IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received October 23, 2020, accepted November 19, 2020, date of publication November 24, 2020, date of current version December 9, 2020.

*Digital Object Identifier 10.1109/ACCESS.2020.3040181*

# Probabilistic Second-Chance Broadcasting With/Without Global Positioning System Information in Wireless Ad Hoc Networks

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This work was supported by the MOST of Taiwan, R.O.C., under Grant 109-2221-E-110-049-MY2.

**ABSTRACT** A flooding algorithm aims to distribute messages to all nodes within the mobile environment. In a simple flooding scheme, every node broadcasts a newly received message. However, this simple mechanism generates massive redundant messages, which is referred to as the broadcast storm problem. To ease the negative effect of the broadcast storm problem, we proposed a novel scheme, Probabilistic Second-chance broadcasting with/without Global positioning system information (PSG) in wireless ad hoc networks, which amalgamates the merits of probability-based and location-based flooding algorithms. PSG eases the broadcast storm problem by reducing the total number of transmissions and does not require hello messages from neighboring nodes, yet achieves better results than Multipoint Relaying Flooding (MPR), a neighbor-knowledge-based flooding scheme, by accurately determining whether subsequent forwarding is advantageous while a node receives a broadcasting message. We also discuss the advantages of a two-phase/second-time algorithm and utilize a simplified topology to further explain and demonstrate the merits of second-time broadcasting. We compare our PSG scheme with the simple flooding scheme, the probabilistic schemes with different pre-assigned probabilities, and the MPR schemes with or without the overhead of hello messages. The simulation results show that our scheme demands fewer forwarding nodes to rebroadcast messages and therefore lowers the total number of transmissions. PSG scales down a large number of collisions and attains high delivery ratios compared to other flooding algorithms.

**INDEX TERMS** Ad hoc networks, broadcasting, global positioning system, flooding, probabilistic.

## I. INTRODUCTION

For wireless ad hoc networks, nodes are connected by wireless links without the involvement of wireless Access Points (APs) or wired routers [1]. To reach the destination requires multiple-hop transmissions and each node can choose when to participate in relaying messages. Flooding is a fundamental routing mechanism in wireless ad hoc networks. Simple flooding is the most straightforward way of flooding. In simple flooding, whenever a node receives a broadcast message for the first time, it helps relay the message. The messages already received before are ignored and dropped. The simply flooding mechanisms introduce many redundant or repetitive transmissions that generate many extra messages. Those messages will lead to network congestion and cause the broadcast storm problem [2], [3].

To alleviate the broadcast storm problem, four categories of flooding mechanisms are proposed, three categories of flooding mechanisms are described in [3] and one more category of flooding schemes, hybrid flooding, is complemented in this article. Four categories are probability-based flooding, location-based flooding, neighbor-knowledge-based flooding, and hybrid flooding. For probability-based flooding mechanisms, nodes relay broadcast messages by calculated or preset probabilities. Location-based flooding mechanisms require some positioning devices such as Global Positioning System (GPS) for geographical positions. In neighbor-knowledge-based mechanisms, nodes exchange hello messages with neighboring nodes periodically to map the topology of 1-hop or 2-hop neighbors. A hybrid flooding

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

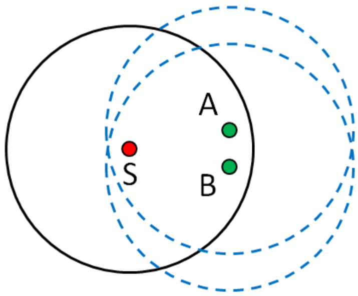


**FIGURE 1.** The scenario of our CL-SCTP scheme.

scheme denotes a scheme utilizing techniques from more than one category

Existing mechanisms have advantages and disadvantages [2], [3]. Probability-based mechanisms can reduce total transmitted messages in a high node-density environment by selecting appropriate relay probabilities for relay nodes. However, they often suffer the problem of low delivery ratios when node densities are low. Location-based mechanisms with GPS information can help decide to relay messages in a low node density environment but may still have difficulty in determining whether to relay messages in a high node density environment. Fig. 1 is an example in which both nodes *A* and node *B* have the same distance to the source node S. We can perceive the coverage area of node *A* and node *B* are highly overlapped, but both nodes are hard to know their relative positions. Neighbor knowledge-based mechanisms are not considered in this article since hello messages incur soaring messages costs to maintain neighboring information by regularly exchanging hello (beacon) messages.

We can have two-phase broadcasting and/or second-time broadcasting. Two-phase broadcasting refers to transmitting a broadcast message with a probability $p_1$ in the first phase and if the message is not sent in the first phase, the node forwards the message in the second phase with a probability $p_2$. Second-time broadcasting refers to transmitting a broadcast message the second time if the transmission node does not overhear other nodes forwarding the same message within a predetermined period. One problem with the probability-based flooding schemes is how we explain high delivery ratios of a two-phase or a second-time broadcasting algorithm [4], what we can benefit from overhearing messages in determining whether to broadcast a message again and why multiple phases of flooding are critical. As stated in lessons learned and open challenges [4], most probabilistic broadcasting schemes are based on heuristics; only a few articles have analytical models. We propose a mathematical analysis by a simplified topology based on our Probabilistic Second-chance broadcasting with/without GPS information (PSG) to explore further. The simplified model demonstrates and illuminates how high delivery ratios are guaranteed from the general design methodologies of the probabilistic-based flooding schemes with second-time broadcasting.

The main contributions of this article are as follows:

- We propose a Probabilistic flooding scheme based on two-phase broadcasting and second-time broadcasting in each phase. Our scheme does not need to exchange hello messages between nodes as neighbor-based mechanisms, yet carries on the benefits of probability-based mechanisms in the high-density environment and location-based mechanisms in the low-density environment and achieves a better performance than the typical neighbor-based mechanism MPR.
- The benefits of two-phase/second-time broadcasting are discussed and analyzed to highlight the necessity of a two-phase/second-time probability scheme. The complementary transmission of the second-phase/second-time broadcasting amends the wrong setting of broadcasting probability in the first-phase/first-time and also eases the pressure of assigning a high broadcasting probability which would result in a high collision rate in the first-phase/first-time. Furthermore, a simplified topology is proposed to explain and enlighten the high-delivery rate of a second-time broadcasting scheme compared to one-time broadcasting.
- Signal strength and GPS information are jointly considered. In the past, either the received signal strength or the distance between neighboring nodes is adopted for determining the forwarding probability for the broadcast messages. In this article, we suggest putting both characteristics into consideration because the signal strength affects the transmission ranges and the relative distance reflects the exploration of messages within the networks.
- Extensive simulations are performed to show the good performance of the PSG scheme. Both the free space model and the shadowing propagation model are simulated. Six schemes which are probabilistic flooding with a broadcasting probability = 0.3 (BP_0.3), probabilistic flooding with a broadcasting probability = 0.6 (BP_0.6), simple flooding (simple), Multipoint Relaying Flooding (MPR) routing [5], MPR routing with the hello message size = 0 (MPR0), and our proposed PSG scheme are compared. The total number of forwarding messages with a different number of ad-hoc nodes, the number of collisions with a various number of nodes, the delivery ratios versus the number of nodes, and the delivery ratios versus time are presented for five schemes.

This article is organized as follows. Related works are introduced in the next section. Our PSG is described in Section III. It is a two-phase and a second-time probabilistic scheme, which determines broadcast probabilities based on received signal strength with/without location information from a GPS unit. We also discuss the advantages of a two-phase/second-time scheme and propose a simple model to demonstrate the reasons behind the high delivery ratios of a second-time broadcasting algorithm. The simulation results of our PSG scheme are in Section IV. Both the free-space propagation model and the shadowing propagation model are simulated. The conclusion is in Section V.

## II. RELATED WORKS

To flood messages between sources and destinations is an important research issue for wireless ad hoc networks. Flooding would be used for broadcasting emergency messages, exchanging control messages, and others. Flooding mechanisms can be reactive routing, proactive routing, or the hybrid of reactive routing and proactive routing. Typical reactive routing schemes include Ad hoc On-demand Distance Vector Routing (AODV) [6], [7], Dynamic Source Routing (DSR) [8], and On-Demand Multicast Routing Protocol (ODMRP) [9]. Representative proactive routing schemes comprise Optimized Link State Routing (OLSR) [10] and Destination-Sequenced Distance Vector (DSDV) [11]. Moreover, the integrated schemes of reactive routing and proactive routing contain Zone Routing Protocol (ZPR) [12] and Independent Zone Routing (IZRP) [13], [14]. One of the main problems with simple flooding is the broadcast storm problem [3]. To ease the broadcast storm problem caused by simple flooding, four main categories of flooding schemes are proposed.

### A. PROBABILITY-BASED FLOODING

To reduce the total number or relay messages, each node would decide whether to relay a message by a chosen probability [15] or by a dynamic probability based on the number of repeated messages received during an interval [16]–[18]. When node densities are high, the probability-based flooding performs well with a low retransmission probability. However, when node densities are low, we would encounter difficulty in picking out retransmission probability. As we set a medium with a low retransmission probability, some nodes may not be able to receive broadcast messages. If we select a high probability, the behavior of probability-based flooding within a dense environment would be similar to simple flooding which has *the broadcast storm problem*.

To assist the setting of retransmission probability, we can use a counter to record the number of repeated messages [17]. While a new flooding message arrives at a node, the node delays the retransmission by generating a Random Access Delay (RAD) and then counts the number of repeated messages received during the RAD interval [17]. The flooding message is only rebroadcasted if the number of repeated messages received within the RAD interval does not exceed a threshold value. With this method, the node has a lower probability of relaying messages while node density is high and a higher probability of relaying messages while node density is low. A node with a smaller RAD value would have a chance to start a transmission earlier. A counter is also adopted for wireless sensor networks [19]. The RAD value of each node is set according to the distance. A node with a longer (shorter) distance to the source would receive a lower (higher) RAD value to enumerate repeated messages, and therefore a higher (lower) probability of relaying messages than a node with a shorter (longer) distance.

In [20], instead of adopting a uniform distribution, a truncated-exponential distribution is proposed to decide RAD delays for nodes. The proposed approach lowers latency for each hop of transmission and brings an accumulated reduction of delays for multi-hop transmissions. Malicious nodes in a hostile environment are considered in [21]. Rebroadcast probability and rebroadcast delay are related to a node's trustworthiness. Optimal stopping theory is applied to conserve energy consumption for wireless networks [22]. The selected nodes for forwarding messages are mainly based on energy instead of reachability, whereas the network still holds a high broadcast efficiency.

The effects of different topologies on successful broadcasts are studied in [23]. Especially, randomly placed nodes bring forward a collision-free result. Nodes placed in lattice-like distributions such as triangular, square, and hexagonal grids are not as good as randomly placed nodes. For lattice-like distributions, collisions and interference are greatly increased.

Probability-based routing is also adopted by Vehicular Ad hoc NETworks (VANETs) [17], [24]–[26] towards primary directions. In [24] each node can relay a received message multiple times. Two variables, the waiting time and the transmission probability, are adjusted according to the repeated messages received. The process continues until reaching a pre-set timer or a pre-determined number of repeated messages. In [26], the broadcast probability is adaptively adjusted by the vehicle speed. Low vehicle speeds on the highway imply high densities, and therefore low rebroadcast probabilities are given. A good survey on the probabilistic scheme can be found in [4].

### B. LOCATION-BASED FLOODING

In location-based flooding, each node is equipped with a Global Positioning System (GPS) to get its geographical position. Whenever a node receives a message of a neighboring node with the geographical position, the node knows relative positions and distance between them. The coverage range of a message would expand further if we choose a node far away from the current node. One way is only exceeding a pre-defined distance can a node relay a received message. Another general way is to set backoff times for candidate nodes depending on distances. Nodes further away from the source have shorter backoff times. In [27] nodes are clustered into four quadrants and the backoff time is set to be inversely proportional to the relative distance between the sender and the receiver in each quadrant. Nodes closer to the source would observe that messages have been relayed by other nodes and give up their relaying messages.

### C. NEIGHBOR-KNOWLEDGE-BASED FLOODING

A neighbor table is maintained in each node for recording the information of neighboring nodes. There are two kinds of neighbor-based flooding: a node itself decides whether to rebroadcast a message and a node decides which of its neighbors to rebroadcast a message. The self-pruning method [28] belongs to the first kind. Each node periodically broadcasts a 1-hop hello message to inform neighboring nodes of its existence. Whenever a new hello message arrives at a node, the node compares its stored neighbor table with the neighbor table carried by the received message. The hello or beacon message is relayed only when there are new nodes in the neighbor table of the received message.

For the second kind, 1-hop information or 2-hop information can also be used to designate neighboring nodes for rebroadcasting a message. In [29], the 1-hop neighbor information contains the chosen neighboring nodes for rebroadcasting messages. At most four neighboring nodes are selected according to the number of neighbors and the distance of neighbors. In [30], the 1-hop information is used to choose forwarding nodes for broadcasting messages in a 3-D environment. MultiPoint Relaying (MPR) flooding is adopted by Optimized Link State Routing (OLSR) for flooding messages [5], [10]. MPR flooding utilizes 2-hop neighboring information to improve the accuracy in determining how to relay flooding messages. Each node broadcasts its 1-hop neighboring information with a hello message. When a node receiving the hello message from a neighbor node, the node knows the information of the neighbor node and the neighbor node's 1-hop neighbor. In this way, each node would keep the 2-hop information in the neighbor table. In MPR, a node only selects several designated nodes as relay nodes for flooding messages. The 1-hop neighbor, which uniquely connects some 2-hop nodes, would be selected first. Then the 1-hop neighbor which can reach the most number of uncovered 2-hop nodes is selected in order until all 2-hop neighbors are covered.

Some other schemes also adopt the 2-hop information approach [31]–[34]. Among them, many try to find the Minimum Connected Dominant Set (MCDS) [28]–[30]. Nodes belonging to the MCDS are chosen as the relay nodes. Finding the MCDS is an NP-complete problem [35] and therefore an approximation solution is proposed in [36]. One problem with the $k$-hop information schemes, where $k \in Z^+$, is that when node density is large, the overhead and collision of hello messages cannot be neglected. In [37], the location information is used to separate a network into several virtual zones. The goal is to decrease the number of topology-control messages. Transmissions between two virtual zones are carefully examined to ascertain that no duplicate retransmissions occur.

### D. HYBRID FLOODING

It is sensible to have schemes combining methodologies of two categories to pursue a better performance [18], [38]–[40]. The scheme in [18] depends on several steps of initial flooding messages to record neighboring information, and therefore can be regarded as a combination of the probability-based flooding and a variation of the neighbor knowledge-based flooding. To be more effective in determining the probability, the scheme further differentiates nodes into three kinds: parent nodes, sibling nodes, and child nodes. Sibling nodes are nodes with the same parent. Except considering the number of repeated messages, a node with more child nodes and/or less sibling nodes has a higher probability to relay flooding messages. The scheme in [38] also combines the methodologies of probability-based flooding and the neighbor knowledge-based flooding. The rebroadcast delays determine the forwarding order among nodes. The node with a greater number of common neighbors has a lower delay. Then the rebroadcast probability is calculated by the additional coverage ratio of a rebroadcast, which denotes the additional number of neighbors covered by the rebroadcast divided by the total number of neighbors, and the connectivity factor, which takes into account the total number of nodes in the network. In [39], dissimilarity metrics instead of Euclidean distance is adopted for assigning the broadcasting probability. The scheme can also be implemented in an indoor environment without GPS signaling. In [40], a scheme that incorporates both the methodologies of neighbor-knowledge-based flooding and the location-based flooding is studied. A self-pruning algorithm based on 1-hop neighbor information is adopted. A positioning system is then added to help construct MCDS and achieve full discovery.

Some pertaining scenarios are also discussed for ad hoc networks. In [41], the cognitive radio network is considered. Since there is not a channel reserved for broadcast, multiple channels would be chosen to gain a high successful transmission probability. One negative effect of using multiple channels is the prolonged delay which can be mitigated by asynchronous selective broadcast [41]. The broadcast in interference-rich open terrains is presented in [42]. The transmission power is adjusted and increased at some periods to improve reliability and goodput. The query-broadcast in mobile ad hoc networks is studied in [43]. A cache-aware approach is suggested for improving the Quality of Service (QoS) of the query-broadcast.

## III. PROBABILISTIC SECOND-CHANCE BROADCASTING WITH/WITHOUT GPS INFORMATION (PSG)

In this section, we describe our PSG scheme in detail. Then we present a simplified model to show why a two-time broadcasting scheme such as our PSG scheme can have a high delivery ratio. There are two basic assumptions for the PSG scheme.

- Each node is equipped with an IEEE 802.11 compliant wireless LAN device.
- Most nodes are equipped with GPS units and are aware of their positions.

The PSG scheme is a two-phase probabilistic and a second-time broadcasting scheme that calls for calculations of flooding probabilities and delays based on signal-strength and GPS-derived distances. A two-phase/second-time scheme bears the inherited advantages of a second chance to complete a broadcast. We have the second opportunity to adjust transmission probabilities in the second-phase/second-time if an implicit ACK is not overheard after the waiting time of the first broadcasting. Besides, we do not adopt three or more phases/times [20] because more phases/times usually lead to more delays. We show that by carefully choosing the probabilities and delays for the first-phase/first-time and the second-phase/second-time the PSG scheme performs well for both low-density and high-density networks with less forwarding nodes, low collisions, and high delivery ratios.

Not like most articles, a node refers to both the relative distance between itself and the sender for choosing a long-distance node to explore further and the received signal strength for choosing a receiver with a good channel quality. Therefore, rebroadcasting probabilities are accurately assigned after receiving a flooding message with location information (such as longitude and latitude or plane grid coordinates). As a result, the reachability can be maintained high whereas the number of forwarding nodes is kept low. In other words, even with a relatively low number of forwarding nodes, those participating forwarding nodes will deliver flooding messages to most nodes and thus have high delivery ratios. Moreover, since fewer nodes are involved in forwarding messages, a lower number of collisions is expected.

### A. PSG SCHEME

The five probable transmission scenarios of our PSG scheme are shown in Fig. 2 and the complete flow chart is depicted in Fig. 3. Each node, except the source node, comprises a broadcast message with its parent node id. For a node with a GPS unit, the GPS positioning information is carried with the broadcast messages. Nodes that receive a broadcast message can participate in relaying the message hop-by-hop. As in Fig. 2, a RAD delay is introduced before each broadcast message. When a node is idle and a broadcast message arrives, the node handles the receiving message depending on if the node having a GPS positioning capability. For clarity, a *GPS* node refers to a node with GPS capability, a *dumb* node refers to a node without GPS capability, and a node refers to both types of nodes hereafter.

The first phase of the broadcast is designed for a GPS node only (first two scenarios of Fig. 2). A GPS node receiving a broadcast message from another GPS node would probably broadcast the message in the first phase. The GPS distance can be derived when both the sender and the receiver are GPS nodes. A first-phase broadcast probability $p_1$ is calculated. If a GPS node decides to broadcast a message in the first phase, the GPS node waits for a random delay RAD before broadcasting its message. Afterword the GPS node waits a fixed time $w_t$ listening to the channel.

The second phase of the broadcast is introduced for a GPS node not broadcasting the message in the first phase or a dumb node (the last three scenarios of Fig. 2). A GPS node (dumb node) calculates a broadcast probability $p_1(p'_1)$ for obtaining the waiting time $d_t(d'_t)$ before starting the second phase of broadcasting. A higher $p'_1$ has a lower delay $d'_t$ and a lower $p'_1$ has a higher delay $d'_t$. This design of both $d_t$ and $d'_t$ is to force the node close to the source node to wait more time listening to the channel and yield the transmission to nodes further from the source node. If a GPS node (dumb node) does not hear any broadcast messages within the waiting time $d_t(d'_t)$, the message is broadcast with probability $p_2(p'_2) = 1$ since no neighbors broadcast the message. If more than one message is received, the message is rebroadcasted by a second probability $p_2$ or $p'_2$ for a GPS node and a dumb node, respectively.

For both phases of broadcasting, if the node hears that the same message is transmitted from a node within the fixed time $w_t$, the node examines the sending node's parent node to see if they have a common parent. If they do not have the same parent, the heard message is regarded as an implicit ACK and the node would enter the idle state waiting for the next broadcasting message. If their parent is the same, the received message will not be recognized as an ACK. As shown in Fig. 4, when node $A$ receives a message from node $S$ and then the same broadcasting message from node $B$, the message will not be seen as an implicit ACK since they have the same parent node $S$. This is to avoid terminating the broadcasting strictly to allow those grey nodes to broadcast the message. Also in Fig, 4, if a broadcasting message is from any grey nodes whose parent nodes are different, the message is regarded as an implicit ACK.

If the same message is not received within the fixed time $w_t$, the first transmitted message is regarded as a loss message, and the node rebroadcasts the message one more time with probability 1 and enters into the idle state waiting for the next broadcast message. There are four possible situations that no broadcast messages are received after a source node broadcasting a message two times. It can be some neighboring nodes have owned the message but do not broadcast the message, some neighboring nodes have rebroadcasted the message but the source node does not receive the message, no neighboring nodes correctly receive the message due to collisions, or no neighboring nodes are within the transmission range of the source node. In the following, we will detail how to calculate $p_1$, $d_t$, $p_2$, $p'_1$, $d'_t$, and $p'_2$.

### B. FIRST-PHASE BROADCASTING PROBABILITY $p_1$

When a sender begins flooding, its transmission power and its longitude and latitude (or grid coordinates) are also included in the flooding message. The node receiving the flooding message can then get a GPS-derived distance $D_{\mathrm{GPS}}$ between the sender and the receiver, a signal-strength distance $D_s$, and a first phase broadcasting probability $p_1$. We calculate a signal-strength distance $D_s$ in (1) by the Friis transmission equation [44].

$$P_r = \frac{G_t G_r \lambda^2 P_t}{(4\pi)^2 D_s^2}, \tag{1}$$

where $G_t$ and $G_r$ are the antenna gain of the transmitter and the receiver, respectively, $\lambda$ is the wavelength, and $D_s$ is the distance between the sender node and receiver node. As in (1), we can calculate the signal-strength distance, $D_s$, in (2). To have a smoother degradation for the receiver signal strength versus the distance, we use dBm instead of W as the

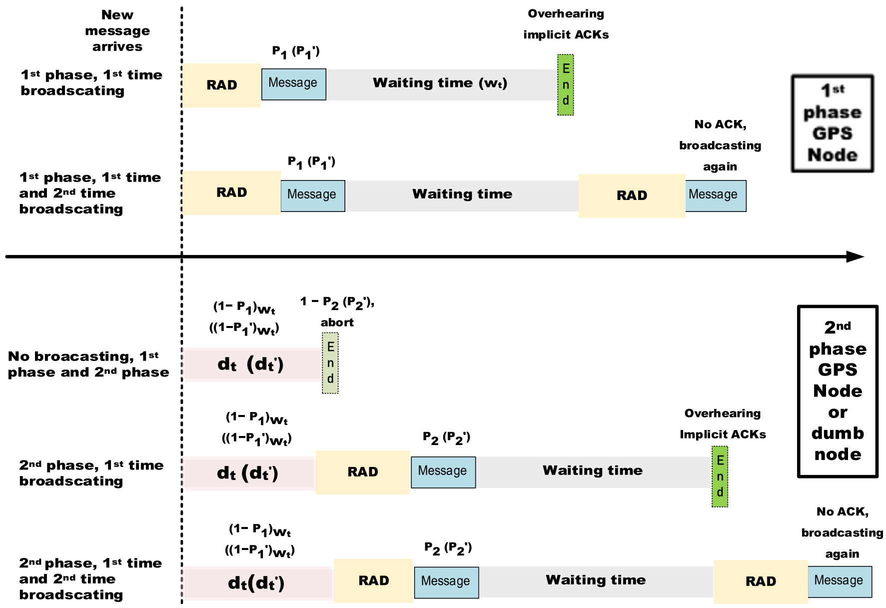


**FIGURE 2.** The five possible scenarios of the PSG scheme during a transmission.

power unit. The conversion formula is as in (3).

$$D_s = \frac{\lambda}{4\pi\sqrt{\frac{P_r}{P_t} \times \frac{1}{G_t G_r}}}. \tag{2}$$

$$\mathrm{P\,(dBm)} = 10 \times log_{10}\frac{P\,(\mathrm{w})}{0.001}. \tag{3}$$

In calculating the first-phase broadcasting probability, we give a higher probability to a node which receives a lower signal strength, and a lower probability to a node which has a higher signal strength. To this purpose, $P'_r$ is introduced to calculate the first phase of broadcasting probability. In (4), we calculate $P'_r$ in which $R_{\max}$ is the maximum transmission distance of a node. We calculate $P_t$, $P_e$, and $\alpha$ as in (5), (6), and (7), respectively. In (5), $P_t$ is the transmission power of the sender in dBm by using (3). In (6), $P_e$ is the received signal strength at the edge of the transmission range. In (7) ,$\alpha$ is the correction factor, which takes into account both the distance from the received signal strength and the distance from the GPS. The value $\alpha$ is set between zero and one to reflect that the value of $D_s$ can be larger than the value of $D_{\mathrm{GPS}}$. The $\alpha$ would be closer to one in free space with no obstacles. The first-phase broadcasting probability $p_1$ is obtained by (8). If there are obstacles between the source and the receiver, it may cause larger signal degradation. The distance $D_s$ we obtain from the free space model can be larger than the distance $D_{GPS}$ we obtain from the GPS. If $R_{max} - D_s > 0$, $p_1$ is calculated as in 8(a). A larger (smaller) $D_s$ will give a higher $P'_r$ and therefore a higher (lower) first-phase broadcasting probability $p_1$ in (8a). If $D_s \geq R_{\max}$, the received signal strength is lower than the threshold and we assign $p_1$ to have a probability 1 (8b).

$$P'_r = 10 \times log_{10}\frac{\left[\frac{P_t(\mathrm{W})G_tG_r\lambda^2}{(4\pi)^2(R_{\max}-D_s)^2}\right]}{0.001}. \tag{4}$$

$$P_t = P_t\,(\mathrm{dBm}) = 10 \times log_{10}\frac{P_t\,(\mathrm{W})}{0.001}. \tag{5}$$

$$P_e = 10 \times log_{10}\frac{\left[\frac{P_t(w)G_tG_r\lambda^2}{(4\pi)^2R_{max}^2}\right]}{0.001}. \tag{6}$$

$$\alpha = \frac{D_{\mathrm{GPS}}}{D_s}. \tag{7}$$

$$p_1 = \begin{cases} \alpha \times \left(\frac{P'_r - P_e}{P_t - P_e}\right) \times 100\%, & \text{if } R_{\max} - D_s > 0, (a) \\ 1, & \text{if } R_{\max} - D_s \leq 0. (\mathrm{b}) \end{cases} \tag{8}$$

*Lemma 1:* The first phase broadcasting probability $p_1$ is a probability function.

*Proof:* When $R_{\max} - D_s \leq 0$, $p_1 = 1$ which is a probability function. We show when $R_{\max} - D_s > 0$, $p_1$ is a probability function. The first term $\alpha$ is between 0 and 1. For the second term $\frac{P'_r - P_e}{P_t - P_e}$, we show that $P_t - P_e > P'_r - P_e > 0$. We first show that $P_t$ is greater than $P'_r$ *if* $R_{\max} - D_s > 0$. We subtract $P_t$ by $P'_r$ and get $P_t - P'_r = 10 \times log_{10}\frac{P_t}{0.001} - 10 \times log_{10}\frac{\left[\frac{P_tG_tG_r\lambda^2}{(4\pi)^2(R_{\max}-D_s)^2}\right]}{0.001}$. To show $P_t > P'_r$, we need to show that $P_t$ is greater than $\left[\frac{P_tG_r\lambda^2}{(4\pi)^2(R_{\max}-D_s)^2}\right]$. We divide $\left[\frac{P_tG_tG_r\lambda^2}{(4\pi)^2(R_{\max}-D_s)^2}\right]$ by $P_t$ and we get $\frac{P_tG_tG_r\lambda^2}{(P_t)(4\pi)^2(R_{\max}-D_s)^2} = \frac{G_tG_r\lambda^2}{(4\pi)^2(R_{\max}-D_s)^2} = \frac{G_tG_r\lambda^2}{(4\pi)^2R'^2} < 1$ by (1) since the received power $P_r$ is less than the transmitted power $P_t$. Therefore,

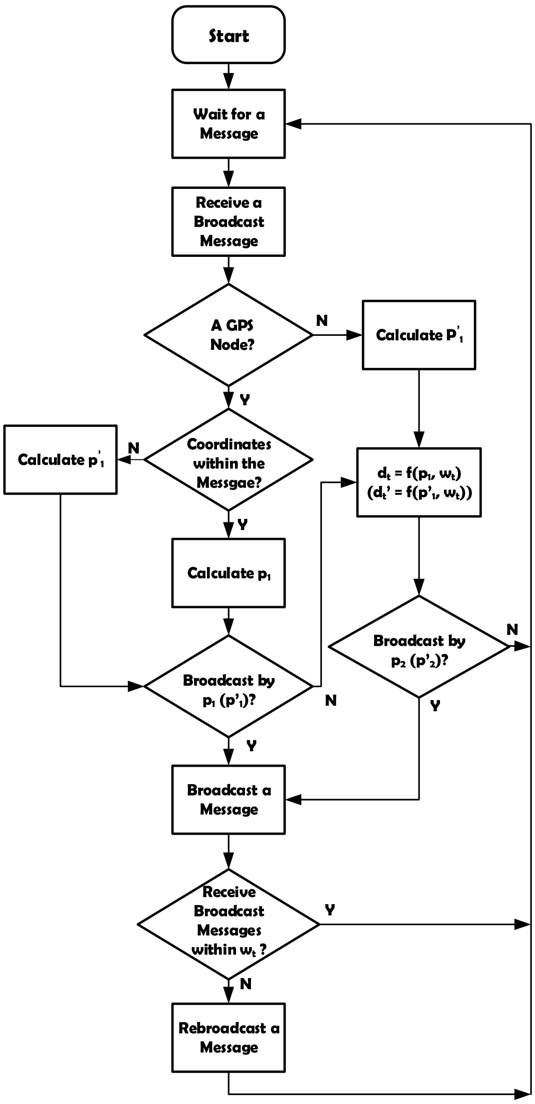


**FIGURE 3.** The flowchart of the PSG scheme.

we have the following:

$$P_t - P_e > P_r' - P_e. \tag{9}$$

From (4) and (6) we know that the value of $P_r'$ is larger than the value of $P_e$.

$$P_r' - P_e > 0. \tag{10}$$

By (9) and (10), we have $1 > \frac{P_r' - P_e}{P_t - P_e} > 0$. Therefore, the first phase broadcasting probability $p_1$ is a probability function. ∎

### C. SECOND-PHASE BROADCASTING PROBABILITY $p_2$

A node is in the second phase because the node receives a message and chooses not to broadcast the message in phase 1. The node waits for a delay time $d_t$ before determining whether to broadcast the message in the second phase. The delay $d_t$ is calculated as follows:

$$d_t = w_t \times (1 - p_1), \tag{11}$$

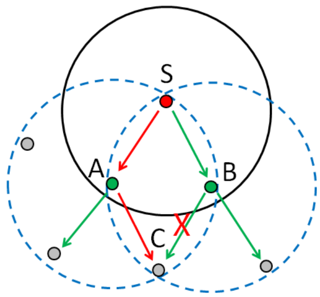


**FIGURE 4.** Nodes A and B have the same parent. Node *C* receives a message from nodes *A* would ignore the message from node *B* in counting $p_2$.

where $w_t$ is a fixed waiting time.

If no broadcast messages received within the delay $d_t$, no neighboring nodes broadcast the message and we broadcast the message with probability 1. If more than one message received, without loss of generality, assuming the node receives $n$ messages from $n$ adjacent nodes, $\{k_1, k_2, \ldots, k_n\}$ within the waiting time $d_t$. From (8a), we can calculate $p_{k1}, p_{k2}, \ldots, p_{kn}$ as follows:

$$p_{k1} = \alpha_1 \times \left(\frac{P_r' - P_e}{P_{k1} - P_e}\right) \times 100\%,$$
$$p_{k2} = \alpha_2 \times \left(\frac{P_r' - P_e}{P_{k2} - P_e}\right) \times 100\%,$$
$$\vdots$$
$$p_{kn} = \alpha_n \times \left(\frac{P_r' - P_e}{P_{kn} - P_e}\right) \times 100\%.$$

Then we calculate the second-phase broadcasting probability $p_2$as follows:

$$p_2 = \begin{cases} min\{p_{k1}, p_{k2}, \ldots, p_{kn}\}, & \text{if one or more messages,} \\ 1, & \text{otherwise.} \end{cases} \tag{12}$$

The value $p_2$ is dependent on the minimum value of $p_{k1}, p_{k2}, \ldots,$ and $p_{kn.}$ The smallest $p_{ki}$ determines the second-phase broadcasting probability $p_2$, where $i = 1, 2, \ldots, n$. That is, unlike the first phase broadcasting probability $p_1$ which only considers a received message, multiple received messages are considered in assigning the second-phase broadcasting probability $p_2$. Note that on counting $p_2$, received messages are examined but not all messages are adopted to ensure most nodes receive the message in the end. As in Fig. 4, while node $C$ has first received a message from node $A$ and then receives the same message from node $B$, the message from node $B$ would be ignored because both nodes $A$ and B have the same parent $S$, which implies that some grey nodes may not have received the message yet.

### D. RECEIVING A MESSAGE FROM A DUMB NODE

When a GPS node receives a message from a dumb node, the correction factor is not included in computing the first broadcasting probability since $D_{GPS}$ cannot be obtained. We can consider estimating the distance based on density as in [39], whereas it will need to exchange neighboring information. Instead, in this article the alternative first-phase broadcasting probability $p'_1$ is adopted as in (13a) and (13b) without the correction factor.

When a dumb node receives a message, $p'_1$ is used for calculating the waiting time $d'_t$ as in (14). That is, the node yields its broadcasting probability in the first phase to other GPS nodes which will have better estimations of their broadcasting probabilities.

$$p'_1 = \begin{cases} \left(\frac{P'_r - P_e}{P_t - P_e}\right) \times 100\%, & R_{\max} - D_s > 0, (a) \\ 1, & R_{\max} - D_s \leq 0.(b) \end{cases} \quad (13)$$

$$d'_t = w_t \times \left(1 - p'_1\right). \quad (14)$$

Similarly, the second-phase broadcasting probability $p'_2$ is computed as in (15).

$$p'_{k1} = \left(\frac{P'_r - P_e}{P_{k1} - P_e}\right) \times 100\%,$$

$$p'_{k2} = \left(\frac{P'_r - P_e}{P_{k2} - P_e}\right) \times 100\%,$$

$$\vdots$$

$$p'_{kn} = \left(\frac{P'_r - P_e}{P_{kn} - P_e}\right) \times 100\%.$$

$$p'_2 = \begin{cases} min\left\{p'_{k1}, p'_{k2}, \ldots, p'_{kn}\right\}, & \text{if one or more messages,} \\ 1, & \text{otherwise.} \end{cases} \quad (15)$$

*Lemma 2:* The first phase broadcasting probability $p'_1$ is a probability function.

*Proof:* $p'_1$ is calculated as $p_1$ without the correction factor $\alpha$. By Lemma 1, it is straightforward to show that it is a probability function. ■

*Lemma 3:* The second-phase broadcasting probability $p_2(p'_2)$is a probability function.

*Proof:* From Lemma 1 and Lemma 2, $p_{k1}, p_{k2}, \ldots, p_{kn}$ and $p'_{k1}, p'_{k2}, \ldots, p'_{kn}$ are all probability functions. From (12) and (15), $p_2 = min\{p_{k1}, p_{k2}, \ldots, p_{kn}\}$ or 1, and $p'_2 = min\left\{p'_{k1}, p'_{k2}, \ldots, p'_{kn}\right\}$ or 1. Therefore, $p_2(p'_2)$ is a probability function. ■

## E. FURTHER DISCUSSIONS

Several points worth further elaboration.

- One phase broadcasting scheme would not obtain a high successful broadcasting probability. Striving a balance with assigning an appropriate broadcasting probability with one phase broadcasting is impractical since the complete topology or the network density is unknown to each node. A high probability in a high-density node environment would result in the broadcasting storm problem; a low probability in a low-density node environment would lead to a prolonged broadcasting process and probably a message loss. That is to say, a one-phase/one-time probabilistic scheme cannot meet our design goal of maintaining high performance for all densities of nodes because the environment changes fast and it is impractical to expect a node to often determine the appropriate probabilities the first-phase/first-time.
- A two-phase/two-time scheme effectually eases the problem of assigning an appropriate broadcasting probability during the first-phase/first-time. GPS Nodes or dumb nodes can listen to the channel for an extended period to perceive the channel condition by collecting information from the received messages and make the conjecture with confidence for the second phase of broadcasting probability. The second-phase broadcasting carries on the broadcasting process for arriving at the destination.
- The adding of a correction factor $\alpha$ brings our PSG scheme to value both the transmission distance and the signal strength in choosing a receiver to facilitate the broadcasting process. Some schemes utilize signal strength as a key factor to select the receiver. Other schemes take into account the physical distance of transmission and give a further node a higher transmission probability to facilitate message dissemination. Our PSG scheme values both since in the real environment a longer distance would not necessarily denote a weaker signal strength.

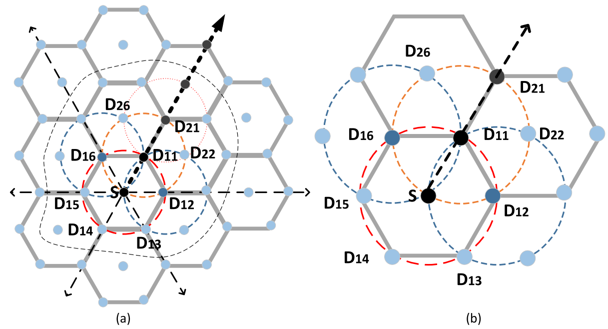


**FIGURE 5. Node deployment. (a) Each node is surrounded by six neighbors. (b) The node S and its neighboring nodes.**

## F. SIMPLIFIED TOPOLOGY FOR ELUCIDATING SECOND-TIME BROADCASTING

We use a simplified topology to demonstrate the high message-receiving rate of our scheme in a low-density environment with second-time broadcasting. The node deployment of the simplified example is as in Fig. 5 (a) with six nodes surrounding a node. Fig. 5 (b) depicts the source node S and its neighboring nodes. The angle between each transmission node and its two neighboring nodes is assumed a multiple of 60°. Therefore, $\angle D_{11}SD_{12}$, $\angle D_{12}SD_{13}$, $\angle D_{13}SD_{14}$, $\angle D_{14}SD_{15}$, $\angle D_{15}SD_{16}$, and $\angle D_{16}SD_{11}$ are all 60°. Here, six nodes at six directions are placed at the furthest transmission distance $R_{\max}$ from

**TABLE 1.** Parameters for the simplified mode.

| Parameter | Meaning |
|---|---|
| $T_p$ | Slot time for broadcasting a message |
| $r_m$ | At most one message is transmitted during a period $r_m$ |
| $b^s_{11}$ | The first-time successful broadcasting probability of the source node |
| $b^s_{12}$ | The second-time successful broadcasting probability of the source node |
| $b^s_1$ | The successful broadcasting probability of the source node by 1-hop transmission |
| $p(h^s_1)$ | The successful transmission probability to a 1-hop neighbor of the source by counting 1-hop, 2-hop, and 3-hop communication. |
| $p(s_N)$ | The successful transmission probability of broadcasting to an N-hop node |
| $S_p$ | The message size |
| $B$ | The link bandwidth |
| $p_{11}$ | The percentage of transmission time to the period time $r_m$ for the first-time broadcasting in the first phase |
| $p_{12}$ | The percentage of transmission time to the period time $r_m$ for the second-time broadcasting in the first phase |
| $p_{21}$ | The percentage of transmission time to the period time $r_m$ for the first-time broadcasting in the second phase |
| $p_{22}$ | The percentage of transmission time to the period time $r_m$ for the second-time broadcasting in the second phase |

the sending node, where nodes have the probability $p_1 = 1$ to broadcast messages, representing winning nodes since $R_{\max} - D_s \leq R_{\max} - D_{GPS} \leq 0$ always holds in (8). Note that since each node only has six surrounding nodes, the high $p_1$ value of 1 would be a good choice. Before the derivation, we list the parameters used in Table 1. We assume the following:

- Each node is a GPS node.
- The message is generated randomly within the period of $[0, r_m - 1]$ time slots.
- A source node broadcasts a message two times to other nodes for each period $r_m$.
- Nodes other than the source node only generate unicast messages. For each period $r_m$, in each node except the source node, a broadcast message or a unicast message is sent twice in two slots.
- The transmission probability of each node is independent and identically distributed (i.i.d.).
- Broadcast messages have a higher priority than unicast messages within each node.
- A node cannot transmit and receive a message at the same time slot.
- A time slot $T_p$ is needed for a node to send a message [45], [46].
- The nodes are not synchronized.
- The propagation delay between two neighboring nodes is small and ignored.

We first derive the probability for the source node. For the receiver $D_{11}$ in Fig. 5, nodes $D_{21}$, $D_{22}$, $D_{12}$, $D_{16}$, and $D_{26}$ might interfere with the reception of a broadcast message from the source node $S$. Besides, the receiver $D_{11}$ could not broadcast its message. Therefore, in total six nodes could interfere with broadcasting. The first-hop successful broadcasting probability of the first phase for source node $S$, $b^s_{11}$, can be calculated [45], [46]. Because each node is located at the furthest distance $R_{\max}$ from the other six neighboring modes, each node would immediately execute the second time of broadcasting since $d_t = w_t \times (1 - p_1) = 0$ as in (11). For simplicity of derivation, the source node would not wait for an ACK or ignore an ACK and broadcast a message a second time within the next time slot of the same $r_m$ period. Since the slot time is not synchronized among nodes, a slot time of one node may overlap with two slot times of a neighboring node. The source node successful broadcasts its message because the other five neighboring nodes of the node $D_{11}$ and the receiver node $D_{11}$ do not transmit messages within the same time slot $T_P$. The first-time successful broadcasting probability of the source node, $b^s_{11}$, is as in (16).

$$b^s_{11} = (1-p)^{2\times 6} = (1-p)^{12}, \tag{16}$$

where $p$ is the transmission probability for the source node within a slot time $T_p$. Similarly, the second-time successful broadcasting probability of the source node, $b^s_{12}$, is the same as the first time in (17).

$$b^s_{12} = b^s_{11}. \tag{17}$$

Therefore, the first-hop successful broadcasting probability of the source node can be expressed as in (18)

$$\begin{aligned} b^s_1 &= 1 - \left(1 - b^s_{11}\right)\left(1 - b^s_{12}\right) \\ &= 1 - (1 - (1-p)^{12})(1 - (1-p)^{12}). \end{aligned} \tag{18}$$

As shown in Fig. 4, a message from a node will be forwarded at least two hops. A message can travel many hops via intermediate nodes before arriving at a one-hop neighboring node. To simplify the analysis and get a conservative result, we only count the arrival messages from a one-hop neighboring node directly or from a one-hop neighboring node indirectly through at most three hops. That is, node $S$ can broadcast a message to node $D_{11}$ by one-hop transmission, 2-hop transmission via an intermediate node, or 3-hop transmission via two intermediate nodes. For a 2-hop transmission, both nodes $D_{12}$ and $D_{16}$ can forward a message from node S to node $D_{11}$ within two hops. Similarly, from node $S$ to node $D_{11}$, there are four paths of three hops. The successful transmission probability $\mathrm{p}\left(h^s_1\right)$ to a 1-hop neighbor for the source by at most 3-hop of transmissions is then calculated as in (19). And the successful transmission probability of the broadcasting to an $N$-hop node is as in (20).

$$\mathrm{p}\left(h^s_1\right) = 1 - \left(1 - b^s_1\right)\left(1 - (b^s_1)^2\right)^2\left(1 - (b^s_1)^4\right)^4. \tag{19}$$

$$\mathrm{p}\left(s_N\right) = \mathrm{p}\left(h^s_1\right)^N. \tag{20}$$

The slot time $T_p$ for a message is as in (21).

$$T_p = \frac{S_p}{B}, \tag{21}$$

where $S_p$ is the message size and $B$ is the network bandwidth.

Since for each period $r_m$, in each node, there are two messages transmitted in each node. The percentage of transmission time $T_p$ to the period $r_m$ for one-time broadcasting in the first phase, $p$, is regarded as the transmission probability of a neighboring node within a period $r_m$ (22).

$$p = \left\lceil \frac{2T_p}{r_m} \right\rceil. \tag{22}$$

Based on the above derivation, we have the following observations.

*Lemma 4:* The value of $b_1^s$ monotonically increases between (0, 1) with $b_{11}^s$.

*Proof:* The can be obtained by differentiating $b_1^s$ to show $\frac{db_1^s}{db_{11}^s} > 0$ between (0, 1).Therefore, a higher $r_m$ value results in a lower $p$-value, a higher $b_{11}^s$ in (16), and hence a higher successful broadcasting probability. ■

However, a higher $r_m$ value also leads to a longer delay for each transmission.

*Lemma 5:* The first-hop successful broadcasting probability $b_1^s$ is larger than or equal to the first-hop successful broadcasting probability of the first phase $b_{11}^s$.

*Proof:* $b_1^s - b_{11}^s = 1 - \left(1 - b_{11}^s\right)\left(1 - b_{12}^s\right) - b_{11}^s$
$= b_{11}^s\left(1 - b_{11}^s\right) = (1-p)^{12}\left(1 - (1-p)^{12}\right) \geq 0.$ ■

This reflects a fact that a second-chance broadcast, overhearing a message and rebroadcasting the message when not receiving an implicit ACK, is important in improving the delivery ratio. An even more important observation is from (18) and (19). A low 1-hop successful broadcasting probability $b_1^s$ still results in a high 1-hop transmission probability $p\left(h_1^s\right)$, and hence a high delivery ratio (20). To give several $b_1^s$ examples, for $b_1^s = 0.6$, $p\left(h_1^s\right) = 0.90596371388$, for $b_1^s = 0.7$, $p\left(h_1^s\right) = 0.97398119268$, for $b_1^s = 0.75$, $p\left(h_1^s\right) = 0.98955066971$, and for $b_1^s = 0.8$, $p\left(h_1^s\right) = 0.99685065388$.

## IV. SIMULATIONS

We use NS-2.35 for our simulations [47]. The common simulation parameters for the free space model and shadowing model are listed in Table 2. The nodes are deployed randomly within the simulation area, generated by using the same seed for different methods to mitigate the effect of node distributions to simulation results. Probabilistic flooding with a preassigned broadcasting probability = 0.3 (BP_0.3), probabilistic flooding with a preassigned broadcasting probability = 0.6 (BP_0.6), simple flooding (simple), MPR routing, MPR routing with the hello message size = 0 (MPR0), and our proposed PSG scheme are compared. For MPR and MPR0, the first 10 secs are the initiation time for hello messages, in which the messages are not counted. The hello message size of MPR is set to 4 bytes according to the field size in RFC 3626. For MPR0, we set the size of the hello message in NS-2.35 to 0, which means that there are no costs of exchanging hello messages and therefore there are no collisions from transmitting hello messages, showing the best performance of the MPR scheme. When hello message size is set to 0, only collisions from data are counted. Table 3 lists average neighbors per node for a various number of nodes. The average neighbors increase proportionally to the total number of nodes. Each simulation result is obtained from averaging 100 times of simulation results. A node is selected randomly as the source node for flooding. Both the free space model and the shadowing propagation model are simulated. In total four performance statistics are simulated.

- Number of forwarding: Total number of forwarding by participating nodes.
- Collision number: Total number of collisions.
- Message delivery ratio (of all nodes): The percentage of nodes receiving the transmitted message.
- Delivery ratio versus time: This is the message delivery ratio along with the time. The less the number of forwarding is, the less the overhead is introduced whereas the message delivery ratio may be lowered.

**TABLE 2. Common simulation parameters.**

| Parameter | Meaning |
|---|---|
| Network Size | 1000m × 1000m |
| Propagation Model | Free space, Shadowing |
| Number of Nodes | 50,100,150,200,250,300,350,400 |
| MAC Layer | IEEE 802.11 |
| Bandwidth | 1Mbps |
| Frequency | 2.4G Hz |
| Message Data Size | 64 bytes, 128 bytes |
| Message Rate | 10 Messages/Second |
| Max Random Access Delay | 0.005 Second |
| Wait time $w_t$ | 0.02 Second |
| Hello Message Period | 1 Second |
| Hello Message Size | 0 byte, 4 bytes |
| GPS Equipment | Yes |

**TABLE 3. Average neighbors per node.**

| Number of nodes | Average neighbors per node |
|---|---|
| 50 | 8.560 |
| 100 | 17.660 |
| 150 | 25.553 |
| 200 | 33.995 |
| 250 | 42.676 |
| 300 | 51.923 |
| 350 | 60.403 |
| 400 | 68.250 |

**TABLE 4. Parameters for Free Space Model [47].**

| Parameter | Value |
|---|---|
| $P_t$ | 0.28183815 w |
| $G_t$ | 1 |
| $G_r$ | 1 |
| $\lambda$ | 0.125 m |
| RXThresh | 4.4619× $10^{-10}$ w |
| Rmax | 250 m |

### A. FREE SPACE MODEL

The parameters for the free space model are listed in Table 4 [47]. The transmission power $P_t$ is 0.28183815 w, the transmitting antenna gain $G_t$ and the receiving antenna gain $G_r$ are 1, the radio wavelength is 0.125 m, the minimum receiving threshold (RXThresh) is set to $4.4619\times10^{-10}$w and the

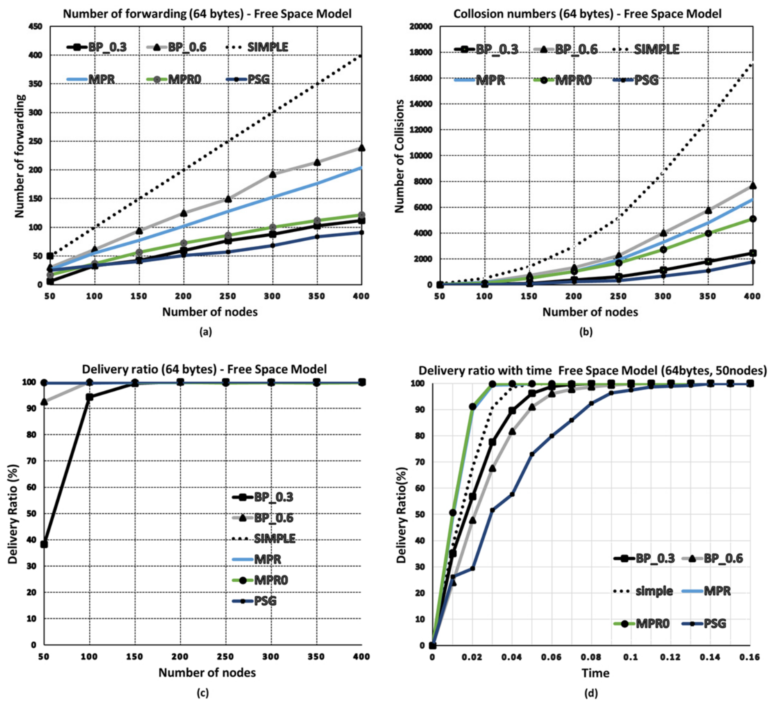


**FIGURE 6. Performance statistics for the free space model in six schemes. The message size is 64 bytes. (a) The number of forwarding vs. a different number of nodes. (b) Collision numbers vs. a different number of nodes. (c) Delivery ratio vs. a different number of nodes. (d) Delivery ratio vs. time with node number = 50.**

maximum communication range is 250 m. Fig. 6 shows performance statistics for a message size of 64 bytes. Fig. 6(a) is the number of forwarding in terms of the total number of nodes. For simple flooding, the total number of forwarding nodes is in correspondence with the total number of nodes. For all other schemes, the total number of forwarding is in general proportional to the total number of nodes. BP_0.6 has a higher number than BP_0.3 because BP_0.6 has a higher forwarding probability, and MPR has a higher number than MPR0 because in MPR0 hello messages do not cause collisions with other messages. Our PSG scheme has the lowest number of total forwarding nodes, except when the node number is less than 100, in which our PSG is slightly higher than MPR0 and BP_0.3. It is because when the node density is low, more forwarding nodes are necessary to achieve a higher delivery ratio. While the total number of node grows, there is a higher probability that some nodes close to the sender give up transmissions in both phases due to low $p_1$ and $p_2$ values. Fig. 6(b) is the collision number vs. the total number of nodes. Our PSG scheme invokes significantly fewer collisions. Simple flooding gives the highest number of collisions. BP_0.6 is higher than BP_0.3. The difference between MPR and MPR0 is enlarged when node number increases, which denotes that hello messages are required and would become a hindering factor for the MPR scheme as node number grows. Fig. 6(c) displays the message delivery ratio versus the total number of nodes. BP_0.3 and BP_0.6 are not as good as other schemes whenever the node number is less than 100, because not enough involved nodes affect both schemes. Fig. 6(d) deliberately illustrates the slow convergence time of PSG for 50 nodes which would not present for 400 nodes. MPR and MPR0 perform best by taking less than 0.03 sec to achieve a 100% delivery ratio, followed by BP_0.3 and BP_0.6. Our PSG scheme takes more time to reach a high delivery ratio partly due to the low number of forwarding nodes and partly due to the intrinsic two-phase characteristic. The stepped curve for our PSG scheme in the early stage of broadcasting is because only a small portion of nodes have received the message within a low-density environment, 50 nodes in an area of 1000 $m^2$, and because most of these nodes have not entered into the second phase. As more nodes having the broadcasting message or entering the second phase, the PSG scheme is more confident in giving the second time and the second phase of broadcasting probability for nodes and the curve displays a smooth growth.

Fig. 7 shows simulation results for a message size of 128 bytes, which shows the broadcast storm problem when message size increases. Fig. 7(a) is the number of forwarding with time. In simple flooding, the total number of forwarding cannot keep up with the total number of nodes when the total number of nodes is larger than 250. A message size of 128 bytes needs more time to finish its transmission, which causes the broadcast storm problem and a higher message loss rate for both simple flooding and MPR. Our PSG has the

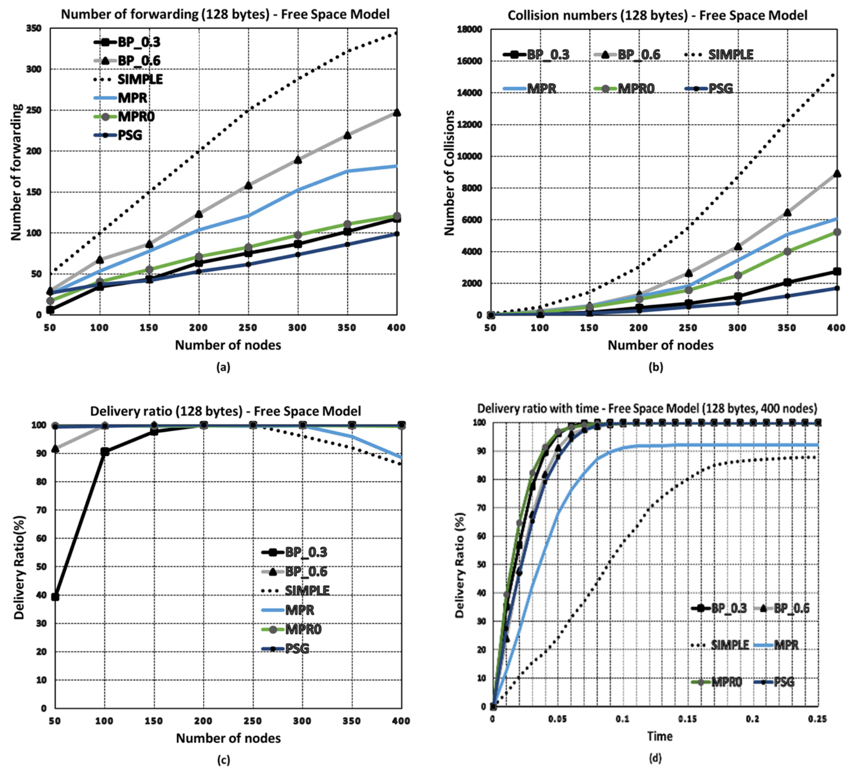


**FIGURE 7.** Performance statistics for the free space model in six schemes. The message size is 128 bytes. (a) The number of forwarding vs. a different number of nodes. (b) Collision numbers vs. a different number of nodes. (c) Delivery ratio vs. a different number of nodes. (d) Delivery ratio vs. time with node number = 400.

lowest number of forwarding. Fig. 7(b) is similar to Fig. 6 (b) and presents a general trend, a higher number of nodes generating a higher number of collisions. Fig. 7(c) points out the weakness of MPR and simple flooding. For the MPR scheme, it becomes a problem while the node number is large and the message size is 128 bytes, which demands a longer time to finish a message transmission. The forwarding by selecting nodes brings out a second problem when chosen nodes cannot successfully broadcast messages. Similarly, simple flooding displays a decreasing delivery ratio as the node number is larger than 250 because of too many collisions. PSG can keep a 100% delivery ratio when the node number is more than 300. Fig. 7(d) plots delivery ratio versus time of 400 nodes. Note that both simple flooding and MPR cannot reach a 100% delivery ratio and need longer times to attain a stable value, which again illuminates the negative effect of hello messages to the MPR scheme. MPR0 seems to have the fastest convergence rate but the relay of hello messages is not counted.

### B. SHADOWING PROPAGATION MODEL

The receiving signal strength of the shadow propagation model at distance $d$, $P_r(d)$, is calculated as in (23) [47].

$$\left[\frac{P_r(d)}{P_r\bar{(}d_0)}\right]_{dB} = -10\beta \times \log\left(\frac{d}{d_0}\right) + X_{dB} \qquad (23)$$

**TABLE 5.** Parameters for shadowing propagation model [47].

| Parameter | Value |
|---|---|
| $\beta$ | 4 |
| $\sigma_{dB}$ | 12 |
| d0 | 1 |
| Pt | 0.28183815 w |
| RXThresh | $6.0137\times 10^{-13}$ |
| RMAX | 300 |

where $P_r\bar{(}d_0)$ is the receiving signaling strength by the free space model from (1) at distance $d_0$, $\beta$ is the pass loss exponent, $X_{dB}$ is a random variable of Gaussian distribution with zero mean and $\sigma_{dB}$ as its standard deviation or shadowing deviation. When $x - X_{dB} \geq 0$, the message can be correctly received. The Cumulative Distribution Function (CDF) can be expressed as in (24).

$$\mathrm{F}(x) = \mathrm{P}(X_{dB} \leq x) = \frac{1}{\sigma_{dB}\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{-x^2}{2\sigma^2}}\,\mathrm{d}x. \qquad (24)$$

For the shadowing propagation model, we simulate a scenario as listed in Table 5, shadowed urban area with a very high shadowing deviation ($\sigma_{dB} = 12$). Fig. 8 is the results for the scenario of the shadowed urban area. Fig. 8(a) is the number of forwarding versus the number of nodes. This figure demonstrates the adaptive characteristic of our

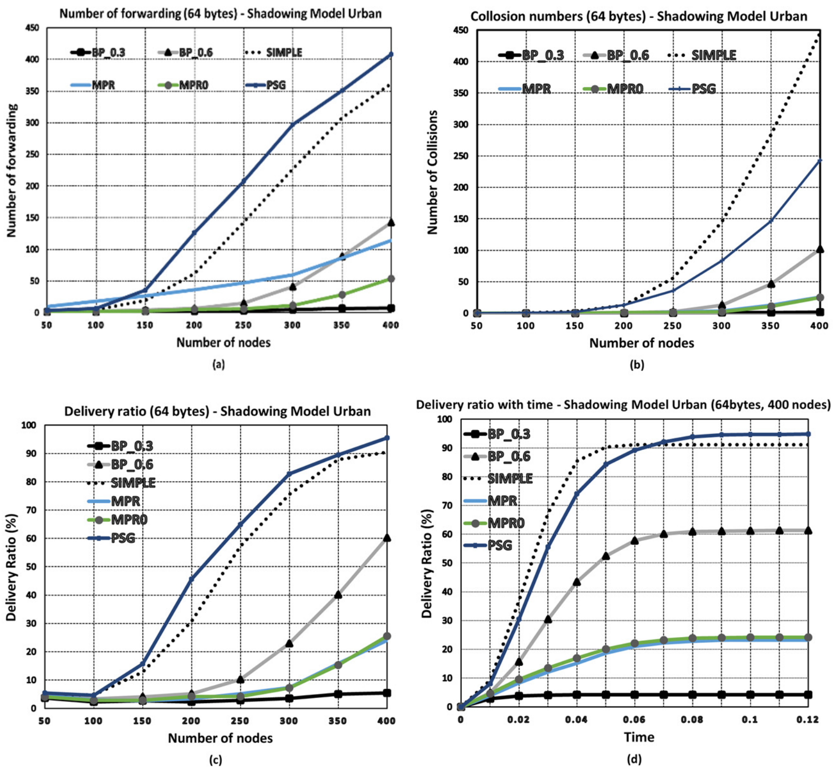


**FIGURE 8.** **Performance statistics for the shadowing propagation model in six schemes. Path loss exponent $\beta = 4$ and shadowing deviation $\sigma_{dB} = 12$, which represents the shadowed urban area. The message size is 64 bytes. (a) The number of forwarding vs. a different number of nodes. (b) Collision numbers vs. a different number of nodes. (c) Delivery ratio vs. a different number of nodes. (d) Delivery ratio vs. time with node number = 400.**

PSG scheme in changing channel conditions. Nodes within a shadowed urban area have higher loss rates than nodes within a free space area. As a result, our PSG performs the most number of forwarding, more than simple flooding. The other four schemes all have low values of forwarding, which results in low delivery ratios as shown later. Fig. 8(b) plots the number of collisions related to the number of nodes. Although our PSG scheme forwards more messages than simple flooding, the number of collisions is not as many as simple flooding because random transmission delays are given to transmission nodes. Low collisions of the other four schemes are together with low delivery ratios that are not wanted. Fig. 8(c) further illuminates the advantage of our PSG scheme. As the node number increased to 400, the delivery ratios from high to low are PSG, simple flooding, BP_0.6, MPR0, MPR, and BP_0.3, with values of 95.525%, 90.025%, 60.28%, 25.555%, 24.03%, 5.495%, respectively. From the low delivery ratio (Fig. 8(c)) and the low number of forwarding (Fig. 8 (a)) by MPR and BP_0.3, we can conjecture that many messages are stopped in intermediate nodes. BP_0.6 has a higher broadcasting probability and therefore has a delivery ratio of around 60%. When the node number is less than 200, all schemes have delivery ratios of less than 50%. The PSG scheme has the best delivery ratio of 45.6 %. Fig. 8(d) is the delivery ratio with time for 400 nodes. Along with time, our PSG scheme outperforms the simple flooding scheme at 0.07 sec. The delivery ratios of the other four schemes are too low to be accepted.

## V. CONCLUSION

We propose a two-phase PSG scheme for broadcasting. The PSG scheme, utilizing signaling strength and GPS coordinates, is self-adaptive and performs well in the free model and urban shadowed model compared to other schemes. In the spare-node environment, the PSG scheme, although taking more time to obtain a high delivery ratio, achieves high performance by the second-phase broadcasting. In a dense-mode environment, the PSG scheme avoids too many broadcasting messages in both the first phase and the second phase and therefore reduces total collisions often encountered. However, the converging time for the PSG scheme would be still high for time-critical applications.

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