GRAB: Greedy Forwarding with Routing Along Boundaries in Wireless Sensor Networks

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Geographic Routing (GR) has emerged as a method of choice for routing in Wireless Sensor Networks (WSNs) due to its inherent features like localized operation, small per-node state, scalability, ability to operate without node addresses, and robustness in highly dynamic network conditions. *Greedy Forwarding* (GF) is generally used as default routing strategy in GR-based schemes due to its efficiency. However, GF alone does not guarantee packet delivery due to its susceptibility to failure at *local minima* or *dead-ends*. Hence, GF is augmented with some standby recovery scheme to implement reliable end-to-end geographic routing. Recovery schemes are generally highly inefficient as compared to greedy forwarding. Hence, it is imperative to induce conditions favouring GF and minimize the application of recovery scheme during end-to-end geographic routing. Most of the recovery schemes are based on the assumption of *Unit Disk Graph* (UDG) model for wireless connectivity. UDG is too ideal to model the behaviour of real radio links. In this paper, a scheme called "*Greedy Forwarding with Routing along Boundaries*" (GRAB) is proposed that combines an efficient form of greedy forwarding called "*Minimal Marking of Trap Regions*" (MMTR) with a novel recovery scheme called "*Rolling Circle Algorithm*" (RCA) to devise an efficient end-to-end geographic routing scheme for WSNs. An early *fallback criterion* is also proposed in this work to terminate recovery process and resume greedy forwarding as early as possible. In simulation, GRAB demonstrates significantly lower Hop Stretch Factor (HSF) when compared with other schemes.

Keywords: Geographic routing, greedy forwarding, dead-end, void region, boundary nodes, rolling circle algorithm

1. INTRODUCTION

Advancement in the fields of digital electronics, wireless communication, Micro-Electro-Mechanical Systems (MEMS) technologies have made it possible to integrate data processing, wireless communication, and sensing capabilities together to realize a small-size, low-power, inexpensive device called *Sensor Node* (SN). These SNs can be unobtrusively deployed in some region of interest to perform collaborative sensing of the physical properties of the surrounding environment. The sensory data captured by the SNs is then mapped to some equivalent events of interest happening around the corresponding SNs. The wireless ad-hoc network formed by the sensor nodes is known as *Wireless Sensor Network* (WSN) that enables mutual collaboration among sensor nodes for sensing, processing, and relaying of sensory data to one or more specially designated nodes called *base stations* or *sink nodes*. The sink node acts as a gateway between the WSN and the end-user space where data is interpreted and utilized in the application context. The embedding of computation, communication, and control (possibly) into physical world is envisaged to benefit many application areas like monitoring of critical natural phenomena, disaster management, toxic chemical monitoring, wildlife tracking and protection, military applications, precision agriculture, smart buildings, critical infrastructure protection, structural health monitoring, healthcare, logistics, factory instrumentation, habitat monitoring, urban traffic monitoring etc [Carl and Willig 2005].

A SN is typically characterized by scarce computational resources, limited and non-replenishable energy source, autonomous, and dispensable nature. A WSN formed by these SNs is also unique in some aspects like multitude of nodes, long-term unattended operation, well-defined traffic-patterns, self-adapting, and application-specific configuration. Resource-constrained sensor nodes are not adequately equipped to handle large routing tables or control messages overheads of traditional routing protocols [Cadger et al. 2013]. These peculiarities of WSNs advocate the need to devise an entirely new generation of routing protocols specifically designed for them. Geographic Routing (GR) technique exhibits many properties particularly suitable for WSNs. Some of the salient features of GR are: localized operation, small state per node, scalability and robustness under highly dynamic network conditions. GR is based on two basic assumptions: (1) every node is aware of its own and its immediate neighbours' locations, and (2) the source of a message knows the location of the destination.

Location awareness is a fundamental requirement in many WSN applications, because data without associated spatial information of its originating node may not be as useful. In WSN applications like tracking, detection, and monitoring, the location and timing of an event is as important as the detection of the event itself. A node can determine its location either directly by using GPS (if available) or indirectly using some other localization techniques [Hightower and Borriello 2001]. Further, the location of the destination can be either fixed (a static sink node), or be obtained from a location service [Li et al. 2000]. Hence, both of the fundamental assumptions for GR hold well in WSNs. Moreover, the communication in WSNs typically use *data-centric* paradigm for node addressing, i.e. a node is identified by the attribute-value pairs rather than a specific address. Position of the node is one of such attributes that represents the location in the physical world being covered by the sensors of the node. These all factors make GR particularly suitable for WSN applications.

In geographic routing, a node utilizes the information about geographic locations of itself, its neighbours and the destination node to choose the next hop. *Greedy Forwarding* (GF) is a simpler and efficient form of geographic routing with worst-case path length of $\Omega(d^2)$ [Kuhn et al. 2008], where d is the Euclidean distance between the source and the destination of the packet. In GF, the current node chooses a neighbour that makes *maximum positive progress* towards the destination as next hop. GF guarantees loop-free operation and yields nearly optimal route in densely deployed networks. The only drawback of greedy forwarding is that it fails at *dead-ends* (also called *local minima* or *concave nodes*). A dead-end is a node that doesn't have any neighbour closer to the destination than itself. Dead-end nodes appear at boundaries of the *voids* or *holes* – uncovered areas or obstacles to radio waves in a given direction. Communication voids are mainly attributable to random deployment of sensor nodes, irregular terrain topography, obstacles, and other sources of obstruction to radio waves.When greedy forwarding fails, the routing mode switches to recovery mode that continues until the packet is delivered or greedy forwarding is feasible again. The recovery mode solutions [Chen and Varshney 2007] are based on techniques like flooding [Stojmenovic and Lin 2001], heuristic methods [Boukerche et al. 2006], planar graph traversal[Karp and Kung 2000; Kuhn et al. 2003], and geometric methods [Fang et al. 2006; Liu and Feng 2009; Rührup and Stojmenoviċ 2010]. Planar graph-based methods and geometric methods have attracted a significant research focus in recent years. Planar graph-based recovery methods progressively traverse the adjacent faces of a planarized graph using "*right-hand rule*" until destination is reached or greedy forwarding can resume again. Geometric methods exploit the geometric aspects of the network to recover from the dead-ends.

The main limitation of planar graph-based and geometric methods is that these methods rely heavily on the assumption of *Unit Disk Graph* (UDG) model for wireless connectivity. UDG is often criticised [Kim et al. 2005b] for being too ideal to model the behaviour of real radio links.

"*Greedy Forwarding with Routing along Boundaries*" (GRAB) method proposed in this paper combines an efficient form of GF called "*Minimal Marking of Trap Regions*" (MMTR) [Sharma et al. 2016] with a novel recovery scheme called "*Rolling Circle Algorithm*" (RCA) to devise an efficient end-to-end geographic routing scheme for WSNs. GRAB does not rely on UDG or any other idealistic assumption and is based on the local view of actual connectivity graph and geometry of the network. An early *fallback criterion* is also proposed in this work to terminate recovery process and resume greedy forwarding as early as possible.

2. RELATED WORK

The first known geographic routing algorithm that guaranteed packet delivery without flooding was *face routing* proposed as Compass Routing-II in [Bose et al. 1999]. Face routing traverses the edges of the faces of planar graphs using "right-hand rule" and progressively switches faces along the edges intersecting with the line connecting the source and the destination. In worst case, these algorithms take $\Omega(n)$ steps before arriving at the destination [Kuhn et al. 2008], where n is the number of nodes in the network. Hence, in worst case, face routing is no better than basic flooding. Variants of face routing were proposed as Adaptive Face Routing (AFR) [Kuhn et al. 2002] in which the routing path length is bounded above by $\Omega(l^2)$, where l is the length of the path of optimal route. It was shown that the execution cost of AFR is the worst-case optimal result any geographic routing algorithm can achieve.

Greedy-Face-Greedy (GFG) [Bose et al. 1999] and GPSR [Karp and Kung 2000] begin to operate in greedy modes and switches to the perimeter/ face routing when a local minimum is encountered. The routing mode switches back to greedy mode as soon as the packet reaches at a node that is closer to the destination than the node that initiated the perimeter routing mode. Integrated Location Service and Routing (ILSR) [Li et al. 2012] is an extension of GFG scheme optimized for mobile sink nodes. ILSR uses restricted flooding for updating the location information about the neighbours whenever a next-hop change is observed by a node. Geographic Landmark Routing (GLR) [Na and Kim 2006] handles the problem of voids through the discovery of paths that bypass voids by remembering the landmark nodes - nodes at which the recovery scheme is terminated and greedy routing resumed.

Face routing requires a planar graph – a graph that does not contain any crossing edges. Hence, a WSN connectivity graph needs to be planarized before performing face routing. Planarization process removes all crossing edges while preserving the connectivity of the original graph. Graph planarization uses planar graph structures like Delaunay Triangulation (DT), Relative Neighborhood Graph (RNG) and the Gabriel Graph (GG) [Jaromczyk and Toussaint 1992]. Whereas there is no known method to construct DT using 1-hop local information only, RNG and GG can be constructed locally. Removal of edges may cause detours while routing. The detours may extend up to stretch factors of $\Theta(sqrt(n))$ for the GG and $\Theta(n)$ for the RNG [Bose et al. 2002]. Furthermore, RNG and GG assume Unit Disk Graph (UDG) model for wireless connectivity (all nodes have perfectly circular radio ranges of radius 1, centred at their own positions). UDG assumption is often violated in practice because of obstructions and the physical characteristics of real radios [Kim et al. 2005b]. Cross-Link Detection Protocol (CLDP) [Kim et al. 2005a] guarantees to produce a planarized subgraph of any arbitrary graph. In CLDP, the nodes independently probe each of their links using a right-hand rule to remove cross-linked edges. CLDP uses a two-phase locking protocol to ensure that no more than one link is removed at any given time from any given face. While CLDP is able to planarize an arbitrary graph, every single link in the network has to be probed multiple times, and has a high cost. In an effort to bound the detour in face routing, Adaptive Face Routing (AFR) proposed by Kuhn et al. [Kuhn et al. 2002] restricts the search area by a bounding ellipse (with source(s) and destination (t) as two foci and $|\overline{s\ t}|$ as major axis) during face traversals. Greedy Other Adaptive Face Routing (GOAFR) uses greedy forwarding in conjunction with AFR as recovery strategy as an end-to-end geographic routing protocol. In Greedy Path Vector Face Routing (GPVFR) [Leong et al. 2005], nodes maintain local face information. When greedy forwarding fails, a node may have knowledge about another node on the same face that is closer to the destination. Such node is chosen as an intermediate target for face routing.

BoundHole [Fang et al. 2006] was one of the early algorithms to use geometric aspects of the network to identify holes. BoundHole uses the term *stuck node* for the nodes on the boundary of a void-region. A node is a stuck node if there exists some location outside its transmission range where it is closer to than any of its 1-hop neighbours. A stuck node may not be a dead-end towards the actual destination, but, it is a potential dead-end candidate for some other destination. Stuck nodes constitute the boundary of a void region. A path can be found either reactively (i.e., when greedy forwarding fails) or proactively and stored locally along the boundaries of holes. The BoundHole protocol uses a rule called TENT rule to identify a hole around a dead-end node.

A path pruning algorithm to shorten the detours in recovery schemes is presented in [Ma et al. 2008].

The recovery schemes are complex and highly inefficient as compared to greedy forwarding. Hence, it is desirable to induce conditions favourable for greedy forwarding throughout the WSN whenever possible. Tan and Kermarrec [Tan and Kermarrec 2012] proposed to decompose the entire network into minimum number of *Greedily Routable Components* (GRC) where greedy forwarding is guaranteed to work within each such component. Dead-end free topology maintenance protocol (DFTM) [Chou et al. 2011] constructs a dead-end free topology using a minimum number of active nodes by making use of Voronoi diagrams. Proactive identification of obstacles to improve the performance of greedy forwarding was proposed in [Moraru et al. 2007] and [Moraru et al. 2008]. A node is marked as non-optimal for greedy forwarding in [Moraru et al. 2007] if the ratio between the number of times the greedy and perimeter modes were previously used by the node is below a threshold value. A node is considered as non-optimal in [Moraru et al. 2008] if it does not have any optimal neighbour which can be used as next hop in greedy forwarding. [Huc et al. 2009] extended the work in [Moraru et al. 2008] to all-to-all traffic pattern. In our previous work [Sharma et al. 2016], a scheme for segregation of various regions relevant to greedy forwarding in WSNs is presented.

Greedy Anti-void Routing (GAR) [Liu and Feng 2009] and Rotational Sweep (RS) [Rührup and Stojmenoviѐ 2010] algorithms handle void region problem by routing packets along the boundary of the WSN. Fayed et al. [Fayed and Mouftah 2009] proposed a solution for detecting edges of a WSN using a geometric shape called α-*shape* [Edelsbrunner et al. 1983]. For a disc of radius $1/\alpha$, the alpha-shape consists of nodes (and joining edges) that are situated on the boundary of the discs containing no other nodes in the network. All nodes included in an α-shape constitute the boundary of the WSN. GAR and RS are based on [Fayed and Mouftah 2009] to compute boundary nodes for perimeter routing. GAR combines Greedy Forwarding (GF) with Rolling-ball UDG boundary Traversal (RUT) to achieve end-to-end geographic routing. RUT uses a rolling ball of radius $r/2$ (r is transmission range of the node) starting from the dead-end node in counter-clockwise direction. The sequence of nodes swept by such rolling ball constitutes the boundary of the void region. The RS algorithm uses a novel contention-based strategy to find the next hop on the network boundary. The algorithm starts at a dead-end node and computes the next hop in counter-clockwise order. The forwarder node broadcasts a Request to Send (RTS) message, all neighbouring nodes called candidates, schedule to respond by a Clear to Send (CTS) message after a certain delay. The DATA packet is forwarded to the first candidate that replies with the CTS. Other candidates then cancel their scheduled CTS transmissions. The delay is a function of the relative locations of the forwarder, the candidate and the previous node. The delay function can be geometrically visualized as a rotating semicircle of radius $r/2$ where r is the radius of the unit disk.

3. SYSTEM MODEL AND TERMINOLOGY

The sensor nodes are randomly deployed in a Euclidean plane $\mathbb{R}^2$, and each node is aware of its geographic location in the form of its Cartesian coordinates (x, y). A WSN is modelled as an undirected graph $G(V, E)$, where V is the set of vertices representing the sensor nodes and E is the set of edges representing the wireless communication links. A node v connected to a node u through a direct wireless link is called a neighbour of u. The set of adjacent neighbours called adjacency set of a node is represented by $\mathcal{N}(u)$. The Euclidean distance between two nodes u and v is represented by $|\overline{u\ v}|$. The links between nodes are symmetric i.e. $v \in \mathcal{N}(u) \Rightarrow u \in \mathcal{N}(v)$. There is no global addressing scheme for nodes and a node is identified by its geographic location only. To ensure that every sensor node in the WSN has a unique location, a cluster of adjacent nodes is formed as proposed in [Kuhn et al. 2003]. The redundant nodes of such a cluster are kept in sleep mode. Many communication voids may be present within a WSN. There is only one static sink node in the WSN, the location of which is known to all the sensor nodes.

Definition 1. *Greedy forwarding set of a node u towards destination d consists of the set of its neighbours which are closer to d than u itself, i.e.* $\mathcal{GFS}_d(u) = \{v : v \in \mathcal{N}(u) \wedge \overline{|vd|} < \overline{|ud|}\}$.

Definition 2. *A node u is said to be a* ***dead-end node*** *towards destination d if none of its neighbours is closer to the d than u itself, i.e.* $\nexists v(v \in \mathcal{N}(u) \wedge \overline{|vd|} < \overline{|ud|})$.

Definition 3. *A node is a* ***non-potential relay node*** *w.r.t. greedy forwarding if it is either a dead-end node or all nodes in its greedy forwarding set are also non-potential relay nodes.*

The set of all non-potential relay nodes $\mathcal{NPR}(G)$ in WSN graph G is recursively defined as: $\mathcal{NPR}(G) = \{v : \mathcal{GFS}_d(v) = \phi \vee \mathcal{GFS}_d(v) \subset \mathcal{NPR}(G)\}$

If a node u selects the node v as its next hop during greedy forwarding towards destination d, we represent it as $u \xrightarrow{gf_d} v$. $\xrightarrow{gf_d^*}$ is the transitive closure of $\xrightarrow{gf_d}$ operator i.e. if $x_1 \xrightarrow{gf_d} x_2$, $x_2 \xrightarrow{gf_d} x_3$, . . ., $x_{n-1} \xrightarrow{gf_d} x_n$, then $x_1 \xrightarrow{gf_d^*} x_n$.

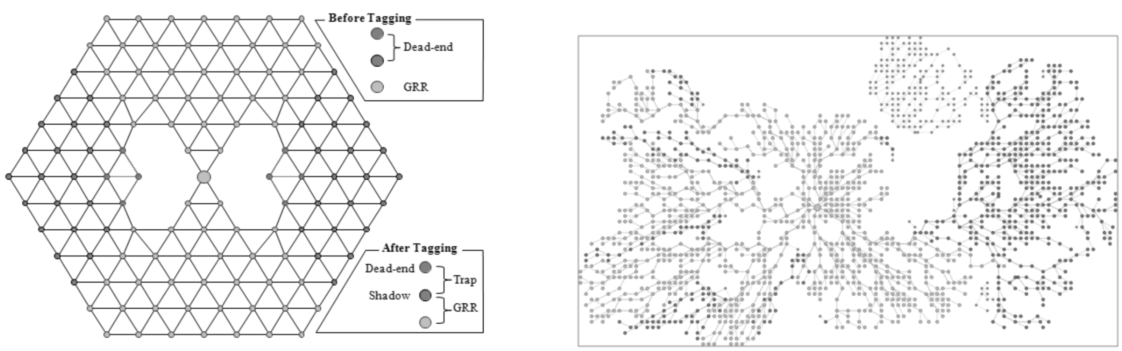
Definition 4. *A* ***trap region*** *of a dead-end node u is a connected subgraph of WSN in which greedy forwarding towards destination d culminates at u, i.e.* $\mathcal{TR}(u) = \{v : v \xrightarrow{gf_d^*} u\}$.

Definition 5. *A* ***dead-end region*** *of a trap region is a consists of nodes in the trap region which do not have any optimal neighbor, i.e.* $\mathcal{DR}(u) = \{v : v \xrightarrow{gf_d^*} u \wedge \mathcal{GFS}_d(v) \subset \mathcal{NPR}(G)\}$, *where u is a dead-end.*

Definition 6. *A* ***shadow region*** *of a trap-region is a connected subgraph consisting of nodes which have at least one optimal neighbour for greedy forwarding towards the destination d. A shadow region consists of nodes of the trap region excluding the nodes in its dead-end region.*

Definition 7. *A subgraph of a WSN is called a* ***Greedily Routable Region****(GRR) w.r.t. destination d, if each of its node u has a greedy path upto destination d.* $\mathcal{GRR}_d(G) = \{v : v \xrightarrow{gf_d^*} d\}$

Fig.1(a) shows various regions relevant in a WSN.



(a) WSN regions classification

(b) A WSN consisting of 1600 nodes tagged using MMTR

. Figure 1:Tagging nodes of WSNs for efficient greedy forwarding

4. PROPOSED SCHEME

The proposed routing algorithm called "Greedy forwarding with Routing Along Boundaries" (GRAB), is a two-phase geographic routing scheme. In the first phase called "greedy phase", a packet is progressively forwarded by each intermediate node to its neighbour situated closest to the destination. Presence of a communication hole between the current node and the destination node causes greedy forwarding to fail. GRAB switches to the second phase called "recovery phase" to circumvent the voids. Recovery phase continues until greedy forwarding can resume again. The working of each phase is described below in detail:

4.1 Greedy forwarding phase

GRAB utilizes a modified version of greedy forwarding called "Minimal Marking of Trap Regions" (MMTR) as proposed in [Sharma et al. 2016]. MMTR tags minimum number of nodes of the WSN as "non-potential relay nodes" which are prohibited to participate in the greedy forwarding. For a given destination, MMTR partitions a WSN into non-overlapping regions consisting of one GRR and possibly many dead-end regions. GRR is a region within a WSN in which greedy forwarding is not blocked at any dead-end. Whereas, greedy forwarding within a dead-end region is bound to fail at the dead-end associated with that region. MMTR algorithm is summarized as:

Algorithm - *MMTR (Node u, Node d, Packet p)*
  To choose the next hop and mark the regions of a WSN.
Input - Current node u, Destination d, and Packet p

```
U ← {v : v ∈ GFS_d(u) ∧ v.is_optimal}
if U = ∅ then
    u.is_optimal ← false
    V ← {v : v ∈ GFS_d(u) ∧ v.is_optimal}
    if V = ∅ then
        p.mode ← RECOVERY
        CALL Rolling_Circle
    else
        next_hop ← w : w ∈ V ∧ |wd| = min_{v∈V}(|vd|)
    end if
else
    next_hop ← w : w ∈ U ∧ |wd| = min_{u∈U}(|ud|)
end if
Forward p to next_hop
```

4.2 Recovery phase

Recovery phase begins when a packet gets stuck at a dead-end during greedy phase. To recover from the dead-ends, the packet is routed along the boundary of the WSN until it reaches a GRR, where greedy phase resumes. Since a dead-end always lies on the boundary of a hole, it provides a starting point for the discovery of the boundary for the purpose of escaping from the hole. GRAB utilizes a scheme called "rolling circle algorithm" (RCA) to discover the nodes along the boundary of the WSN. RCA is localized α-shape based method for on-demand discovery of the next boundary node. The working principle of RCA is given in Theorem 1.

THEOREM 1. *Given a dead-end node* $\boldsymbol{u}$ *towards the destination* $\boldsymbol{d}$*, the first node swept by the clockwise rolling circle of diameter* $\overline{|u\ d|}$ *hinged at* $\boldsymbol{u}$ *and passing through* $\boldsymbol{u}$ *and* $\boldsymbol{d}$ *is always a boundary node.*

PROOF. Since u is a dead-end node, so the circle of diameter $\overline{|u\ d|}$ passing through u and d does not contain any neighbour of u. Also, $d \notin \mathcal{N}(u) \Rightarrow \overline{|u\ d|} \geqslant r$, where r is the transmission range of u. Hence, all the neighbours of u will be no farther than $\overline{|u\ d|}$ from u and will eventually be swept by the rolling circle of diameter $\overline{|u\ d|}$ passing through u and d and hinged at u. Let v be the first neighbour of u swept by the rolling circle. So, there will be no node inside the rolled circle with u and v sitting on its perimeter. This scenario depicts the empty disc criterion of an α-shape with $\alpha=2/\overline{|u\ d|}$, and u, v as α-neighbours of the α-shape. Hence, by the empty disc property of α-shapes, both u and v are at the boundary of the WSN □

Working of RCA is described below:

Initialization: The dead-end node u towards the destination d initiates the recovery mode with the mid-point of the line joining u and d (point c) as the initial center and $\overline{|u\ d|}/2$ as the initial radius of the rolling circle as depicted in Fig. 2(a).

Termination: The recovery mode terminates in either of the following conditions:

(i) Greedy mode resumes on encountering greedily routable region during recovery.

(ii) On detecting a network partition i.e. when a packet returns back to the dead-end node that initiated recovery mode. The location of the node that initiated the perimeter mode is piggybacked in the packet to ensure loop-free operation.

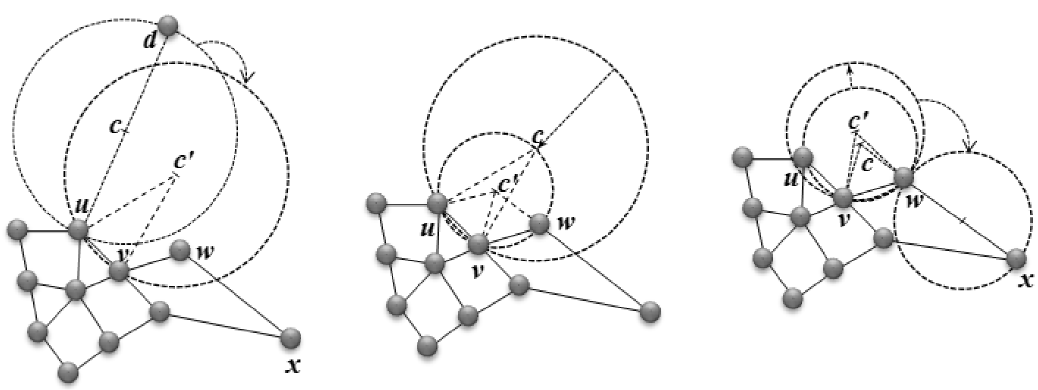
Radius adjustment: When a packet is received by a boundary node v from the node u in recovery mode, some of the neighbours of $v(w$ in Fig. 2(b)) may lie inside the rolling circle due to larger value of the rolling circle radius. In this case, the circle is deflated so as to make it a circumcircle of the $\triangle uvw$. The center of the new circle is computed as the intersection point c' of the perpendicular bisector lines of $uv$and vw. The radius of the new circle is set as $\overline{|v\ c'|}$. Similarly, some of the neighbours may not ever get swapped by the rolling circle (neighbour x of w in Fig. 2(c)) due to smaller value of the rolling circle radius. In such a case the circle is inflated upto the radius $\overline{|v\ c'|}/2$ where x is the farthest neighbour of w. The new center of the circle passing through w and x having radius $\overline{|v\ c'|}/2$ is then computed.

Rolling: The forwarding node u determines the sweep angles for all its neighbours. The sweep angle for a neighbour v is the minimum angle by which the rolling circle is to be rotated about the forwarding node u so that the node v is swept by the circle. The node having minimum sweep angle is chosen as the next boundary node. The new center of the rolling circle $c'(x', y')$ and sweep angles $\delta\theta_i$ can be computed as:

$$x' = \frac{x_u+x_v}{2} + \frac{y_v-y_u}{\overline{|u\ v|}}\sqrt{\overline{|u\ c|}^2 - \left(\frac{\overline{|u\ v|}}{2}\right)^2}$$

$$y' = \frac{y_u+y_v}{2} - \frac{x_v-x_u}{\overline{|u\ v|}}\sqrt{\overline{|u\ c|}^2 - \left(\frac{\overline{|u\ v|}}{2}\right)^2}$$

$\delta\theta_v = \theta_1 - \theta_2$, where $\theta_1 = tan^{-1}\left(\frac{y_u-y_c}{x_u-x_c}\right)$ and $\theta_2 = tan^{-1}\left(\frac{y_u-y'}{x_u-x'}\right)$ normalized to positive value in the domain $[0..2\pi)$.



(a) Initialization phase (b) Deflating the rolling circle (c) Inflating the rolling circle

. Figure 2:Working of RCA

4.3 Further optimization

RCA assigns monotonically increasing *sequence numbers* (*seq_no*) to the successively adjacent boundary nodes. During recovery phase, if a node with a *seq_no* greater than the *seq_no* of the

Algorithm - *Rolling_Circle (Node u, Node d, Packet p)*
Objective - To forward the stuck packet to the next node along the boundary.
Input - Current node: u, Destination: d, Packet: p,
Packet Header - Forwarding node: $p.prev\_node$, Recovery mode initiator: $p.init\_node$, Center of the rolling circle: $p.rc\_center$, Sequence No.: $p.seq\_no$, Routing mode: $p.mode$

begin
  /*Drop packet and exit if network partition is detected.*/
  if $p.mode = RECOVERY \wedge p.init\_node = u$ ***then exit***
  $c \leftarrow p.rc\_center$
  $U \leftarrow \{w : w \in \mathcal{N}(u) \wedge w.is\_optimal\}$
  if $U \neq \varnothing$ ***then*** ***// Switch back to GREEDY mode.***
    $p.mode \leftarrow GREEDY$
    $next\_hop \leftarrow w : w \in U \wedge \overline{|w\ d|} = \min_{v \in V}(\overline{|v\ d|})$
    Forward p ***to*** $next\_hop$
  else if $p.mode = GREEDY$ ***then***
    if $\mathcal{GFS}_d(u) \neq \varnothing$ ***then*** ***// Greedy forwarding within dead-end region.***
      $next\_hop \leftarrow w : w \in GFS_d(u) \wedge \overline{|w\ d|} = \min_{v \in GFS_d(u)}(\overline{|v\ d|})$
      Forward p ***to*** $next\_hop$
    else ***// Switch to RECOVERY mode at dead-ends.***
      $p.mode \leftarrow RECOVERY$, $p.rc\_center = d$,
      $p.init\_node \leftarrow p.prev\_node \leftarrow u$, $p.seq\_no \leftarrow 0$
    end if
  end if
  /* Deflate the rolling circle if required. */
  while $\exists w(w \in \mathcal{N}(u) \wedge \overline{|w\ c|} < \overline{|u\ c|})$
    $c \leftarrow getCenter(u, p.prev\_node, \overline{|w\ c|})$
  end while
  /* Inflate the rolling circle if required. */
  while $\exists w(w \in \mathcal{N}(u) \wedge \overline{|u\ w|} < 2\overline{|u\ c|})$
    $c \leftarrow getCenter(u, p.prev\_node, \frac{\overline{|u\ w|}}{2})$
  end while
  $\theta_1 \leftarrow getAngle(u, c)$
  $l \leftarrow \sqrt{(u.x - c.x)^2 + (u.y - c.y)^2}$
  /* Calculate the required rotation of the rolling circle for each neighbour. */
  for each $w \in \mathcal{N}(u)$
    $c_w \leftarrow getCenter(u, w, l)$, $\theta_2 \leftarrow getAngle(u, c_w)$, $\delta\theta \leftarrow \theta_2 - \theta_1$
  end for
  /* Choose a neighbour with minimum calculated rotation as next hop. */
  $next\_hop \leftarrow w : \delta_w = \min_{x \in \mathcal{N}(u)}(\delta_x)$
  /* Update packet header before forwarding. */
  $p.rc\_center \leftarrow c_w$, $p.prev\_node \leftarrow u$
  $u.seq\_no \leftarrow p.seq\_no$, $p.seq\_no \leftarrow p.seq\_no + 1$
  Forward p ***to*** $next\_hop$
end.

Function *getAngle (Node u, Node v)*

  $\delta x \leftarrow x_u - x_v$
  $\delta y \leftarrow y_u - y_v$
  if $\delta x = 0$ ***then*** $\theta \leftarrow \frac{\pi}{2}$ ***else*** $\theta \leftarrow tan^{-1}\left(\frac{\delta y}{\delta x}\right)$
  if $\delta x \leqslant 0$ ***then*** $\theta \leftarrow \theta + \pi$ ***else if*** $\delta y \leqslant 0$ ***then*** $\theta \leftarrow \theta + 2\pi$
  return θ

Function *getCenter (Node u, Node v, Radius r)*

  $p \leftarrow \sqrt{(x_v - x_u)^2 + (y_v - y_u)^2}$
  $c.x \leftarrow \frac{x_u + x_v}{2} + \frac{y_v - y_u}{p}\sqrt{r^2 - \left(\frac{p}{2}\right)^2}$
  $c.y \leftarrow \frac{y_u + y_v}{2} - \frac{x_v - x_u}{p}\sqrt{r^2 - \left(\frac{p}{2}\right)^2}$
  return c

current node is discovered, the packet is forwarded to a neighbour with highest *seq_no*. This strategy prunes the path along the boundary to minimum number of hops. GRAB also utilizes an "*early fallback*" mechanism to exit the recover phase and resume greedy phase as soon as a node is reached that is on the boundary of GRR.

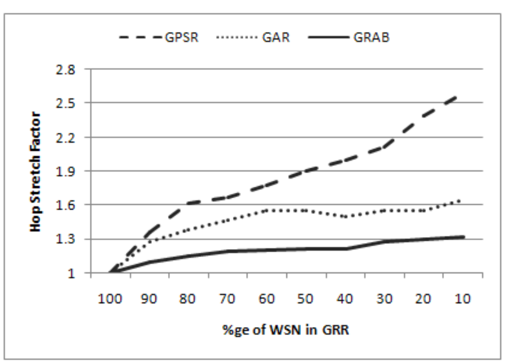
5. SIMULATION AND RESULTS

Table I. Simulation Parameters

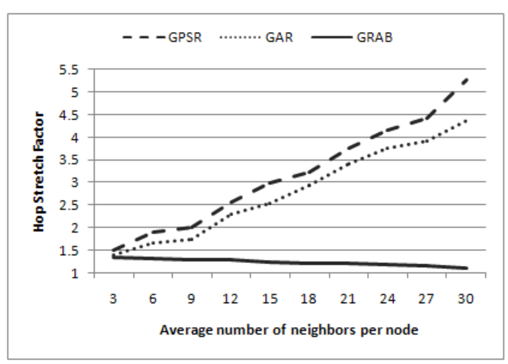
Deployment Terrain	$1000m \times 1000m$
Number of Nodes	Ranging from 100 to 2000
Node Placement	Random
Node Density	Uniform Distribution $0 \cdots 1$ *per* $900m^2$
Application Traffic	Constant Packet Rate @ 1 pkt/sec
Payload Size	16 byte
Channel Data Rate	250 kbps
Radio Range	60m

The proposed scheme is simulated in OMNeT++ simulator [Varga 2010]. Simulation parameters used in this work are as mentioned in Table-I. The comparison of hop stretch factor achieved by GPSR [Karp and Kung 2000], GAR [Liu and Feng 2009] and GRAB under varying node densities in different terrain topographies is carried out in the simulation. RNG graph structure is used to implement planarization for GPSR. "*hop stretch factor*" (HSF) is used as the performance metric to compare various schemes. HSF is the ratio of the number of hops taken by a routing method to the minimum number of hops required to route packets from source to destination. In simulation, each node sends one packet to a specific destination (sink node) at a random instant of time. We take the average of the number of hops for each such end-to-end routing to compute hop stretch factors. For the purpose of our simulation, we define node density in terms of average number of neighbours per node of the WSN.

In a void-free deployment case (Fig. 3(a)), the hop stretch factor achieved by each of GPSR, GAR and GRAB approaches 1 as all packets are routed using greedy mode only. We compare the average hop stretch factor under varying GRR compositions (Fig. 3(a)) and under varying node densities (Fig. 3(b)). GPSR shows a steep increase in the hop stretch factor with a decreasing portion of WSN in Greedily Routable Region (GRR). Though GAR and GRAB identify the same boundary nodes while routing in recovery mode, the performance of GRAB gets better due to use of sequence numbers during recovery mode.



(a) Effect of GRR compositions on HSF



(b) Effect of node densities on HSF

. Figure 3:Simulation Results

6. CONCLUSION

The effect of node densities on hop stretch factor is presented in Fig. 3(b). In simulation 50% of WSN is taken as GRR and 50% as dead-end region. Interestingly the hop stretch factor for both GPSR and GAR increase with increase in density, because the number of hops in the shortest path decrease with density and number of faces in the planarized graph (in case of GPSR) and number of boundary nodes (in case of GAR) increase with node density. On the contrary, the performance of GRAB gets better with increase in node densities. This is due to the fact that GRAB utilizes sequence number of boundary nodes for greedy forwarding during recovery.

End-to-end geographic routing schemes generally use greedy forwarding as their primary routing mode and switch to recovery modes whenever a dead-end is encountered during greedy forwarding. Overall performance of end-to-end geographic routing in these schemes is affected by three important factors: greedy mode operation, recovery mode operation, and the criteria adopted to switch between routing modes. A novel geographic routing scheme for WSNs called GRAB is presented in this paper. GRAB utilizes an optimized version of greedy forwarding called MMTR and a boundary-based recovery mechanism called RCA to implement end-to-end geographic routing. Where most of the existing recovery methods are based on a very unrealistic UDG model of wireless connectivity, GRAB is based on local topology and geometry of the nodes' immediate neighbours. GRAB ensures that recovery mode operation is not invoked more than once during end-to-end routing. Tagging boundary nodes with sequence numbers significantly improves the performance of routing along the boundaries of the WSN during recovery. The proposed scheme switches back from recovery mode to greedy mode as soon as a potential relay node is discovered during recovery. Expanded scope of greedy forwarding, efficient and reliable recovery phase, and early fallback from recovery phase to greedy phase; make GRAB the most efficient scheme among the contemporary geographic routing schemes for WSNs. Simulation results reveal a significant improvement in "*hop stretch factor*" for end-to-end geographic routing over schemes like GPSR and GAR.

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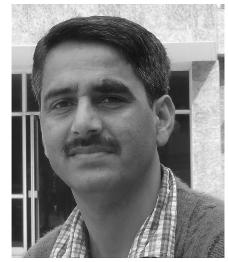

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