope with traffic heterogeneity problems among sensor nodes, a Traffic and Energy Aware Routing (TEAR) protocol is presented in [1]. TEAR considered sensor nodes with multiple random levels energy and traffic heterogeneities. TEAR avoids selecting node with low energy and high traffic rate for CH role. However, TEAR do not avoid redundant transmission from the sensor nodes that are in close distances [14]. Moreover, TEAR do not provide necessary energy conservation mechanism that conserves and minimizes the fast energy consumption of high traffic nodes. In dense WSNs deployments, the problem of data redundancy may arise. This is owing to the fact that the sensor nodes located in close proximity captured the same data and forward it to the base station [15]. In spite of the data aggregation mechanism provided at the CH in TEAR, this redundant data will result in unnecessary data transmission and collision that degrade the performance of the network [16].

Inspired by the above observations, we proposed a hybrid method called energy and traffic aware sleep-awake (ETASA) mechanism to improve energy efficiency and enhance load balancing in heterogeneous WSN scenario. ETASA employed pairing approach in which sensor nodes of close proximity are group together for data transmission. Contrary to prior methods, in ETASA, the paired nodes alternate into sleep and awake mode based on node's energy and traffic rate to enhance energy efficiency and load balancing. We revise the conventional TDMA scheduling to reduce length of idle operation of the CMs and CH to minimize the energy consumption by allocating one slot for a group of pairs. To ensure the reliability of our proposed approach, we compare our method with SEED and TEAR routing protocols.

The main contribution of this paper is summarized as follows:

- We proposed a hybrid mechanism for energy efficiency and load balancing in heterogeneous WSN
- We improve CH selection in which the node with high energy, low traffic and higher number of pairs has greater advantage of being selected as CH. This CH selection approach enhances load balancing.

- We extend the conventional TDMA scheduling by allocating one slot to a group of pairs to minimize the number of allocated slot to reduce idle listening in the network to minimize energy consumption.
- Comparison of the performance of our approach using existing state-of-the-art baseline routing protocols.

The rest of the paper is organized as follows. Section 2 presents the review of the related work. In Section 3 network model and assumptions are outlined. Section 4 discusses the proposed approach. In section 5, the simulation setting is defined while section 6 is the performance evaluation. Section 7 contains the conclusion of the paper.

II. RELATED WORK

As described in the prior section, this section describes the review of the relevant literature on cluster-based routing process. Clustering has been adopted as the most common and efficient approach for enhancing WSN lifetime and management [17], [18]. As appropriate clustering minimizes unnecessary exchange of messages among sensor nodes, which lead to prolong network lifetime. In clustering, as shown in Figure 1, the sensor nodes are joined together to form non-interfering subsets known as clusters. The nodes within each cluster are referred to as cluster members (CMs). The CMs capture the data about the area of interest. The member nodes of each cluster have localized interactions. In each cluster, a leader node called cluster head (CH) is selected. The selected CH is responsible for data collection from CMs, performing data aggregation on the data and forwarding the aggregated data to the BS. Clustering promotes efficient resources utilization such as energy and bandwidth by letting them to be used simultaneous by non-overlapping clusters. Moreover, clustering localizes network topology maintenance and thus cut down topology maintenance overhead. With cluster-based approach, the CMs are only concerned with connection to their respective CHs. Therefore, would not be influenced by the changes at inter-CH level [19]. Additionally, the CHs can device an improved management strategies to avoid redundancy in coverage, prevent medium access collision and decreases the number of relayed packets [20].

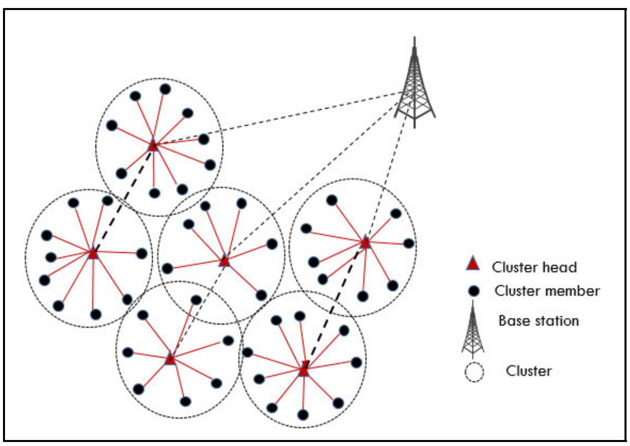

FIGURE 1. **Clustering process.**

The most widely known earliest cluster-based routing protocol for WSN is LEACH [21]. LEACH is a periodic round-based clustering algorithm in which each round in LEACH is separated into two phases, i.e cluster formation and data transmission. During cluster formation phase, a CH is randomly but rotationally selected among the network nodes based on probability. To form clusters in LEACH, each node generates a random number between zero and one. If the number generated by the sensor node is less than the predefined threshold value, the node broadcast its decision to become CH to other nodes within its transmission range. On receiving the broadcast message by the other nodes, each sensor node sends a request message to join its closest CH based on received signal strength indicator (RSSI). During data transmission phase, the CH collects the sensed data from its CMs, performs data aggregation and forward aggregated data to the sink directly. Consequently, the CH dissipates more energy compared to its member nodes, as such die quickly if allow to remain for the rest data transmission rounds. This problem is handled in LEACH by randomize replacement of CH in order to save the battery of individual node. LEACH has numerous advantages which include, employing clustering strategy that reduces communication between the network nodes and the base stattion (BS), which saves network energy consumption. The CH in LEACH eliminates data redundancy locally by means of data aggregation techniques which save considerable amount of network energy. Furthermore, the CH allocates time slot to cluster members using TDMA schedules. This lets the cluster members to be into sleep mode which avoids intra cluster collision and prolong the network lifespan. The randomized rotation of CH by the LEACH protocol enhances load balancing and improve network lifetime. However, despite the aforementioned benefits of LEACH protocol, it has numerous drawbacks. Firstly, in LEACH, the sensor nodes have equal chance to become CH without considering the energy level of each node. If the node with a smaller amount energy is chosen for CH role, it dies quickly. This degrades network performance. Secondly, since LEACH uses randomized formation of cluster, the CH position, number of clusters and cluster density cannot be guaranteed. This leads to uneven energy consumption. Finally, LEACH uses single hop to communicate directly between CH and the BS. The CHs that are at long distance from the BS dissipate more energy in comparison to CHs which are close to BS. This leads to unequal energy consumption which shortens the lifetime of the network.

Apart from LEACH another popular clustering algorithm for Ad-hoc sensor networks called Hybrid, Energy-Efficient, Distributed (HEED) clustering approach is proposed in [22]. In HEED, node residual energy and neighbor's proximity or degree are the two key parameters considered for CH selection. HEED uses multi-hop for data transmission to BS. One of the improvements in HEED over LEACH is the reduction of intra-cluster and inter-cluster communication cost. Panag & Dhillon proposed a dual static CH selection approach in [23]. According to Panag & Dhillon, the network is divided into static cluster of equal sizes. Two CHs are selected for each cluster in every communication round. One of the CHs is used for data aggregation while the other is used for data transmission. The CHs selection criteria in this approach is based on node's residual energy and distance from other members of cluster and from the sink. A node with smaller average distance from the other nodes within the cluster has the high chance of being selected as aggregation CH, while a node with shorter distance from the sink will be selected as transmission CH. However, selecting two CHs in every communication round can lead to significant overhead in the network due to number of messages exchange during CHs selection process. In order to minimize overhead energy consumption in clustering, a reservation based CH selection is proposed in [24]. In this approach each node is allocated the time of being a CH to eliminates the need to send messages competing for CH selection among the network nodes. During the initial round, the CHs are selected following LEACH based approach. In reservation phase, each node determines the round it will act as CH and form a reservation matrix with one row and R column. Then, each node assigns 1 to entries corresponding to the rounds when it will act as CH and 0 entries identifying when it will act as normal node. After reservation phase ends, each node sends it reservation matrix to all other nodes. Based on this matrix, a comprehensive matrix called total matrix is formed. The total matrix shows which node will become CH in each round R and this matrix is available to all other nodes. Despite the reduction in messages overhead by this approach, it is still presumed to be not energy efficient since an important CH selection criteria are ignored. These include, residual energy, node density, etc., and only suitable for small scale network as it requires significant amount of memory space for storing total matrix in each node. Moreover, minimizing redundant data sensing and transmission among the network nodes is not considered.

Even though the above approaches have shown significant improvement in the network performance, they did not eliminate redundant data transmission from the sensor nodes that are in close proximity in a densely deployed WSNs. This issue is addressed in [25] by proposing an Energy Efficient Sleep Awake Aware (EESAA) protocol. EESAA introduced the concept of characteristic pairing among sensor nodes. The sensor nodes within the minimum distance between them and sending redundant data become pairs for environment sensing and communication. The pair nodes alternate between "Sleep" and "Awake" mode after every single data transmission interval. Even though this approach has improved the network lifetime, nodes switching between sleep and awake after every communication round will increase network energy consumption due to energy spend on recurrent ON and OFF of sensor nodes radios. Also, there is no consideration of energy of the nodes during sleep and awake alternation among the pair nodes, so it is possible that the next node to be awaked do not have sufficient energy to transmit data at a given round. Moreover, this approach used conventional TDMA to allocate time slot to each CM to send data to CHs. This will increase delay and energy consumption due to idle listening since each CM will have to wake up during its allocated time slot even if the node has no data to pass to CH. EESAA is designed with the assumption that the sensor nodes possess homogeneous energy and traffic rate.

With respect to real life applications, WSN with heterogeneous nodes is more suitable compared to its homogeneous counterpart since the network nodes may differ in term of their functionality in the network due to variation in their configurations, capabilities and/or behaviors [26]. Node's resources heterogeneity is categorized into computational heterogeneity, link heterogeneity and energy heterogeneity [26]. The earlier attempt to study about node heterogeneity is Stable Election Protocol (SEP) [27]. Energy heterogeneity is considered in SEP by assigning more energy to certain percentage of nodes than the other nodes. The percentage of nodes with high energy are called advanced nodes while the remaining nodes are called normal nodes. The probability of CH election in SEP is weighted based on node's initial energy relative to other nodes in the network. With this scheme, the high energy node has more chance to be elected as CH than normal node. SEP significantly improve the lifetime of the network compared to LEACH. However, the major drawback with SEP is that, the high energy nodes are penalized due to high frequency of reselection as CHs without considering their current energy at a given round and only two-level energy heterogeneity is considered in SEP, which make not suitable for multi-level energy scenario. Qing et al., [28] proposed a multilevel energy heterogeneity routing protocol known as Distributed Energy-Efficient Clustering (DEEC). In DEEC the criteria for CH election is based on probabilities defined by node's initial energy, residual energy and average energy of the network. The rotation epoch of each node is directly correlated to its initial and residual energy. The chances of nodes being selected for CH role in DEEC is high for those nodes with high initial and residual energy compared to low energy nodes. In another approach, three levels energy heterogeneity is considered in [29]. In this protocol, the CH election of each node is obtained by using weighted probability in terms of residual energy in each node. Parvati [30] proposed a Sleep-Awake-Aware (SAA) routing protocol for heterogeneous sensor network. In SAA protocol certain percentage of nodes are equip with extra energy compared to normal nodes. Each node in SAA computes its position, type and identity with the help of GPS and communicate this information to BS. The BS uses the information received from sensor nodes to select CHs based on node's initial energy, distance from BS and density. Nodes of the same application type and located at short distance are paired by BS. Then, the BS forward the pairing information to CHs, which will in turn broadcast it to other nodes in the network. The pair nodes alternate between sleep and awake mode after every one communication round interval. The main drawback with SAA is that the energy of the nodes during sleep and awake alternation among the pair nodes is not considered and the use of conventional TDMA among the paired groups will increase latency and energy consumption.

Similarly in [12], SEED clustering algorithm that employed sleep-awake mechanism is proposed. In this approach two or more nodes of the same application and within the same transmission range of each other, are grouped to form sub-clusters. In a sub-cluster (paired group), only one sensor node wakes up and sense the surrounding and forward its sensed data to CH while remaining nodes stay in sleep mode to save battery power. The limitation of this approach is that, no consideration of energy of the nodes within the sub-cluster during sleep and awake alternation. Also SEED did not consider traffic heterogeneity among the sensor nodes during sleep and awake alternation, which makes it not suitable for WSNs with traffic heterogeneous sensor nodes. Moreover, SEED also uses conventional TDMA among the paired groups, which will increase energy consumption. However, the effect of energy heterogeneity has been demonstrated over the years [26], [31]–[34] but little attention has been paid to traffic heterogeneities. Some of the few researches that discuss about traffic heterogeneities are explain in the subsequent paragraph.

The effect of traffic heterogeneity in homogeneous scenario in hierarchically clustered routing protocol (LEACH) is analyzed by Sharma et al. [35]. A new CH selection approach which considers traffic heterogeneity in LEACH is presented. Similarly, Sharma et al. analyzed the effect of traffic and energy heterogeneity using SEP as baseline algorithm in [11]. In this analysis, instead of two level energy heterogeneity in the original SEP, [11] test SEP by using two-level traffic heterogeneous nodes, normal nodes with normal traffic and advanced nodes with high traffic in a similar manner to two-level energy heterogeneity in SEP. The result shows that the performance of SEP degrades significantly with increase in traffic load. Sharma et al. [11] proposed an improved CH selection method, which shows significant improvement under different heterogeneous scenario. However, selection of appropriate CH alone cannot mitigate the effect of traffic heterogeneity since high traffic node will keep on generating more data, which could result in early depletion of its energy. Moreover, this protocol is designed for two-level traffic heterogeneous sensor nodes, which makes it not suitable for WSN with multilevel heterogeneous sensor nodes. To address this issue, a multi-level traffic and energy heterogeneous sensor network is designed in [1] called TEAR protocol. It follows that, in TEAR multi-level disparities among the sensor nodes in terms of their energy and in the data generation rate (multi-level heterogeneity) is considered. The CH election probability in TEAR is based on node's energy (initial and residual), traffic load and the average energy of the round. The rationale behind TEAR protocol is to avoid selecting nodes with high traffic and low energy while at the same time ensuring selection of high energy nodes with low traffic rate for CH role. The node with low energy and high traffic tends to die faster due to high data rate compared to high energy node with low traffic rate. The TEAR approach is useful for modeling the realistic WSN. However, it does not provide necessary energy conservation mechanism that conserves and minimizes the fast energy consumption of high traffic nodes such as minimizing redundant data transmission among others.

In order to reduce the energy consumption of high traffic node another routing protocol for traffic heterogeneous network known as Distributed Efficient Fuzzy Logic (DEFL) based routing is proposed in [36]. The DEFL protocol considered nodes to be heterogeneous possessing variable traffic loads. This algorithm followed shortest path routing approach with least cost. The main objective of this approach is to avoid selection of path with high traffic load. The input to the fuzzy in DEFL includes, traffic rate, transmission energy and node remaining energy. This approach increases the lifetime of the network by not burden the high traffic nodes with message relaying task. The drawback with this approach is that the node close to the vicinity of the monitored event will continue to suffer due to high traffic rate. Apart from that, this approach employed flat routing which increases communication complexity in the network thereby degrading the network performance. Table 3 (see **appendix**) summarizes existing related works.

Several routing protocols that are designed to achieved energy efficiency and load balancing in WSN scenario were reviewed. Different approaches were employed by these routing protocols, including, avoiding redundant transmission, efficient selection of CHs, minimizing cluster formation overhead, minimizing intra and inter-cluster communication cost, cluster head rotation, efficient utilization of heterogeneity among the sensor nodes and so on. However, in all these researches the energy-efficiency and load-balancing still remain challenging issues due to idle listening problem and poor load balancing among traffic heterogeneous sensor nodes. The novelty in this research is our ability to minimize idle listening problem and ensure load-balancing among traffic and energy heterogeneous sensor nodes. Meanwhile, in all these reviewed protocols, the SEED algorithm and TEAR protocol were chosen to measure the reliability of our proposed ETASA protocol. The SEED protocol was chosen owing to its common energy heterogeneity consideration and the use of pairing approach with duty-cycling to minimize redundant transmission from the sensor nodes that are in close distances to achieve energy-efficiency. The TEAR protocol is also chosen due to common multilevel energy and traffic heterogeneity consideration with our proposed approach to achieve load balancing.

III. PROPOSED APPROACH

To minimize redundant transmission and enhanced load balancing, our research considers a WSNs with densily deployed sensor nodes. The sensor nodes deployed in the network area are application based. Consequently, the data forwarded by the sensor nodes of the same application within short distances is highly correlated which lead to redundant sensing. This redundant data will result in unnecessary data transmission that degrade the performance of the network. This paper considers sensor nodes with heterogeneous energy and data rate with multiple random levels similar to TEAR. This means that the amount of data transmitted by the sensor is based on node's data rate. Therefore, the sensor node reports data with different transmission rate. The sensor nodes with high data rate tend to have increase in number of messages reported per round compared to sensor nodes with low data rate. This leads to uneven energy dissipation in the network. To address this issue, the proposed ETASA utilized the concept of pairing whereby two or more sensor nodes of close proximity and of the same application will become pairs for data sensing and transmission. The paired nodes alternate between sleep and awake mode based on energy and traffic rate criteria. The sleep-awake operation in ETESA works in two fold. At the beginning of the network operation, the paired nodes alternate between sleep and awake mode based on round-robin rotation similar to SEED. After one round of data transmission for each node among the paired nodes in the network, the sensor nodes alternate between sleep and awake mode based on of their energy and data transmission rate to avoid early death of nodes with high traffic rate. The details of the formation of pairs is decribed in section 3.A.

Following the formation of pairs is the selection of CHs. The CH selection is based on probability define by node's energy, low traffic and higher number of pairs. This selection approach enhances load balancing by avoiding selecting isolated nodes for CH role. The CH selection process is described in section 3.B. It follows that after the selection of CH, each sensor node becomes a member of the most nearest CH. Accordingly, the selected CH computes the number of paired groups and isolated nodes within its vicinity using nodes pairing identification information. Subsequently, the CH schedules TDMA for data transmission between CMs, performs data collection and aggregation as well as serves as the communication gateway between the CMs and the BS. To minimize idle listening problem (the duration of time when sensor node's radio transceiver is active but not data is transmitted or received by sensor node) among the CHs and CMs, we revisited the conventional TDMA. In conventional TDMA, the CH allocates time slots to CMs according to the number of member nodes in a cluster. Consequently, each node in a cluster must wakes up during its time slot even if the node has no data to transmit to CH. This leads to idle operation between the member node and current CH during this period, which lead to waste of energy. We modify the conventional TDMA by allocating slot to CMs according number of paired groups and isolated nodes within the cluster to reduce length of idle operation of current CH and CMs to minimize the energy consumption. The detail description of our proposed methods is described in the subsequent sections. Figure 2 below summarizes the details of our proposed approach.

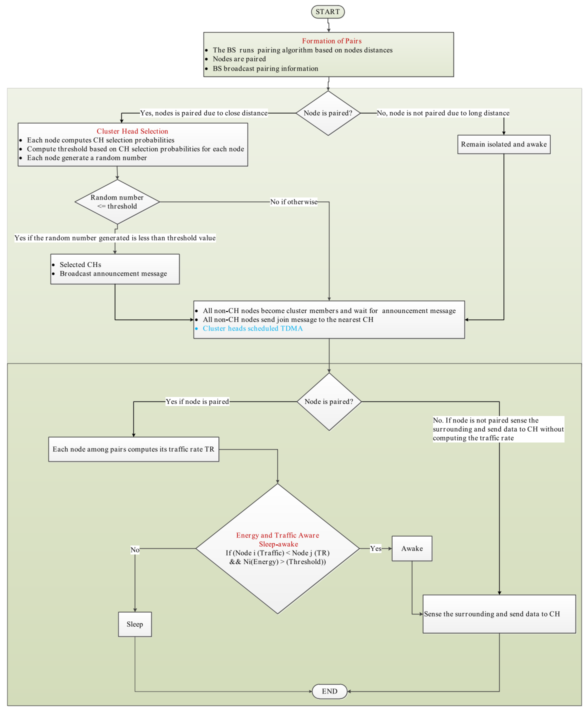

FIGURE 2. System flowchart.

A. FORMATION OF PAIRS

This section describes the formation of pairing among sensor nodes in the network. The pairing strategy have been used by many authors [12], [25], [30]. However, instead of using pairing strategy for homogeneous traffic scenario as in the previous approaches, our proposed method utilized pairing strategy for traffic heterogenous scenario. The utilization of pairing strategy is expected to improve load balancing due to energy and traffic consideration during sleep and awake alternation among the sensor nodes. With pairing strategy, the sensor nodes of the same application and located at short distances to each other within the same intra-cluster communication range are paired together. This is owing to the fact that the sensor nodes located in close proximity captured the same data and forward it to the base station [15]. Consequently, this result in unnecessary data transmission and collision that degrade network performance. The paired nodes alternate for data sensing and transmission tasks. Then, an energy and traffic aware sleep-awake mechanism is introduced among the pairs. Accordingly, among the pair nodes only one node at a time can perform data sensing and transmission tasks to the CH. The other pairs remain in sleep mode by ceasing their communication with the CH to save energy. The formation of pairs uses centralized approach whereby at the begining of the network deployment, each sensor node is preconfigured with measured position and location. Each node then sends its position and identity (ID) information to the BS. This information is used by the BS to calculate the distances between the member nodes. The nodes that are within short distances of less than 10 meters (as in [37]) in their intra-cluster communication range and of the same functionality with respect to application are paired. This pairing information is broadcast by the BS to all the nodes in the network. At this stage, each member node is aware of its pairs. The nodes without pair will remain isolated since they are not in close communication distance with any other nodes. The Algorithm 1 below describes the nodes pairing process.

Algorithm 1 Formation of Pairs

```
Initialization
Formation of pairs at the BS
temp dist=0;
 For each node i G (1 ...N)
   distl = infinity
 // Ni(E) is the node i energy and Ni(NB) is the
        node i neighbors
    If Ni(E) > B && Ni(NB) ==0
       NIGid =0
 // neighbors counter initialization
         For each node h €(1 ...N)
 // Nh(E) is the node h energy and Nh(NB)
        is the neighbors of node h
    If Nh(E) > 0 && Nh(NB) ==0
           While h ~= i DO
              Compute distance among the nodes
        (dist)
         temp dist = 7((Ni.X-Nh.X)^2+(Ni.Y-Nh.V)^2)
        // X and V are coordinates
        // range is the allowable distance between
        pairs (10 m)
               If (temp dist <= range)
                 If (temp dist <distl)
                     distl = temp dist
                       NB ID = h //count the number
                     of neighbors for node i
                 end If
               end If
             end of While
           end If
       endFor
     end If
     If (NB ID >0)
       Ni(NB) = NB ID
         Form pairs for sleep and awake
       Else
         Ni(NB) = NB ID
           Remain awake
     end If
 endFor
```

B. CLUSTER HEAD SELECTION

The CH is responsible for cluster coordination, scheduling of data transmission between CMs, performing data collection and aggregation as well as serving as the communication gateway between the CMs and the BS. In this approach, the CHs selection and rotations is based on weighted probabilities as defined in [38] where node i becomes a CH in the current round if the generated random number by the node i is below the threshold T(i,r).

$$T(i,r) = \begin{cases} \frac{p_i(r)}{1-p_i(r)\left(r \bmod \frac{1}{p_i(r)}\right)}, & \textit{if node } i \in < G(r) \\ 0, & \textit{otherwise} \end{cases} \tag{1}$$

where $p_i(r)$ is the node i CH selection probability in round r, $G(r)$ is the set of entitled CH nodes for the current round r, and rotation epoch for each nodes to be entitled for CH role again is depicted by $1/p_i(r)$. To enhance the network lifetime, the CH selection should avoid selecting node with higher traffic rate, low energy and less number of pairs. The node with high traffic dissipates more energy in sensing and transmission tasks than the node with less traffic rate. Furthermore, selecting node with higher number of pairs will increase load balancing by avoiding more energy intensive roles to isolated nodes. Therefore, the selection of CHs in the proposed ETASA is similar to TEAR. However, unlike TEAR, we modified the election probability to avoid selecting isolated nodes for CH role. The equation (2) computes the CH selection probabilities among the sensor nodes. The node with higher energy (initial and residual), low traffic and higher number of pairs has high chance of being selected for the role of CHs.

The ratio of number of pairs for node i at r round is calculated by $\frac{Nb_i(r)}{N-Nb_i(r)}$, where $Nb_i(r)$ is the number of pairs of node i at r round. Therefore, the CH selection probability for node i is given by

$$P_i(r) = \frac{p_{opt}N(1+\beta_{ehi})N(1+\beta_{th}-\beta_{thi})E_i(r)\mathrm{Nb}_i(r)}{(N+\sum_i^N \beta_{ehi})(N+N\beta_{th}-\beta_{TL})E_{Avg}(r)(N-Nb_i(r))} \tag{2}$$

where $E_{Avg}(r)$ is the average energy spent per round, β_{ehi} is the energy heterogeneity value for node i, β_{th} is the traffic heterogeniety parameter defining the upper bound, β_{thi} represents the traffic heterogeneity value for node i, $E_i(r)$ is the node $i's$ energy that remains at r round, and p_{opt} is optimum percentage of nodes to become CH, which is given by $p_{opt} = \frac{k_{opt}}{N}$. The average energy spent for a given round can be calculated as follows:

$$E_{Avg}(r) = \frac{1}{N}E_{TIE}(1-\frac{1}{R}), \tag{3}$$

where $R = \frac{\mathrm{E_{TIE}}}{E_{rnd}}$. $\mathrm{E_{TIE}}$ is the total initial energy in the network and E_{rnd} is the average energy dissipated per round and K_{opt} is the optimim number of clusters.

C. CLUSTER HEAD TDMA SCHEDULE

The selected CH as described previously schedules TDMA to CMs for data transmission to avoid collision so that the sensor node can go to sleep during its idle time to save energy. As briefly described in the prior section, existing conventional TDMA assumes that the nodes continuously contain data to be conveyed, which is not always true for some applications. Moreover, with the traditional TDMA, the sensor node must be awaked and turn its radio ON during its scheduled time slot, even if the node has no data to report to CH. Therefore, the node operate in unnecessary idle listening state, which is one of the major source of energy waste [39]. Likewise, the current CH operates in idle state, during this idle time slots and waste energy. Existing approaches used conventional TDMA schedules to allocate time slots to CMs. Accordingly, in conventional TDMA, if there are n CMs in a cluster, then the number of slot in contention period is

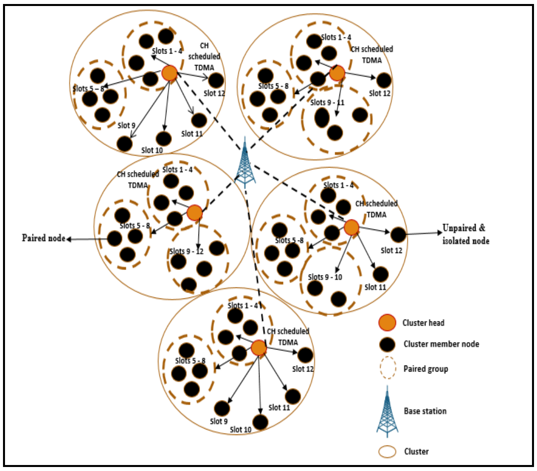

FIGURE 3. Paired groups and isolated nodes.

exactly n-1. As illustrated in Figure 3, the nodes inside cycles within a cluster are referred to as paired nodes and the cycle into which paired nodes belong is referred to paired group. Similarly, we refer to the sensor nodes within the cluster that are not within any paired group cycles as unpaired and isolated. These sensor nodes maybe located in a less dense area and at a maximum distance to other CMs. Accordingly, in the existing approaches, each node in paired groups is allocated a slot despite the fact that among the paired nodes only one node will sense the surrounding and send data to CH as depicted in Figure 4.

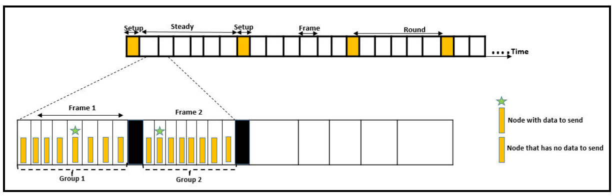

FIGURE 4. Conventional TDMA schedule architecture.

Therefore, the number of allocated slot in a cluster is determined by the number of paired groups in a cluster (Pg) multiply by the number of nodes per paired group (Ng) plus the number of isolated nodes (Un) in a cluster. Therefore, the number of slots (N_{slot}) per cluster in conventional approach is given by

$$N_{slot} = ((Pg.Ng) + Un) - 1 = n - 1$$

If the turnaround time for each node is T_s, the total time spent per cluster (T_{TC1}) is given by

$$T_{TC1} = T_s(n-1)$$

Assuming a uniform distribution of paired groups, number of nodes per group and number of isolated nodes across all clusters in the network, given a numerical example for instance, the number of paired group is 4, number of nodes for each group is 5 and number of isolated nodes is 5. Then total slot per cluster in conventional approach is given below

$$N_{slot} = (4 \times 5 + 5) - 1 = 24$$

If T_s =10s, then

$$T_{TC1} = 10 \times 24 = 240s$$

Heidemann and Estrin [40], defined average packet latency (L) as the average time taken from the data generation by the source node until data is recived by the CH. Therefore, average packet lantency (L_1) for conventional approach TDMA per cluster is computed by equation (4) as follows:

$$L_1 = \frac{nT_r + T_{ch} + T_{TC1}}{n-1}, \qquad (4)$$

where T_r is the duration of time to transmit/receive control packet and T_{ch} is time required for CH to broadcast control packet.

However, in our approach, the traditional TDMA convention is modified by minimizing the number of allocated slot in order to reduce length of idle operation (contention period) of current CH and CMs to minimize the energy consumption. In our approach, the allocation of TDMA slots is determined by the number of isolated nodes (Un) and number of paired groups (Pg) in a cluster.

The Un is computed as follows:

$$U_n = \frac{N}{K} - pg.Ng, \qquad (5)$$

where Ng is the number of nodes per paired group, N is the number of nodes in the network, K is the number of required clusters. Therefore, the number of nodes in a cluster is $\frac{N}{K}$. Each group of pairs is allocated one slot as shown in Figure 5 since only one node among the paired nodes can send data to CH at a time. Similarly, each isolated node is allocated one slot. Consequently, if the total number of CMs in a cluster is n, then the total number of time slots (N_{tslot}) per cluster in one round is calculated by equation (5)

$$N_{tslot} = (Un + pg) - 1, \qquad (6)$$

If the duration of time required to transmit (turnaround time) data to CH is T_t, therefore, the total time spent per cluster (T_{TC}) is given by

$$T_{TC} = T_t N_{tslot}$$

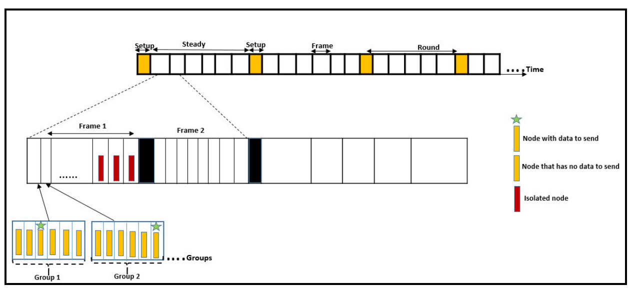

FIGURE 5. Proposed TDMA schedule architecture.

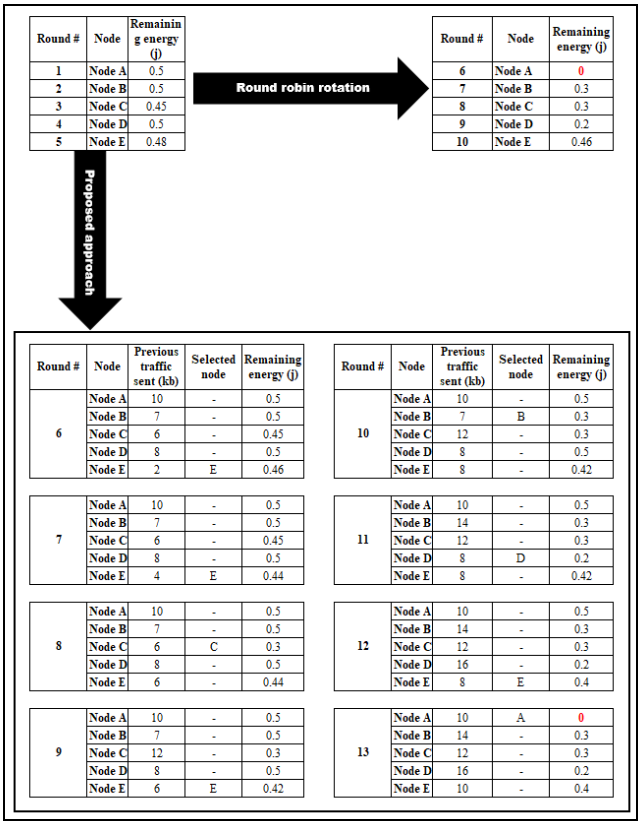

FIGURE 6. **Sleep-awake rotation lifetime (i) round-robin (ii) proposed approach.**

Given numerical example, if the number of paired group is 4, number of nodes per group is 5 and number of unpaired nodes is 5, the total slot per cluster is given below

$$N_{slot} = (4 + 5) - 1 = 8$$

If T_t =10s, then

$$T_{TC} = 10 \times 8 = 80s$$

The total idle time save by our approach in comparison with conventional approach is 160s.

In order to determine the number of paired groups and isolated nodes in a cluster, at the time of sensor nodes joining the CH, each sensor node is aware of its pairs. Each paired group is defined by unique identification number (*id*). The sensor nodes send join request message containing information about its identity (*id)* and pairing information to CH. The CH uses this information to determine the number of isolated nodes and paired groups within its vicinity. The CH assign one TDMA time slot to each paired group as among each paired group, only one node can picked-up the slot and send data to CH. With this approach, the energy wasted during contention and idle listening between CH and CMs is conserved. The duration of time required to transmit/receive a data packet, time to transmit/receive control packet and time required for CH to broadcast control packet T_t, T_r and T_{ch} respectively is minimized. In this approach, during contention period, the awake node transmit its control packet within its allocated slot and stay idle for (Nt_{slot} -1) slots. Therefore, we compute the average packet lantency (L) per cluster for our proposed approach as follows:

$$L = \frac{nT_r + T_{ch} + T_{TC}}{n-1}, \tag{7}$$

where n is the number of cluster members. The algorithm 2 describes CH-TMDA schedules among the paired groups and isolated nodes.

Algorithm 2 CH-TDMA Schedule

```
Begin
    // N is number of nodes in the network and
    // K is number of required clusters
Let n =N/K
for i 1 to n
 for j = 2 to n
    // PID is the pairing information identification
 If node (node (i) PID == node (j) PID
      node i and node j are paired
         count++ // Count paired groups
 end If
node i and node j are unpaired
 countl++ // Count unpaired nodes
 endFor
endFor
total slot= (count + countl) −1
   // nodes in the same paired group receive the same
      time slot
Broadcast TDMA according to the total slot to n−1
      nodes
End
```

D. ENERGY AND TRAFFIC AWARE SLEEP-AWAKE APPROACH

We introduce energy and traffic aware sleep-awake mechanisms in our proposed ETASA to improve the lifetime of the network. The paired nodes alternate between sleep and awake mode with respect to their energy level and traffic rate. The operation of this approach is in two fold. Firstly, at the initial round, the paired nodes transmit data in round robin fashion. Secondly, in the subsequent communication rounds, each sensor computes the amount of messages its transmitted with respect to the previous communication round. Nodes with high traffic rate tend to have an increase in number of messages sent compared with the nodes with low data rate. It is assumed that each sensor node is using free space energy model to send data to CH. Therefore, the energy consumption is largely affected by the traffic rate (paket size). As illustrated in Figure 7, node E has the lowest traffic rate. As a result, it is expected to consume less energy compared to other nodes in the group whereas node A as depicted in Figure 7, has the largest traffic rate. The energy consumed by node A in a single transmission can be five times more than the energy consumed by node E. Therefore, this approach is aimed at enhancing load balancing by making maximum utilization of node E while at the same time making optimal utilization of node A to improve network lifetime.

Without the loss of generality, we assume, the sensor nodes are heterogeneous in terms of their initial energy and traffic

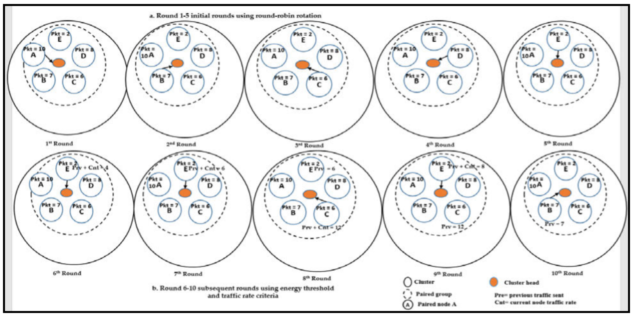

FIGURE 7. Traffic and energy sleep-awake rotation.

rate (packet sizes) according to the differences in their configurations. The packet size of each node, M_i is defined by equation (8).

$$M_i = (\frac{prksize}{dr}) \tag{8}$$

where d_r is the node's trafffic rate. The *prksize* is the maximum allowable traffic rate (packet size) in the network controlling the upper bound.

$$dr = (1 + \alpha) \tag{9}$$

where α defined the traffic heterogeniety factor of node i.

The number of messages transmitted by node i $(Mbx(i))$ with respect to the previous communication rounds is calculated by

$$Mbx(i) = \sum_{i=1}^{r} M_i(i) \tag{10}$$

where $M_i(i)$ is data sent by the nodes i with M_i packet-size at a round to the CH and r is the current round.

The average traffic rate (T_R) of node i at the current r round is given by

$$T_R(i) = \frac{Mbx(i)}{r} \tag{11}$$

Consequently, node with larger traffic rate (packet size) will have larger average traffic rate (T_R) with respect to previous rounds. Therefore, to alternate sleep-awake schedule among the paired nodes, each node obtains the knowledge about the energy and traffic rate of all its pairs by eavesdropping. The node E with the lowest data rate (packet size) of 2kb as shown in Figure 7 will obtain the information about the traffic information of its pairs after each completed data transmission round. The operation of sleep and awake rotation is as follows: Firstly, in each round, each node computes its average traffic rate with respect to previously sent messages and compares its traffic rate with the average traffic rate of its pairs. Secondly, the current awake node checks its energy status according to the threshold value (the minimum energy node is required to survive in the network). If the current awake node's energy is above the threshold value and has the lowest traffic rate, then the awake node senses the surroundings and send data to CH. Thirdly, if the traffic rate of the current awake node is above the traffic rate of any one of its pairs, the current awake node broadcast its status and the status of the preferred node among its pairs and then go to sleep. After receiving the status of the current awake node by the preferred node among the pairs, the preferred nodes among the pairs wakes up for data sensing and transmission task to CH. Fourthly, if two nodes have the same average traffic rate, the node with higher residual energy is chosen. Figure 7 illustrate the energy and traffic aware sleep-awake rotation among the nodes within a cluster.

The threshold value is computed according to the estimated energy consumption in the whole network per round. To estimate the energy consumption in round (E_{round}), we assume that the sensor nodes are uniformly distributed in $K \times K$ square region and the BS is fixed at the centre of the region as defined in [28]. The $N_{tslot} = (Un+pg)-1$ nodes send data to CH in a round. We have taken the worse case scenario where each node sends *prksize* (maximum allowable traffic rate in the network) in a round. Thus, the total energy consumption in a round in the network is computed by

$$E_{round} = prksize * (2N_{tslot}E_{elec} + N_{tslot}E_{DA} + k\varepsilon_{mp}d^4_{t\_BS} + N_{tslot}\varepsilon fsd^2_{t\_CH})$$

where k is the number of clusters.

Considering the distribution of heterogeneous sensor nodes as depicted in Figure 6 and Figure 7, the numerical examples for round-robin rotation and our proposed energy and traffic aware sleep-awake rotation is illustrated in Figure 7. It is assumed that each sensor node is using free-space energy model to send data to CH as stated earlier. Therefore, the node's energy consumption is mostly affected by traffic rate. To illustrate the operation of the round-robin rotation against the operation of our proposed approach, the following assumptions were made as shown in Table 1.

TABLE 1. Traffic rate and energy consumption.

Node	Traffic rate (kb)	Initial energy (J)	Energy consumed to send data to CH (J)
Node A	10	1	0.5
Node B	7	0.7	0.2
Node C	6	0.6	0.15
Node D	8	0.8	0.3
Node E	2	0.5	0.02

As depicted in Figure 6, if the network lifetime is consider as the rounds of communication until first node dies, the the network lifetime using round-robin rotation among the paired nodes is 6, whereas our proposed approach network lifetime is 13. This shows that our proposed approach is more energy-efficient and can lead to prolong network lifetime compared to the existing approach.

Similarly, Figure 8 depicts paired and isolated nodes data sensing and transmission process to CH. The isolated nodes always have data to send to CH in every round to ensure

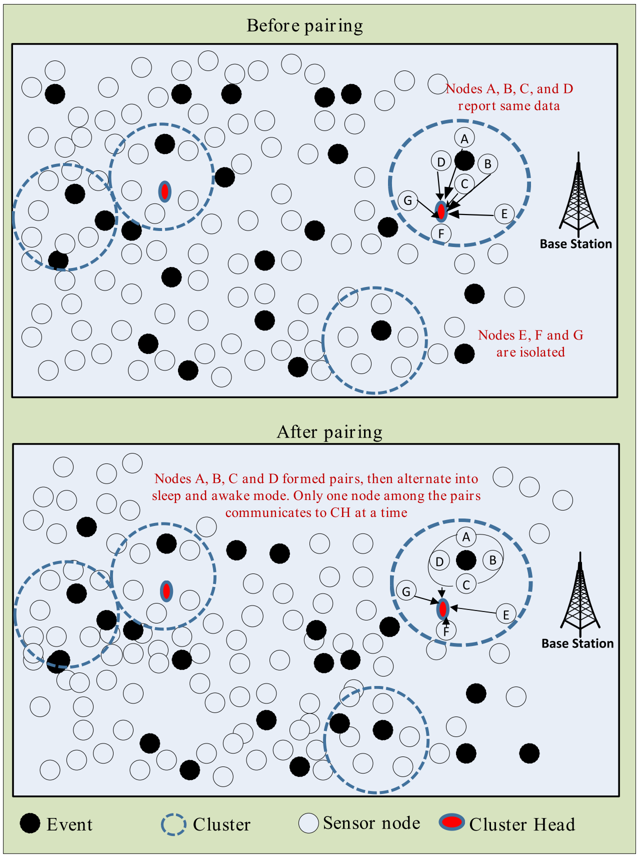

FIGURE 8. **Paired and isolated nodes data transmission.**

effective monitoring. Therefore, the isolated nodes sleep-awake schedule is similar to conventional approach as they can only go to sleep during other nodes schedule time slot to save energy, see algorithm 3.

IV. SIMULATION SETTINGS

This section expresses the detail description of our simulation set up. The total of 100 sensor nodes are deployed in a 100m × 100m target area for periodic monitoring. The sink node (base station) is position at the center of the region. As shown in the Figure 9 below

We implemented the proposed approach by simulation using MATLAB. During the course of this simulation, we followed similar network simulation parameters as specified in [1], [41] contained in Table 2 below.

V. NETWORK MODEL

This section focuses on the description of the assumptions made about the network model and the detail explanation of the model. This work considers a WSN with N sensor node $N_i(i=1, 2,\ldots, N)$ which are randomly distributed over a target area with $K \times K$ square size for environmental monitoring. It is practically difficult to deterministically deploy sensor nodes manually in a large area or hostile environment. So random deployment is used in this work to create the network. The sensor nodes remain stationary after deployment. The

Algorithm 3 Energy and Traffic Aware Sleep-Awake

```
Begin
While i ∈ (1...N)
  While (node_A(i)_Energy >0)
    If (node_A(i)_Mode ==Awake &&
        node_A(i)_is_CH)==False)
     NodeA_(i)_Mode=Sleep;
     ElseIf(node_A(i).Mode==Sleep)
       node_A(i)_Mode=Awake
    While (node_A(i)_Mode==awake &&
        nodeA(i)_neighbor==1)
     While j ∈(1..nbr_A) &&
        node_A(i)_ TR =1)) && node_A(j)_ TR ==6
   // nbr_A is the neighbor of A
             broadcast status among the pairs //
             Round-robin section
             node_A(i)_mode=sleep;
      Else
            node_A(i)_mode=Awake
           End If
      EndWhile
     While TR ∀ i∈ e (1...N) ≠ 0// All nodes sent
    data once
    If(((node_A(i)_Energy < Threshold) &&
        (node_A(i)_ TR >nbr_A(j)_ TR))) || //
              broadcast status among the pairs
               node_A(i)_mode=sleep;
           ElseIf((node_A(i)_Energy > Threshold) &&
              (node_A(i)_ TR < nbr_A(j)_ TR))
              node_A(i)_mode = awake
           ElseIf(((node_A(i)_Energy <
        nbr_A(j)_Energy) &&
        (node_A(i)_ TR ==nbr_A(j)_ TR)))
              node_A(j)_mode=Awake;
              node_A(i)_mode=sleep;
           EndElse
           EndElse
         EndElse
       EndWhile
       EndElse
    End If
  Endwhile
  EndWhile
Endwhile
End
```

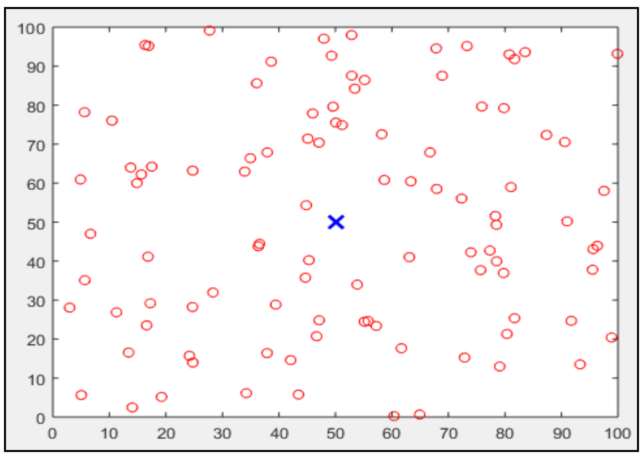

FIGURE 9. **Simulation environment.**

deployed sensor nodes are heterogeneous based on their energy and traffic rate with multiple levels similar to [1]. This means that the data rate at each node is dependent on its physical configuration and capacity rather than a uniform at each node. The high traffic nodes have an increase in packet lengths and an increase in a number of message per round for

TABLE 2. Simulation parameters.

Parameter	Value
Number of sensor nodes (N)	100
WSN Area (K x K)	100m x 100m
Initial energy lower bound (E_0)	0.5J
Energy consumed in *Tx/Rx* electronics (E_{elec})	50nJ/bit
Tx Amplifier energy dissipation in free space scenario (E_{fs})	10pJ/bit/m^2
Tx Amplifier energy dissipation in Multipath scenario (ϵ_{mp})	0.0013pJ/bit/m^4
Energy consume in Data Aggregation (E_{DA})	5nJ/bit/signal
Packet length lower bound (M_0)	4000bits
Idle power consumption	19.5mW

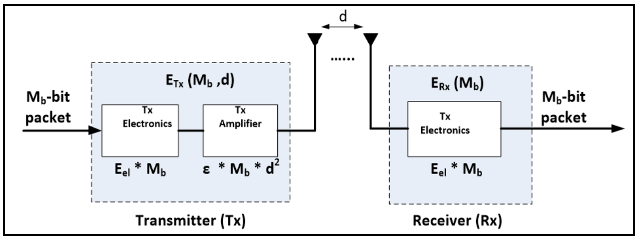

FIGURE 10. Radio model.

communication. We adopt the first order radio model depicts in Figure 10 as in [38]. The energy consumed by the radio to communicate M_b-bit message to distance d, E_{TX}, is given by

$$E_{TX} = M_b.E_{el} + M_b.\varepsilon_{fs}.d^2, \quad \text{if } d < d_0, \text{ or}$$
$$E_{TX} = M_b.E_{el} + M_b.\varepsilon_{mp}.d^4, \text{ if } d > d_0 \tag{12}$$

where $d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}$
where E_{el} is the receiver's circuit or transmitter's circuit per bit consumed energy and d represent the distance between the transmitter (Tx) and the receiver (Rx). The $\epsilon_{fs}.d^2$ and $\epsilon_{mp}.d^4$, are amplifier losses for the free space and the multipath fading accordingly. The energy loss (E_{RX}) for receiving M_b-bits message is as follows:

$$E_{RX} = M_b.E_{el} \tag{13}$$

This research adopts the cluster-based approach as in [1], [27], [28], [35], [38], with random distribution of N heterogeneous nodes in $K \times K$ square region. The BS is placed at the center of the region and the nodes distance from the BS is within the range of free space model d_0. The member nodes in each cluster send their readings to their corresponding CH, which in turn performs data aggregation and convey the aggregated data to the BS. The distribution of energy is random over the range between [E_0, $E_0(1+\beta_{eh})$] similar to [1], [28] which is more realistic representation of energy heterogeneity, E_0 is the lower limit and β_{eh} represent energy heterogeneity factor maintaining the upper limit which is random number ranges between [0,1].

The total initial energy (E_{TIE}) of the network is given below

$$E_{TIE} = \sum_{i=1}^{N} E_0(1 + \beta_{ehi}) \tag{14}$$

where β_{ehi} represents energy heterogeneity value for the node i.

The sensor nodes generate different types of traffic depending on its sensing capacity and configuration in terms of number of packet size as in [1]. The traffic heterogeneity of node i with factor β_{thi} is given by $M_i = M_0(1+\beta_{thi})$, which is randomly dispersed over [M_0, $M_0(1+\beta_{th})$], where M_0 is the lower limit and β_{th} is the upper bound traffic heterogeneity factor which is a random number between [0,1]. It is expected that the system satisfies the bandwidth requirement for such heterogeniety.

According to [1], [27], [28] the mean distance between member node to CH (d_{t_CH}) and between CH to BS (d_{t_BS}) in a uniformly distributed network can be calculated by

$$d_{t\_CH} = \frac{R}{\sqrt{2\pi R}} \tag{15}$$
$$d_{t\_BS} = 0.765\frac{R}{2} \tag{16}$$

where k represents cluster number and R represent the estimated network lifetime based on number of rounds considering of equal energy dissipation in each round. According to [38] the total energy consume for a single round (E_{rnd}) is calculated by

$$E_{rnd} = k(E_{CH} + (\frac{N}{K} - 1)E_{nCH}) \tag{17}$$

Since among the paired nodes only one node will participate in data sensing and transmission in a round, therefore, the number of participating node (N_p) is determined by the total number of paired groups (P_g) and number of unpaired nodes (U_p). The number of unpaired nodes is expressed by

$$Up = \frac{N}{K} - Pg.Ng \tag{18}$$

where Ng is the number of nodes in each paired group.

In each group, only one node will participate in data transmission per round. Therefore, the number of participating node for data sensing and transmission in a cluster is calculated by equation 19 below

$$N_p = (Up + Pg) \tag{19}$$

The number of non-cluster head node in the network $N_{nCH} = (N_p - 1)k$. Therefore, E_{rnd} becomes

$$E_{rnd} \approx k.E_{CH} + K.N_{nCH}.E_{nCH} \tag{20}$$

where the number of participating nodes per cluster is represented by N_p and k represent the number of clusters. The total participating nodes (N_T) in the network $= k.Np$.

Likewise, the energy consumed by CH node and non-CH nodes is represesnted as E_{CH} and E_{nCH} respectively. The energy consumed by N_{nCH} in k clusters per round ($k.N_{nCH}.E_{nCH}$) is expressed by

$$\begin{aligned} N_{nCH}.E_{nCH} &= \sum_{i=1}^{N_T-k} (M_i.E_{el} + M_i.\varepsilon_{fs}.d_{t\_CH}^2) \\ &= M_0(E_{el} + \varepsilon_{fs}.d_{t\_CH}^2)(N_{nCH} + \sum_{i=1}^{N_T-k} \beta_{thi}), \end{aligned} \tag{21}$$

The total traffic heterogeneity in the network (β_{Tl}) is expressed by

$$\beta_{Tl} = \sum_{i=1}^{N} \beta_{thi}, \tag{22}$$

where β_{thi} is the traffic heterogeneity value for node i.

Considering equation (15) and (21) and total traffic heterogeneity in the network (β_{Tl}), then the energy consumed by non-CH, N_{nCH} nodes is computed by equation (23).

$$N_{nCH}.E_{nCH} = M_0(N_{nCH} + \beta_{Tl})(E_{el} + \varepsilon_{fs}\frac{R^2}{2\pi k}) \tag{23}$$

From [1], the sum up message transmitted from any CH to BS is $M_{xt} = M_0(1+\beta_{th})$ bits long. Likewise, energy spent in the k CH nodes in a single communication round for receiving N_T-k CMs data, for data aggregation and forwarding to the BS is expressed in the equation (24).

$$\begin{aligned} K.E_{CH} = &\sum_{i=1}^{N_T-k} (M_i.E_{el}) + \sum_{i=1}^{N_T-K} (M_i.E_{DA}) \\ &+ \sum_{i=N_T-k}^{N_T} (M_{xt}.E_{el} + M_{xt}.\varepsilon_{fs}.d_{t\_BS}^2) \end{aligned} \tag{24}$$

where E_{DA} is the data aggregation energy spend per bit. Considering the total traffic heterogeneity among the nodes

$$\sum_{i=1}^{N_T-K} \beta_{thi} \approx \frac{N_T-k}{N} \sum_{i=1}^{N_T} \beta_{thi} \approx \frac{N_T-k}{N}\beta_{Tl}$$

then

$$\begin{aligned} k.E_{CH} = &\frac{N_T-k}{N} M_0(N_T+\beta_{Tl})E_{el} + M_0(N_T+\beta_{Tl})E_{DA} \\ &+ k.M_0(1+\beta_{th})E_{el} + k.M_0(1+\beta_{th})\varepsilon_{fs}.d_{t\_BS}^2 \end{aligned} \tag{25}$$

Equations (21), (23) and (25) are used to derive the equation for total consumed energy in a single transmission round. This equation can be calculated as follows.

$$\begin{aligned} E_{rnd} = &\frac{N_T-k}{N} M_0(N+\beta_{Tl})E_{el} + M_0(N+\beta_{Tl})E_{DA} \\ &+ k.M_0(1+\beta_{th})E_{el} + k.M_0(1+\beta_{th})\varepsilon_{fs}.d_{t\_BS}^2 \\ &+ M_0(N+\beta_{Tl})(E_{el} + \varepsilon_{fs}\frac{R^2}{2\pi K}) \end{aligned} \tag{26}$$

The required number of clusters per round (k_{opt}) is computed in equation (27) which is derived by getting the derivative of equation (26) with respect to k, where k = 0.

$$k_{opt=k} = \sqrt{\frac{N(N+\beta_{Tl})\varepsilon_{fs}.R^2}{2\pi((N.\beta_{th}-\beta_{Tl})E_{el} + N(1+\beta_{th})\varepsilon_{fs}.d_{t\_BS}^2)}} \tag{27}$$

Without traffic heterogeneity, $\beta_{th} = \beta_{Tl}$ Then

$$= \sqrt{\frac{N.R^2}{2\pi(d_{t\_BS}^2)}} = \sqrt{\frac{N}{2\pi}}.\frac{R}{d_{t\_BS}}$$

VI. PERFORMANCE EVALUATION

We evaluate the performance of the proposed approach in this section. The proposed approach performance (ETASA) is compared with the performance of SEED [12] clustering algorithm due to common used of pairing and sleep-awake approach and TEAR [1] owing to the common traffic heterogeneity consideration. The SEED protocol employed pairing approach with duty-cycling to minimize redundant transmission from the sensor nodes that are in close distances to achieve energy-efficiency. The drawbacks with SEED is idle listening problem due to the use of conventional TDMA scheduling among CMs. Idle listening leads to unnecessary energy consumption. Moreover, SEED protocol cannot cope with environment with traffic heterogeneous sensor nodes. The TEAR on the other hand, addresses traffic heterogeneity issues by avoiding selecting high traffic nodes for CH role to achieve load balancing. However, TEAR protocol cannot avoid redundant transmission from the sensor nodes that are in close distances. Moreover, TEAR did not provide necessary energy saving conservation mechanisms that can minimize the energy consumption of high traffic nodes. Therefore, our proposed ETASA protocol is evaluated and compared against SEED and TEAR using the following evaluation metrics:

NETWORK LIFETIME

Network lifetime is the time taken by the network right from the node deployment to the point in time when the network becomes non-functional. This can be viewed from different perspectives depending on the area of application. For instance, it can be considered as the rounds of communication until the first node dies or the rounds until a certain percentage of nodes die and also it can be considered as the rounds until the last node depletes its energy stored in the network. In this research, we consider network lifetime in three different perspectives. Firstly, we considered the network lifetime as the time when the first node dies as in [42] and secondly, the lifetime when fifty percent of nodes died (half nodes died). Lastly, we also considered the network lifetime as the time when the last node in the network lost all of its energy. The equations (28) - (32) are the mathematical equations used to generate the necessary data about the lifetime of our proposed ETASA protocol. The illustrations about ETASA performance in comparison with SEED and TEAR algorithms in term of network lifetime is presented in Figure 5.

- The first node died (FND): is the time taken in sensing and communication rounds until first node in the network exhausts its energy entirely.

$$\left(\sum_{r=1}^{r_{\max}}\sum_{i=1}^{N}\begin{matrix}(Node(i).E \leq 0, (dead = dead + 1;\\ if\,(dead == 1, first\_dead = r)))\end{matrix}\right) \quad (28)$$

- Fifty percent nodes died (TND): is the time taken in sensing and communication rounds until fifty percent of nodes depleted their entire energy stored.

$$\left(\sum_{r=1}^{r_{\max}}\sum_{i=1}^{N}\begin{matrix}(Node(i).E \leq 0, (dead = dead + 1;\\ if\,(dead == 0.5 * N, half\_dead = r)))\end{matrix}\right) \quad (29)$$

- Round until last node died (LND): is the time elapsed in rounds until the last node in the network depleted its entire energy.

$$\left(\left(\sum_{r=1}^{r_{\max}}\sum_{i=1}^{N}\begin{matrix}(Node(i).E \leq 0, (dead = dead + 1;\\ if\,(dead == N, last\_dead = r)))\end{matrix}\right)\right) \quad (30)$$

- Number of alive nodes: is the number of alive nodes per round. *(N−dead).*
- Number of dead nodes: is the number of dead nodes in a round. *(dead = dead),*

THROUGHPUT

Throughput refers to the total number successful bits transmitted to the destination in a period of time. The throughput defines the effectiveness of the network capacity. The network throughput can be computed as follows

$$Throughput = \frac{NR}{NS} \quad (31)$$

where *NR* is the total packet received by the destination and *NS* is the total number of packets transmitted by the source.

REMAINING ENERGY

Remaining energy (RE) also referred to as residual energy. The remaining energy reflects the protocol ability to make efficient use of network energy as possible [43]. The average residual energy is computed by equation (34)

$$RE = \frac{E_0 - CE}{E_0} \quad (32)$$

where *Eo* is the average initial energy and *CE* is the average energy consumption.

A. DISCUSSION

This section describes the results of our findings between SEED, TEAR and ETASA with respect to the evaluation metric described above as follows.

1) NETWORK LIFETIME

As shown in the Figure 11-15 a comparison on the network lifetime according to number of alive nodes, number of dead nodes, first node died (FND), half of nodes died (HND) and last node died (LND) between the proposed ETASA, SEED and TEAR is performed. It is clearly evident that from the result obtained the proposed ETASA has shown better performance compared to SEED and TEAR in terms of network lifetime. The reason is that the proposed ETASA considers traffic heterogeneity by minimizing the utilization

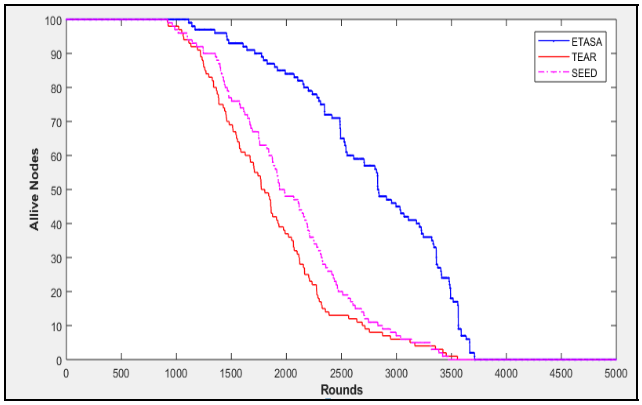

FIGURE 11. Number of Alive nodes.

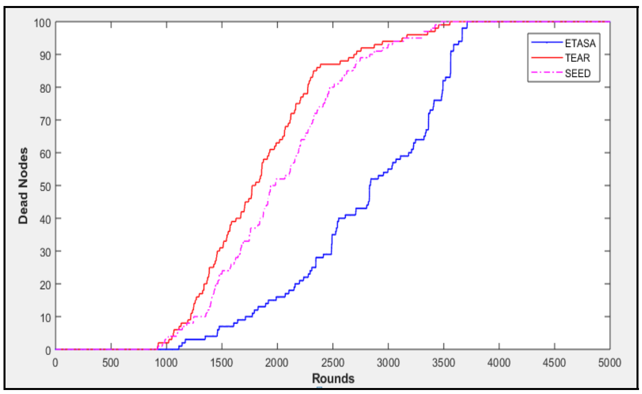

FIGURE 12. Number of dead nodes.

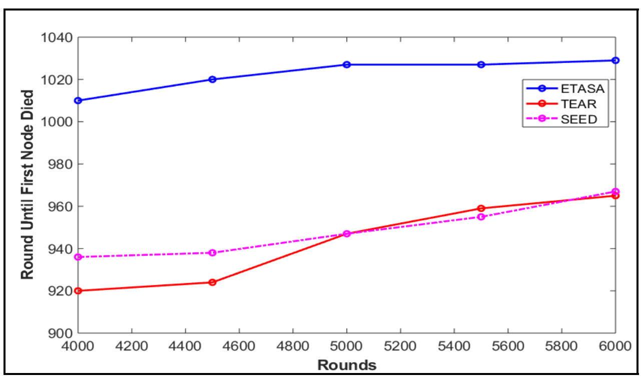

FIGURE 13. First node died.

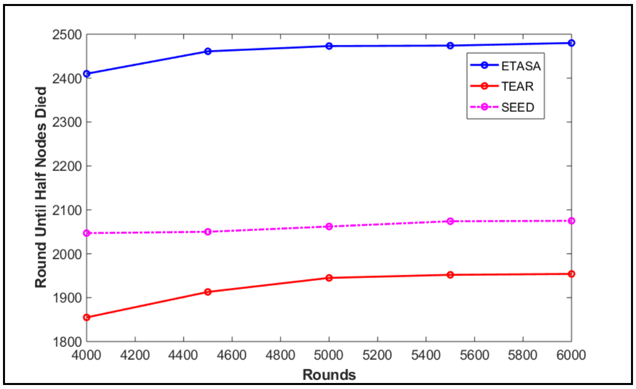

FIGURE 14. Half nodes died.

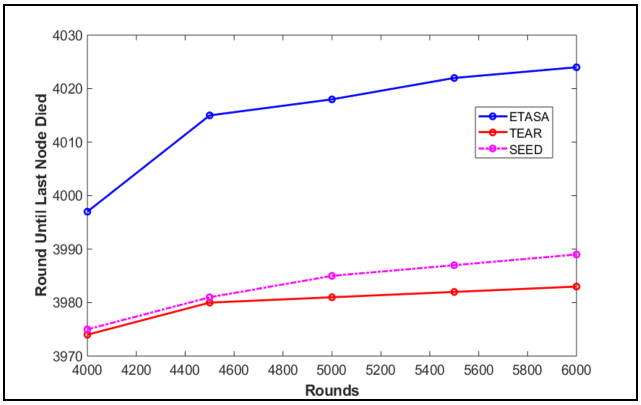

FIGURE 15. Last node died.

of the nodes that have high traffic rate for sensing and transmission tasks. This is achieved by using energy and traffic aware sleep-awake mechanism that prevent the early death of high traffic nodes contrary to TEAR, which concerns only to avoid selecting of nodes with high traffic for CH roles. The SEED used sleep-awake mechanism in similar manner to ETASA but performed poorly as a result of lack of energy and traffic heterogeneity consideration during sleep and awake alternation among paired nodes. In addition, the ETASA also ensures that only the node with high energy, high number of pairs and low traffic is selected for CHs role. This saves a substantial amount of energy dissipation by avoiding isolated nodes from CH roles, thereby improving the network lifetime. As shown in the FIGURE 11-15, TEAR has not shown good performance in terms of the network lifetime. This proofs that avoiding selecting nodes with high traffic alone cannot save the battery of such nodes.

The number of alive nodes as depicted in Figure 11, it was observed that using pairing and sleep-awake mechanism can improve the network lifetime. Both SEED and ETASA has shown an improved network lifetime in terms of FND compared to TEAR. However, the performance of SEED falls short below that of ETASA due to the absence of traffic heterogeneity consideration in SEED. Additionally, in SEED substantial amount of energy is wasted due to idle listening.

Figure 12 depicts the number of dead nodes per round which shows that the number of dead nodes in ETASA is delayed unlike in TEAR and SEED which show rapid increase in the number of dead nodes. The Figure 13 illustrates the network stability until the first node died (FND). The proposed ETASA algorithm takes longer rounds of communication until FND compared to TEAR and SEED. This is due to energy saving mechanism incorporated in ETASA such as avoiding selection of isolated nodes for CH role, ensuring load balancing among traffic heterogeneous nodes using traffic aware sleep-awake approach and so on. The SEED's network lifetime in terms of FND is short compared to ETASA. This is due to the fact that SEED used round-robin based sleep and awake alternation among the paired nodes without concern with the traffic and energy variation among the nodes. Moreover, the selection of CH in SEED did not consider nodes traffic heterogeneities. Eventually, if the high traffic node is selected for CH roles could lead to fast energy drainage of node with high traffic rate. However, despite the lack of traffic heterogeneity consideration in SEED, in terms of FND it has shown an improve performance in comparison to TEAR due to energy saving mechanism incorporated in SEED by avoiding unnecessary data transmission.

The Figure 14 illustrates the communication rounds until HND in the network. Considering the round until HND, the SEED has shown significant improvements in the network lifetime compared to TEAR. This can be as a result of sleep-awake mechanism used in SEED. ETASA has shown longer network lifetime in comparison to TEAR and SEED in terms of HND. This is due to the load balancing mechanisms used in ETASA by ensuring that only nodes with high energy and low traffic rate become CHs and also by making optimal utilization of heterogeneities among the sensor nodes.

The Figure 15 shows the number of rounds until last node died in the network. The TEAR and SEED algorithm have shown shorter network lifespan compared to ETASA as a result of lack of a proper energy-saving mechanism in them. The early LND in TEAR is due to ignoring high traffic nodes to keep on transmitting more data to CH without providing a mechanism that will relieve the burden of high traffic nodes. Similarly, despite the sleep-aware mechanism used in SEED, yet all the nodes have equal chance of data sensing and transmission. Therefore, using round-based sleep-awake alternation cannot save the limited battery of high traffic nodes. However, ETASA allows only the sensor nodes with high energy and low traffic to frequently partake in data sensing, communication with CH and CH roles. Therefore, ETASA has shown longer network lifetime in terms of LND with respect to rounds of communication as demonstrated in Figure 15.

2) THROUGHPUT

Throughput refers to the total number of bits transmitted to the destination in a period of time [26]. The **Figure 16** below shows that the proposed ETASA has slightly better throughput despite the fact that the proposed approach

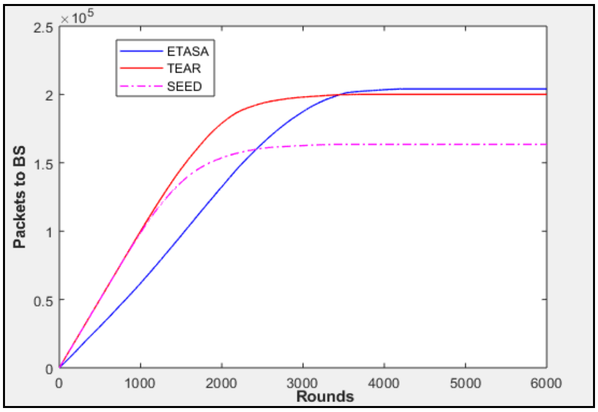

FIGURE 16. Throughput.

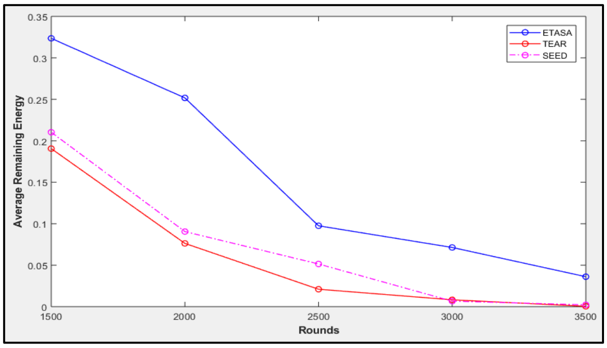

FIGURE 17. Average remaining energy.

used sleep-awake mechanism among the network nodes. This means that redundant data transmission among the pair nodes is restricted contrary to TEAR in which no such redundant transmission is restricted. The SEED has the lowest throughput since it did not take into consideration the energy and traffic heterogeneity among the paired node during sleep and awake alternation. Therefore, in some data transmission rounds, the next node to transmit data could be dead which affect the throughput performance in SEED. The proposed ETASA protocol has shown increase in throughput to BS with the increase in the round of communication than TEAR. This can be attributed to the longer network lifetime of the proposed ETASA. As demonstrated in the **Figure 16**, the TEAR protocols has shown good performance in terms of throughput to BS at the beginning of communication rounds. This is due to the lack of necessary mechanisms presented in TEAR that minimize redundant data sensing and communication among the network nodes. This consumes considerable amount of network energy. Therefore, as the network communication rounds progress, the performance of TEAR drops whereas in ETASA the data delivery progresses gracefully with the increase in communication rounds. This is due to energy saving mechanisms implemented in ETASA.

3) AVERAGE REMAINING ENERGY

As shown in **Figure 17**, the ETASA algorithm has higher remaining energy compared to TEAR and SEED. This happens as a result of energy-saving methods applied in ETASA, ranging from CH selection, the use of traffic aware sleep-awake mechanism and minimizing energy dissipation due to idle listening during steady state. The CH selection method used in ETASA enhances load balancing, since selecting node with a high number of pairs in ETASA avoids selection of isolated nodes for CH roles, whereas in TEAR, the CH selection process only concentrates on a selection of high energy and low traffic nodes. Moreover, in TEAR, the selected CH may be located in a less dense area and at a maximum distance to the CMs. This could lead to selection of isolated nodes for CH roles, which eventually causes the early death of isolated nodes. The CH selection process in SEED is based on probabilities in terms of node's residual energy. Selecting CH based on this parameter alone in SEED cannot ensure balanced intra-cluster communication. Therefore, as clearly depicted in **Figure 17**, appropriate selection of CH in ETASA and reducing redundant data transmission among the pair nodes by introducing energy and traffic aware sleep-awake mechanism have a significant impact in saving the network energy consumption. This is true since at every communication round only one node with high energy and low data rate among the pairs send data to CH. Moreover, using effective TDMA time allocation among paired groups and unpaired nodes contributed immensely in saving nodes energy consumption. Consequently, as depicted in **Figure 17**, ETASA has shown high network average remaining energy compared with SEED and TEAR.

VII. CONCLUSION

In this paper, we investigate energy efficiency and load balancing issues in heterogeneous WSN scenario. Heterogeneity among the sensor nodes if not properly utilized could lead to uneven energy consumption and load imbalanced across the network, which degrade the performance of the network. Routing algorithms should try to achieve energy efficiency and load balancing among the heterogeneous nodes to prolong the lifetime of the network. One of the solutions is by using duty-cycling in cluster-based routing such as in Sleep-awake Energy Efficient Distributed (SEED) algorithm to minimize redundant transmission to achieve energy efficiency. Though this scheme able to minimize redundant transmission, it suffers from idle listening problem, which lead to unnecessary energy consumption across the network. Moreover, SEED cannot cope with an environment with sensor nodes with heterogeneous data rate. To cope with energy and traffic heterogeneity issues among sensor nodes, a traffic and energy aware routing protocol called TEAR is proposed. TEAR avoids selecting node with low energy and high traffic rate for energy intensive task such as cluster head role to achieve load balancing. However, TEAR does not avoid redundant transmission from the sensor nodes that are in close distances. To address these issues, we proposed an approach that jointly considered characteristics of MAC layer and network layer to address idle listening and redundant transmission problems to achieve energy efficiency and load balancing. In this paper, a hybrid method is proposed called

TABLE 3. Summary of the existing works.

REF	DESCRIPTION	CONTRIBUTION	LIMITATION
LEACH [21]	LEACH is a periodic round-based clustering algorithm in which each round in LEACH is separated into two phases, i.e. cluster formation and data transmission. During cluster formation phase, a CH is randomly but rotationally selected among the network nodes based on probability. During data transmission phase, the CH collects the sensed data from its CMs, performs data aggregation and forward aggregated data to the sink directly	▪ improve load balancing among the nodes by rotation role of CH among the sensor nodes. ▪ Reduces communication between the network nodes and the BS, which saves network energy consumption ▪ Eliminates data redundancy locally by means of data aggregation techniques at the CH which save considerable amount of network energy.	▪ LEACH used randomized formation of cluster, therefore, the CH position, number of clusters and cluster density cannot be guaranteed. This leads to uneven energy consumption ▪ LEACH was designed for homogeneous network scenario
HEED [22]	In HEED, the selection of CH was based on node residual energy and node degree. HEED uses multi-hop for inter-cluster communication to send data to BS.	▪ Reduce intra-cluster and inter-cluster communication cost by considering node density during CH selection and the used of multi-hop routing.	▪ HEED was designed for homogeneous network scenario. ▪ The selection of CHs in HEED requires several iterations
[24]	In this approach, each node is allocated the time of being a CH using reservations to eliminates the need to send messages competing for CH selection among the network nodes. During the initial round, the CHs are selected following LEACH based approach. In reservation phase, each node determines the round it will act as CH and form a reservation matrix with one row and R column. Then, each node assigns one to entries corresponding to the rounds when it will act as CH and zero entries identifying when it will act as normal node. After reservation phase ends, each node broadcast its reservation matrix to all other nodes. Based on this matrix, a total matrix called comprehensive matrix for all the nodes is formed. The comprehensive matrix shows which nodes will become CHs in each round *R* and this matrix is available to all other nodes	▪ Reduced cluster head selection overhead	▪ It is not energy efficient since an important CH selection criteria are ignored such node's residual energy, density, distance from BS and so on. ▪ Designed for homogeneous network scenario. ▪ Suitable only for small scale network as it requires significant amount of memory space for storing total matrix in each node ▪ Did not minimize redundant data sensing and transmission among the network nodes.
EESAA [25]	EESAA introduced the concept of characteristics pairing among sensor nodes. The sensor nodes within the minimum distance between them and sending redundant data become pairs for environment sensing and communication. The pair nodes alternate between "Sleep" and "Awake" mode after every single data transmission interval.	▪ Improved energy efficiency by minimizing redundant transmission from sensor nodes that are in close distances	▪ Designed for homogeneous network scenario. ▪ EESAA suffers from idle listening problem
SEP [27]	Energy heterogeneity is considered in SEP by assigning more energy to certain percentage of nodes than the other nodes. The percentage of nodes with high energy are called advanced nodes while the remaining nodes are referred to as normal nodes. The probability of CH election in SEP is weighted based on initial energy of the node relative to other nodes in the network. With this scheme, the high energy node has more chance to be elected as CH than normal node	▪ SEP significantly improve the lifetime of the network compared to LEACH.	▪ The major drawback with SEP is that, the high energy nodes are penalized due to high frequency of reselection as CHs without considering their current energy at a given round. ▪ SEP is not suitable for multilevel energy heterogeneous scenario

TABLE 3. ***(Continued.)*** **Summary of the existing works.**

DEEC [28]	A routing protocol with multi-level energy heterogeneity consideration known as DEEC is proposed. In DEEC the criteria for CH election is based on probabilities defined by node's initial energy, residual energy and average energy of the network. The rotation epoch of each node is directly correlated to its initial and residual energy.	▪ Improved energy efficiency compared to SEP.	▪ This approach is not suitable for network with traffic heterogeneous sensor nodes.
[30]	A sleep-awake aware routing known as SAA for heterogeneous sensor network is proposed. In SAA protocol certain percentage of nodes are equip with extra energy compared to normal nodes. Each node in SAA computes its position, type and identity with the help of GPS and communicate this information to BS. The BS uses the information received from sensor nodes to select the CHs based on node's initial energy, distance from BS and density. The nodes of closer distance and of the same application are paired. The pair nodes alternate between sleep and awake mode after every one communication round interval	▪ Improved energy efficiency by minimizing redundant transmission from sensor nodes that are in close distances.	▪ Not suitable for traffic heterogeneous network scenario. ▪ SAA also suffers from idle listening problem.
SEED [12]	In this approach two or more nodes of the same application and within the same transmission range of each other, are grouped to form sub-clusters. In a sub-cluster (paired group), only one sensor node wakes up and sense the surrounding and forward its sensed data to CH while remaining nodes stay in sleep mode to save battery power.	▪ Improved energy efficiency by minimizing redundant transmission from sensor nodes that are in close distances.	▪ SEED did not consider traffic heterogeneity among the sensor nodes during CH selection and sleep-awake alternation among the paired nodes ▪ SEED suffers from idle listening problem
[35]	Analyzes the effect of traffic heterogeneity LEACH, which is designed for homogeneous scenario .	▪ A new CH selection approach which considers traffic heterogeneity in LEACH is presented, which improved network lifetime	▪ Do not minimize redundant transmission from the sensor nodes that are in closed distances
[11]	Studied the effect of traffic and energy heterogeneity using SEP as baseline algorithm. SEP is tested by using two-level traffic heterogeneous nodes, normal nodes with normal traffic and advanced nodes with high traffic in a similar manner to two-level energy heterogeneity in SEP	▪ Improve network lifetime by improving CH selection method.	▪ Not suitable for multilevel heterogeneous scenario ▪ Do not minimize redundant transmission from the sensor nodes that are in closed distances
[1]	A multi-level traffic and energy heterogeneous sensor network is designed called TEAR protocol. In TEAR a multi-level disparity among the sensor nodes in based on their energy and in the data generation rate (multi-level heterogeneity) is considered. The CH election probability in TEAR is based on initial and residual energy of the node, node's traffic load and the average energy of the round. The rationale behind TEAR protocol is to avoid selecting nodes with high traffic and low energy while at the same time ensuring selection of high energy nodes with low traffic rate for CH role	▪ The TEAR approach is useful for modeling the realistic WSN. The result shows that TEAR achieved prolong network lifetime compared with LEACH, SEP and DEEC.	▪ TEAR do not provide necessary energy conservation mechanism that conserves and minimizes the fast energy consumption of high traffic nodes such as minimizing redundant data transmission among others

TABLE 3. *(Continued.)* **Summary of the existing works.**

DEFL [36]	The DEFL protocol considered nodes to be heterogeneous possessing variable traffic loads. This algorithm followed shortest path routing approach with least cost. The main objective of this approach is to avoid selection of path with high traffic load. The input to the fuzzy in DEFL includes, traffic rate, transmission energy and node remaining energy	▪ This approach increases the lifetime of the network by not burden the high traffic nodes with message relaying task	▪ This approach employed flat routing, which increases communication complexity in the network thereby degrading the network performance

energy and traffic aware sleep-awake (ETASA) mechanism to improve energy efficiency and enhanced load balancing in heterogeneous WSN scenario. Unlike prior methods, in ETASA, the paired nodes alternate into sleep and awake mode based on node's energy and traffic rate. Moreover, we revised the conventional TDMA scheduling in SEED by allocating one slot for each group of pairs in a cluster instead of SEED which allocates slots to all members of paired groups even though not all nodes have data to report to cluster head. This is done to address idle listening problem to minimize energy consumption. The proposed method includes an improved cluster head selection technique that selects high energy, low traffic and nodes with high number of pairs to improve balanced energy consumption. The proposed approach is evaluated and compared against TEAR and SEED in terms of network lifetime, remaining energy and throughput. The result shows that the proposed ETASA has 16% lifetime improvements against TEAR and 15% against SEED. In the future, we will consider traffic heterogeneity in the context of different zones in the same network.

APPENDIX

See Table 3.

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