PSGR: Priority-based Stateless Geo-Routing in Wireless Sensor Networks

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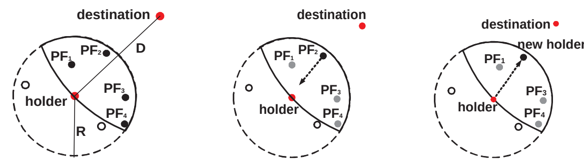
***Abstract*— Volunteer forwarding, as an emerging routing idea for large scale, location-aware wireless sensor networks, recently has attracted a significant amount of research attention. However, several critical research issues raised by volunteer forwarding, including priority assignment, acknowledgement collisions and communication voids, have not been well addressed by the existing work. In this paper, we propose a priority-based stateless geo-routing (PSGR) protocol to address these issues. Based on PSGR, sensor nodes are able to locally determine their priority to serve as the next relay node using dynamically estimated network density. This effectively suppresses potential communication collisions without prolonging routing delays. PSGR also overcomes the communication void problem using two alternative stateless schemes, rebroadcast and bypass. We analyze energy consumption and delivery rate of PSGR as functions of transmission range. An extensive performance evaluation has been conducted to compare PSGR with competing protocols, including GeRaf, IGF, GPSR and Flooding. Simulation results show that PSGR exhibits superior performance in terms of energy consumption, routing latency and delivery rate, and soundly outperforms all of the compared protocols.**

I. Introduction

Geo-routing protocols have been widely adopted in the design of wireless sensor networks [12], [14]. Most existing geo-routing protocols [3], [5], [9] are *stateful*, i.e., make routing decisions based on cached geographical information of neighboring sensor nodes. However, possible node movements, node failures and energy conservation techniques in sensor networks result in *dynamic* networks with frequent topology transients, and thus pose a major challenge to stateful packet routing algorithms. Recently, a number of studies (including our own work [17] and others [1], [4], [6], [21]) have proposed *stateless* geo-routing protocols for dynamic wireless sensor networks.

These stateless routing protocols leverage the key idea of *volunteer forwarding* in which the relay node is not chosen by the *packet holder* (the node presently holding the packet), but instead by a set of volunteering neighbor nodes based on their geographical locations. Volunteer forwarding avoids the communication overhead of exchanging state information among sensor nodes, which in turn effectively reduces communication collisions and improves the energy efficiency of a routing protocol. Figure 1 illustrates the volunteer forwarding steps. Specifically, the packet holder broadcasts a forwarding probe message to its neighbors (Figure 1(a)). The neighbors eligible for forwarding the packet are called *potential forwarders* (PFs). The area where PFs reside is called a *forwarding region*, and is determined by the geographical



(a) Probe (b) Ack (c) Forward

Fig. 1. Volunteer forwarding

locations of the packet holder and the destination: routing via PFs is expected to make geographical progress towards the destination. Upon receiving the probe, the PFs acknowledge according to some pre-designated priority (Figure 1(b)). The first acknowledger receives the packet and becomes a new packet holder (Figure 1(c)). This process is repeated until the delivery succeeds or fails. There are two fundamental research issues involved in volunteer forwarding: 1) how to have PFs autonomously determine their acknowledgement precedence without leading to excessive message collisions and routing delay; 2) how to detect and overcome the communication void problem (in case no PFs exist). Unfortunately, these two important issues have been only partially addressed in the existing studies, which either employ simple heuristics (so that the system performance is not optimized) or overlook the challenging communication void issue (see Section II for a detailed review).

In this paper, we present an in-depth study into the research issues of volunteer forwarding. A novel protocol, called *priority-based stateless geo-routing (PSGR)*, is proposed by exploiting two important concepts: a) dynamic forwarding zone formation based on the sensor node density estimated on-the-fly, and b) autonomous acknowledgement. Moreover, we address the communication void problem by using two complementary approaches (i.e., rebroadcast and bypass), which favor different network scenarios. Additionally, an analytical model is developed to derive PSGR's energy consumption and delivery rate as functions of *transmission range*. The analysis, providing important insights on selecting radio transmission range, is critical for planning and deployment of large-scale wireless sensor networks. Finally, an extensive simulation is conducted to evaluate the performance of PSGR and the state-of-the-art geo-routing protocols, including GeRaf [20], [21], IGF [1], GPSR [9], and Flooding. PSGR exhibits superior performances (in measured metrics of energy consumption, routing latency, and delivery rate) under various network conditions, and soundly outperforms all compared protocols.

The rest of the paper is outlined as follows. Section II presents the preliminaries and examines the related work. Section III presents the design of PSGR and Section IV analyzes the appropriate transmission range for use in PSGR. Section V reports our performance evaluation results. Finally, Section VI concludes the paper with a summary and discussion of future work.

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II. Assumptions and Related Work

Here we present the assumptions made in this work and examine some closely related research.

A. Assumptions

We assume that a number of sensor nodes are deployed within a vast field which, for clarity of the presentation, is assumed to be a two-dimensional space. Each sensor node is location-aware [13], [16]. Sensor nodes can adjust their transmission range R between $(0, R_{max}]$, where R_{max} is the maximum transmission range. Energy consumption for transmitting one bit with transmission range R is captured as $Etx(R) = E_{elec} + E_{amp}R^{\alpha}$, where E_{elec} and E_{amp} denote the energy consumed by the radio transmitter and the transmission amplifier, respectively; α, called the path loss factor, usually satisfies $2 \leq \alpha \leq 4$. It takes $Erx(R) = E_{elec}$ to receive one bit. The topology of sensor networks may dynamically change during operation, due to 1) node mobility (sensor nodes may be mobile); 2) energy conservation (sensor nodes may periodically switch to sleep mode [15]); 3) unreliable links and node failures. Due to space limitation, we only present our work for network dynamics resulting from node mobility; studies for network dynamics resulting from energy conservation is available in [18]. Without loss of generality, we assume each sensor node may move without exceeding a maximum speed of V_{max} (the sensor nodes are stationary when $V_{max} = 0$).

This paper focuses on the routing of data packets from a source node to a geographic location rather than to a specific sensor node. The routing process terminates when 1) the data packet reaches a sensor node located within a distance threshold from the destination (e.g., within R), or 2) a sensor node believes the destination is not reachable and drops the packet. The first condition designates a *successful delivery* while the second one represents a *delivery failure*. The exact criteria for a node to decide when to drop a packet depends on the strategies for overcoming the communication void problem; this is discussed in Section III-B.

B. Related Work

Next, we review the key features of a number of geo-routing protocols, paying special attention to those we study in our performance evaluation (i.e., GPSR, IGF and GeRaf).

GPSR [9] is a representative stateful geo-routing protocol in which each node maintains the location information about its neighbors by periodic exchange of beacon messages. A packet holder, based on the cached neighbor locations, chooses the neighbor closest to the destination as the next relay node. When reaching a void region, a right-hand rule is used for bypassing the void region. Due to the dynamic network topology, the cached information could be obsolete and the chosen relay node may be outside the holder's transmission range, which results in broken links. Once a broken link is detected, the holder updates its cache and resends the packet to the second closest neighbor to the destination in its cache. This procedure could be repeated multiple times before the packet is successfully forwarded, thus consumes considerable energy.

IGF [1] is a stateless algorithm based on volunteer forwarding. In IGF, a forwarding region is defined as a 60-degree fan-shaped area that faces toward the destination such that all PFs are closer to the destination than the holder and all PFs can hear each other. A PF holds its acknowledgement for a period of time calculated based on its distance to the destination plus a random delay. PFs closer to the destination acknowledge earlier. However, because there are potentially infinite numbers of location points in the forwarding region, a packet holder may have to wait for a long time before hearing an acknowledgement back. IGF proposes *forwarding region shift* to address the communications void problem, without providing details.

GeRaf [20], [21] is also a stateless geo-routing protocol based on volunteer forwarding. The forwarding region in GeRaf contains all PFs that will make positive progress toward the destination, which compared with IGF, improves the chance of locating a PF. Similar to our proposal, GeRaf divides the forwarding region into a number of sub-regions (called *forwarding zones (FZ)* in PSGR), each of which qualifies a distance to the destination. PFs located in the same FZ are assigned the same priority and thus will compete with each other. GeRaf does not try to minimize acknowledgement collisions, but rather provides a resolution for it. Thus, it does not determine appropriate forwarding zones and acknowledgement delays as PSGR does. In GeRaf, the packet holder has to send explicit messages for retransmission, or for acknowledgements from other forwarding zones. For the void problem, GeRaf considers the dynamics of network topology and suggests that the holder wait for a period of time then search its forwarding region again. However, no details have been provided.

BLR [6] and CBF [4] are two other stateless geo-routing algorithms that are not examined in our performance evaluation due to the lack of design details and system settings.

III. Design of PSGR

As we pointed out earlier, acknowledgement collision, which has a significant impact on energy efficiency, latency and robustness of volunteer forwarding, is one of the core issues that must be addressed. In order to effectively suppress competing acknowledgements and message collisions, we develop a priority-based autonomous acknowledgement mechanism based on online estimation of node density, dynamic formation of forwarding zones, and minimized acknowledgement delay for each forwarding zone. We also propose two alternative stateless strategies, namely *rebroadcast* and *bypass* as solutions for communication void problem.

A. Prioritized Acknowledgement

The basic idea of prioritized acknowledgement is to assign *acknowledgement precedences* to all the PFs such that the PFs can respond to a forwarding probe without competing with each other. An intuitive scheme is to assign a unique acknowledgement precedence value (denoted as *AckP*) to every location point in the forwarding region in accordance with a total order relationship among all the location points. This total order relationship can be governed based on various heuristics such as the distance to the destination.

This naive scheme faces a challenge in terms of the acknowledgement delay (i.e., waiting time); many location points are not occupied by any PF, so a packet holder may wait for a long time before receiving an acknowledgement. Our design chooses to assign an AckP to a forwarding zone instead of to a location point. The forwarding zones can be formed flexibly based on various heuristics and performance requirements. Similar to PSGR, GeRaf [20] also adopts a forwarding zone approach. However, they choose to simply divide the forwarding region into a given number of zones and focus on providing an algorithm to resolve acknowledgement collisions. We focus on dynamically forming a forwarding zone in which an acknowledgement collision rarely happens and acknowledgement delay is minimized. Furthermore, PFs (whether within the same or different zones) determine their acknowledgement delay autonomously without any intervention from the packet holder. Since formation of forwarding zones is an important task in the design of prioritized acknowledgement mechanisms, we next discuss three important aspects of zone formation in PSGR, namely, *scope*, *size* and *acknowledgment delay*.

1) Zone Scope: The scope of a forwarding zone refers to the covered area of the zone.Two heuristics for forming forwarding zones are explored here, aiming at optimizing the energy consumption and routing latency, respectively.

(a) DTD (b) M_DTD

Fig. 2. Forwarding zones

The first heuristic, called *distance to the destination* (DTD) aims at maximizing the spatial forwarding progress at each hop. The forwarding region (denoted as FR) is partitioned into Z forwarding zones FZ_i ($1 \le i \le Z$). An FZ_i in PSGR is represented with a pair of distances to the destination, i.e., $\langle d_{i-1}, d_i \rangle$, such that $FZ_i = \{p | d_{i-1} \le |p - p_D| \le d_i \wedge |p - p_S| \le R\}$ and $FR = \cup_{1 \le i \le Z} FZ_i$, where R is the radio transmission range, and p_S and p_D are the positions of the holder and destination, respectively. If D denotes the distance between the holder and the destination, d_0 is set to $D - R$, and d_i ($1 \le i \le Z$) is selected such that the area of each FZ_i equals the expected zone size (see next subsection). Figure 2(a) shows three forwarding zones created based on DTD. For FZ_i, its AckP equals i. Thus, a PF located in a zone closer to the destination has a lower AckP (i.e., a higher priority). Two PFs located in the same zone have the same priority. In Figure 2(a), PF_1 has a lower AckP than PF_2.

The second heuristic, called modified DTD (M_DTD), first splits the forwarding region into three sectors, such that a PF can hear all the communications originated from the sector in which it resides. As shown in Figure 2(b) sector 1, with vertices V_1, V_2, and the holder, is surrounded by three arcs. An arc between any two vertices is a partial circumference of the circle centered at the remaining vertex with the transmission radius R. The sectors 2 and 3 are on either side of sector 1. Within each sector, M_DTD further forms FZs by applying the DTD heuristic, as marked by the dotted lines in Figure 2(b). Hence, two PFs located in adjacent FZs that are in the same sector can hear each other. This has a positive effect on reducing the acknowledgement delay, which will be explained shortly in Section III-A.3. The AckP of a forwarding zone is assigned based on a combination of its sector number and its distance to the destination.

2) Zone Size: The size of an FZ determines the number of zones within an FR. When the size of the FZ is set to the size of the FR, the holder faces the issue of duplicated acknowledgements and collisions. On the other hand, when the FZ is reduced to a location point, the holder faces the issue of long acknowledgement delay. PSGR avoids these two extremes by dynamically setting the forwarding zone to an area that contains only one PF. This design goal, achieved by taking dynamically estimated node density into account, contributes significantly to the novelty and excellent performance of PSGR.

Let $A(d, r_1, r_2)$ denote the size of an area intersected by two circles with radii being r_1 and r_2, respectively and the distance between their centers being d. Let D be the distance between the holder and the destination. The area of the holder's forwarding region can be represented by $A(D, D, R)$. Suppose the estimated density of sensor nodes is ρ (see the next paragraph for the estimation method); the FZ size is obtained as $1/\rho$. Thus, the total number of FZs can be obtained as $Z = \lceil A(D, D, R)/\rho \rceil$. The exact scope of an FZ and its corresponding acknowledgement precedence value (i.e., AckP) can then be obtained as described in the previous subsection.

To estimate the density of neighbor sensor nodes, ρ, the holder records the number of unique nodes residing in its radio coverage region (i.e., with an area of πR^2) within certain time window. This is obtained from the messages the holder overhears/hears. We set the time window as the average time a neighbor node remains active inside the coverage area of the given sensor node. Let *crossing rate*, τ, denote the number of nodes crossing a given region per second. According to [2], $\tau = \frac{\rho V_{max} C}{\pi}$, where V_{max} is the maximum moving speed of sensor nodes, and C, the perimeter of the given region is $C = 2\pi R$. Thus the crossing rate is $\tau = 2\rho V_{max} R$. Since the average number of nodes in the coverage area of the given sensor node is $\rho \pi R^2$, we obtain the average time that a node remains in an FR as $\frac{\rho \pi R^2}{\tau} = \frac{\pi R}{2 V_{max}}$. This estimation method works only when the network traffic is dense enough. When few communications happen inside the network, the sensor node may have an estimate lower than the real density of its neighbor nodes. Therefore, we set a lower bound for the node density, ρ_d, which is obtained by assuming a uniform node distribution in the operational area. We remark that this density estimation does not conflict with the key idea of *stateless* volunteer forwarding, since no state information of neighboring nodes, only a count of messages, needs to be maintained and updated.

3) Acknowledgment Delay: We use an acknowledgement timer to specify the acknowledgment delay (denoted as AckT) that a PF needs to wait before it responds to the holder. Let ATI_i denote the acknowledgement timer interval associated with FZ_i. For a PF located in FZ_i, $AckT_i$ can be obtained as follows:

$$AckT_i = AckT_{i-1} + ATI_i = \sum_{j=1}^{AckP_i} ATI_j, \quad \text{where } ATI_1 = 0.$$

To optimize acknowledgement delay, ATI_i ($1 < i \le Z$) should be as small as possible, yet it should be long enough that a PF can hear the acknowledgement from high-priority PFs or the packet from the holder before its timer expires. In other words, ATI_i should be long enough to accommodate the *hop delay*, the elapsed time from the instance when a sensor node initiates a message to its farthest neighbor node to the instance when the neighbor node receives it. The hop delay can be estimated by *hop delay = propagation delay + transmission delay + 2×queueing delay*. Thus, ATI_i for FZ_i can be set as one hop delay if all the PFs inside FZ_i can hear possible acknowledgements sent from FZ_{i-1}; otherwise, ATI_i is set to twice the hop delay (i.e., the extra hop delay is for the PF inside FZ_i to hear whether the packet has been forwarded from the packet holder). Insuring the PFs in two adjacent FZs hear each other (as M_DTD shown in Figure 2(b)) allows a smaller ATI, which reduces the forwarding delay.

PSGR attempts to form zones that have only one PF in order to avoid acknowledgement collisions. However, with possibly non-uniform node distribution and imperfect estimate of node density, there is no guarantee that there is only one PF in each FZ. The solution to this problem is to add a small jitter (i.e., a random delay) to each ATI_i. This simple, yet effective, method is widely adopted in sensor networks [1], [8], [9].

B. Communication Void Problem

In a static sensor network, the void regions are usually permanent, caused by physical obstacles (e.g., a mountain) or poor communication conditions. Thus, they can be handled by planning the routing a priori. Given a dynamic network topology, however, the void regions may be temporary. In PSGR, a void region is detected if a packet holder does not receive any acknowledgment after all the forwarding zones time out. In this case, the packet holder is called a *stuck node*. We propose complementary *stateless rebroadcast* and *stateless bypass* strategies to go across or to go around the void region, respectively, without requiring a priori knowledge about network and neighbor states.

1) Rebroadcast: The rebroadcast strategy is based on the belief that a PF may exist near the void forwarding region. Thus, after waiting for a period of time after the previous failed probe, the packet holder may rebroadcast the probe message, hoping that a PF moves into the void forwarding region.

Our rebroadcast algorithm for the void communication problem runs as follows. Once a void region is identified, the holder resets a rebroadcast timer in hopes a sensor node will become available in its forwarding region. When the timer expires, the forwarding request is rebroadcast with the maximum transmission range R_{max} (if it has not been used) in order to increase the probability of hitting a PF in this extended forwarding region. If the holder receives an acknowledgement, it sends out the data packet and returns to the regular forwarding process. Otherwise, the rebroadcast repeats until a sensor node enters into the forwarding region or a preset number of rebroadcasts is reached.[1] In PSGR, the rebroadcast timer is determined by considering the mobility of the sensor nodes. As mentioned in Section III-A.2, τ denotes the crossing rate, and equals $\frac{\rho V_{max} C}{\pi}$, where ρ is estimated by the method described previously. Given the transmission range R and the distance between the holder and the destination D, the perimeter of the forwarding region is $C = 2R\cos^{-1}(\frac{R}{2D}) + 2D\cos^{-1}(\frac{2D^2-R^2}{2D^2})$. The average time for a sensor node to move into a given FR is given by $1/\tau$, which is the rebroadcast timer. Prolonging the timer increases the chance of a node appearing in the forwarding region, reduces the number of rebroadcasts needed and improves the delivery rate, at the cost of forwarding latency.

2) Bypass: The rebroadcast strategy is not expected to perform well when the packet holder encounters a permanent void region or when the sensor nodes move very slowly. Thus, the traditional bypass strategy is still necessary. Existing bypassing algorithms are typically based on the well-known *right hand rule*[2]. This strategy has been shown to work well in static networks [3], [9], [11]; however, they require the cached neighbor state information. Based on the same idea as volunteer forwarding, we adopt the right hand rule for the PSGR bypassing algorithm. Our principle is to select the bypassing nodes at one *side* of the void region such that the packet will travel along that side of the void region border. The different sides are separated by the straight line connecting the stuck node and the destination. Due to space limitations, we only briefly outline the stateless bypass algorithm in the following; interested readers are referred to [18] for details.

During the regular forwarding process, the sensor nodes located in the packet holder's transmission range but not within the forwarding region (thus called *potential bypassing nodes (PBs)*) anticipate the potential bypass events by setting their *bypassing* acknowledgement precedence and timers when receiving a forwarding request message from the holder. Acknowledgment priority and timer, determined by the right hand rule, are employed again to control the waiting time and to suppress duplicate messages from PBs. The AckTs for PBs are longer than the AckTs of all the PFs, so PBs do not compete with PFs. A PB stops its timer if it overhears a message from the holder, PFs, or any other PBs before the timer expires. Otherwise, it acknowledges the holder (i.e., the stuck node). Then, the routing process switches from forwarding to bypassing mode. If the selected PB is closer to the destination than the stuck node, the forwarding mode is resumed. Otherwise, the PB becomes a bypassing node and broadcasts a *bypassing probe* message. For subsequent selections of bypassing nodes, all the neighbor nodes located within the transmission range are PBs. During the bypass, the location of the stuck node is sent along with the data packet to the subsequent bypassing nodes in order to decide when to switch back to the forwarding mode. Moreover, to prevent loops (since the sensor nodes have no knowledge of network topology or network underlying graph), bypassing nodes keep track of the packets they have previously received for bypass and disqualify themselves as the PBs when they hear the same bypassing probe again. In a rare occasion where a sensor node cannot be quickly found to bring the routing back to the regular forwarding mode, a maximum count of bypass hops is used to terminate the packet delivery.

IV. Analysis of Transmission Ranges

In this section, we develop an analytical model to derive PSGR's energy consumption and delivery rate as functions of sensor nodes' transmission range. We show that, while using R_{max} has the advantages of requiring fewer forwarding hops, increasing network connectivity (and thus delivery rate), and finding more volunteer forwarders, the energy expense for each hop forwarding is higher than using a shorter transmission range. Therefore, the transmission range of the sensor node has significant impacts on energy consumption, delivery rate and communication collision. We assume the number of sensor nodes in a unit area follows a Poisson distribution, which has been widely used to model the node distribution in a wireless network [10]. Our analysis reveals insights on selecting appropriate transmission range for deployment and operations of the sensor networks. The notations used in this analysis are summarized in Table I.

Consider the volunteer forwarding at the i^{th} holder with a distance D_i from the destination (D_0 denotes the distance between the source and destination). Suppose that a PF at location p is selected as the next hop. The **forwarding progress**, f_i, made by this PF is $D_i - dist(p)$, where $dist(p)$

[1] The maximum number of rebroadcasts is to conserve the energy in case that a permanent void exists in the network.

[2] The right hand rule states that, by sweeping the edge between the current and the previous holder with certain *bypassing direction* (counter-clockwise or clockwise), the first swept node is chosen as the next hop for bypass.

Notation	Meaning
D_i $(i \geq 0)$	the distance between the i^{th} holder and destination. The 0^{th} holder is the source.
R	sensor nodes' transmission range
B_{max}	the maximum number of rebroadcasts at each hop
b_i	number of rebroadcasts needed before the i^{th} holder finds a PF
f_i	the forwarding progress at the i^{th} hop toward the destination
h_s	number of hops needed for a successful delivery
h_f	number of hops passed through before a delivery is failed
P^{bc}	the probability of a broadcast being successed
P^{rbc}	the probability of a rebroadcast with R_{max} being successful
P^{hop}	the probability that a holder can find a PF
$e_{fwd}(R)$, $e_{ack}(R)$, $e_{pkt}(R)$	energy consumption for transmitting a forwarding request packet, an acknowledgement packet and a data packet

TABLE I

SUMMARY OF NOTATIONS USED IN ANALYSIS

is the distance of the PF located at p to the destination. According to PSGR, a PF is chosen if and only if there is no other PF closer to the destination. Thus, the probability of choosing the PF as the next hop equals the probability of the area $A(D_i, D_i - f_i, R)$ being empty. The cumulative density function (CDF) of f_i is:

$$\mathbf{F}_{f_i}(r) = \mathbf{P}(f_i \leq r) = e^{-\rho A(D_i, D_i - r, R)}$$

Hence, the expected progress at the i^{th} hops $\bar{f}_i$ is:

$$\begin{aligned}\bar{f}_i &= \int_0^{\infty} (1 - \mathbf{F}_{f_i}(r))\, dr - \int_{-\infty}^{0} \mathbf{F}_{f_i}(r) dr \\ &= R - \int_0^R e^{-\rho A(D_i, D_i - r, R)}\, dr\end{aligned}$$

Based on the above equation, $\bar{f}_i$ decreases with D_i, since $A(D_i, D_i - r, R) < A(D_j, D_j - r, R)$ when $D_i < D_j$. Next, we study the number of hops h_s needed to reach the destination successfully. A delivery succeeds when

$$D_0 - R \leq \bar{f}_0 + \bar{f}_1 + \ldots + \bar{f}_{h_s} \leq h_s \cdot \bar{f}_0$$

Thus, the lower bound of the number of hops for forwarding through the distance D_0 is given by $h_s \geq (D_0 - R)/\bar{f}_0$. To obtain the delivery rate and energy consumption, we need to take rebroadcasts into consideration. Assuming the maximum number of rebroadcasts before a node gives up the forwarding is B_{max}, the probability of a broadcast being successful at i^{th} hop, P_i^{bc}, is

$$P_i^{bc} = 1 - e^{-\rho A(D_i, D_i, R)}$$

The probability of a rebroadcast with R_{max} being successful, P_i^{rbc}, is

$$P_i^{rbc} = 1 - e^{-\rho A(D_i, D_i, R_{max})}$$

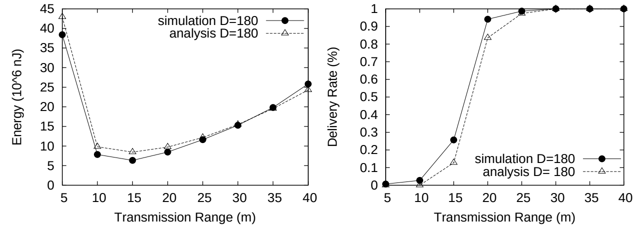
Let b_i denote the number of rebroadcasts needed for the i^{th} hop to find a PF in its forwarding region. The expected number of rebroadcasts at the i^{th} hop is:

$$\bar{b}_i = \sum_{j=1}^{B_{max}} (j+1) \sum_{k=1}^{j} (1 - P_i^{rbc})^{k-1} P_i^{rbc}$$

The probability of the i^{th} holder successfully finding a PF, P_i^{hop}, is derived as follows:

$$P_i^{hop} = P_i^{bc} + (1 - P_i^{bc}) \sum_{j=1}^{B_{max}} (1 - P_i^{rbc})^{j-1} P_i^{rbc}$$

Let h_f denote the number of hops a packet traversed before the forwarding is failed (i.e., no PF is found after B_{max} rebroadcasts at the ${h_f}^{th}$ hop). The probability of routing failure is the probability that the number of hops that successfully find a PF is less than h_s:



(a) Energy (b) Delivery Rate

Fig. 3. analytical results for PSGR performance

$$\mathbf{P}(h_f < h_s) = \sum_{j=1}^{h_s - 1} \prod_{k=0}^{k=j-1} P_k^{hop} (1 - P_j^{hop})$$

Hence, the *delivery rate* of PSGR is given by $\mathbf{P}(h_f \geq h_s) = 1 - \mathbf{P}(h_f < h_s)$. Finally, let $e_{fwd}(R)$, $e_{ack}(R)$, and $e_{pkt}(R)$ denote the energy consumption for transmitting a forwarding request, an acknowledgement, and a data packet, respectively. The total energy consumption, e_{total}(R), is derived as:

$$\begin{aligned}e_{total}(R) &= h_s \cdot [e_{pkt}(R) + e_{ack}(R) + e_{fwd}(R)] \\ &+ h_s \cdot \bar{b}_i \cdot e_{fwd}(R_{max}),\end{aligned}$$

We compare derived analytical results with simulation results (shown in Figure 3). The simulation setup follows what is described in Section V-A. In this set of experiments, D_0 is set to 180 m and V_{max} is set to 20 m/sec. As shown in Figure 3, PSGR's analytical result approximates the experimental result very well. Figure 3(a) plots the energy consumption. The small R (i.e., less than 10 m) incurs high energy cost due to the poor network connectivity and hence a large number of rebroadcasts at each hop. The energy consumption dramatically decreases as the R increases, and reaches its minimum at $R = 15$ m. After that, as the packets can be routed for more hops before being dropped or arriving at the destination, the energy consumption moderately increases. Even though the energy cost is minimized at $R = 15$ m, it may not be a good choice considering the delivery rate shown in Figure 3(b). The delivery rate radically increases with R, before it hits 20 m. When R is larger than 30 m, both simulation and analytical results achieve at least 99% delivery rate. Transmission range should be chosen by considering both energy efficiency and delivery rate. Therefore, 20 m, 25 m, and 30 m are all reasonable choices for transmission range.

V. PERFORMANCE EVALUATION

To evaluate the performance of PSGR, we developed a simulator to test its sensitivity to various system factors (e.g., mobility, network scalability, and location error). Several state-of-the-art routing protocols, namely, flooding, IGF [1], GeRaf [20], [21] and GPSR [9], were included in the evaluation for comparison.

A. Metrics and Settings

We implemented the proposed PSGR as well as counterpart routing protocols in ns-2 (with the CMU wireless extensions). Similar to [8], [9], we adopt IEEE 802.11b as the MAC layer protocol. The maximum transmission range of a sensor node, R_{max}, is set to 40 m [7]. The path loss factor for radio transmission, α, is set to 3. We extended the transmission power control module in ns-2 to capture the power consumption for dynamically adjusted radio transmission ranges. For PSGR, we set the maximum number of rebroadcasts and the maximum number of bypassing hops both to 6, which is the same as the number of forwarding-region shifts in IGF [1]. According

Parameters	Values	Parameters	Values
R_{max} (m)	40	α	3
Number of nodes	100	Simulation (s)	600
Network size (m^2)	160x160	Speed (m/s)	0 - 30
Pause time (s)	0	ρ	15, 20
Packet size(bytes)	32	Number of trials	25

TABLE II

EXPERIMENT SETTINGS

to [20], [21], we simulate GeRaf with four forwarding zones that divide the forwarding region evenly; the total times of transmissions allowed for a packet holder before dropping the packet is 10. We tested GPSR with different beacon intervals (i.e., 1.0 sec, 1.5 sec and 3.0 sec), but show the results with a beacon interval of 3.0 sec only, as this setting consumes much less energy than the other two settings while maintaining a reasonable delivery rate and latency.

We simulate the mobility of sensor nodes using a *sound random waypoint* mobility model [19], which generates stable sensor node movements, e.g., a fixed average speed and a fixed speed variance. The spatial distribution of sensor nodes moving according to this model is *nonuniform* even though the nodes are initially placed uniformly inside the experiment region. Generally, a node randomly chooses a destination within the simulated field and a speed, and then moves to the destination from its current location at the chosen speed. Upon arriving at the destination, the node pauses for a configurable period, called *pause time*, before repeating the same process. In our simulation, the pause time is set to 0, so that the mobility of sensor nodes is totally controlled by varying V_{max} (with a default value of 15 m/sec). For each packet routing request, source and destination locations are randomly chosen within the simulated field.

Each simulation run lasted for 600 sec of simulated time. The results are obtained by averaging the performances over 25 runs of randomly generated movement traces. Table II summarizes the parameter settings in the simulation. Three metrics are studied in our evaluation. **Energy consumption** denotes the average energy cost of a packet routing request, including the energy cost of packet transmission and reception operations; **Delivery rate** is the ratio of the number of successfully delivered packets to the *total* number of packet routing requests; **Latency** is the average elapsed time for a *successful* packet delivery.

B. Mobility of Sensor Nodes

We first consider the impact of network dynamics caused by mobility of sensor nodes on the routing protocols. In the following, we examine the prioritized acknowledgement mechanism and the two strategies for the communication void problem by varying the maximum moving speed of sensor nodes V_{max} from 0 m/sec to 30 m/sec.

1) Prioritized Acknowledgement: To isolate the impact of the void communication problem from the prioritized acknowledgement mechanism on the performance, we only consider dense networks in this set of experiments (i.e., $\rho = 20$) such that communication void regions rarely occur. In addition to $R = 40$ m, we also plot the curves of PSGR with $R = 30$ m (obtained based on our analysis in Section IV) to show the improvement obtained with a dynamic transmission range.

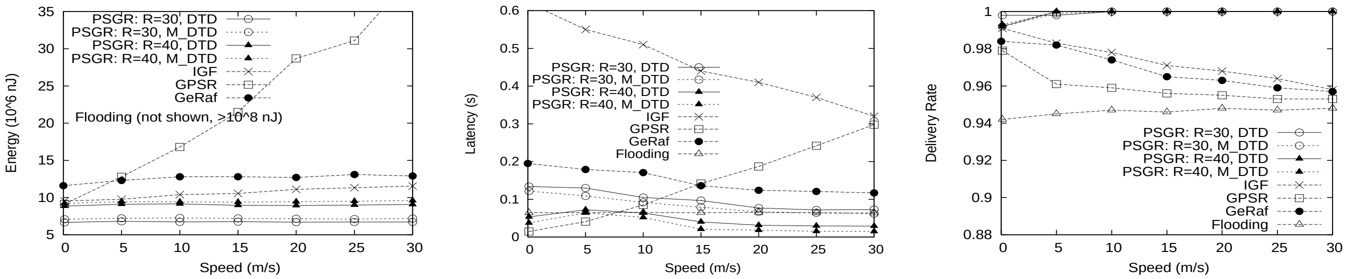
Figure 4(a) compares the energy consumption of all routing algorithms. The flooding algorithm has a very high energy consumption (i.e., 3.7×10^8nJ), so is not shown for clarity of the presentation. When the sensor nodes are static (V_{max} =0 m/sec), all algorithms except GeRaf have similar performance, whereas PSGR using R =30 m is clearly better than the others. As the mobility of sensor nodes increases, the energy expense of GPSR rises dramatically since the increasing number of broken links causes more retransmissions. On the other hand, the impact of network dynamics on the stateless algorithms (i.e., PSGR, GeRaf and IGF) is not that obvious. PSGR has the lowest and stablest energy consumption in all cases tested, and obviously is superior to all the others. DTD performs better than M_DTD since DTD was designed to minimize the number of forwarding hops. GeRaf performs poorly due to acknowledgement collisions occurred in the non-optimized forwarding zones.

Figure 4(b) compares the routing latency for all algorithms. IGF has an overwhelmingly longer latency than the other algorithms due to its long acknowledgment delay and small forwarding region. GeRaf suffers from its ineffective collision resolution algorithm, which may take several tries before a successful packet forwarding. In GPSR, as broken links cause more retransmissions, a longer delay at each hop happens when the network becomes more dynamic. Nevertheless, PSGR performs the best in dynamic networks. Setting the radio transmission range to the maximum has a positive impact on latency, since the average number of relays during the routing is reduced. Furthermore, because of a shorter acknowledgement timer, PSGR-M_DTD performs better than PSGR-DTD.

Figure 4(c) shows the delivery rate of all algorithms. The flooding algorithm performs the worst; this is because a lot of broadcast packets are dropped in collisions. GPSR has a worse performance than IGF and PSGR because of the inaccuracy of cached state information and the communication collisions caused by excessive beacon exchanges. GeRaf also shows a decreasing delivery rate with increasing sensor node mobility, due to few forwarding zones and its inefficient collision resolution algorithm. Conversely, the network dynamics has a positive impact on the delivery rate of PSGR, as it uses a large forwarding region and has more robust solutions for handling void regions. PSGR reaches a delivery rate of 100% when the sensor nodes move faster than 10 m/sec, whereas other algorithms perform no better than 98% in most cases.

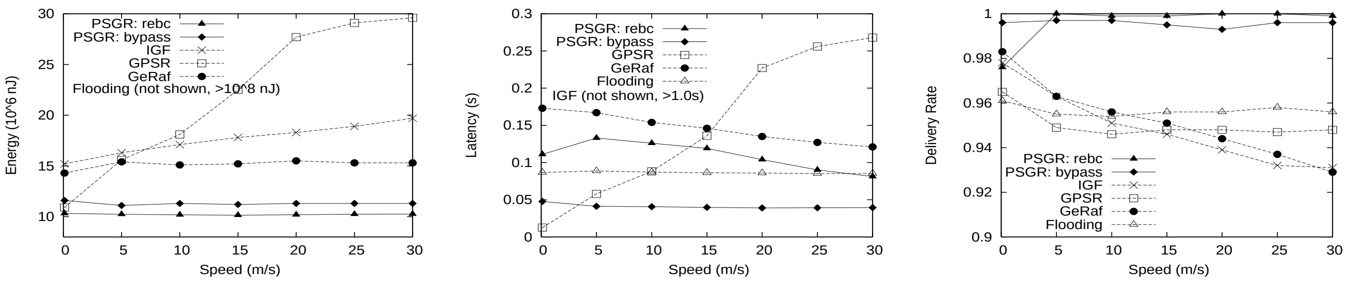
2) Communication Void Problem: In this section, we investigate the resilience of PSGR to the communication void problem in a relatively sparse sensor network (i.e., $\rho = 15$). For this and the rest of the experiments, we fix the transmission range R to 40 m in all the algorithms for a fair comparison. The heuristic used in PSGR for prioritized acknowledgement is fixed to DTD. The two strategies for PSGR to overcome communication void regions, rebroadcast (labelled as PSGR:rebc) and bypass (labelled as PSGR:bypass), are examined separately. Figure 5 compares the performance of PSGR:rebc, PSGR:bypass, IGF, GeRaf and GPSR.

Figure 5(a) shows the energy consumption of the compared algorithms. Again, the energy expense of the flooding algorithm is significantly higher than the others and thus is not shown. In PSGR, the bypass scheme has a higher energy cost than the rebroadcast; this is because each extra bypassing hop takes three transmissions (i.e., request, acknowledgement, and data packet forwarding), whereas a rebroadcast incurs one forwarding request only. Moreover, the rebroadcast tries to go across a void region in a straight line fashion (thus resulting in fewer hops) while the bypass takes extra hops to circumvent the void. Nevertheless, the superiority of the bypass is clearly demonstrated in Figure 5(b), where it has the best latency



(a) Energy consumption (b) Latency (c) Delivery rate

Fig. 4. Heuristics for forming sub forwarding region ($\rho = 20$)



(a) Energy consumption (b) Latency (c) Delivery rate

Fig. 5. Communication void problem ($\rho = 15$)

among all the algorithms. PSGR:rebc works better in a more dynamic network because a potential forwarder may come into the void region sooner. Figure 5(c) shows the delivery rate. PSGR:bypass has the highest delivery rate in a static sensor network and remains almost constant regardless of the moving speed of sensor nodes. However, in a static network, PSGR:rebc has a slightly lower delivery rate than IGF. The delivery rate of PSGR:rebc improves remarkably when nodes increase moving speed.

C. Scalability

In this section, we examine the scalability of PSGR and other counterpart protocols by increasing the number of sensor nodes deployed in a proportionally enlarged field (i.e., the network density is fixed such that $\rho = 20$). We choose a moderately dynamic network with $V_{max} = 15m/sec$.

Two observations are obtained from Figure 6(a). First, the energy consumption of all algorithms increases with increasing number of nodes (and field size), as the average path length of packet routing increases. Second, the volunteer forwarding based stateless routing protocols (i.e., PSGR, GeRaf, and IGF) demonstrate superb scalability over the stateful GPSR, which incurs more beacon exchanges to maintain the cached state information as the number of nodes increases. Figure 6(b) compares the routing latency. The latencies of IGF and GPSR increase rapidly as the network grows. For IGF, this is due to the cumulative cost of routing packets for a longer distance. For GPSR, in addition to the cumulative cost due to the longer distance, there are more broken links to be fixed along the routes. On the other hand, GeRaf does not prolong the routing latency, as we regulate the maximum number of control packets (i.e., 10) for each packet holder. It is encouraging to note that PSGR demonstrates a good scalability to a large network. The routing latency of PSGR increases only slightly as the routing distance is increased. Figure 6(c) shows that the delivery rate of GeRaf, IGF and GPSR decreases due to the higher probability of failing in routing a packet along a longer routing distance. However, thanks to the robust solutions to the void problem, PSGR can maintain a high delivery rate in all cases tested.

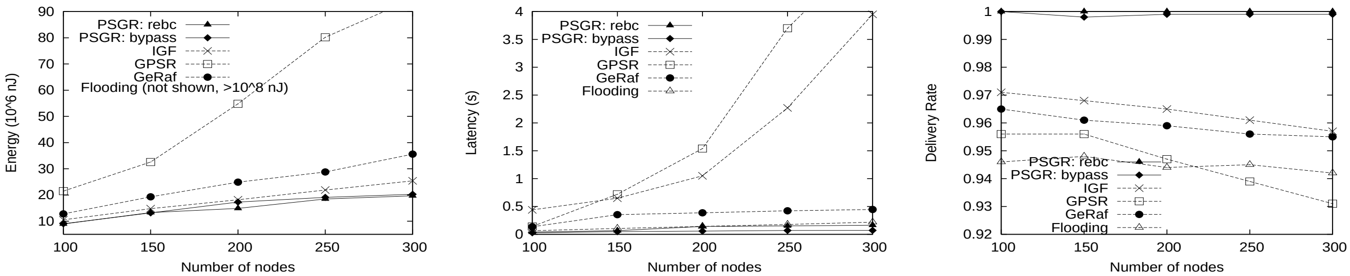
D. Resilience to Location Errors

Geo-routing protocols require all the sensor nodes to be location-aware. However, high-precision location information is difficult or expensive to obtain. Moreover, errors are unavoidable in many positioning/localization techniques. This section examines the impact of location errors on the performance of the compared routing protocols. We fix $\rho = 20$ and $V_{max} = 15m/sec$. Location errors are independently introduced to the coordinates of a sensor node by randomly adding a value drawn from [-$\mu * R_{max}$, $\mu * R_{max}$], where μ is a variable to control the degree of errors. Meanwhile, we redefine a successful delivery as a data packet reaching a distance within $(1 - \mu) * R_{max}$ from the destination. Figure 7 shows the performance of routing algorithms with μ varied from 10% to 50%. As expected, Figure 7(a) shows that the energy consumption increases with location error for all algorithms except the flooding. When the location inaccuracy is more than 40% of R_{max}, PSGR:bypass consumes more energy than IGF. This is because the imprecision in location may result in more hops for the bypass scheme since the forwarding nodes selected may not always be the best nodes.

The same reason also explains Figure 7(b), where PSGR:bypass has a longer latency for a higher location inaccuracy. The delivery rate is reduced with less accurate location information for all routing algorithms except the flooding (see Figure 7(c)). The impact on GPSR and IGF is most significant. As for IGF, it is because its small forwarding region excludes the best PF but likely selects some node outside the real forwarding region. With a much larger forwarding region, PSGR and GeRaf have a better tolerance to this problem.

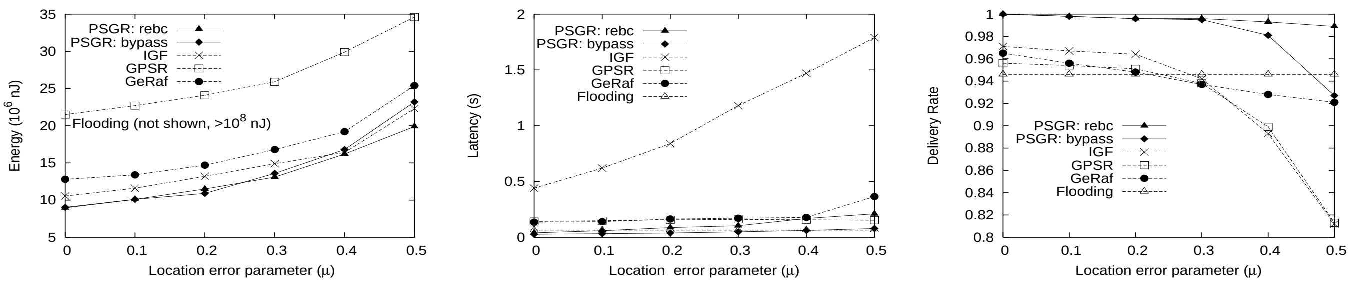
VI. Conclusion and Future Work

In this paper, we proposed a novel and robust stateless geo-routing protocol, namely, PSGR, for large-scale location-aware wireless sensor networks. The proposed priority-based acknowledgement mechanism exploits two crucial concepts in our design which contribute significantly to the novelty, robustness and high performance of PSGR: 1) dynamic zone formation (based on sensor node density estimated on-the-fly);



(a) Energy consumption (b) Latency (c) Delivery rate

Fig. 6. Scalability ($V_{max} = 15\ m/sec$, $\rho = 20$)



(a) Energy consumption (b) Latency (c) Delivery rate

Fig. 7. Location errors ($V_{max} = 15\ m/sec$, $\rho = 20$)

and 2) autonomous acknowledgements that avoid collisions. In addition, we employ two stateless strategies, namely rebroadcast and bypass, to address the communication void problem in PSGR. These two strategies favor responsiveness and energy efficiency, respectively. We derived analytical model on energy consumption and delivery rate of PSGR. The analysis, providing critical insights on selecting transmission range, is very important for planning and deployment of large scale wireless sensor networks. Finally, an extensive performance evaluation was conducted to compare the performance of PSGR and the state-of-the-art geo-routing protocols for wireless sensor networks, including flooding, IGF [1], GeRaf [20], [21], and GPSR [9]. Various network conditions were simulated and tested on the compared protocols. To the best of our knowledge, this is the most extensive performance evaluation conducted to compare stateless geo-routing protocols. Simulation results show that PSGR exhibits a superior performance in terms of energy consumption, routing latency, and delivery rate, and soundly outperforms all the compared protocols. For static or less dynamic sensor networks, PSGR with the bypass strategy is the best choice. In a dynamic sensor network, PSGR with rebroadcast is preferred.

PSGR has been shown to be a promising routing algorithm for location-aware wireless sensor networks. We plan to extend our design of PSGR in support of multicast routing (i.e., routing a message to multiple locations) and multipath routing (to further enhance robustness). Finally, we plan to implement PSGR protocol on real sensor motes to further examine its performance.

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