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Parametric-based mobility for providing opportunistic geocasting in spatially separated wireless sensor networks

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Abstract: Uneven deployment and environment constraint leads to the formation of a spatially separated wireless sensor network (SS-WSN). Most of the traditional WSN architectures consist of static nodes that are densely deployed over a sensing area and are fully connected. SS-WSN is a group of disjoint subnetworks where connectivity is generally maintained by energy rich mobile nodes (ERMN), which roam about from one subnetwork to another. We propose an algorithm whereby the mobility of ERMN helps in distributing the geo message opportunistically in the region of interest. The routing consists of two phases: (1) transmission of the geo message from the source node to the ERMN based on a proactive mobility predictive scheme (PMPS) within a subnetwork (intra-routing); (2) relaying the geo message from the source subnetwork to the destination subnetwork (inter-routing). This is achieved with the help of an ERMN that traverses on a parametric curve, visiting each subnetwork. The key issue addressed here is to minimize latency and improve reliability, thereby keeping the network virtually connected at variable period of time. Extensive simulation shows that the proposed solution performed better than random path-based mobility routing.

Key words: Greedy forwarding, parametrized mobility, opportunistic routing, wireless sensor networks

1. Introduction

Wireless sensor networks (WSNs) typically consist of a large number of sensor nodes to gather data in a human-constrained environment. The main purposes of sensor nodes are to monitor an area, including detecting, identifying, localizing, and tracking one or more objects. A large number of small and simple sensor devices communicate over short-range wireless interfaces to deliver observations over multiple hops to a special node called a sink. With these properties, WSNs are considered for several critical application scenarios including battlefield surveillance, habitat monitoring, traffic monitoring, health care, and security applications [1–4]. Sensor nodes and these applications are subject to constraints such as limited processing, storage, communication capabilities, and power supplies. The major challenge in WSNs is it is not always possible to deploy a fully connected network. Physical and environmental constraints or unavoidable disaster may leave islands of subnetworks that are distanced geographically apart and this restricts effective communication among them. This spatially separated (SS) network needs a heterogeneous architecture composing mobile nodes [1] that can move randomly and collect/deliver data opportunistically from/to sensors in their direct communication range. Geocasting is a process of delivering a packet to all the nodes that are confined to a geographical area. There are studies where geocasting is implemented for a fully connected network [2,3] and an intermittently connected

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network [4,5]. To the best of our knowledge, this is the first work that implements geocasting for SS-WSN. The opportunistic geocast takes the help of ERMNs that travel between these subnetworks with a regular or random mobility pattern to reach the region of interest. The ERMN will switch between an inter-network movement state and an intra-subnetwork data delivering state to distribute the packet in the destined area of the subnetwork.

Many geocasting algorithms are proposed for ad hoc networks [2], MANET [6], and VANET [7]. These protocols cannot be adapted for SS-WSNs easily due to the disjoint architecture. The partition makes SS-WSNs delay tolerant and the routing to take place opportunistically. There are two types of routing schemes used in delay tolerant networks. One is auxiliary nodes assisted (ANA) routing and the other is independent mobile nodes (IMN) routing schemes. ANA routing is a set of special nodes needed to forward and distribute data. IMN exploits node mobility to route data. SS-WSNs generally use the ANA routing scheme, which creates contact opportunity actively by a special auxiliary node for carrying data [8,9]. In this paper, an ERMN is the auxiliary node moving according to a schedule and has a fixed mobility model like the bus mobility model. Henceforth, the SS-WSN uses an ERMN, which can take a random mobility model, or fixed mobility model, which could be history based, and assist for an effective routing among the subnetworks.

The proposed work makes a basic assumption that each node knows its position based on a GPS device or from any localization protocol [7]. The sender nodes know the destination subnetwork position. The ERMN takes either the cubical or linear route. Inter-contact times are calculated based on the parametric equation the ERMN uses for its traversal. It is the duration of time between two subsequent contacts of the ERMN. The contact time is considered to be sufficient for packet exchange between the ERMN and the neighboring node.

In intra-routing, inside each partition, static nodes forward data greedily using a PMPS. Each mobile node has a mobility history. When a source node has a geo message to be sent outside its home subnetwork, it looks out for the availability of an ERMN. After the identification of the ERMN, it enquires whether the ERMN moves in the direction of the destination based on the history of mobility patterns. If an ERMN moves towards the destination, inter-routing is performed. The main purpose of the mobile node is collecting and forwarding the data until it reaches the destination subnetwork.

The rest of the paper is organized as follows. Section 2 summarizes related work. Section 3 investigates the SS-WSN with a few mobile relays and gives a joint mobility and routing algorithm. Section 4 gives the simulation results for a finite number of nodes and ERMN. Finally, Section 5 concludes the paper.

2. Related work

The literature on SS-WSNs mostly concentrates on mules that work as a data collector and deliver it to the sink. These mules could have random mobility or controlled mobility. In controlled mobility the previous works have concentrated on path planning to minimize latency. The path minimizing algorithm for mules to gather data in a SS-WSN is proposed in [8]. Sensor nodes are partitioned into several isolated subnetworks. Mobile mules are adopted to traverse these subnetworks and collect data [8,9]. The energy mule travelling salesman problem (EM-TSP) is used to address issues of data collection latency and network lifetime simultaneously. The mule traversal path has at least one landing port in each subnetwork. The energy consumption of sensors is bounded and the traversal path lengths of mules are minimized [8].

The mobility pattern of the mobile nodes can be taken as a regular predictable model [10] or an irregular one that appears in object tracking [11]. These patterns can be conjoined based on our routine social activity. One such human mobility described as a stochastic process with attributes of visiting pattern, inter-contact time, and aggregate inter-contact time predicting a probability distribution is presented in [12]. The framework is a social graph describing the mobility of a human on a predictable account; scenarios where the nodes deviate are not considered. Human mobility modeled by a bipartite graph with spatial, temporal, and social features observed from the real world data set is proposed in [13]. The hierarchical model of geocommunities with nodes temporal information is extracted from the instant (t) the node goes to a geo-community, and the period it spends within the community and outside the community.

The path establishment in a partitioned network in an opportunistic way is proposed in [14]. The mobility of nodes creates paths between source and destination at an instance of time. Henceforth the aim is to identify a path in space and time to forward packets. The routing table apart from the space information updates the temporal information of the node, which is the cache overhead the node has to pay. A greedy forwarding virtual destination algorithm considers the virtual destination instead of real destinations [15]. When a packet is sent to a stuck node, this node will select the next hop based on the position of the virtual destination. The algorithm modifies temporarily the destination of the packet until it is out of a local minima situation.

Mobility of sink is considered in studies where mules are not used. A local sink collects data from source nodes in a local and adjacent area and later disseminates aggregated data to a global sink. This local sink is one of the sensor nodes selected by the global sink, based on location information and other attributes of sensor nodes [16]. Butterfly (BFLY) is a lightweight, localized network coding protocol. BFLY allows the forwarding of coded messages to reduce the bandwidth requirement of multiple unicast sessions and thus increases the throughput capacity of multihop wireless networks. It uses an isolated wireless sensor network that is disconnected from the outside world most of the time. It thus relies on mobile mules to visit it and carry its sensory data to the outside world [17]. In [18] the mobility pattern of a bus is considered with two sample routes of butterfly and linear route. The bus traverses on this route such that they have a sequence of inter-meeting times determined based on their schedule assigned to the buses. Our parametric mobility for ERMN is a regular kind of movement based on human and social communities, which have a predictable traversal. The opportunistic geocast routes the packet intentionally towards the ERMN via subnetwork specific gateway nodes called sentinel nodes. The contribution of this paper is as follows: 1. Parametric resource distributions that can help the static sensor node communicate in a partitioned network. 2. The joint mobility and routing algorithm enables reliable delivery, which is theoretically analyzed in section 3 justified through simulation and performance analysis. 3. We compare the performance of our approach with random mobility and show predictive parametric mobility outperforms random mobility for an ERMN.

3. Parametric-based opportunistic routing

Message ferrying [19] or messenger mobility [20] considers controlled mobility with a simple straightforward traversal, based on which a proactive route can be framed between two disjoint clusters. The parametric-based traversal of ERMN is a cubic and linear trajectory. The ERMN m_i travels on this path passing through a set of subnetworks referred to as traversal set TS^i. The future traversal set is a subset of TS^i. FTS^i is defined as set subnetworks that are yet to be traversed by m_i. This set endorses the opportunistic routing among the nodes in a different subnetwork.

3.1. Problem statement

An SS-WSN is modeled as an undirected graph G = (V, E), where V is the set of sensor nodes in the subnetwork and E is the set of communication links between nodes in the subnetwork. The location of each sensor node $n_i \in$ V is denoted by (x_i, y_i). A special node $m_0 \in$ V is designated as the ERMN and is responsible for collecting sensory data from the source subnetwork and forwarding the collected data to the destination subnetwork. Each node has a communication range of R_c. Constrained by R_c and the physical environment, the network G is spatially separated in the sense that it is partitioned into multiple connected subnetworks G_0, G_1,..., G_K. The SS-WSN uses mobile nodes to collect and disseminate data from one subnetwork to the other. Without loss of generality, let us assume the ERMN m_j is responsible for moving around these subnetworks to collect and deliver their sensing data to G_k, where $k = \{1, 2,..., K\}$. We also assume that the ERMN m_j where $j = 1$ to p also has a communication range as R_c. When a mobile node enters the subnetwork, it must obtain the data from the corresponding subnetwork. In this subnetwork, a source node (static sensor node) must transmit the data to a mobile node using an intra-routing algorithm. By using the intermediate and sentinel nodes in a subnetwork the data are forwarded to the ERMN. Sentinel nodes are the one-hop neighbors of the ERMN that broadcast the beacon message of m_j, announcing its visit in the subnetwork.

Two phases of routing are categorized in the SS-WSN, intra- and inter-routing. Intra-routing takes place irrespective of whether the destination lies within the same or in a different subnetwork. If the packet has to move out of the home subnetwork, then the packet is forwarded towards the ERMN. Inter-routing takes place via the ERMN during continuous patrol of the ERMN following a parametric curve that traverses over the subnetwork, spread out in a butterfly pattern. The basic assumptions for the opportunistic routing are as follows: 1. Each subnetwork has m number of static nodes that are fully connected. 2. All nodes know their geographical position. 3. The ERMN has more energy and enough motor cycle capability to cycle on the parametric curve. 4. Static nodes are aware about the nodes in their subnetwork.

Figure 1 shows the architecture of the SS-WSN with an ERMN m_i, sensor node n, sentinel node n^r, and disjoint subnetwork G_k where $k = 1$ to 5. The G_k is a subgraph with a set of nodes that are connected to their local neighbors in the subnetwork. When a source node has a packet to be delivered to a particular destination, it initiates the intra-routing, which ends up at the destined node or at the ERMN via the sentinel node as indicated in the architecture diagram. The m_i visits the G_k at regular intervals during its traversal around the network on a cubical curve described in section 3.3. The beacon message of the m_i announces its presence in the subnetwork via sentinel nodes. The sentinel nodes are the sensor nodes that are one hop away from m_i. These nodes eventually pave the way for the static node to predict m_i future movement analyzing its traversal set TS^i. The FTS^i is predicted from the parametric equation and TS^i, where $FTS^i \subseteq TS^i$. When more than one ERMN is available in a G_k, FTS^i of each m_i is ordered temporally to select the appropriate ERMN. In the case the packet is handed to ERMN, inter-routing routes the packet to the destined subnetwork through direct or indirect inter-routing.

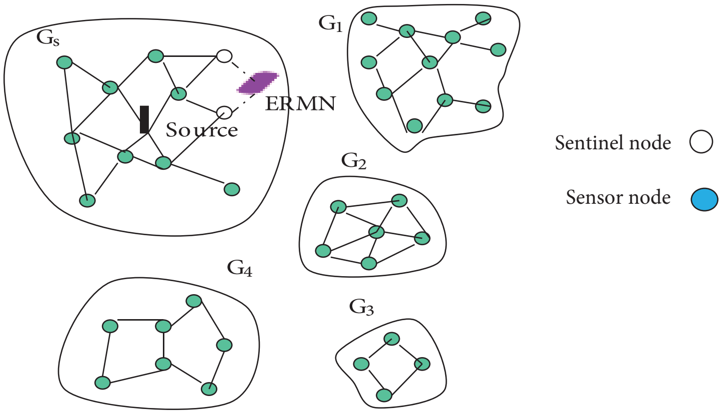
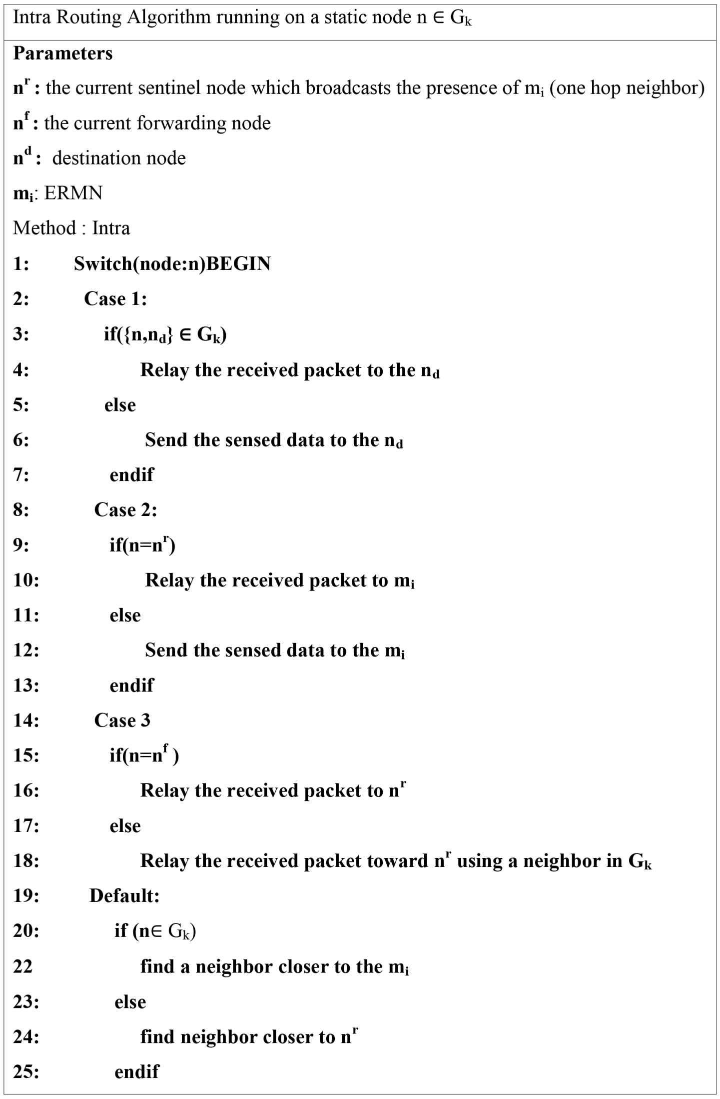


Figure 1. I Architecture of SS-WSN.

3.2. Intra-routing

In intra-routing greedy distance routing is performed by a PMPS. All sensor nodes know the presence of the ERMN in their subnetwork. Given the history based mobility trace of the ERMN, which consists of the location of ERMN (x_i, y_i), visit history of G_i, and direction of ERMN $?_i$, the future traversal of ERMN can be predicted. When the ERMN enters a particular subnetwork, it must broadcast its beacon message in the corresponding subnetworks. Henceforth the static nodes will know of the arrival of the ERMN in its G_i. After the announcement of the ERMN presence in this subnetwork, data forwarding is done by the intra-routing algorithm given in Figure 2. The intuition behind this algorithm is that any node n can forward the packet directly or through intermediate forwarders to the destination node n^d if it belongs to the same subnetwork. Otherwise the packet is forwarded to ERMN m_i via the sentinel node n^r. The whole idea of forwarding data revolves on the fact conceived by mobility history, which was announced recently by the ERMN in the subnetwork. By using the ERMN mobility traces, static nodes can predict the ERMN by PMPS.



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Intra Routing Algorithm running on a static node $n \in G_k$
Parameters
$n^r$ : the current sentinel node which broadcasts the presence of $m_i$ (one hop neighbor)
$n^f$ : the current forwarding node
$n^d$ :  destination node
$m_i$: ERMN
Method : Intra
Switch(node:n)BEGIN
  Case 1:
    if($\{n,n_d\} \in G_k$)
      Relay the received packet to the $n_d$
    else
      Send the sensed data to the $n_d$
    endif
  Case 2:
    if($n=n^r$)
      Relay the received packet to $m_i$
    else
      Send the sensed data to the $m_i$
    endif
  Case 3
    if($n=n^f$ )
      Relay the received packet to $n^r$
    else
      Relay the received packet toward $n^r$ using a neighbor in $G_k$
  Default:
    if ($n \in G_k$)
      find a neighbor closer to the $m_i$
    else
      find neighbor closer to $n^r$
    endif
```

Figure 2. Intra-routing algorithm.

3.3. Proactive mobility predictive scheme (PMPS)

The spatially separated subnetworks G_i are spread out in a butterfly pattern. The PMPS formulates a simple idea based on the mixed but regular mobility patterns for the set of four ERMN 'm_i' {for i = 1, 2, 3, 4}. The mobility pattern of two ERMNs say m_1 and m_2 takes a route that traverses on parameterized cubical curves $C_1(t)$ and $C_2(t)$ given in Eqs. (2) and (4), respectively. Figures 3a and 3b shows the graphical representation of the mobility pattern traversed in the forward direction by m_1 and m_2 individually. Figure 3c shows the combined trajectory of both ERMNs. The ERMNs m_3 and m_4 traverse on a parameterized line segment $L_1(t)$ and $L_2(t)$ is given in Eqs. (6) and (8), respectively, which joins the curve $C_1(t)$ and $C_2(t)$ on the vertical axis as shown in Figure 3d. The mobility pattern makes sure that the cubical and linear curves have inter-meeting points that connect them temporally based on the parameter 't' at different spatial positions.

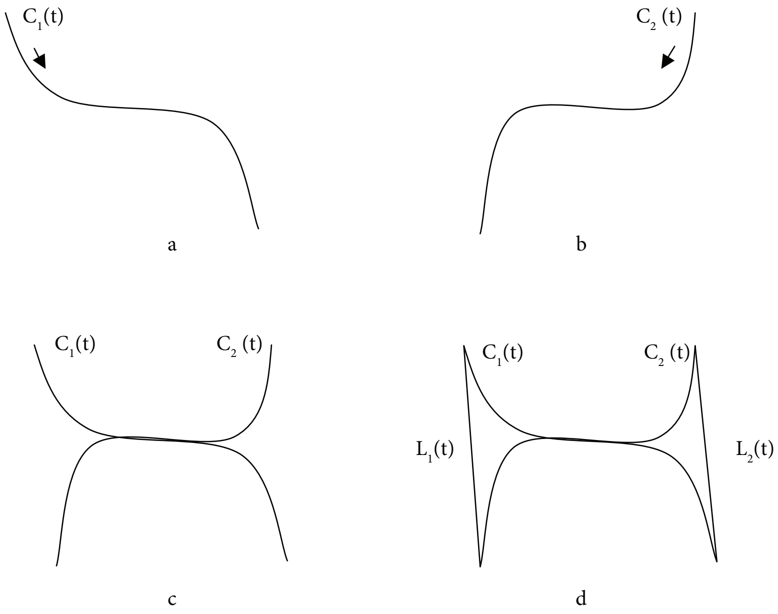

Figure 3. Parametric mobility pattern of ERMN (a) and (b) cubic traversal of m_1 and m_2 (c) overlapping traversal of cubic curve (d) combined parametric traversal of m_1, m_2, m_3, and m_4.

3.3.1. Parametrization

The ERMN m_1 traverses by the cubical curve

$$y = -0.1x^3 + 50, \tag{1}$$

which is parametrized on time variable 't' such that $C_1(0) = (-8, 101.2)$.

The parametric curve of m_1, which starts the traversal from the left topmost point $p_1(t_0)$ and trace towards down of the cubic curve $C_1(t)$ as shown in Figure 3c, is given as

$$C_1(t) = f(t-8, -0.1t^3 + 2.4t^2 - 19.2t + 101.2), \tag{2}$$

where $x_1(t) = t - 8$ and $y_1(t) = -0.1t^3 + 2.4t^2 - 19.2t + 101.2$ such that $0 \leq t \leq 16$.

After the completion of the forward traversal, which ends at point $p_1(t_e)$, m_1 traverses back from the right bottom to the top left on the previously traversed cubic curve, which is now parametrized as in Eq. (3). The ending point of $C_1(t)$ becomes the starting point for $C_1'(t)$

$$C_1'(t) = f(t+8, -0.1t^3 - 2.4t^2 - 19.2t - 1.2) \text{ where } 0 \leq t \leq 16. \tag{3}$$

A similar forward and backward traversal is done by m_2, which is parametrized in both directions between the point $p_2(t_0)$ and $p_2(t_e)$ as given in Eqs. (4) and (5), respectively. The cubic curve $C_2(t)$ considers $p_2(t_0)$ as its starting location and $p_2(t_e)$ as the ending point on it vice versa for $C_2'(t)$

$$C_2(t) = f(t-8, -0.1t^3 + 2.4t^2 - 19.2t + 101.2) \text{ where } 0 \leq t \leq 16 \tag{4}$$

$$C_2'(t) = f(t+8, -0.1t^3 - 2.4t^2 - 19.2t - 1.2) \text{ where } 0 \leq t \leq 16 \tag{5}$$

The ERMN m_3 and m_4 traverse on the line segment $L_1(t)$ and $L_2(t)$, respectively, as shown in Figure 3d. The parametrized line L_1 touches the curve C_1 at $p_1(t_0)$ = (–8, 101.2) and curve C_2 at $p_2(t_e)$ = (–8,0); similarly L_2 touches the curve C_2 at $p_2(t_0)$ = (8, 101.2) and curve C_1 at $p_1(t_e)$ = (8,0). Henceforth the parametrization of both line segments where $0 \leq t \leq 16$ is given in Eqs. (6) and (8) in the forward direction and Eqs. (7) and (9) represent the backward traversal.

$$L_1(t) = f(-8(1+t), 101.2) \tag{6}$$

$$L_1'(t) = f(-8(1+t), 101.2t) \tag{7}$$

$$L_2(t) = f(8(1+t), 101.2) \tag{8}$$

$$L_2'(t) = f(8(1+t), 101.2t) \tag{9}$$

The points p_1 and p_2 ensure that ERMN m_3 and m_4 have definite contact points with m_1 and m_2 at various time slots of their traversal. Apart from this, the traversal curves $C_1(t)$ and $C_2(t)$ of m_1 and m_2, respectively, do intersect midway leading to a contact point. The overall traversal of ERMN ensures that the paths intersect each other at regular intervals, giving rise to a periodic inter-contact time for packet exchange among ERMNs. When the ERMN visits a G_i it beacons its parametric curve, which enables the sensor to predict its future G_i traversal. It can find whether the ERMN would move towards the destination subnetwork and decides accordingly. The static node within the subnetwork can send the data to the ERMN using the greedy forwarding approach. In the greedy forwarding approach, the source node computes the distance between itself and the mobile node in the subnetwork. Then it computes the distance between each of its neighbor nodes and mobile node by distance formula. Compare these distances. If the source node is close to the mobile node, it can directly forward the data to the available ERMN. Otherwise data forwarding is done using the intermediate nodes greedily.

3.3.2. ERMN identification and routing

The ERMN periodically broadcasts a beacon message, which enables the sensor node to know about its presence in the current subnetwork G_v and predict its future traversal of other G_i in the network. The source node greedily forwards the packet towards the ERMN, m_i. When more than one m_i visits a $G_{i,}$ the m_i that is predicted to traverse towards the destination G_d is chosen according to its designated parametric curve. In the case where the destination lies within the G_i the source node actively transmits to the desired node as soon as it has the data to be delivered. However, when it is inter-subnetwork traversal, the source node has to wait for the arrival of the desired m_i, which can carry or relay the packet to the destination G_d. Once the packet is handed over to the sentinel node in the destination G_d, the sentinel node forwards the packet using greedy distance routing towards the destination node.

3.4. Inter-routing

The sender node finds the ERMN moving towards the direction of the destination subnetwork. The following two cases are considered: the first case deals with direct routing and the second case deals with indirect routing. If the mobile nodes move directly towards the destination subnetwork then it is called direct routing and if they do not move directly it is called indirect routing. Opportunistic routing is implemented in inter-routing and geocast is implemented at the destination subnetwork G_d in the intra-routing technique. The ERMN can forward the data to a region of interest (RoI) in the destination subnetwork by flooding the packet via sentinel node, which happens to be the boundary node of the RoI.

In direct routing, only one ERMN moves towards the destination direction. If any sensor node in the particular subnetwork wants to forward the data to the destination partition then it must make use of this ERMN. Opportunistic routing initially selects the suitable ERMN for inter-routing as given in Figure 4, based on the availability the packet could be directly relayed to the G_d. In indirect routing, two cases are considered. The first case is based on the movement of many ERMNs towards the destination direction or destination subnetwork. If more than one ERMN moves toward the destination subnetwork, then select an ERMN that reaches the destination earlier. The arrival at the destination subnetwork can be decided by sorting temporally the future traversal set. The logical time based on the parametrized traversal of the ERMN is used to achieve the timestamp order of reaching the destination.

The second case is based on nonavailability of a mobile node towards a destination subnetwork. If no ERMN moves towards the destination direction, then forward the data to any available ERMN that moves to the nearest destination subnetwork. When the mobile nodes move towards the next subnetwork, they have to hand over the data to another relaying ERMN that might reach the destination subnetwork earlier. Instead of waiting for the ERMN that directly moves towards the destination direction, it uses the opportunity of available ERMN and forwards the data. The handover of data is such that the packet reaches the G_i nearest to the destination subnetwork and is ultimately delivered to the G_d. Finally, when the packet reaches one of the destination nodes in the RoI, geocasting service is implemented by directed flooding, which makes sure that all the nodes in region get a copy and avoids unnecessary transmission to the neighboring nodes.

4. Performance evaluation

In this section, we analyze the performance of the proposed opportunistic geocast. A comprehensive simulation-based evaluation of the routing algorithm is done using the popular NS-2 simulator. The simulation environment of SS-WSN contains 20 to 100 sensor nodes in a 1250 x 1115 m^2 field that has a maximum of 12 subnetworks (partition) G_i. The G_1 to G_{12} are deployed in an isolated manner. Each G_i consists of a minimum of 4 to a maximum of 20 nodes in its subnetwork. There are four ERMNs that move around the network based on the parametric equation described in section 3.3.1. The ERMN moves according to their cubic and linear paths and ensures that their transmission radio overlaps at the contact points p_1 and p_2, respectively. The transmission

```
ERMN based Inter Routing Algorithm
Parameters
($X_i^m$, $Y_i^m$) : the current position of $m_i$ (cartesian coordinate)
$TS^i$ : Traversal Set for $m_i$, $TS^i = \{G_1^i(t), G_2^i(t), G_3^i(t), \ldots, G_p^i(t)\}$
$FTS^i$ : Future Traversal Set of $m_i$, $FTS^i \subseteq TS^i$
$n^r$ : the current sentinel node which broadcasts the presence of $m_i$ (one hop neighbor)
$n^f$ : the current forwarding node
$n^d$ : destination node
$m_i$: ERMN
Method : Inter
$m_i$ Broadcast ($X_i^m$, $Y_i^m$), $FTS^i$ and $TS^i$
while ($m_i$ is in $G_k$ )
      { if( $G_d \in FTS^i$ )
            Call DirectRoute
        elseif(( $G_d \in TS^i$ )&&($m_i$ is the only ERMN in $G_d$))
            Call DirectRoute
        endif
        If(( any ERMN of{$m_1,m_2,..,m_m$} is in $G_k$)&&( $G_d \in FTS^i$ ))
            { sort $FTS^i$ temporally
              select $m_i$ with minimal $FTS^i(t)$
              Call DirectRoute }
        elseif($G_d$ does not $\in TS^i(t)$)
            Call InDirectRoute
        endif
    }
END
```

```
DirectRoute()
Pick up one sentinel node $n^r_i$ for $m_i$
Broadcast ID of $n^r$
Relay packet from $n^r$ to $m_i$
```

```
InDirectRoute()
if($G_D$ IS NOT in $TS^i$)
   select $m_i$ such that $d(Gd, G^i_p(t)$ is the smallest in $TS^i$
else
  Call Direct Route
```

Figure 4. Inter-routing algorithm.

range of each node is 250 m and CBR traffic with the packet size of 256 and 512 bytes is considered. The packet arrival rate at the source and intermediate nodes is constant. We simulate the IEEE 802.11b as the MAC protocol and assume a two-ray ground propagation model. The objective of the simulation study is to provide a comparison between number of partitions and number of mobile nodes, for both fixed and random movement.

4.1. Performance Metrics

We focus on two key performance measures: 1) packet delivery ratio (PDR) and 2) delay. The performance is evaluated prominently with two packet rates for delay and PDR. Delay is defined as the average time taken to send a message from the source node to the destination. PDR is defined as the ratio of the data packets delivered to the destinations to those generated by the source using CBR traffic. Since there is more than one node in the destination region, the total packets at these nodes are normalized by the number of nodes in the region of interest R. The source-destination traffic flow is randomly simulated. The result obtained here is averaged over 10 runs.

4.2. PDR by varying number of partitions for different mobile nodes

In a SS-WSN a packet is transmitted from a random source subnetwork to a destination subnetwork. Figures 5a and 5b show the variation of PDR for different number of partitions with packet size 256 and 512 bytes, respectively. In both cases the simulations with two ERMNs have better PDR for a sparse network having four partitions. This behavior is attributed to the contact points that the ERMNs make during their traversal. However, the case with four ERMNs does not seem to be better for a sparse network; even the parametric traversal did not have fine-tuned contact points for the packets to be handed over such that they can reach the destination partition. As the networks become denser with more number of nodes and still keeping the partition intact, the parametric controlled mobility for the four ERMNs has a linear rise in PDR. The improved PDR compared to the scenario of one and two ERMNs is due to the parametric contact points p_1, p_2 at initial and end points of the curve. An additional ERMN in this plot can keep the reliable PDR as the previous cases, making the network more resourceful. In Figure 5b the steep fall in PDR is attributed to the fact that a high data rate needs smaller intervals of inter-contact times, which the smaller number of ERMNs fail to make. The contact points between the ERMNs are very important for a good PDR.

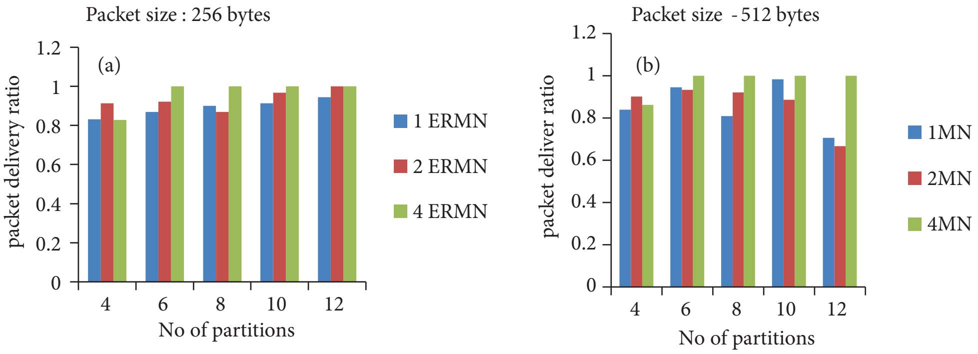

Figure 5. PDR variation for packet size of (a) 256 and (b) 512 bytes.

4.3. Delay by varying number of partitions for different mobile nodes

The end-to-end delay for a packet transmitted from a source subnetwork to destination subnetwork is analyzed. Figures 6a and 6b show the comparative end-to-end delay for different numbers of ERMNs. This is a pretty straightforward story with a linear rise in delay for all three cases of ERMN. If the number of ERMNs is less, the message needs a moderately larger time to reach the destination. The end-to-end delay almost doubles for a larger message to be passed as could be analyzed from Figures 6a and 6b. In the case the number of ERMNs is further increased, the delay could be further reduced. A randomly high number of ERMNs can hide the fact that the partitions are isolated and make it look like an almost connected network.

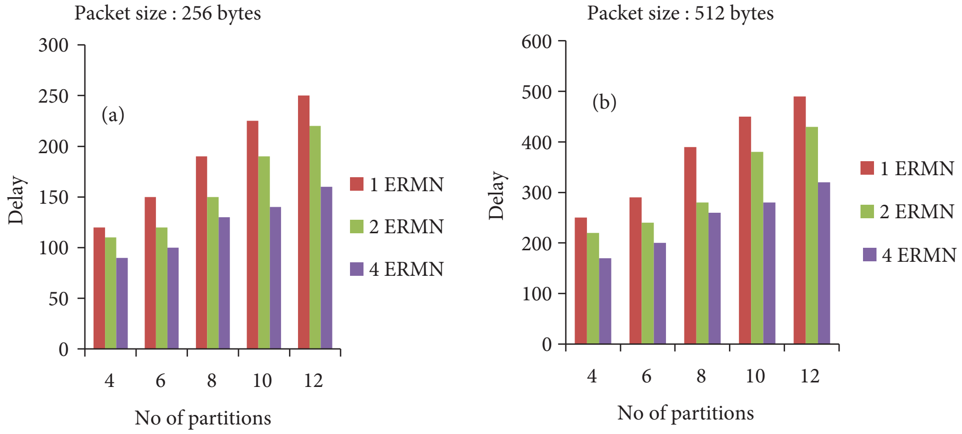

Figure 6. Delay variation for packet length of (a) 256 bytes and (b) 512 bytes.

4.4. PDR by varying number of nodes for mobile nodes movement

Figure 7 shows the PDR vs. number of partitions for the two-mobility pattern. When a packet is transmitted with the help of four ERMNs on the parametric path between a random source and a destination subnetwork, it has an average 20% improved PDR compared to the random path. In the random path, the packet is transmitted to the destination subnetwork despite data loss. The mobile node can forward the packet in any path towards the destination. In the random path, it ensures packet transmission to the destination subnetwork based on a best effort concept, whereas the parametric path makes a guaranteed effort to deliver the packet.

4.5. End-to-end delay by varying number of nodes for mobile nodes movement

The end-to-end delay is the time elapsed between the packet originated from the source and the waiting time while the ERMN carries the packet, until the packet is delivered to the destination node. Figure 8 shows that the parametric path has less delay compared to the random mobility model. The performance is evaluated for four ERMNs. There is a significant time saved for a denser network, when controlled mobility happens to be an added advantage. The random path performs better in a sparse environment. In the random path, the packet is transmitted to the destination subnetwork although in a probabilistic manner. Here, until the node variation of 60, the delay for both patterns goes hand in hand. Once the node density rises, the parametric delay saves an average of 30% of time. The benefits of controlled mobility could be realized in many realistic network scenarios, where the ERMN is a ferry or a mule, which generally has a regular path. The predictability of this path can reduce the routing overhead and the number of transmissions needed to send the packet to the destination. The limitation of parametric mobility is that if any partition does not intersect on the path traversed by the ERMN, then that subnetwork becomes detached from the network.

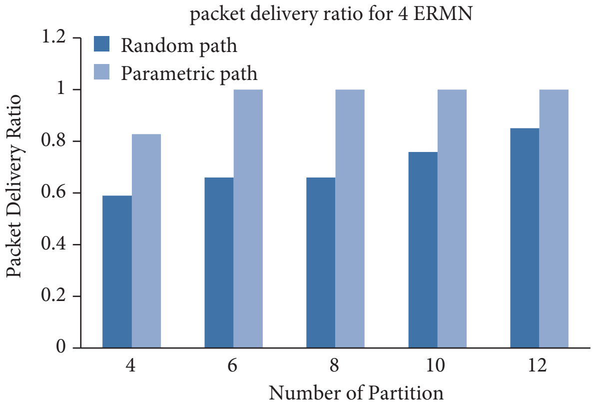

Figure 7. Packet delivery ratio by varying number of partitions.

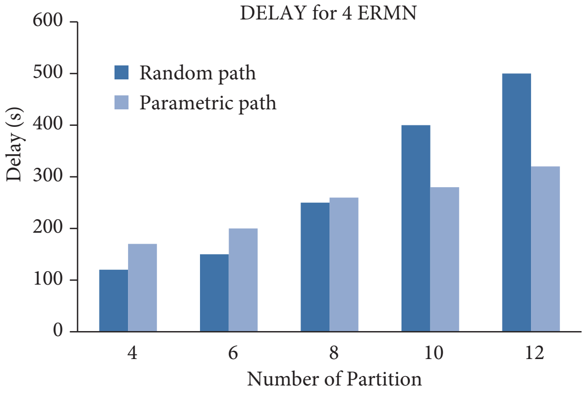

Figure 8. End-to-end delay variation for random and fixed path.

5. Conclusion

In this paper we proposed an opportunistic geocast for SS-WSNs that is implemented in two phases, intra- and inter-routing. We identified the necessity of an ERMN that can keep the isolated subnetwork virtually connected. We mathematically define each path using parametric curves and show that these curves have intersection points between them. The cubic and linear parametric traversal ensures at least two contact points between the ERMN. The traversal path has a history of subnetworks visited during its tour called the traversal set. This traversal set is used to predict the future traversal of an ERMN. Lastly when the packet reaches the RoI, geocasting is implemented by directed flooding. We compare the parametric mobility movement with other random movements by varying number of nodes and partition with traffic in NS2. The simulation results show, when four ERMNs are used to traverse about the partition, sufficient contact points are made for reliable delivery. A further rise in the number of ERMNs can reduce end-to-end delay and making the network literally connected. This routing can be further extended for the grid-based SS-WSN and analyzed with different traverses of the ERMN. The parametric traversal of the ERMN can be conjoined with dynamic topology of the partitioned network. The geocasting can be further refined by implementing the last phase utilizing restricted flooding or a minimum energy multicast tree to deliver the packet.

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