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Mobility-Aware Hierarchical Clustering in Mobile Wireless Sensor Networks

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ABSTRACT Wireless sensor networks (WSNs) are one of the chief enabling technologies for the Internet of Things. These networks are severely resource-constrained which calls for designing energy-efficient and effective routing techniques. The hierarchical- or clustering-based routing approaches have shown to improve both energy-efficiency and scalability in WSNs. However, when clustering is implemented in mobile WSNs (MWSNs), the mobility of sensor nodes results in high data loss due to possible dis-association of nodes with their cluster heads which negatively affects the data rates and energy consumption. In order to mitigate the impact of node mobility on clustering, we propose two mobility-aware hierarchical clustering algorithms for MWSN based on three-layer clustering hierarchy: mobility-aware centralized clustering algorithm (MCCA) and mobility-aware hybrid clustering algorithm (MHCA). The MCCA algorithm employs centralized gridding at both layers of clustering hierarchy, and the MHCA algorithm employs centralized gridding at the upper layer and distributed clustering at the lower layer. The simulation results show that our proposed algorithms improve network lifetime, reduce energy consumption, stabilize cluster formation, and enhance data rates in mobile sensor networks. We also observe that the centralized clustering approach is superior to the hybrid clustering approach.

INDEX TERMS Distributed clustering, hierarchical clustering, Internet of Things, mobile sensor networks, node mobility.

I. INTRODUCTION

The Internet of things is a network of embedded devices aka things which transmit sensed data to a central server or cloud for processing and further action. The evolving IoT applications are revolutionizing the world around us in areas such as healthcare, home automation, structural monitoring, agriculture, security and surveillance, and smart grid etc. A Wireless Sensor Network (WSN) is effectively the interface between the IoT and the physical world. The WSN comprises of a large number of autonomous sensor nodes, severely constrained in terms of size, memory, battery power, and radio range and capable of wireless transmission of the sensed data to a sink or a base station. A Mobile Wireless Sensor Network (MWSN) is a WSN with sensor nodes that can be mobile. The mobility of sensor nodes in a MWSN poses additional challenges to the design of energy-efficient routing protocols for the constrained sensor networks due to the detrimental effect of mobility on network connectivity, data rates and scalability.

Instead of flat routing, the hierarchical or clustering based routing is deemed suitable for the constrained sensor networks. In cluster based approaches, the nodes which are in physical proximity form clusters; each cluster selects a cluster head which assumes the role of the data aggregator and router, in addition to controlling the duty cycle of the nodes. The network is organized into several clusters and the cluster heads route data from their clusters to the sink or base station. The cluster heads are renewed in every round in order to share the responsibilities of routing among the sensor nodes. The clustering results in reduced redundant data transmissions and lower data loss. A number of routing and clustering techniques have been designed for the WSNs such as Low-Energy Adaptive Clustering Hierarchy (LEACH), Three-Layered LEACH (TL-LEACH) and LEACH-Centralized (LEACH-C) etc. [1]–[4].

Most of the earlier clustering approaches such as LEACH [5] and LEACH-C [6] were based on two-layer

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hierarchy. However, the two-layer clustering hierarchy becomes inefficient in large networks due to the formation of large-sized clusters resulting in overburdening the cluster head and its neighboring nodes which route data to the cluster head. The TL-LEACH implements three-layer clustering hierarchy built on the distributed approach of the LEACH algorithm where cluster heads are randomly selected [7]. The Hybrid Hierarchical Clustering Algorithm (HHCA) is a promising three-layer approach inspired by the TL-LEACH. It uses centralized gridding, based on Fuzzy C-Means (FCM) algorithm at the upper layer to select the grid heads and a distributed clustering, based on energy-aware LEACH algorithm at the lower layer to select the cluster heads [8]. The HHCA technique outperforms most of the previously proposed clustering methods. However, all of the above mentioned clustering approaches were developed for the static WSNs and perform poorly when implemented in mobile sensor networks.

In MWSNs, there are frequent changes in network topology due to node mobility, resulting in dis-association between the sensor nodes and their cluster heads which results in high data loss and reduced data rates. This led to the development of clustering techniques which take into account the node mobility in addition to node energy and location such as LEACH-Mobile, LEACH-ME etc. [9]–[12]. Although these techniques handle node mobility and improve data rates in MWSNs, but since these are based on two-layer distributed clustering therefore they fail to achieve optimal energy efficiency and scalability.

In this paper, we propose two mobility-aware clustering algorithms based on three-layered clustering: MCCA; Mobility-aware Centralized Clustering Algorithm and MHCA; Mobility-aware Hybrid Clustering Algorithm. The MCCA implements mobility-aware Fuzzy C-Means method based gridding at two levels of clustering hierarchy. The MHCA implements mobility-aware Fuzzy C-Means method based gridding at the upper level and mobility-aware distributed clustering at the lower level. Our proposed algorithms are inspired by the HHCA algorithm, however our algorithms have been designed for mobile WSNs while HHCA was designed for the static WSNs. We carried out simulations using the open source Cooja simulator with Contiki 3.0 operating system developed for the constrained WSN. The simulation results demonstrate the effectiveness of our proposed algorithms in limiting the negative impact of mobility on data rates and energy consumption in MWSN. Our paper is structured in the following order. In section II, we provide the background for our research and outline some of the notable related work. In section III, we present the detailed design of our proposed MCCA and MHCA clustering algorithms. In section IV, we explain the simulation environment and present our simulation results and findings. Finally, section V concludes our paper and summarizes the results.

II. PRELIMINARIES

A primary concern for routing in MWSNs is energy efficiency due to irreplaceable severely-constrained battery-powered mobile sensor nodes, unpredictable topology changes and frequent path failures [10]. The hierarchical routing falls in the category of network-based routing protocols. The approach in these protocols is to dynamically organize network nodes into sectors called clusters which are further grouped into larger sectors and so on. Each cluster selects a cluster head which aggregates data prior to forwarding it, thus reducing data and minimizing energy consumption [4]–[8]. This section summarizes the basic design of some of the notable hierarchical clustering approaches which form much of the basis of our proposed algorithms.

A. LEACH AND LEACH-MOBILE

LEACH is an energy-efficient two-layer clustering algorithm based on distributed approach where all nodes make decisions autonomously for the selection of the cluster head. At the beginning of a round, a node selects itself a cluster head with probability $Pj(t)$ such that the number of awaiting heads of clusters for the trip is m. In a round r, every node among the N nodes in the network is selected as cluster head with probability given below [5]:

$$Pj(t) \begin{cases} m/N - m * \left(r \bmod \dfrac{n}{m}\right): & C_j(t) = 1 \\ 0: & C_j(t) = 0 \end{cases} \tag{1}$$

where $C_j(t)$ indicates whether the node j is selected as a cluster head for the last round (r mod N/m). $C_j(t) = 0$ implies that the node j is selected as the cluster head. The nodes which are not already selected as cluster heads recently i.e., $C_j(t) = 1$ have the chance to become cluster heads in the next round $r + 1$. When a node is selected as cluster head, it broadcasts Cluster Head Notification and waits for join request from the cluster nodes. A node receiving the Cluster Head Notification, selects the nearest cluster head in the grid and sends join request to it. A cluster head defines and sends Time Division Multiple Access (TDMA) plan to all members of the cluster. A layer-0 sensor node sends it sensed data to the layer 1 cluster head which gathers data from all other layer-0 sensor nodes which are associated with it and route it to the layer 2 sink or base station.

LEACH-Mobile protocol improves upon the LEACH protocol which was proposed for the static WSN. It supports sensor network applications which comprise both static and mobile nodes. The basic operation of LEACH-Mobile is same as LEACH protocol but a modification has been proposed to support node mobility. Contrary to the LEACH protocol where the cluster head waits for the nodes to send their data to it in the allocated timeslots, the cluster head in LEACH-Mobile protocol is proactive and solicits data from the nodes by sending request message to them. Once data transmission is complete, the cluster head verifies that all sensor nodes in the cluster have sent data. Those nodes which do not send data in a frame are marked in a list and in case those nodes do not send data again, they are considered having moved out of the cluster, the TDMA frame is modified and the modified frame is shared with all other nodes in the network [9].

B. FUZZY C-MEANS CLUSTERING PROTOCOL

Fuzzy C-Means is an efficient two-layer clustering protocol based on the idea of centralized gridding [13]. The algorithm comprises of three phases of operation namely, cluster formation, cluster head(s) selection and data transfer. Initially the base station receives the geographical location information from all the sensor nodes in the network and runs the FCM algorithm to identify cluster centers and form clusters based on proximity of sensor nodes from the center. In FCM algorithm, each node is assigned a degree of belongingness or association with the cluster head(s) by assigning it a coefficient for being a member of a cluster and repeatedly computing the centroid of each cluster until the algorithm converges. Once the clusters are formed, the base station selects the cluster heads from among the centrally located nodes with node energy as a consideration. In a network of N nodes resulting in C clusters, the clusters are formed by diminishing the objective function given in Equation 1 where u_{ij} is the degree of association between the sensor node j with the cluster i and d_{ij} is the distance from the sensor node j to the center of the cluster i.

$$J_m = \sum_{i=1}^{C} \sum\nolimits_{j=1}^{N} u_{ij}^{m} d_{ij}^{2} \tag{2}$$

This degree of association is fuzzified once it has been calculated. The base station performs cluster head selection only at the first round. After the first round, the subsequent cluster head(s) selection is accomplished by the current cluster heads based on the node energy level reported by the nodes. The cluster heads generate the TDMA schedule for data transfer by the sensor nodes of the clusters. The FCM method has shown to outperform other algorithms such as LEACH in terms of energy-efficiency and network lifetime.

C. HYBRID HIERARCHICAL CLUSTERING APPROACH

HHCA algorithm has been proposed by Lee and Kao for WSN and is inspired by TL-LEACH which is based on three-layer network hierarchy instead of the typical two-layer hierarchy. Contrary to the distributed approach of TL-LEACH, the HHCA uses a hybrid of centralized and distributed approaches for cluster formations [8]. A key assumption in HHCA is that all sensor nodes are randomly positioned, and all sensor nodes are stationary. Thus HHCA has been designed for the static WSN. The HHCA implements two-level cluster head selection. The selection of upper tier cluster heads called the Grid Heads (GH) is based on the centralized gridding-based FCM algorithm and the selection of the lower level cluster heads called the Cluster Heads (CH) is based on the LEACH-based distributed clustering. The layer-0 sensor nodes sense a phenomenon and send the sensed data to the layer-1 cluster head, from where it reaches the layer-2 grid head and ultimately the sink. The grid heads and cluster heads are re-selected in each round. There are two rounds, namely gridding round and clustering round.

1) GRIDDING ROUND IN HHCA

In each gridding round, all sensor nodes inform the sink about their location and energy state, the sink then carries out the gridding operation using centralized Fuzzy C-Means (FCM) algorithm which we explained previously.

2) CLUSTERING ROUND IN HHCA

In each clustering round, the non-grid head nodes select cluster heads using distributed LEACH method with an extension of the consideration of node energy. If a node is the cluster head then it would broadcast the cluster head message and receive join requests from the cluster nodes.

III. DESIGN OF MOBILITY-AWARE HIERARCHICAL CLUSTERING ALGORITHMS FOR MWSN

A. NETWORK MODEL AND ASSUMPTIONS

We consider a MWSN comprising of mobile sensor nodes which are randomly deployed in an area M x Mm^2 for sensing and reporting the sensed data to a stationary base station positioned at some distance from the deployed area. We make the following basic assumptions for both MCCA and MHCA algorithms:

1) The base station is stationary but the sensor nodes are mobile with variable speeds and pause times.
2) The nodes can move at any time. All sensor nodes are aware of their location, residual energy and velocity.
3) All nodes have the same initial energy.
4) The transmit power of the nodes is adjustable according to the distance from the receiving node.
5) The energy spent in data transmission is same in both directions.

B. PROPOSED MCCA CLUSTERING ALGORITHM

In MCCA, centralized gridding is implemented at two tiers. The mobile sensor nodes can function in two modes; sensing mode (only senses the phenomenon and sends data to the associated grid head) and grid head (collects data from nodes/grid-heads in the grid, compresses it and forwards it to the upper tier grid head or base station). Fig. 1 shows the network model for MCCA.

In this model, the device classification is as follows: BS; a stationary Base Station at the top of the hierarchy which is placed at a distance from the network and is the ultimate destination of the sensor data, GH2; layer-2 Grid Heads, GH1: layer-1 Grid Heads and sensor nodes at layer-0. The data transfer is from bottom to top that is sensor nodes send data to their respective GH1s which forward this data after compression to GH2s which forward it to the BS (shown by the arrows in Fig. 1, node mobility is shown by the shooting symbol).

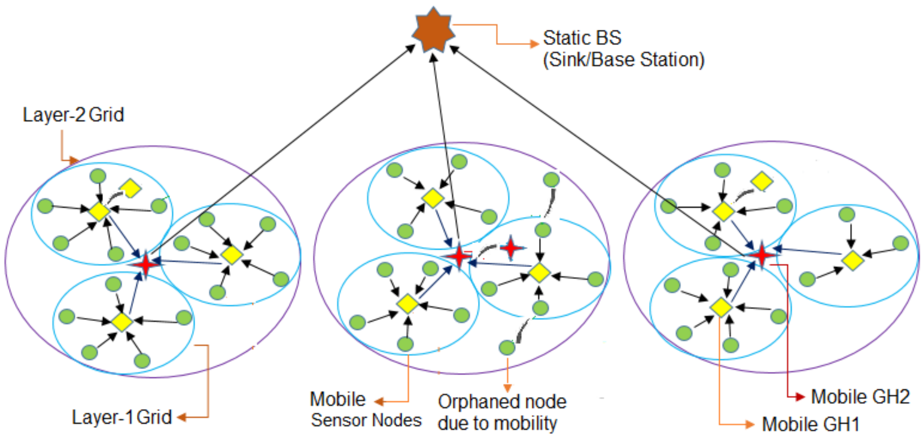

FIGURE 1. MCCA: Mobility-aware Centralized Clustering Algorithm for Mobile WSN.

The pseudo-code of MCCA is given as Algorithm 1. There are two phases of this algorithm; setup phase and steady-state phase. In the setup phase, the upper-tier and lower-tier grids are formed, layer-2 GH2 and layer-1 GH1 are selected and all sensor nodes associate themselves with their respective grid heads. In the steady-state phase, data transfer takes place. The operations in these phases are explained as follows:

In the setup phase, the first step is upper-tier or layer-2 cluster formation and Grid Heads GH2 selection. It is accomplished as follows: The process is initiated by the BS once all sensor nodes send their location, residual energy and velocity to the base station. The BS uses the geographical location parameter to run the FuzzyGridding algorithm to compute the cluster centers and to arrange nodes into clusters. Then GH2(s) are selected by the BS from amongst the nodes positioned closest to the cluster center with optimal residual energy and minimum velocity. If a node is selected by the BS as GH2, it would broadcast the GH2 message and await the later JOIN-REQ messages from the layer-1 GH1s.

The next step is lower-tier or layer-1 cluster formation and Grid Heads GH1 selection. It is accomplished as follows: The BS sends the position, residual energy and velocity of sensor nodes which are not selected as GH2 to the GH2(s) which use the FuzzyGridding algorithm to compute cluster centers and form lower-tier clusters. The GH2(s) then select layer-1 GH1(s) from among the center positioned nodes with optimal residual energy and lowest velocity. At this time all layer-0 sensor nodes associate with layer-1 GH1(s). After a fixed interval, every GH1 creates its TDMA schedule and shares it with the nodes associated with it. This completes the setup phase. After the initial setup phase, the subsequent setup phases are not initiated by the BS but old GH2(s) select new GH2(s) and new GH2(s) select new GH1(s) based on the same algorithm, parameters and criteria as explained above. The nodes keep their Grid Heads informed about their position, residual energy and mobility by updating this information in every data packet that is sent.

In the steady-state phase, normal data transfer takes place from layer-0 sensor nodes terminating at the BS. The layer-0 sensor nodes send sensed data to GH1 following the advertised TDMA schedule. The GH1 aggregates and compresses data from all layer-0 sensor nodes in its cluster and sends it to GH2 via Carrier Sense Multiple Access (CSMA). The GH2 also uses CSMA to send data to the BS.

The node mobility is addressed in the following manner: Every GH2 maintains a list of GH1s associated with it and every GH1 maintains a list of sensor nodes associated with it. Upon not hearing from a GH1/node in two consecutive frames, the GH1/node is considered to have moved out of the cluster range therefore it is removed from the list. The TDMA schedule is updated by the GH1 and shared with the associated nodes. For mobility management, we introduce Cumulative Acknowledgement which is broadcast by the GH2/GH1 after every frame. The GH2 acknowledges the receipt of data from its GH1s and the GH1 acknowledges the receipt of data from nodes. If a GH1/node does not receive acknowledgement from its GH2/GH1, it considers itself orphaned due to mobility. The orphaned GH1/node solicits a new GH2/GH1 and associates with it by sending JOIN-REQ which is accepted based on a degree of association. When a new GH1/node joins a GH2/GH1, the GH2/GH1 updates its node list. The GH1 updates its TDMA schedule and shares it with all nodes in its cluster.

C. PROPOSED MHCA CLUSTERING ALGORITHM

In MHCA, Fuzzy C-Means method based centralized gridding is implemented at the upper tier and LEACH-Mobile inspired distributed clustering is implemented at the lower tier. The mobile sensor nodes can function in three modes; sensing mode (only senses the phenomenon and sends data to the associated cluster head), cluster head (gathers data from nodes in the cluster, compresses it and forwards it to the grid head) or grid head (gathers data from the associated cluster

Algorithm 1 MCCA: Mobility-Aware Centralized Clustering Algorithm

```
Input:
    SN: Sensor Network
    BS: Base Station of SN
    UG: {ug | ug is upper-tier grid of SN}
    LG: {lg | lg is lower-tier grid of SN}
    N: {n|n is a node of SN}
    NL: Nodes List (n/GH1)
Output:
    GH2(n): the upper-tier GridHead of node n
    isGridHead2(n): true if GH2(n) == n
    GH1(n): the lower-tier Grid Head of node n
    isGridHead1(n): true if GH1(n) == n
Function:
    broadcast (message, range);
    send (message, destination-node);
    fuzzyGridding (position (N), energy(N),
    velocity(N));
    position(n): returns the position of node n
    energy(n): returns the residual energy of node n
    velocity(n) : returns the velocity of noden
Initialization:
    isGridHead2 (n) = false;
    isGridHead1(n) = false;
    isdata(n) = false;
Main:
/* for each upper-tier gridding round */
send(position(n) & energy(n) & velocity(n), BS);
BSexecutes GH2(n) ←fuzzyGridding(position(N), energy(N), velocity(N));
BSexecutes broadcast(GH2(N), UG); // Gridding-Message
Upon receiving Gridding-Message from BS;
if(GH2(n) == n)
    isGridHead2 (n) ← true;
    broadcast(GH2-Message, ug);
    Upon receiving JOIN-REQ message from GH1s;
    Update Nodes List (GH1);
else isGridHead2 (n) ← false;
end if
/* for each lower-tier gridding round */
send(position(n) & energy(n) & velocity(n), GH2);
if(isGridHead2 (n) == false)
    GH1(n) ←fuzzyGridding(position(N), energy(N),
    velocity(N));
    if(GH1(n) == n)
        isGridHead1 (n) ←true;
        broadcast(GH1-Message, lg);
        Upon receiving JOIN-REQ message from sensor nodes at layer 0;
        Update Nodes List (n);
        Create TDMA schedule and share with nodes in the Nodes List (n);
    else isGridHead1 (n) ←false;
        Upon receiving GH1-Message;
```

Algorithm 1 *(Continued.)* MCCA: Mobility-Aware Centralized Clustering Algorithm

```
        Send JOIN-REQ message to the selected GH1;
        Upon receiving TDMA schedule;
    end if
end if
/* for steady-state phase */
if (isGridHead2(n) == false && isGridHead1(n) == false) and there is sensed data to send
Follow TDMA schedule
send (sensed data & position(n) & energy(n) & velocity(n), GH1);
    if(Cum-ACK(NL) ! <> n)
        Send JOIN-REQ message to solicit GH1
    end if
else if (isGridHead1(n) == true)
    collect and aggregate received data
    Use CSMA
    send (Cum-ACK (NL), n)
    send (aggregated data, GH2);
    isdata(n) = true;
    if (isdata(n) == false) //for 2 rounds
        Update Nodes List(n)
        Share updated TDMA schedule
    end if
    if(Cum-ACK(NL) ! <> GH1)
        Send JOIN-REQ message to solicit GH2
    end if
else if (isGridHead2(n) == true)
    Use CSMA
    send (Cum-ACK(NL), GH1)
    send (collected data, BS);
    isdata(n) = true;
    if (isdata(n) == false) //for 2 rounds
        Update Nodes List(GH1)
    end if
end if
```

heads and forwards it to the base station). Fig. 2 shows the network model for MHCA.

In this model, the device classification is as follows: a stationary base station (BS) at the top of the hierarchy which is placed at a distance from the network and is the ultimate destination of the sensor data, GH; layer-2 Grid Heads, CH: layer-1 Cluster Heads and sensor nodes at layer-0. The data transfer is from bottom to top that is sensor nodes send data to their respective CHs which forward this data after compression and aggregation to GHs which forward it to the base station (shown by the arrows in Fig. 2, node mobility is shown by the shooting symbol).

The pseudo-code of MHCA is given as Algorithm 2. There are two phases of this algorithm. In the setup phase, the grids

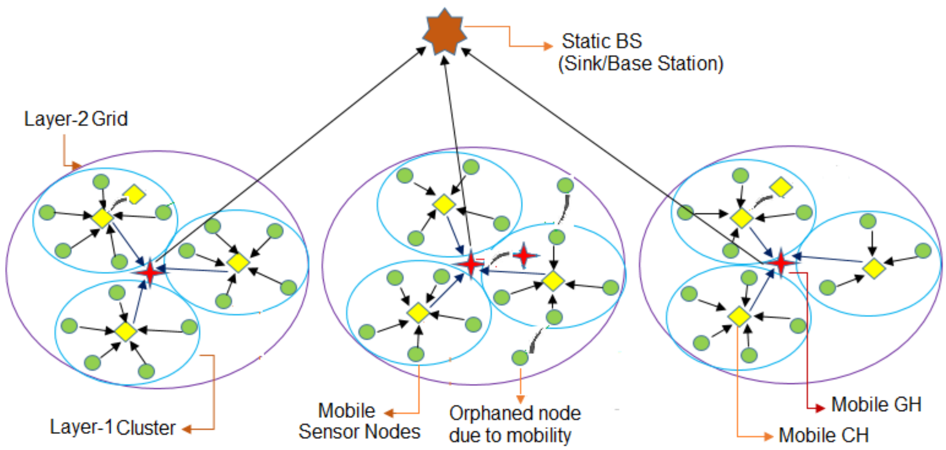

FIGURE 2. MHCA: Mobility-aware Hybrid Clustering Algorithm for Mobile WSN.

and clusters are formed, Grid Heads and Cluster Heads are selected and all sensor nodes associate themselves with their respective GHs/CHs. In the steady-state phase, data transfer takes place. The operations in these phases are explained as follows:

In the setup phase, layer-2 grids are formed and Grid Heads are selected in exactly the same manner as in MCCA. However, the layer-1 cluster formation and Cluster Heads selection is based on distributed clustering. The nodes which are not selected as GHs, select CHs based on the LEACH approach with a consideration of node energy and node velocity. The CHs broadcast the CH-Message and in response to it, receive JOIN-REQ messages from those nodes that are closest to the CH and are neither GHs nor CHs. Each CH creates its TDMA schedule and shares it with nodes of the cluster.

In the steady-state phase, layer-0 sensor nodes send sensed data to CHs following the advertised TDMA schedule. The CH aggregates and compresses data from all layer-0 sensor nodes in its cluster and sends it to the GH via Carrier Sense Multiple Access (CSMA). The GH uses CSMA to send data to the BS. The node mobility is addressed in the same way as it is managed in MCCA, as explained in the previous section.

IV. SIMULATION ENVIRONMENT

A. FIRST ORDER RADIO MODEL

We assume that a node's energy is depleted primarily due to sending and receiving data. The First Order Radio Energy Model is by far the most suitable energy dissipation model for low-power radio [14]. Therefore we employ this model in our simulations for energy consumption in data transmission and reception by the sensor nodes. According to the First Order Radio Model, the Free Space Model (power loss proportional to d^2) is employed when the transmitter and the receiver are within distance (d_0) from each other, and the Multipath Fading Channel Model (power loss proportional to d^4) is employed when the separation between the transmitter and the receiver exceeds this distance. The energy expended in transmitting a packet comprising of k-bits over a transmission distance d, $E_{Tx}(k, d)$ is given by:

$$E_{Tx}(k, d) = \begin{cases} E_{Elec}(T)^{*}k + \varepsilon_{fs}{}^{*}k^{*}d^2; & d < d_0 \\ E_{Elec}(R)^{*}k + \varepsilon_{amp}{}^{*}k^{*}d^4; & d < d_0 \end{cases} \quad (3)$$

The energy consumed in receiving a packet comprising of k-bits is $E_{Rx}(k)$ and is given by:

$$E_{Rx}(k) = E_{Elec}{}^{*}k \quad (4)$$

$E_{Elec}(T)$ is per-bit energy consumption in transmitter, ε_{fs} is energy consumption amplification factor for the free space model. $E_{Elec}(R)$ is per-bit energy consumption in receiver and ε_{amp} is energy consumption amplification factor for the multipath radio model. The distance threshold d_0 is given by

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{amp}}} \quad (5)$$

B. MOBILITY MODEL

A number of mobility models have been proposed for mobile networks based on the various factors such as the type of application, the geographical location, extending the network lifetime or simplicity [15]. In mobile networks, the mobility models are broadly classified into two categories: group mobility model and entity (individual) mobility model [16]. Our algorithms have been designed for the entity mobility model category. Since the Random Waypoint mobility model [17] is the simplest, the most popular and widely used mobility model in the entity mobility model category therefore in our simulations, we have used it. It is by far the most thoroughly studied mobility model for the next generation wireless networks. In this model, there is a pause period and a motion period. In the pause period, a node stays in its current position for some period of time. In the motion period, the node chooses a random direction and moves in that direction at a random speed. Upon reaching the new position, the node again goes into the pause period. Normally in Random Waypoint model, the pause period can

Algorithm 2 MHCA: Mobility-Aware Hybrid Clustering Algorithm

```
Input:
    SN: Sensor Network
    BS: Base Station of SN
    UG: {ug | ug is upper-tier grid of SN}
    LC: {lc | lc is lower-tier cluster of SN}
    N: {n|n is a node of SN}
    NL: Nodes List (n/CH)
Output:
    GH(n): the upper-tier GridHead of node n
    isGridHead(n): true if GH(n) == n
    CH(n): the lower-tier Cluster Head of node n
    isClusterHead(n): true if CH(n) == n
Function:
    broadcast (message, range);
    send (message, destination-node);
    fuzzyGridding (position (N), energy(N), velocity(N));
    leachClustering(energy(N), velocity(N), UG);
    position(n): returns the position of node n
    energy(n): returns the residual energy of node n
    velocity (n) : returns the velocity of node n
Initialization:
    isGridHead (n) = false;
    isClusterHead(n) = false;
    isdata(n) = false;
Main:
1.  /* for each upper-tier gridding round */
2.  send(position(n) & energy(n) & velocity(n), BS);
3.  BSexecutes GH(n) ←fuzzyGridding(position(N),
    energy(N), velocity(N));
4.  BSexecutes broadcast(GH(N), UG); // Gridding-
    Message
5.  Upon receiving Gridding-Message from BS;
6.  if(GH(n) == n)
7.  isGridHead (n) ←true;
8.  broadcast(GH-Message, ug);
9.  Upon receiving JOIN-REQ message from CHs;
10. Update Nodes List (CH);
11. else isGridHead (n) ←false;
12. end if
13. /* for each lower-tier clustering round */
14. send(position(n) & energy(n) & velocity(n), GH);
15. if (isGridHead (n) == false)
16.   CH(n) ←leachClustering(energy(n) & velocity(n),
      ug);
17.   if (CH(n) == n)
18.     isClusterHead (n) ←true;
19.     broadcast(CH-Message, lc);
20.     Upon receiving JOIN-REQ message from sensor
        nodes at layer 0;
21.     Update Nodes List (n);
22.     Create TDMA schedule and share with nodes in
        the Nodes List (n);
```

Algorithm 2 *(Continued.)* MHCA: Mobility-Aware Hybrid Clustering Algorithm

```
23.   else isClusterHead (n) ←false;
24.     Upon receiving CH-Message;
25.     Send JOIN-REQ message to the selected CH;
26.     On receiving TDMA schedule;
27.   end if
28. end if
29. /* for steady-state phase */
30. if (isGridHead(n) == false && isClusterHead(n) == false) and there is sensed
    data to send
31.   Follow TDMA schedule
32.   send (sensed data & position(n) & energy(n) &
        velocity(n), CH);
33. if (Cum-ACK(NL) ! <> n)
34.   Send JOIN-REQ message to solicit CH
35.  end if
36. else if (isClusterHead(n) == true)
37.   collect and aggregate received data
38.   Use CSMA
39.   send (Cum-ACK (NL), n)
40.   send (aggregated data, GH);
41.   isdata(n) = true;
42.   if (isdata(n) == false) //for 2 rounds
43.     Update Nodes List(n)
44.     Share updated TDMA schedule
45. end if
46. if(Cum-ACK(NL) ! <> CH)
47.   Send JOIN-REQ message to solicit GH
48.  end if
49. else if (isGridHead(n) == true)
50.   Use CSMA
51.   send (Cum-ACK(NL), CH)
52.   send (collected data, BS);
53.   isdata(n) = true;
54.   if (isdata(n) == false) //for 2 rounds
55.   Update Nodes List(CH)
56.  end if
57. end if
```

be in the range 0-20 seconds and motion speed can be in a range 0.01-20 m/s.

C. SPECIFICATIONS OF SIMULATIONS

We carried out simulations to assess the performance of our proposed MCCA and MHCA algorithms against LEACH-Mobile, TL-LEACH and HHCA. The simulations were carried out using the open source Cooja simulator with Contiki 3.0 operating system developed for the constrained WSN [18]. This simulation platform is widely accepted due to its compliance and aptness for creating simulation environments for evaluating the protocols and innovations in the fields of WSNs and the Internet of Things. We created a 300-nodes network of mobile nodes which were randomly and uniformly distributed in an area of 300 × 300 m^2 with a single static sink. The simulation parameters are listed in Table 1.

TABLE 1. Simulation parameters.

Symbol	Quantity
Network Area	300X300 m^2
Number of Mobile Nodes	300
Sink Node	Single and static
Sink Node Location	180m/90m
Mobility Model	Random Waypoint Model
Max Node Speed	2 m/s
Max Node Pause Period	5 sec
Data Packet Size	500 bytes
Packet Header Size	20 bytes
Broadcast Packet Size	16 bytes
Bandwidth	1 Mbps
Initial Node Energy	2 J
E_{Tx}/E_{Rx}	50 nJ/bit
εfs	10 pJ/bit/m^2

D. SIMULATION RESULTS AND DISCUSSION

In this section, we present the results of our simulations to evaluate the performance of MCCA and MHCA. Our main interests are the network lifetime in terms of the number of alive nodes as a function of the simulation time, the energy consumption, the distribution of clusters and the number of received packets. The network lifetime can be represented by metrics such as First-Node-Dies (FND), Half-the-Nodes-Alive (HNA), Last-Node-Dies (LND) or Number of Alive Nodes [19]. We select the Number of Alive Nodes to represent network lifetime. It represents the total number of nodes which are alive with respect to simulation time and shows the pattern which the network nodes follow as they die out. The results in Fig. 3 show the Number of Alive Nodes as a function of number of rounds.

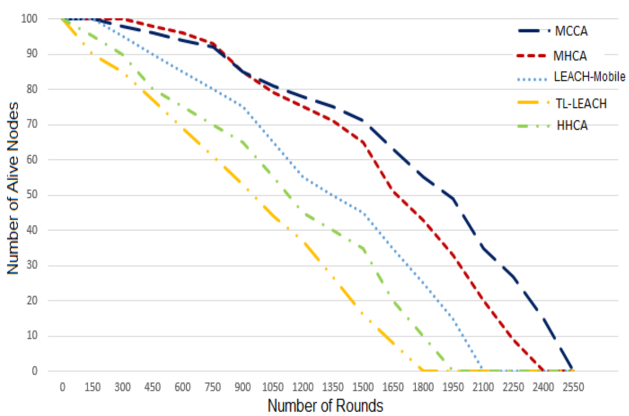

FIGURE 3. Lifetime of network.

We observe that for initial 300 rounds, the number of alive nodes are same for MCCA, MHCA and LEACH-Mobile but beyond that MCCA and MHCA outperform other protocols because in these protocols, residual energy of node and mobility are taken into consideration in both cluster head selection and data transfer phase. Between 750 to 900 rounds, MCCA has less number of alive nodes as compared to MHCA because the overhead of cluster head selection at the upper tier in the centralized approach is slightly more than the distributed approach therefore the first node dies early in MCCA. However beyond 900 rounds, MCCA gives best performance because as the number of rounds increase, more nodes die in MHCA due to LEACH approach in the lower layer where all nodes participate in cluster head selection resulting in more energy consumption.

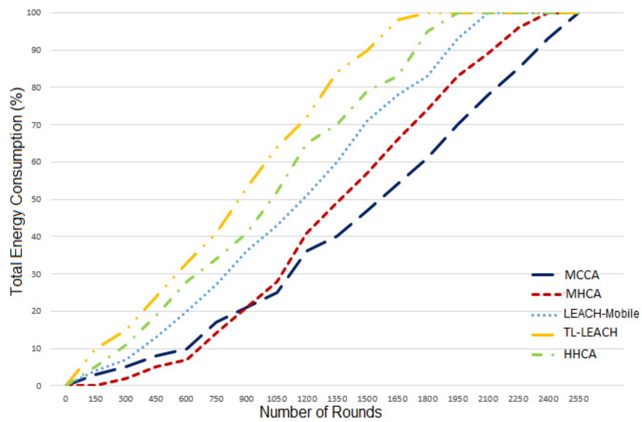

FIGURE 4. Total energy consumption (%) versus number of rounds.

Fig. 4 compares the energy consumption in all protocols. MCCA and MHCA give best performance due to two reasons; 1) optimal selection of cluster heads taking into consideration node mobility in addition to position and energy and 2) hierarchical clustering which reduces data transfer energy because distance between nodes and their cluster heads is less. The MCCA uses centralized clustering therefore there are more chances for the cluster head to be around the center of the cluster.

This results in less data transfer energy consumption as compared to MHCA in which the cluster head can be located at any position (center or edge) within the cluster.

Fig. 5 shows the distribution of number of clusters versus simulation time (number of rounds) for each algorithm. It is desirable for a clustering algorithm to exhibit stable distribution of clusters which is reflected by a flat graph and least number of sharp and frequent transitions. It has been reported that the fully centralized approaches like FCM and LEACH-C generate a constant number of clusters for a long duration while distributed approaches like LEACH and TL-LEACH give sharp transitions and the hybrid approach HHCA gives a constant number of clusters for a fairly long duration [8]. Fig. 5 shows the distribution of clusters in MCCA and MHCA and compares it against LEACH-Mobile, TL-LEACH and HHCA. As expected TL-LEACH performs poorly while HHCA gives stable clusters till 300, LEACH-Mobile is highly unstable throughout due to distributed clustering and mobility. We observe that MCCA and

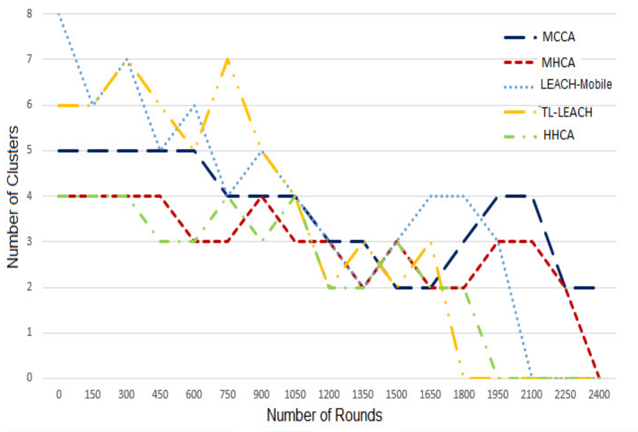

FIGURE 5. Distribution of number of clusters versus number of rounds.

MHCA algorithms generate stable number of clusters till 600 and 450 respectively which is a fairly long duration as compared to all other algorithms and the MCCA algorithm gives less transitions as compared to MHCA algorithm. This is because MCCA is based on centralized clustering while MHCA is a hybrid clustering algorithm. We conclude that both MCCA and MHCA outperform LEACH-Mobile as well as TL-LEACH and HHCA in terms of stable number of clusters and MCCA is more stable as compared to MHCA algorithm. Towards the end of the graph, the number of clusters approach to zero as nodes die out in each algorithm. Since MCCA algorithm has the longest network lifetime therefore the nodes die out later than all other algorithms.

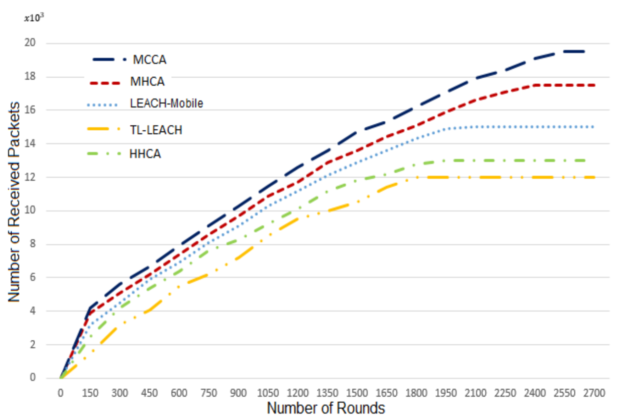

FIGURE 6. Total Number of Received Packets at the base station.

Fig. 6 compares the protocols in respect of the total number of received packets at the base station. This is a very important parameter to be examined because node mobility increases the packet drop probability resulting in a reduced number of received packets at the sink. It is a major challenge for clustering protocols in mobile environments.

It can be seen that when node mobility is not handled as in TL-LEACH and HHCA, the number of received packets is very low. LEACH-Mobile improves this because it is a mobility-aware protocol. MHCA improves this further while MCCA outperforms other protocols by a clear margin.

V. CONCLUSION

Minimizing data loss and maximizing energy efficiency are two of the most critical challenges for clustering in Mobile WSNs. This paper has proposed two clustering techniques for Mobile WSN, based on three-layer hierarchy with a goal to achieve energy-efficient clustering and minimize data loss. Our first technique, MCCA implements centralized gridding at the two clustering levels. Our second technique, MHCA implements centralized gridding at the upper level and distributed clustering at the lower level. Both techniques optimize hierarchical clustering for node mobility. The simulation results show that our proposed algorithms mitigate the effect of mobility on clustering and improve performance with respect to network lifetime, energy consumption, distribution of clusters versus time and the number of packets received at the base station. We observe that the centralized hierarchical clustering is superior to the hybrid hierarchical clustering when used in mobile environments.

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