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A Survey on Probabilistic Broadcast Schemes for Wireless Ad Hoc Networks

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Abstract

Broadcast or flooding is a dissemination technique of paramount importance in wireless ad hoc networks. The broadcast scheme is widely used within routing protocols by a wide range of wireless ad hoc networks such as mobile ad hoc networks, vehicular ad hoc networks, and wireless sensor networks, and used to spread emergency messages in critical scenarios after a disaster scenario and/or an accidents. As the type broadcast scheme used plays an important role in the performance of the network, it has to be selected carefully. Though several types of broadcast schemes have been proposed, probabilistic broadcast schemes have been demonstrated to be suitable schemes for wireless ad hoc networks due to a range of benefits offered by them such as low overhead, balanced energy consumption, and robustness against failures and mobility of nodes. In the last decade, many probabilistic broadcast schemes have been proposed by researchers. In addition to reviewing the main features of the probabilistic schemes found in the literature, we also present a classification of the probabilistic schemes, an exhaustive review of the evaluation methodology including their performance metrics, types of network simulators, their comparisons, and present some examples of real implementations, in this paper.

Keywords: Probabilistic Broadcast, Flooding, Routing Protocols, Wireless Ad Hoc Networks.

1. Introduction

Broadcasting is a widely used dissemination technique in which nodes send out the same information simultaneously to all their neighbors. Broadcasting is used in ad hoc networks such as Wireless Sensor Networks (WSNs) [7, 121, 106], Mobile Ad Hoc Networks (MANETs) [48], and Vehicular Ad Hoc Networks (VANETs) [107, 116]. In routing protocols for ad hoc networks, broadcasting is part of the discovery phase, which is responsible for finding a communication path to route the application data from a source node to one or more destination nodes (unicast [18] or multicast routing protocols[6, 5, 26]). Broadcasting is also used in the maintenance of routes since nodes exchange Hello packets to collect neighboring information. In addition, broadcasting is also employed to disseminate emergency or warning messages in disaster scenarios, which is one of the main applications of MANETs [96, 95, 92]. In such harsh conditions,

an efficient broadcast mechanism is vital and may be the only possible way to disseminate crucial information [40, 97]. Furthermore, in VANETs the dissemination of warning messages is also important to warn the motorists of congestions due to traffic accidents.

The simplest way of broadcasting is flooding, in which each node in the network retransmits an incoming message once. The main benefit of using flooding is the ease of implementation. However, this technique also has several issues, one of them being its inefficiency in terms of resource consumption such as bandwidth and energy. While the former impacts the network in terms of efficiency and capacity, the latter is crucial for the lifetime of the network. The main problem of flooding in wireless ad hoc networks is that it causes the well-known broadcast storm problem [109] due to collisions and contention. Since all the nodes share the same wireless medium, the broadcast storm problem leads to dramatic deterioration of the performance in wireless ad hoc networks. In order to alleviate the broadcast storm problem many broadcast protocols have been proposed in the last decade [31]. A basic classification of broadcast schemes divides them into two categories, deterministic schemes and probabilistic schemes. In deterministic techniques, only a subset of nodes are allowed to take part in the broadcasting process. Multi Point Relay (MPR) [65] and Connected Dominant Set (CDS) are some examples of deterministic broadcast algorithms. However, this could lead to repeated use of the same nodes. In addition, under mobility conditions this set of nodes should change very frequently because of the topological changes. Probabilistic broadcast schemes however balance the power consumption among all the nodes in the network by selecting well balanced routes over the network lifetime. In probabilistic broadcast, nodes forward the incoming broadcast packets according to certain probability value, so all nodes are allowed to participate in the broadcast process. Moreover, probabilistic schemes are more robust against failures, attacks, and are unaffected by the mobility of nodes like the deterministic schemes.

This paper surveys the main probabilistic schemes proposed in the literature for wireless ad hoc networks. As fas as we know, this is the first survey of probabilistic broadcast in ad hoc networks. The main contributions of this paper are:

- A classification of probabilistic broadcast schemes in wireless ad hoc networks.

- A thorough review of the proposed schemes found in the literature.

- A review of the evaluation methodology for probabilistic broadcast, including performance metrics, simulation platforms, comparisons and real implementations.

- To provide a set of open challenges of probabilistic broadcast schemes that have not been covered yet.

This survey continues as follows, the proposed classification of probabilistic broadcast schemes is presented in section 2, and section 3 reviews all the probabilistic schemes found in the literature that fall into the proposed classification. The methodology used to evaluate and compare the probabilistic schemes is reviewed in section 4. Section 5 presents a discussion on the main findings of the proposed survey and provide a set of open challenges that have not been sufficiently covered in the literature so far. Finally, section 6 includes the main conclusions of this survey.

2. Classification of Probabilistic Broadcast Schemes in Wireless Ad Hoc Networks

The objective of this section is to classify the probabilistic broadcast schemes found in the literature. We have classified the probabilistic broadcast schemes into two main categories, (1) fixed probability schemes and (2) adaptive schemes (see Fig. 1). These main categories can be further divided into different subcategories as shown in Fig. 2 and explained below.

Fixed probability schemes

These schemes use a constant forwarding probability value so every node has the same forwarding probability in the network. Fixed probabilistic schemes have been studied using percolation theory and the phase transition phenomenon used in random networks [102, 101, 42, 104]. However, there are important differences from random networks and ad hoc networks so the results observed in random networks cannot be said to be true for ad hoc networks. Consequently, there is not an optimal forwarding probability for all possible scenarios. This optimal forwarding probability may depend on many parameters such as density, distance among nodes, and speed.

Adaptive schemes

In adaptive schemes local or global parameters, such as density metrics, speed, energy are used to determine the forwarding probability. The adaptive schemes can also be classified into two categories, (1) non-counter-based schemes and (2) counter-based schemes (see Fig. 2). The main difference between these two categories is that the counter-based schemes use the number of copies of a given broadcast packet as a feedback from the broadcast process in the node's neighborhood. The objective of the counter-based mechanism is to avoid the die out problem of broadcasting. The die out problem happens when the broadcast process is stopped due to forwarding decisions. Both counter-based and non counter-based adaptive schemes can be further classified according to the parameters used to adjust the forwarding probability such as density, distance, speed, number of neighbors covered (self-pruning), energy and artificial intelligence (see Fig. 2).

- **Density-based schemes:** These schemes use density metrics to adjust the forwarding probability. With regard to the density metrics used in adaptive schemes, these metrics range from local metrics such as a node's degree (number of neighbors) to global metrics such as the total number of nodes in the network. The main rationale behind density-based schemes is that the higher the density, the lower the forwarding probability.

- ***Distance-based schemes:*** These schemes use the distance among nodes as the main parameter to adjust the forwarding probability. The Euclidean distance is the most used type of distance, however, approximations based on the density of nodes, the Received Signal Strength (RSS) and hop count are also employed. The basic idea is that nodes located further away from the senders are preferred since they avoid redundant retransmissions.

- ***Speed-based schemes:*** These schemes calculate the forwarding probability as a function of the node's speed. These schemes are intended for vehicular networks where the speed of the vehicles plays an important role.

- **Self-pruning schemes:** These schemes make the forwarding decision on the basis of the node's uncovered neighbors (self-pruning mechanims). The objective is to cover all of 2 hops neighbors of a node efficiently. Broadcast packets have to carry the sender's list of neighbors in order for the receiver to calculate the uncovered nodes.

- **Energy-based schemes:** These schemes use metrics related to the battery level of nodes to calculate the forwarding probability. These schemes are aimed at extending the network's lifetime. The idea is to favor nodes with more remaining energy.

- **Artifitial intelligence-based:** These schemes use artifitial intelligence to adjust the forwarding probability. Genetic algorithms are normally employed to adjust the forwarding probability.
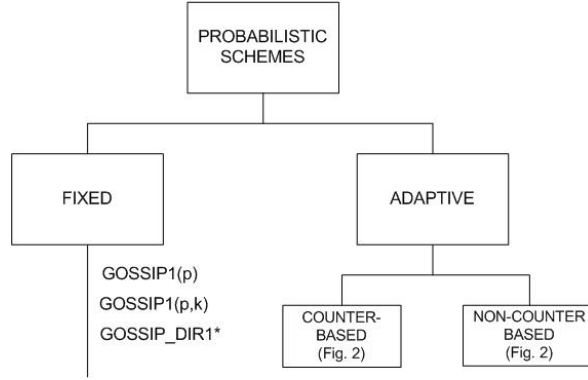
Figure 1: Classification of probabilistic schemes

3. Review of existing probabilistic broadcast schemes

This section reviews the main proposed probabilistic broadcast schemes found in the literature. It is organized according to the classification presented in the previous section 2, see Fig.1 and Fig. 2. A summary table (Table 2 - Table 10) has been included in each subsection. These tables present the main features of the reviewed schemes such as the name of proposed scheme (Fig. 1 and Fig. 2), the expression used to calculate the forwarding probability, the data that nodes need to collect to calculate the forwarding probability, the parameters that need to be adjusted, and the target application scenario of the broadcast schemes such as MANETs, VANETs and WSNs. Table 1 presents some notations widely used throughout this section.

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ADAPTIVE

NON-COUNTER BASED

COUNTER-BASED

DENSITY
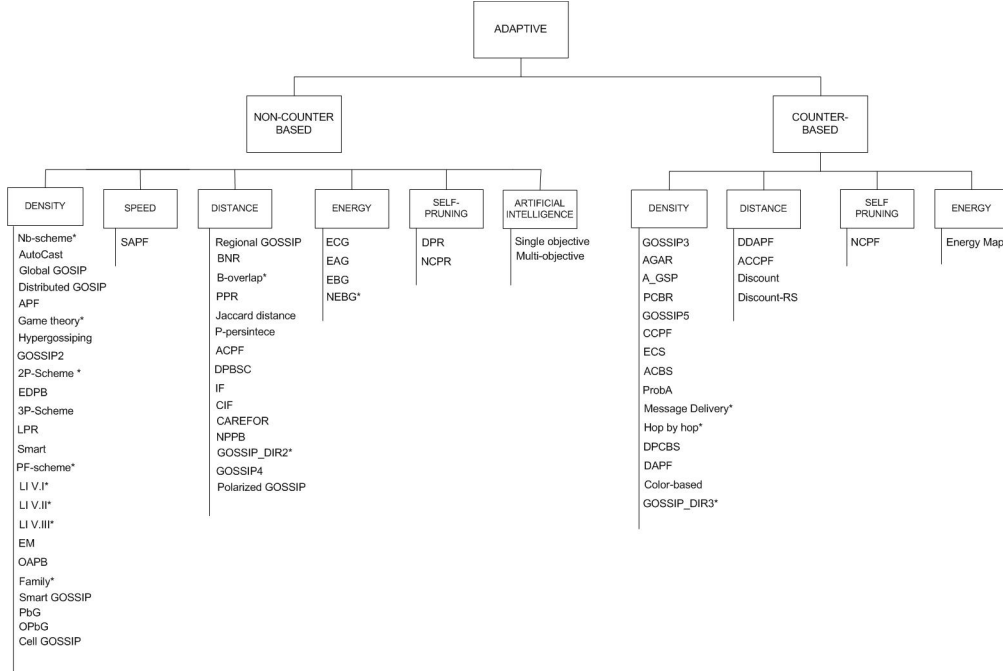Nb-scheme*
AutoCast
Global GOSIP
Distributed GOSIP
APF
Game theory*
Hypergossiping
GOSSIP2
2P-Scheme *
EDPB
3P-Scheme
LPR
Smart
PF-scheme*
LI V.I*
LI V.II*
LI V.III*
EM
OAPB
Family*
Smart GOSSIP
PbG
OPbG
Cell GOSSIP

SPEED
SAPF

DISTANCE
Regional GOSSIP
BNR
B-overlap*
PPR
Jaccard distance
P-persintece
ACPF
DPBSC
IF
CIF
CAREFOR
NPPB
GOSSIP_DIR2*
GOSSIP4
Polarized GOSSIP

ENERGY
ECG
EAG
EBG
NEBG*

SELF-PRUNING
DPR
NCPR

ARTIFICIAL INTELLIGENCE
Single objective
Multi-objective

DENSITY
GOSSIP3
AGAR
A_GSP
PCBR
GOSSIP5
CCPF
ECS
ACBS
ProbA
Message Delivery*
Hop by hop*
DPCBS
DAPF
Color-based
GOSSIP_DIR3*

DISTANCE
DDAPF
ACCPF
Discount
Discount-RS

SELF PRUNING
NCPF

ENERGY
Energy Map

Figure 2: Classification of adaptive schemes

Table 1: Notation

Parameter	Description
d	Euclidean distance between two nodes
h	Counter-based threshold
m	Number of copies received of a given message
N	Total number of nodes in the network
n_{avg}	Average number of neighbors of a given node
n_b	Number of neighbors of a given node
P_r	Power of a message received by a given node
P_t	Power transmission of a given node
p	Forwarding probability
p_i	Initial forwarding probability used in schemes with different forwarding probabilities
r	Node's radio transmission range

3.1. Fixed Probability Schemes

As mentioned earlier, in fixed probability schemes, every node in the network forwards incoming broadcast packets with the same forwarding probability. The simplest probabilistic scheme is known as GOSSIP [42][41]. In this scheme, nodes forward an incoming packet with a fixed probability p, and the probability of not forwarding the incoming packet is $1 - p$. This scheme is called as GOSSIP1(p). A further expansion is GOS-

SIP1(p,k) [42] in which nodes forward an incoming packet with a probability equal to 1 for the first k hops. This ensures certain connectivity among nodes up to a distance of k hops from the source node. The main problem of GOSSIP1 is determining the optimal forwarding probability for a given scenario. In [42], the authors demonstrated that the optimal probability is between $[0.65, 0.75]$ in scenarios where the number of nodes is less than 1000. Moreover, the authors suggest that 0.5 could also be a good forwarding probability for a rectangle layout of 1650 m x 600 m containing 150 nodes. Another important issue is how to fix the value of k. The authors used $k = 4$ for large networks (more than 1000 nodes) with distances up to 45 hops. However, they used $k = 1$ when they implemented GOSSIP over AODV [91] routing protocol in a more realistic scenario with 150 nodes. The results in [13] demonstrate that $p = 0.5$ and $p = 0.4$ can be optimum values for the forwarding probability to ensure reachability in networks with a number of nodes less than 100 (small to medium size networks). On the other hand, in [102] the authors evaluated GOSSIP1 with IEEE 802.11 MAC layer in DCF mode and high congestion conditions. The results show that a probability value as low as $p = 0.1$ is sufficient to achieve high reachability in small to medium size network scenarios. A variant of GOSSIP1 is GOSSIP_DIR1 [104], which uses directional antennas instead of omnidirectional antennas. A summary of features of the probability schemes is shown in Table 2.

Table 2: Fixed Probabilistic Schemes

Probabilistic Scheme	Forwarding Probability	Application
GOSSIP1(p)[41, 42]	$p = p_i$	MANET
GOSSIP1(p,k) [41, 42]	$p = 1 \quad if \quad nh < k$ $else \quad p = p_i$	MANET
GOSSIP_DIR1 [104]	$\vec{p} = (p_1, ..., p_N)$	MANET

3.2. Adaptive Probabilistic Schemes

Adaptive schemes tune the forwarding probability using any local or global parameter such as density, distance, etc. As a general classification, we have classified adaptive schemes into two main categories: non counter-based schemes and counter-based schemes (see Fig. 2).

3.2.1. Adaptive non-counter-based schemes

As shown in Fig. 2, the non counter-based schemes can be divided into six groups based on density, distance, speed, self-pruning, energy and articial intelligence schemes.

Density-Based Schemes

The density-based schemes can be further classified as shown in Fig. 3, where they are categorized into node's degree, density thresholds, and 2 hops information. The simplest parameter to tune the forwarding probability is the node's degree. The basic assumption is that the higher a node's degree, the lower its forwarding probability. An alternative is to take into account different density threholds to adapt the forwarding probability. These thresholds are normally based on the node's degree. Moreover, in 2 hops information schemes, nodes should collect information from neighbor nodes (2

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hops neighbors) and they adjust the forwarding probability according to the relationship between 1 hop and 2 hops neighbors.
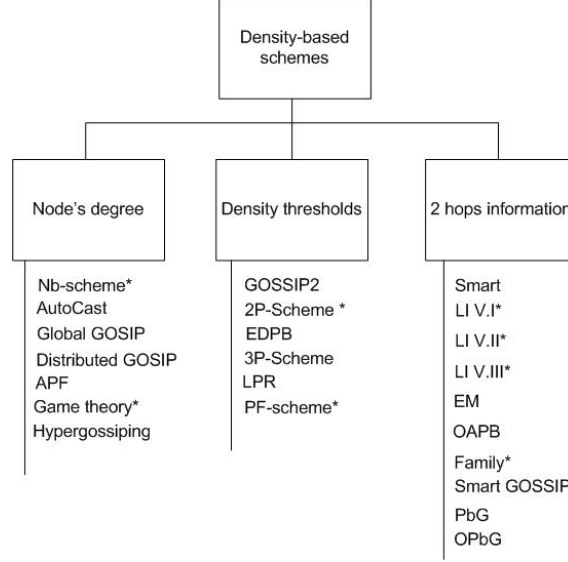

Figure 3: Classification of density-based schemes

a) Node's degree or number of neighbors:

In [32][33] (nb-scheme) the forwarding probability is adjusted to the inverse proportional of the number of neighbors of a node so $p = \frac{k}{n_b}$, where k is the propagation factor and by adjusting its value, the maximum and minimum probability can be adjusted. The value of n_b can be easily obtained via hello packets. Although this scheme is very simple, the optimum value of k can depend on many topological parameters.

In AutoCast scheme [112], the authors propose the following retransmission probability calculation:

$$p = \frac{2}{n_b \cdot 0.4} \qquad (1)$$

In addition, nodes broadcast messages periodically in order to improve the reliability of the proposed scheme. The broadcast interval is also adjusted based on the number of neighbors:

$$T = \frac{n_b}{\alpha} \qquad (2)$$

Where α is a constant, which defines the number of broadcasts per second.

In Global GOSSIP [70], the authors demonstrated that if the nodes forward incoming packets with a probability $p = \frac{\theta^{-1}(\gamma)}{\phi}$ in a network with average degree $\phi > \theta^{-1}(\gamma)$, the probability of a successful broadcast procedure is γ. Where γ is the target gossip coverage level (target reachability), ϕ the average node degree, and $\theta^{-1}(\gamma)$ is the minimum average degree so that the fraction of nodes in the largest connected component of a network with

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infinite size is at least γ. The average node's degree ϕ is defined as $\phi = \lambda \pi r$, λ is the intensity of homogeneous Poisson process H_λ, which is used to distribute nodes in the network. Although this scheme is suitable from the theoretical point of view, it makes assumptions on the level of knowledge available at individual nodes, which would either incur huge cost or impossible to attain. First, nodes have to know the average node degree of the network ϕ, which is a global information and it can be costly in terms of information exchanges. Another issue is how nodes can know the value of $\theta^{-1}(\gamma)$ in a real network.

An improved version of Global GOSSIP is presented as Distributed GOSSIP in [70]. Nodes use the node's number of neighbors n_b instead of using the average node degree ϕ in the network. According to Distributed GOSSIP, nodes have to forward the incoming packets with a probability $p = min(1, \frac{\theta^{-1}(\gamma)}{n_b})$ in order to achieve the target coverage level γ. In addition, the authors estimated that above a certain average degree ϕ_u, distributed GOSSIP outperforms global GOSSIP since the coverage level achieved will be higher than the target coverage level. However, this scheme still has the problem of the nodes having to obtain the value for $\theta^{-1}(\gamma)$.

In [44, 45] (APF), the forwarding probability is also adjusted using the node's number of neighbors. The main difference from the previous schemes is that two probability boundaries p_{max} and p_{min}, are defined by the present scheme. Consequently, the forwarding probability is within the interval (p_{min}, p_{max}). The forwarding probability is calculated by the following expression:

$$p = max\left(p_{max}(\frac{p_{max}^{n_b-1} - p_{max}^{n_b}}{1 - p_{max}}), p_{min}\right) \qquad (3)$$

The authors conducted simulations to determine the optimal values of p_{max} and p_{min}.

In [80] the authors apply game theory [86], and proposed a framework called Forwarding Dilemma Game (FDG). The game is played whenever a node receives a packet from other nodes in the network. The player (a node) has two strategies: 1) forward the packet or 2) drop the packet. The FDG has three components: 1) the number of players, which is the number of nodes receiving the broadcast packet, 2) the forwarding cost C, and 3) the network gain factor G. The FDG is formally defined as follows:

$$G = \{n_b, (S_i)_{i \epsilon n_b}, (U_i)_{i \epsilon n_b}\} \qquad (4)$$

Where S_i is the strategy set, and U_i is the utility function. The strategy set of a node i is the number of actions that the node can carry out. When $S_i = 1$ the node forwards the incoming packet, by contrast, if $S_i = 0$ the node drops the packet. Moreover, each node will receive utility function U_i on choosing a strategy set value S_i. The authors proposed the mixed Nash equilibrium [86] to derive the forwarding probability.

$$p = 1 - \left(\frac{C}{G}\right)^{\frac{1}{n_b-1}} \qquad (5)$$

According to (5), the probability decreases as the number of neighbors n_b increases, in the limit $n_b \to \infty$, $p \to 0$. The authors assumed $C = 1$ and demonstrated that the value of G should satisfy $3 \leqslant log(G) \leq 6$.

In [57] (Hypergossiping), the authors proposed an adaptive broadcasting scheme intended for partitioned MANETs. Whenever a partition occurs the broadcasting procedure stops because of the impossibility of new retransmissions. Identifying a partition is challenging due to the lack of global point of view of nodes in a wireless network. The authors proposed implementing a list of "Last Broadcast Received" LBR at nodes to identify partitions. The LBR lists include the last few broadcast packets received by a given node. The main assumption is that two nodes within the same partition will have similar LBR lists, and if two nodes have dissimilar LBRs, they will be located in different partitions. The LBRs are exchanged by nodes using hello packets, so nodes can discern if they are joining a new partition by comparing the received LBR with its own LBR. In order to reduce the overhead of hello packets, the LBR is only necessary if a new neighbor is detected. The performance of Hypergossiping can be divided into two strategies, (1) intra-partition forwarding and (2) broadcast repetition. The intra-partition forwarding consists of disseminating the broadcasting messages efficiently within the node's partition. The forwarding probability is adjusted using the node's density. They developed a calibration procedure to get and store in a look up table the optimum values for forwarding probability according to the node's neighbors. In addition, nodes do not retransmit immediately after receiving an incoming packet, they delay the retransmissions for a random time.

b) Density thresholds:

In [42] GOSSIP2, a scheme based on a density threshold is proposed. This density threshold is based on the number of neighbors n_b . Two values of forwarding probabilities p_h and p_l are used. When a given node has n_b higher than n_c (density threshold), the probability is p_l, otherwise, the probability is p_h, where $p_h > p_l$. As a consequence, nodes with low degree have more probability to forward the incoming packets. The main shortcoming of this scheme is how the nodes could determine the optimum values of n_c , p_h and p_l. These values can vary drastically depending on the application scenario.

A similiar idea is used in 2P-Scheme [13, 119], but in this scheme the average number of neighbors n_h of a given node is used as the density threshold ($n_h = n_c$).

In [3] (EDPB), the average number of neighbors in the network n_{avg} is used as a threshold instead of n_h. It is worth pointing out the difference between n_{avg} and n_h at this point. While n_{avg} is calculated using global information (6) so that every node in the network is considered, n_h is calculated locally at a node without using any global information.

Other authors proposed to use more than one density threshold as in 3P-Scheme [3], in smart scheme [118], and in Level Probabilistic Routing (LPR) [127]. In 3P-scheme, the authors classified the nodes based on the number of neighbors. The average number of neighbors of nodes in a network can be calculated as follows using global information:

$$n_{avg} = \frac{\sum_{i=1}^{N} n_{b_i}}{N} \qquad (6)$$

Moreover, the expected maximum and minimum average values for the number of neighbors can be calculated as follows:

$$n_{avg_{min}} = \frac{\sum_{i=1}^{M_{min}} n_{b_i}}{M_{min}} \quad where \quad n_{b_i} \leq n_{avg}$$
$$n_{avg_{max}} = \frac{\sum_{i=1}^{M_{max}} n_{b_i}}{M_{max}} \quad where \quad n_{b_i} > n_{avg} \tag{7}$$

Where M_{min} and M_{max} are the number of nodes with a number of neighbors below n_{avg} and above n_{avg} respectively. A node i is considered to be in high density area if $n_{b_i} > n_{avg_{max}}$ so a low forwarding probability will be given to node i. In contrast, if $n_{b_i} < n_{avg_{min}}$ the node will be considered to be in a sparsely populated area so a high forwarding probability will be assigned to it. In summary the forwarding probability is adjusted as follows:

$$
\begin{aligned}
p &= p_1 \quad if & n_b &\leq n_{avg_{min}} \\
p &= p_2 \quad if & n_{avg_{min}} < n_b &\leq n_{avg_{max}} \\
p &= p_3 \quad if & n_b &\geq n_{avg_{max}}
\end{aligned} \tag{8}
$$

Where $p_1 > p_2 > p_3$.

In smart scheme, three threshold values are defined to determine the forwarding probability [118] and up to four forwarding probability values are defined. As in the 3P-Scheme [3], the main drawback of this method is that it uses global density measures like n_{avg}, $n_{avg_{min}}$, and $n_{avg_{max}}$.

In LPR scheme [127], nodes are divided into four groups based on their degrees. The group 1 is composed of nodes with a degree higher than all their neighbors. In contrast, nodes with a lesser degree than their neighbors are included in group 4. The group 2 is composed of nodes with most of the neighbors having a lower degree than them. Finally, the rest of nodes are included in group 3. Nodes in each group have different forwarding probabilities, which are p_1, p_2, p_3 and p_4 respectively. The forwarding probabilities are selected such that $p_1 \geq p_2 \geq p_3 \geq p_4$.

In [51] (PF), the authors proposed a piecewise probability function with the number of neighbors as the independent variable, and the forwarding probability as the dependent variable. The number of neighbors n_b is compared to n_{avg} according to the deployed topology, it can be estimated by using the following equation:

$$n_{avg} = (N - 1) \frac{\pi r^2}{A_{net}} \tag{9}$$

Where A_{net} is the size of the network scenario. According to n_{avg}, a given node is in a dense area if $n_b > n_{avg}$, otherwise it is considered to be in a sparse area. A forwarding probability function is defined based on the value of n_b as given below:

$$
\begin{aligned}
p &= 1 \quad if & n_b &< n_{avg} \\
p &= p_i \quad if & n_{avg} < n_b &\leq 2n_{avg} \\
p &= \frac{p_i}{2} \quad if & 2n_{avg} < n_b &\leq 3n_{avg} \\
p &= \frac{p_i}{3} \quad if & 3n_{avg} < n_b &\leq 4n_{avg} \\
- & \quad - & - \\
p &= \frac{p_i}{r} \quad if & \theta n_{avg} < n_b &\leq (\theta + 1)n_{avg}
\end{aligned} \tag{10}
$$

Where $p_i = 0.7$, this value is chosen for ensuring certain reachability. The forwarding probability decreases as the number of neighbors of a given node increases. Although the results obtained from performance are good, the approach is very dependent on the

deployed scenario. Moreover, the value of $p_i = 0.7$ may also be dependent on the deployed scenario.

c) 2 hops information:

In [99], the authors proposed three probabilistic approaches based on the number of neighbors at one-hop and two-hops levels of a node (LI.I, LI.II, and LI.III). In version I (LI.I), the forwarding probability is adjusted according to the number of two-hops neighbors that can only be reached through one-hop neighbors.

$$p = \frac{1}{n_b} \sum_{k=1}^{n_b} n\left(x_i, x_k\right) \tag{11}$$

Where $n\left(x_i, x_k\right)$ is the set of two-hops neighbors that can only be reached through one-hop neighbor x_k from a given node x_i (for $k = 1, 2, 3, ..., n_b$ and $i = 1, 2, 3, ..., N$). The version I (LI.I) tries to avoid isolated nodes by giving a high probability value to those nodes that are the only possible way to connect to two-hops neighbors. In version II, the retransmission probability is calculated as the fraction of one-hop neighbors within two-hops coverage.

$$p = \frac{n_b}{n_b + n_b^{2h}} \tag{12}$$

Where n_b^{2h} is the set of two-hops neighbors of a given node x_i. In version II (LI.II), higher the number of one-hop neighbors, higher the forwarding probability. In the third version (LI.III), the forwarding probability is calculated as the fraction of two-hops neighbors within two-hops coverage.

$$p = \frac{n_b^{2h}}{n_b + n_b^{2h}} \tag{13}$$

In version III, higher the number of two-hops neighbors, higher the forwarding probability.

In [97], the authors proposed a new expansion metric to measure how the density of the network changes over the propagation path of the broadcast process. The expansion metric is calculated as follows:

$$EM = \frac{n_b^{2h}}{n_b} \tag{14}$$

This metric is used by nodes hop by hop along the broadcast path to recalculate the forwarding probability as follows:

$$\begin{aligned} p &= p_i + p_{EM} \quad if \quad EM_t < EM_{t-1} \\ p &= p_i - p_{EM} \quad if \quad EM_t > EM_{t-1} \\ p &= p_i \quad if \quad EM_t = EM_{t-1} \end{aligned} \tag{15}$$

Where, p_i is a constant probability value used to ensure high reachability and p_{EM} is a probability value that is added or subtracted depending on the EM values, EM_t

is the expansion metric of the current node and EM_{t-1} is the expansion metric of the previous node. If $EM_t < EM_{t-1}$, it means that the network density is decreasing along the broadcast path so the term p_{EM} is added to increase the forwarding probability. On the other hand, if $EM_t > EM_{t-1}$, the network density is increasing along broadcast path so the forwarding probability should be reduced.

In OAPB [8], the authors combined the three versions proposed in [99] (LI.I, LI.II, and LI.III). These versions are averaged to achieve a forwarding probability value based on up to two-hops neighbor information. The retransmission probability is calculated as follows:

$$p = \frac{p_1 + p_2 + p_3}{3} \tag{16}$$

Where, p_1, p_2, and p_3 are calculated using (11), (12), and (13) respectively. In addition, the authors proposed delaying the retransmissions based on the p value obtained at each node by,

$$\triangle(t) = \triangle(t)_{max}(1 - p) + \delta \tag{17}$$

Where, $\triangle(t)_{max}$ is the maximum delay and δ is a random variable whose value is in the order of milliseconds.

In [53](Family classification), the node's neighbors are grouped into three levels: parent nodes (upper level), sibling nodes (same level), and child nodes (lower level). This classification is made during an initial phase in which the nodes use simple flooding to collect neighbor information. The source node's 1 hop neighbors are considered sibling nodes, whereas the source node's 2 hops neighbors are considered child nodes. Intuitively, the more siblings a node has, the less necessity for retransmission as all of the node's children may have received a broadcast packet. Although the node may not forward the packet, its children will likely to have received the packet from aunt nodes (siblings of the parent). This scheme is composed of three phases, (1) nodes collect neighboring information by using hello packets, (2) nodes determine their level within the topology tree and compute their relationship with all their neighbors, and (3) nodes determine their forwarding probabilities based on the number of child and sibling nodes. In summary, the forwarding probability is proportional to the number of child nodes and inversely proportional to the number of sibling nodes as shown in (18).

$$p = max \left[\left(\frac{1}{n_{sibling} + 1} + p_i \frac{n_{child}}{N} \right), 1 \right] \quad \begin{array}{lll} p = 0 & if & n_{child} = 0 \\ & if & otherwise \\ p = 1 & if & n_{child} > 0, n_{sibling} = 0 \end{array} \tag{18}$$

Where n_{child} is the number of child nodes, $n_{sibling}$ is the number of sibling nodes, and p_i is an initial probability depending on the node density. The authors used p_i within the range [1,0.5].

A similar scheme is presented in Smart Gossip [60, 61], which is also based on the dependencies among nodes in a wireless network. The main difference between Smart Gossip and the previous scheme (Familiy classification) is that in Smart Gossip nodes adjust the forwarding probability in order to achieve a target reliability level. One important feature of this scheme is that it works on a per originator basis so a node X chooses a probability p, which is independent of the incoming packet. Notice that, most broadcasting schemes work on a packet basis since nodes recompute the forwarding

probability each time a new packet is received. Furthermore, this scheme does not rely on hello packets. It is based on proximity overhearing of broadcast messages. As a consequence, nodes collect the neighboring information as they receive the broadcast packets. Overhearing these broadcast messages, a node can deduce what type of node the sender is. Therefore a node can distinguish between parent nodes, sibling nodes, and child nodes. The broadcast packets contain a parent identifier field p_{id} and a required gossip probability field $p_{required}$. The required gossip probability that a node is related to the target reliability that a node advertizes to its parents. The gossip probability p is calculated by the children of a node. The p of a node is given by $p = max(p_{required}^i)$. So the p of node X is determined by the maximum $p_{required}$ announced by any child i of X. This scheme starts with an initial phase in which the nodes do not know their dependencies so they forward with a probability $p = 1$. Over time, nodes recompute their $p_{required}$ so that p can be recomputed. As mentioned, each node advertizes a $p_{required}$. This probability value is adjusted according to a defined reliability level. The authors presented the average reception percentage τ_{arp} as a metric to assign a target reliability level. The reception percentage of a node X, with respect to an originator node O, is the percentage of messages originated at O and received at X. The average reception percentage τ_{arp} is the reception percentage, averaged over all nodes in the network. For a target τ_{arp} the authors translate it into a per-hop reception probability τ_{rel}. The main objective is that the node's children receive τ_{rel} fraction of the originator node's packets. Since the decision of a node to forward a packet is made independently, τ_{rel} can be estimated by solving the equation $(\tau_{rel})^\delta = \tau_{arp}$, where δ is the network's diameter. If a node has only one parent, $p_{required}$ will be equal to τ_{rel}. However, when a node has k parents, then it suffices to assign a p, which ensures that the probability of at least one parent retransmits is greater than τ_{rel}. As a result, the $p_{required}$ announced by a node with k parents can be estimated as follows:

$$(1 - p_{required})^k < (1 - (\tau_{rel})) \tag{19}$$

Ensuring that condition (19) is met, the target reliability will be met for the determined service as well. In [60, 61] the authors also combined the proposed probabilistic scheme with a deterministic enhancement for when the packet loss is likely to happen. In this case, nodes insert a sequence number in the broadcast messages to check whether they miss any packet. If a given node misses any broadcast packet, it will explicitly request one of its parents to retransmit the missing packet.

This scheme presents several shortcomings that prevents its application to mobile networks [11]: 1) the reception percentage between two nodes is based on the quality of the link, however, in mobile networks mobility is the main reason for broken links. 2) the hierarchy is established in a static way and no renewal of neighborhood information is considered. Moreover, it is demonstrated in [11] that smart gossip fails when more than one source node is considered.

In PbG [11], the authors applied the aforementioned dependencies among nodes [60] to VANETs. They considered positioning data to calculate the relationships among nodes. These relationships take the direction of the dissemination process into consideration. As the proposed scheme is intended for vehicular networks, two possible directions can be considered. Fig. 4 illustrates the dependencies for a vehicular network composed of 4 nodes. In this example the hierarchy is built against driving direction. Vehicles

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are approaching the traffic congestion and they have to be informed. The node D is considered as the source node. An important difference of PbG from smart gossip is that in PbG nodes use Hello packets to collect positioning information. Since this scheme is aimed at VANETs, the dependencies among nodes must be updated frequently.
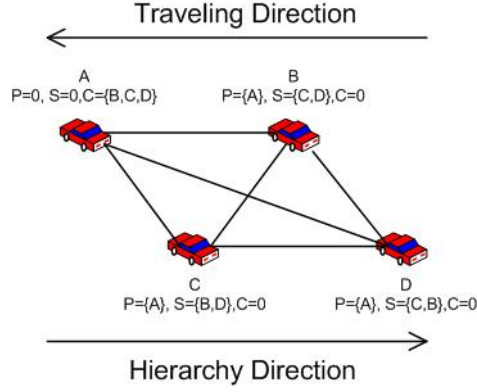

Figure 4: Node's relationships in PbG

In [12] the PbG scheme is enhanced by including three extensions (OPbG). 1) Two table extension, this improvement solves the problem of two source nodes of smart gossip [60]. Nodes consider a different neighboring table for each possible directions. As a result, distinct dependencies are defined for each direction. 2) Network density extension, this reduces the forwarding probability for dense networks. The authors introduced an additional reduction factor red that depends on the network density. They conducted simulations to derive the following expression for red:

$$red(n_b) = \frac{0.5}{1 + e^{-a(n_b - b)}} \tag{20}$$

The parameters a and b are obtained by simulation. Finally, the reduction factor red is applied to the average reception percentage τ_{arp}.

$$\tau_{arp}{}' = \tau_{arp} - red \tag{21}$$

3) Fallback mechanism extension, this is a counter-based [109] improvement to avoid collisions.

A summary of the reviewed density-based schemes is presented in Table 3 and Table 4.

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Table 3: Adaptive non counter-based density-based probabilistic schemes I

Scheme	Subtype	Forwarding Probability	Collected Data	Adjusted Parameters	Application
nb-Scheme [33]	degree	$p = \frac{k}{n_b}$	n_b	k	MANET
Autocast [112]	degree	$p = \frac{2}{n_b \cdot 0.4}$	n_b	α	VANET
Global GOSSIP [70]	degree	$p = \frac{\theta^{-1}(\gamma)}{\phi}$	ϕ and $\theta^{-1}(\gamma)$	γ	MANET
Distributed GOSSIP [70]	degree	$p = \frac{\theta^{-1}(\gamma)}{n_b}$	n_b and $\theta^{-1}(\gamma)$	γ	MANET
APF [44, 45]	degree	(3)	n_b	p_{max} and p_{min}	MANET
Game Theory [80]	degree	$p = 1 - (\frac{C}{G})^{\frac{1}{n_b - 1}}$	n_b	C and G	MANET
Two Thresholds (GOSSIP2) [41, 42]	thresholds	$p = p_h \quad if \quad n_b < n_c$ $else \quad p = p_l$	n_b	n_c, p_h, and p_l	MANET
2P-Scheme [3]	thresholds	$p = p_h \quad if \quad n_b < n_h$ $otherwise \quad p = p_l$	n_b	p_h and p_l	MANET
EDPB [13, 35]	thresholds	$p = p_h \quad if \quad n_b < n_{avg}$ $otherwise \quad p = p_l$	n_b	p_h and p_l	MANET
3P-Scheme [3]	thresholds	(8)	n_b	p_1, p_2, p_3	MANET
PF [51]	thresholds	$p = 1 \quad if \quad n_b < n_{avg}$ $else \quad p = \frac{p_i}{\theta}$	n_b	p_i and n_{avg}	MANET
LI.I [99]	2 hops	$p = \frac{1}{n_b} \sum_{k=1}^{n_b} n(x_i, x_k)$	n_b and $n(x_i, x_k)$	-	MANET
LI.II [99]	2 hops	$p = \frac{n_b}{n_b + n_b^{2h}}$	n_b and n_b^{2h}	-	MANET
LI.III [99]	2 hops	$p = \frac{n_b^{2h}}{n_b + n_b^{2h}}$	n_b and n_b^{2h}	-	MANET

Distance-based Schemes

The schemes based on distance can be further divided into two main categories: area-based and location based schemes. In the former category, the main idea is to use the

Table 4: Adaptive non counter-based density-based probabilistic schemes II

Scheme	Subtype	Forwarding Probability	Collected Data	Adjusted Parameters	Application
EM [97]	2 hops	(15)	n_b and n_b^{2h}	p_i	MANET
OAPB [8]	2 hops	$p = \frac{p_1+p_2+p_3}{3}$	n_b and n_b^{2h}	-	VANET
Family Classification [53]	2 hops	(18)	n_b, n_{child}, $n_{sibling}$, and N	p_i	MANET
Smart GOSSIP [60]	2 hops	$(1 - p_{required})^k < (1 - (\tau_{rel}))$	τ_{rel}, $ParentSet$, $SiblingSet$, $ChildSet$	τ_{arp}	WSN
OPbG [12]	2 hops	$(1 - p_{required})^k < (1 - (\tau_{rel}))$	τ_{rel}, $ParentSet$, $SiblingSet$, $ChildSet$	τ_{arp} red	VANET

relative distance between two nodes to adjust the forwarding probability, so nodes do not need global information of other nodes in the network. These schemes can also be categorized as density-based, RSS (Received Signal Strength), Euclidean distance, hop count, and hints-based (see Fig. 4). In density-based schemes, the relative distance between two nodes is estimated using the distribution of neighbors within a node's transmission range [33, 32, 103]. The main advantage of these schemes is that nodes do not need a positioning system. However, the validity of such estimation may depend on a constant distribution of nodes in the networks, an assumption that is always not true. In RSS-based schemes, nodes calculate the relative distance as a function of the received signal power [69, 114, 115] (the readers are referred to [90] for further information on estimation techniques). In Euclidean distance-based schemes, nodes have to be equipped with a positioning system like a GPS in order to obtain the Euclidean distance between two nodes [115, 69]. Alternatively, as the number of hops is the common metric used by routing protocols to measure the distance between the source node and the destination node [72], this can also be used by the probabilistic broadcast schemes to determine the distance between two nodes. In hints-based schemes, nodes estimate the relative distance between two nodes based on the history of connectivity of the two nodes [17].

On the other hand, in location-based schemes, nodes have to implement a location service so that nodes can exchange positioning data in order to create a map of the network.
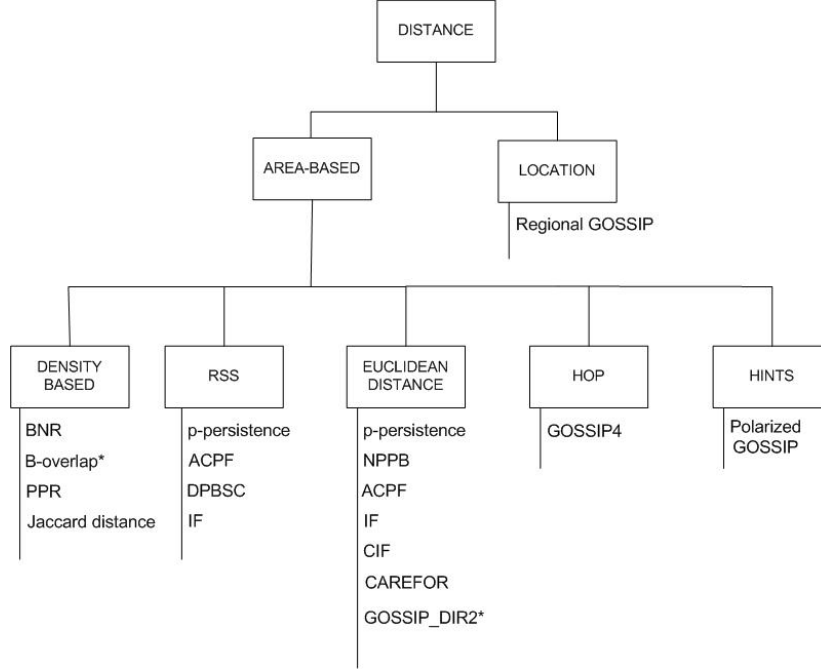
Figure 5: Classification of distance-based schemes

Area-Based Schemes

This subsection reviews the main area-based schemes found in the literature that fall into the classification made in Fig. 5.

a) Density-based:

There are several area-based schemes that estimate the relative distance between two nodes using density information such as BNR [33], B-overlap [103], PPR [103], and Jaccard distance [98].

In BNR scheme [33], the authors studied the intersection of two nodes' coverage areas, three zones Z_a, Z_b, and Z_c can be defined as shown in Fig. 6. The zone Z_a is the communication area covered only by node i, The zone Z_b is the communication area covered only by node j, and the zone Z_c is the communication area covered by both nodes i and j. However, these areas can be characterized by the number of mobile nodes inside them. The authors defined the ratio $\mu = \frac{N_b}{N_a+N_c}$, where N_a, N_b, and N_c are the number of mobile nodes inside the areas Z_a, Z_b, and Z_c respectively. If the node i is considered as the source node and the node j as the destination node, μ gives the ratio of unexplored nodes divided by the redundant nodes. This ratio becomes larger as the Euclidean distance between the two nodes becomes larger (if a uniform distribution of nodes is considered). In BNR, the forwarding probability is calculated by the following expression:

$$p = \frac{A - \alpha}{M^\sigma} \mu^\sigma + \alpha \tag{22}$$

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Where A and α are the roof and floor probability levels. The authors defined $A = 1$ and $\alpha = 0$, σ as the coefficient of convexity, and M as a constant, which represents the maximum value of μ, $M \cong 0.601$. Three values of σ are considered $\sigma = 1, 2$, and 3 resulting in three different probability functions.
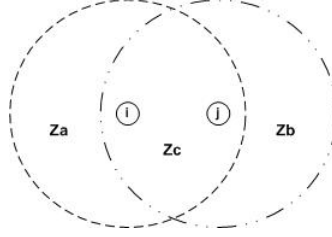

Figure 6: Intersection of the radio transmission areas of two nodes

In B-overlap scheme [103], the authors compute the proportional ratio (PR) of the overlap between the source and the destination nodes to the total broadcast area of the source node as:

$$S = \int_{\frac{r}{2}}^{r} \sqrt{r^2 - x^2} dx \tag{23}$$

Identical transmission ranges for the two nodes is assumed in (23), and $S_{max} = 0.41\pi r^2$. This limit is achieved when the two nodes are located at the border of the transmission range. The authors defined the number of nodes in the overlap area (NNOA) which can be calculated as the node density multiplied by the proportional relationship between the broadcast area and the overlap area. The NNOA can be expressed as:

$$NNOA = LND \cdot 0.41 \tag{24}$$

Where LND is the local node density which can be calculated by exchanging hello packets. The source node can calculate the forwarding probability, using NNOA, as:

$$p = \frac{DR}{NNOA} \tag{25}$$

Where DR is the desired number of retransmissions per overlap area. As a result, if each node in the overlap area retransmits with a probability p, the desired number of retransmissions is generated. In this scheme, nodes can adjust the reliability by tuning the parameter DR. If higher reliability is desired, the DR value should be higher. It is worth pointing out that this scheme also assumes that the nodes are deployed uniformly. In addition, in [103] the authors propose PPR, a scheme, which favors nodes located at the perimeter of node's transmission range. Similar to the previous scheme, this is also based on the local density to estimate the number of nodes at the perimeter zone of a node's transmission area. The source node can ignore nearby nodes by computing the desired retransmission volume based on the occupancy of a rim of some width ε around the perimeter, see Fig. 7.

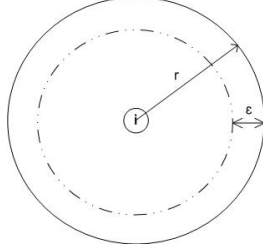In this scheme, nodes calculate the forwarding probability as

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Figure 7: Proportional perimeter scheme

$$p \quad = \quad \frac{DR}{(1-\varepsilon^2)}LND$$

Where LND is the local node density, and a rim of width $r(1-\varepsilon)$is considered, DR is the desired retransmissions along the rim.

In [98], the authors use the Jaccard distance [46] to estimate the Euclidean distance between two nodes. The main idea is to favor dissimilar nodes in order to reduce reduntant messages. The Jaccard distance is calculated using one hop neighboring information, considering two neighbors i and j (see Fig. 8) the Jaccard distance is expressed as:

$$Jd = 1 - \frac{a_1}{a_1 + a_2 + a_3} \tag{26}$$

Where, a_1 represents the common neighbors of the nodes i and j, a_2 is the number of neighbors of the node i that are not neighbors of the node j, and a_3 is the number of neighbors of the node j which are not neighbors of the node i. In order to calculate the Jaccard distance, nodes include their lists of neighbors in the hello packets.
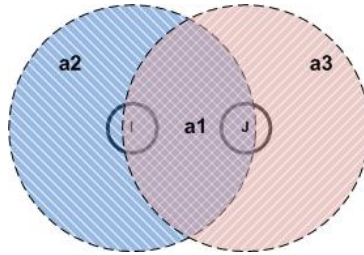
Figure 8: Jaccard distance in MANETs

The authors demonstrate in [98] that the Jaccard distance is correlated to the Euclidean distance. They assigned a linear probability based on the Jaccard distance between two nodes.

$$p = Jd \tag{27}$$

Where, Jd is calculated using (26) and $Jd \in [0, 1]$. In addition, they also adjusted the forwarding delay based on the Jaccard distance, so nodes located further away from a node have a lower retransmission delay.

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b) Euclidean distance-based and RSS-based:

In this subsection we have combined Euclidean distance-based and RSS-based schemes since in many aspects the schemes are similar and the only difference is the use of RSS levels instead of the Euclidean distance.

In [115, 114] (weighted p-persistence) the basic forwarding scheme based on the Euclidean distance is presented as:

$$p = \frac{d_{ij}}{r} \tag{28}$$

The proposed p-persistence is enhanced in [114, 115] by proposing the slotted p-persistence. In this scheme the retransmissions are delayed according to the relative distance between the sender and the receiver. The assigned time slot T_{Sij} is calculated as follows:

$$T_{sij} = Slot_{ij} \times l_d \tag{29}$$

Where l_d is the estimated link propagation delay and $Slot_{ij}$ is the assigned slot number expressed as,

$$Slot_{ij} = N_{slot} - \left\lceil \frac{d_{ij} \times N_{slot}}{r} \right\rceil \tag{30}$$

Where N_{slot} is the pre-determined number of slots. The authors also proposed using the RSS level to estimate the distance between nodes.

An extension of the p-persistence scheme is presented in [130] (NPPB), the authors define that a node have a forwarding probability higher than 0.5, when the weighted p-persistence is used up to $\frac{3}{4}$ of a node's neighbors. As a result, in a dense network, the effect of weighted persistence in saturated networks is not perceptible. They proposed an nth-powered probabilistic scheme to further reduce the forwarding probability in dense VANETs. In NPPB the forwarding probability is calculated as,

$$p = (\frac{d}{r})^k \tag{31}$$

Where k is the exponent for controlling the forwarding probability in NPPB. The larger the value of k, higher the concentration of retransmission nodes to the border of the node's transmission range. A similar approach of NPPB is proposed in [27] namely polynomial broadcast.

On the other hand, there are several schemes that consider the overlapping transmission areas between two neighbor nodes. In [69] (ACPF), the authors evaluated the overlapped transmission areas of two neighbor nodes i and j (see Fig. 9). This shared area $S(i, j)$ is represented in Fig. 9.
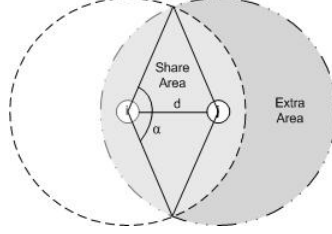
Figure 9: Share and extra area of two nodes

The shared area $S(i,j)$ can be calculated as,

$$S(i,j) = \pi r^2 + d \cdot \sqrt{r^2 - \frac{d^2}{4}} - \frac{arccos\frac{d}{2r}}{90}\pi r^2 \tag{32}$$

The maximum value of $S(i,j)$ is $S_{max} = 0.61\pi r^2$ and it is achieved when $d = r$. The authors also proposed estimating $d(i,j)$ using the received power. In ACPF the forwarding probability is calculated based on $S(i,j)$ as follows:

$$p = p_i e^{k\frac{S(i,j)-Smax}{\pi r^2}} \tag{33}$$

The parameter k is used to control the forwarding probability. A similar approach is proposed in [111] (DPBSC), where the authors used the additional coverage of rebroadcast to determine the forwarding probability. When a node receives a broadcasting packet, it refers to its additional coverage of rebroadcast to determine the rebroadcast probability. If the packet is received for the first time, the node applying DPBSC uses its coverage area to determine its rebroadcast probability as follows:

$$p = \frac{S(i,j)}{S_{max}(i,j)} \qquad if \qquad 0 < d < r$$
$$p = 0 \quad otherwise$$

In[89, 87, 88] (Irresponsible Forwarding, IF), a scheme that combines the distance between two nodes and the density of nodes to calculate the forwarding probability is presented for VANETs. The forwarding probability is calculated using the relative distance between two vehicles and the spacing distribution of the vehicles in the network. For every possible spacing distribution, the forwarding probability is calculated using the following expression:

$$p = (1 - F_x(z - d))^{1/k} \tag{34}$$

Where k is a shaping parameter and $F_x(z - d)$ is the cumulative distributed function (CDF) of a random variable X representing the space between two vehicles. In [89], the authors used an exponential spacing distribution so the forwarding probability is:

$$p = e^{-\frac{\varphi_s(r-d_{i,j})}{k}} \tag{35}$$

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Where, φ_s is the spatial density distribution of nodes and in [28] IF is evaluated on 802.11 MAC protocol. In [87] IF is analyzed under general inter-vehicle spacing distributions. Recently in [88], the authors evaluated the IF scheme under real inter-vehicle spacing distributions. They used real traffic traces obtained from Berkeley Highway Laboratory. The main shortcoming of this scheme is how the nodes can be aware of the spacing distribution using only local information without a central system. The authors proposed using the historical traffic data to estimate the spacing distribution. The main assumption is that the spacing distribution is repeated over time. Furthermore, the authors extended the IF scheme applying the silencing technique in [27]. In IF with silencing whenever a node transmits a broadcast packet, it silences the rest of nodes in the same transmission area.

Despite the good results of IF [28], the authors pointed out a shortcoming of IF scheme in high density scenarios. The problem occurs when there are several nodes located at the same high distance from the source node, there will be several nodes with a high forwarding probability; and as a result of this situation, there will be a high probability of collision of messages. To avoid this problem, the authors extended the IF scheme by introducing the concept of Ephemeral Cluster (EC). They denoted this new scheme as Cluster-based Irresponsible Forwarding (CIF). In CIF, an EC is formed whenever there are several nodes located closely to each other in the sender's transmission range during a short period of time. Among the nodes forming the EC, it is sufficient to disseminate the message if only one of them retransmits.

In [77] the CAREFOR protocol is proposed. Although CAREFOR is based on IF, the authors in [77] stated that the assumption that each node in the network has the same transmission range may not be real. Consequently, they modified the above equation (35) by including the transmission ranges of the nodes in the vicinity of the source node as follows:

$$p = e^{-\frac{\varphi_s (r - d_{i,j})}{k} \frac{r}{r_i}} \tag{36}$$

being r_i the radio transmission range of the ith receiving node. It is noticeable that the ratio $\frac{r}{r_i}$ accounts for the differences in the nodes' transmission ranges. One of the main differences of CAREFOR from IF is that CAREFOR uses two hops information to calculate the forwarding probability. In addition, the authors also pointed out the problem of possible collisions for nodes located at higher distances from the sender as exhibited by IF scheme. This issue is aggravated if nodes with different transmission ranges are considered. In order to resolve this issue, the authors defined the following collision threshold based on density and the node's radio transmission range:

$$Th_{coll} = 1 - e^{-\varphi_s r_i} \tag{37}$$

The authors demonstrated that using the above collision threshold (37) the collision probability can be reduced. The mechanism of CAREFOR algorithm to avoid collisions is to compare the results of the collision threshold (37) with the collision probability at each node, which can be calculated as:

$$P_{coll} = P_{busy}(1 - P_t) \tag{38}$$

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Being Pbusy the probability of at least one node retransmits a given message and Pt the probability that there is only one node using the channel at this time. Both Pbusy and Pt are calculated as follows:

$$P_{busy} = 1 - (1-p)^{(n-1)} \qquad (39)$$

$$P_t = \frac{1 - (1-p)^{(n-1)}}{P_{busy}} \qquad (40)$$

Where p is the forwarding probability calculated using (36) and n is the number of nodes interfering with each other's transmission. According to [77], the performance of CAREFOR is divided into three phases: 1) RTB transmission phase, in this phase the source node sends a Request-to-Broadcast (RTB) control packet, including local information such as the GPS coordinates, the number of neighbors, and the transmission power in order to calculate the radio transmission range. 2) Collision Assessment, in this phase nodes use the equation (37) to determine the collision threshold using the information provided in the RTB control messages. Then, nodes use equation (38) to determine whether they are allowed to retransmit or not. Enabled nodes are those with a collision probability lower than the calculated collision threshold. These enabled nodes go to the third phase, the CTB transmission phase in which nodes send back to the source node a Clear-to-Broadcast (CTB) packet. This packet is only used to inform the source node about the potential forwarders. Finally, CAREFOR algorithm also uses silencing mechanism based on the forwarding probability (36).

In [104] (GOSSIP_DIR2), the authors used directional antennas and Euclidean distance. The additional coverage area is calculated independently for each sector. Thus, a different forwarding probability is assigned to each sector in order to construct the probability vector $p = (p_1, ..., p_{S_c})$ where S_c is the number of sectors of the directional antennas. The distance between the sender S and the receiver R and the Angle of Arrival (AOA). In [104] the authors proposed an estimation technique to calculate the additional coverage area in each sector. Using the proposed estimation technique, the forwarding probability for each section can be calculated as,

$$p_i = max(0, 1 - (\frac{d_i'}{r})^2) \qquad (41)$$

Where d' is the estimated Euclidean distance.

c) hop count-based:

The hop count is used in [42], where the authors proposed GOSSIP4, a scheme based on the performance of the hybrid routing protocol ZRP [43]. The nodes act reactively or proactively depending on the distance from the source node. Such distance is measured in number of hops. Nodes maintain a zone that is composed of nodes located within Λ hops from the source node. Nodes perform proactively inside these zones, so as to trigger the exchange of neighboring information each time a change occurs in the zone. On the other hand, nodes located out of the zone are called peripheral nodes and they perform reactively. In [42] the authors defined $GOSSIP4(p, k, k')$, which performs similar to

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$GOSSIP1(p,k)$ but the nodes have a zone of radius k'. In summary, this scheme performs as $GOSSIP1(p,k)$ for those nodes located out of the zone, and as simple flooding for those nodes inside the zone.

d) hints-based:

A quite different type of broadcast scheme is proposed in [17, 16, 19] where, the authors presented polarized GOSSIP a scheme based on the relative positions between a given node and the destination node. A node forwards an incoming packet with probability p_h if it is closer to the destination than the previous node, otherwise the forwarding probability is p_l. The relative distance between a node and the destination node is estimated by "hints". The hint of a node i with respect to the destination node j is 0 if the two nodes are one hop neighbors, otherwise $hint_{i,j} = \frac{\triangle T_{i,j}}{dur_{i,j}}$. Here, $\triangle T_{i,j}$ is the time elapsed since the last time i and j were neighbors and $dur_{i,j}$ is the last link's duration between i and j. The correlation between $hint_{i,j}$ and the Euclidean distance has been empirically studied [19]. In polarized GOSSIP a node sends heartbeat packets to its neighbors (similar to hello packets) every $\triangle T_S$ and uses a vector of time information VH_i.

Location-Based Schemes

In[64] (regional GOSSIP), nodes have to use some location service to collect positioning data. The main objective behind Regional GOSSIP is to limit the number of retransmissions, and only the nodes that are in certain regions linking the source and the destination nodes are allowed to forward the incoming messages. The forwarding regions defined by the nodes are elliptical areas using the source node and destination node as the foci, see Fig. 10.
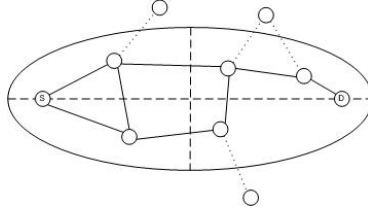

Figure 10: Forwarding area in regional GOSSIP

Furthermore, the forwarding probability is also adjusted dynamically by using the density of nodes within these ellipses. To carry out the propagation of messages, the geometrical information of the source node and the destination node and also the current route is piggybacked on the broadcast packets. Whenever a node v receives a new message it has to check whether it is inside the ellipse defined. If the nodes is inside the ellipse, it uses the following forwarding probability:

In [64] the authors derived the forwarding probability in the regional gossiping area as,

$$p \simeq \frac{\ln(N\pi l^2 \tilde{/} 4)}{N\pi^2 \tilde{l}^2 \tilde{r}^2 / 4}$$

(42)

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Where l is the ellipse factor, $\hat{l}^2 = l\sqrt{l^2 - 1}$, $\tilde{r}^2 = \frac{r}{a}$, and a is the length of site in a square scenario. The simulation results showed that the number of retransmissions generated using this scheme is less than the simple GOSSIP. In fact, up to 94% of messages can be saved compared to simple GOSSIP. However, this approach presents several disadvantages: 1) the nodes need to develop a location service in order to collect positioning data, 2) this location service adds overhead to the network so care must be taken in order not to worsen the performance of the network. In addition, the forwarding probability expression (42) depends on the total number of nodes in the network, which is a global parameter that in most cases is unknown to the nodes.

A summary of the main parameters of the reviewed distance-based schemes is presented in Table 5.

Table 5: Adaptive non-counter and area based-probabilistic schemes

Scheme	Subtype	Forwarding Probability	Collected Data	Adjusted Parameters	Application
BNR [33]	Density	$p = \frac{A-\alpha}{M^\sigma}\mu^\sigma + \alpha$	μ	A, α, σ	MANET
B-Overlap [103]	Density	$p = \frac{DR}{NNOA}$	n_b	DR	MANET
PPR [103]	Density	$p = \frac{DR}{(1-\varepsilon^2)}LND$	n_b	DR and ε	MANET
Jaccard distance [98]	Density	$p = Jd$	Jd		MANET
Weighted p-persistence [115]	Euclidean and RSS	$p = \frac{d_{ij}}{r}$	d or RSS	-	VANET
NPPB [130]	Euclidean	$p = (\frac{d_{ij}}{r})^k$	d	k	VANET
ACPF [69]	Euclidean and RSS	$p = p_i e^{k\frac{S(i,j)-Smax}{\pi r^2}}$	d or RSS	k and p_i	MANET
DPBSC [111]	RSS	$p = \frac{S(i,j)}{S_{max}(i,j)}$ $\quad if \quad 0 < d < r$; $\quad 0 \quad Otherwise$	RSS	-	MANET
IF [89] and CIF [29]	Euclidean and RSS	$p = (1 - F_x(z-d))^{\frac{1}{c}}$	d and φ	k	VANET
CAERFOR [77]	Euclidean	$p = e^{-\frac{\varphi_s(r-d_{i,j})}{k}}\frac{r}{r_i}$	d and φ	k	VANET
GOSSIP_DIR2 [104]	Euclidean	$p_i = max(0, 1 - (\frac{d}{r})^2)$	d and ϑ	-	MANET
GOSSIP4	Hop	$p = p_i$ $\quad if \quad hops < \Lambda$; $\quad else \quad p = 1$	$hops$	Λ	MANET
Polarized GOSSIP [17]	Hints	$p = p_h$ $\quad if \quad hint_{i,j_i} > hint_{i,j_{i-1}}$; $\quad else \quad p = p_l$	$VH_i[j]$	p_h and p_l	MANET

Speed-Based Schemes

The speed of nodes is specially relevant in VANETs where the speed of nodes is much higher than in other types of ad hoc networks such as MANETs or WSNs.

In [79] (SAPF), the authors proposed estimating the network's density in VANETs based on the node's speed. In SAPF the forwarding probability is adjusted as follows:

$$p = 0.0557v - 0.033 \tag{43}$$

Where v is the vehicle's speed. Two speed thresholds are defined v_l and v_h. The

authors indicated that if $v > v_h$, it is impossible to estimate the vehicle's density. On the other hand, if $v < v_l$, the network has almost reached its capacity and so the probability can be constant.

Self-pruning based Schemes

In self-pruning schemes, the main objtective is to cover the set of 2 hops neighbors of a given node. In this type of probabilistic schemes, the forwarding probability is adjusted by considering how this set of 2 hops neighbors is covered.

In [4] (DPR), the authors used a self-pruning mechanism to calculate the forwarding probability that is adjusted according to the number of neighbors uncovered. The following expression is used:

$$p = \frac{n_b - n_{cov}}{n_{avg}} \quad if \quad n_b \leq n_{avg}$$

$$p = \frac{n_b - n_{cov}}{n_b} \quad if \quad n_b > n_{avg}$$

Where n_{cov} is the number of neighbors which have already been covered by previous copies of the same broadcast packet. The authors estimate the average number of neighbors using the following expression,

$$n_{avg} = \frac{(N-1)\pi r^2}{A_{net}}\alpha \tag{44}$$

Where α is estimated using massive number of simulations [4].

In NCPR [129], the forwarding probability is calculated as a function of two metrics, a) the additional coverage ratio, and b) the connectivity factor. The additional coverage factor is calculated as follows:

$$R_a(i) = \frac{|U(i)|}{N_b(i)} \tag{45}$$

Where $U(i)$ is the uncovered neighbors of node i (self-pruning mechanims), which can be calculated using the following expression,

$$U(i) = N_b(i) - [N_b(i) \cap N_b(i-1)] - \{i - 1\} \tag{46}$$

Notice that the additional coverage metric measures the set of new nodes that is covered if node i forwards the packet. On the other hand, the connectivity factor is expressed as follows:

$$F_c(i) = \frac{N_c}{N_{b(i)}} \tag{47}$$

Where $N_c = 5.1774 log(N)$. The value of N_c is derived in [117], in this paper the authors estimated that if each node is connected to more than $5.1774 log(N)$ of its nearest neighbors, then the probability of the network being connected approaches 1, as the number of nodes in the network increases. Although this metric is suitable to ensure connectivity in the network, it is impractical in most cases, since it relies on knowing the

Table 6: Adaptive non-counter-based self-pruning based probabilistic schemes

Scheme	Forwarding Probability	Collected Data	Adjusted Parameters	Application
DPR [4]	$p = \frac{n_b - n_{cov}}{n_{avg}}$ $\quad if \quad n_b < n_{avg}$ $p = \frac{n_b - n_{cov}}{n_b}$ $\quad if \quad n_b < n_{avg}$	n_b and N	-	MANET
NCPR [129]	$p = F_c R_a$	n_b and N	-	MANET

total number of nodes in the network, which is a global network parameter. Finally, the forwarding probability is given by:

$$p(i) = F_c(i) \cdot R_a(i) \tag{48}$$

According to equations (45) and (47) the value of forwarding probability given by (48) can be higher than 1. In order to avoid such condition, the maximum probability is fixed to 1. In addition, the authors proposed to calculate the rebroadcast delay based on the number of common neighbors of a given node with its previous node in the communication path. They predicted that if the number of shared neighbors is higher, the forwarding delay should be lower, and therefore, more neighbors can be reached. The rebroadcast delay is calculated as follows;

$$T_p(i) = MaxDelay \times t_p(i) \tag{49}$$

Where $t_p(i)$ is the delay ratio of node i, which is calculated using the following expression,

$$t_p(i) = 1 - \frac{|N_b(i-1) - N_b(i)|}{|N_b(i-1)|} \tag{50}$$

Where $N_b(i)$ is the set of neighbors of node i.

A summary of the described self-pruning schemes is presented in Table 6.

Energy-based Schemes

The following schemes are focused on reducing the power consumption of the broadcast schemes so energy-based parameters are used to adjust the forwarding probability. In general power consumption is an important issue in wireless ad hoc networks since nodes are normally powered by batteries.

In [83] a simple probabilistic scheme based on the node's energy level is proposed (ECG). The authors defined an energy level threshold E_{th}. Whenever a given node receives a broadcast packet, it checks its energy level and if it is lower than E_{th}, it will not forward the incoming packet. Otherwise, the node forwards the packet with a probability $p = 0.75$. Moreover, if the node has only one neighbor, the forwarding probability is 1.

In [50] (EAG), the residual energy of nodes is used in [50] as the key parameter to adjust the node's forwarding probability. The forwarding probability is calculated as follows:

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Table 7: Dynamic Energy Based Probabilistic Schemes

Scheme	Forwarding Probability	Collected Data	Adjusted Parameters	Application
ECG [83]	$p = 0.75 \quad if \quad E > E_{th}$ $else \quad p = 0$	E	E_{t_h}	MANET
EAG [50]	$p = 0.2\varphi_i + 0.6 \quad if \quad n_b > 5$ $else \quad p = 0$	n_b and φ	n_c	MANET
EBG [84]	$p = \frac{E(\%)}{100}$	$E(\%)$	-	MANET
NEBG [93]	$p = \frac{E - E_{min}}{E_{max} - E_{min}}$	E	-	MANET

$$p = 0.6\varphi_i \quad if \quad n_b > 5 \tag{51}$$

$$else \quad p = 1 \tag{52}$$

Where φ_i is the residual energy of a node i and the constant value 0.6 is fixed to ensure certain level of reachability. Furthermore, a threshold $n_c = 5$ is defined.

In [84] (EBG), nodes use their battery levels to adjust the retransmission probability as follows:

$$p = \frac{E(\%)}{100} \tag{53}$$

Where $E(\%)$ is the percentage of remaining energy. As a consequence, nodes with higher battery level have higher forwarding probability.

In NEBG scheme [93] the energy levels of nodes located in the node's neighborhood are considered to determine the forwarding probability. This scheme adapts the forwarding probability to the neighborhood energy conditions. On receiving a new broadcast packet a node i calculates the forwarding probability according to the following expression:

$$p = \frac{E_i - E_{min}}{E_{max} - E_{min}} \tag{54}$$

Where E_{max} and E_{min} are the maximum and minimum energy levels in the node's neighborhood. This is more advantageous in scenarios where the nodes can have similar values of energy level.

A summary of the reviewed energy-based schemes is presented in Table 7.

Based on artificial intelligence

The following schemes use artificial intelligence to adjust the forwarding probability of nodes. In [2] a genetic algorithm is used to calculate the forwarding probability. Other parameters such as number of repeats that a given node retransmits an incoming packet, delay between repeats, and Time To Live (TTL) for a packet, are taken into consideration to evaluate the fitness function. The parameters to be minimized are number of collisions,

propagation time, and number of retransmissions. The authors evaluated the proposed approach under different densities in VANET scenarios.

In [94], a multi-objective genetic algorithm is used to optimize probabilistic broadcast in disaster scenarios. The main difference from the single objective optimization problem is that several output metrics are considered to obtain the set of non dominanted solutions (Pareto front).

3.2.2. Adaptive counter-based schemes

In counter-based schemes, nodes use the number of received copies of a given broadcast packet as a metric to determine the state of the broacast process in their vicinities. Thus, the main idea is to avoid the die out problem of the broadcast process. As shown in Fig. 2, other factors can also be combined to adjust the forwarding probability such as density metrics in density-based schemes, the relative distance in distance-based schemes, self-pruning mechanisms, and the energy of nodes.

Density-based Schemes

Similar to the non counter-based schemes, the adaptive counter-based schemes based on density can be further divided into different categories (Fig. 11) such as pure counter-based, node's degree, density thresholds, and color-based. The pure schemes use only the number of copies received as the factor to determine the forwarding probability. In node's degree-based schemes, the number of received copies is combined with the number of node's neighbors. In addition, density thresholds can also be defined based on the number of neighbors and the number of received copies. Finally the color-based scheme is a similar approach to the pure counter-based schemes but considering a color-field as the main parameter to adjust the forwarding probabilty.
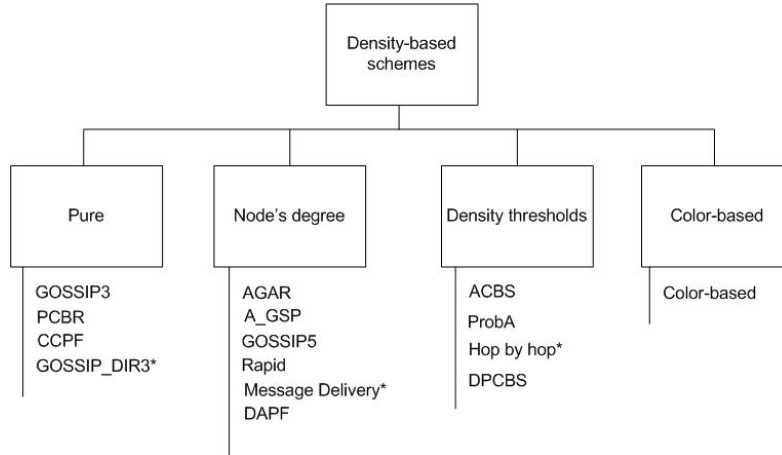

Figure 11: Classification of density-based schemes

a) Pure:

GOSSIP3 is proposed in [42, 41], which is the basic counter-based scheme. Normally, it is very difficult to know if the Gossip is dying out, however this occurrence could

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be predicted based on the number of received copies of a packet that a node receives from its neighbors. A node with n_b neighbors and a forwarding probability p should receive $m = n_b p$ copies of a given packet. If a given node receives fewer than m copies, it is reasonable to say that the die out problem is happening. This approach is called $GOSSIP3(p, k, m)$ and it requires the node to count the number of copies for a given packet. If a node could not forward a packet due to the probabilistic decision, then the node waits for a period of time counting the number of copies, and if this number of copies is higher than m, the node will decide that it is not necessary to retransmit the packet. Otherwise, the node will retransmit the packet with $p = 1$ after the waiting time. Two important parameters should be correctly adjusted, (1) the threshold value of the number of copies h and (2) how long should the nodes wait before retransmitting the packet. This time is random and is known as the Random Assessment Delay (RAD). In [42], the authors estimated that h should be equal to 1 and the waiting time RAD should be quite small in order not to delay the communications. The main disadvantages of GOSSIP3 are 1) a delay in communications due to the RAD delay and 2) the isolated node problem, which is represented in the Fig. 12. The node H can only be reached via node F, but node F will forward the incoming packet with a low probability since it has many neighbors (three neighbors). As a consequence, the node H could not be reached.
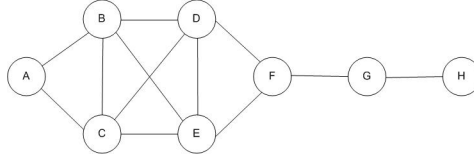

Figure 12: The isolated node problem

Another similar version of GOSSIP3 is PCBR proposed in [76]. However, there are two main differences of PCBR from GOSSIP3: 1) GOSSIP3 employs simple flooding during the first k hops, whereas PCBR always uses probabilistic broadcast and 2) In PCBR the retransmissions are always delayed by RAD timer, in contrast, GOSSIP3 only delays retransmissions as long as the probabilistic operation decides not to retransmit. Fig. 13 illustrates the latter.

In CCPF scheme [69], the authors used an exponential function based on the number of received copies to adjust the forwarding probability. The forwarding probability is calculated as,

$$p = p_i \cdot e^{-km} \tag{55}$$

Where p_i is a constant probability to ensure connectivity and k is a parameter to control the maximum and minimum probabilities. There are two main differences with respect to GOSSIP3: (1) Nodes do not attempt to retransmit before the waiting time RAD, consequently, the retransmissions are always delayed and (2) there is no defined threshold for the number of copies m so nodes always retransmit with a forwarding probability determined by (55) after waiting for a period of time RAD.

In GOSSIP_DIR3 [104], the authors combine the probabilistic counter-based scheme with the use of directional antennas. A different counter threshold h_j is defined for each sector j of the directional antenna. The values of the probability vector $\vec{p} = (p_1, ... p_{S_c})$ are calculated as follows:
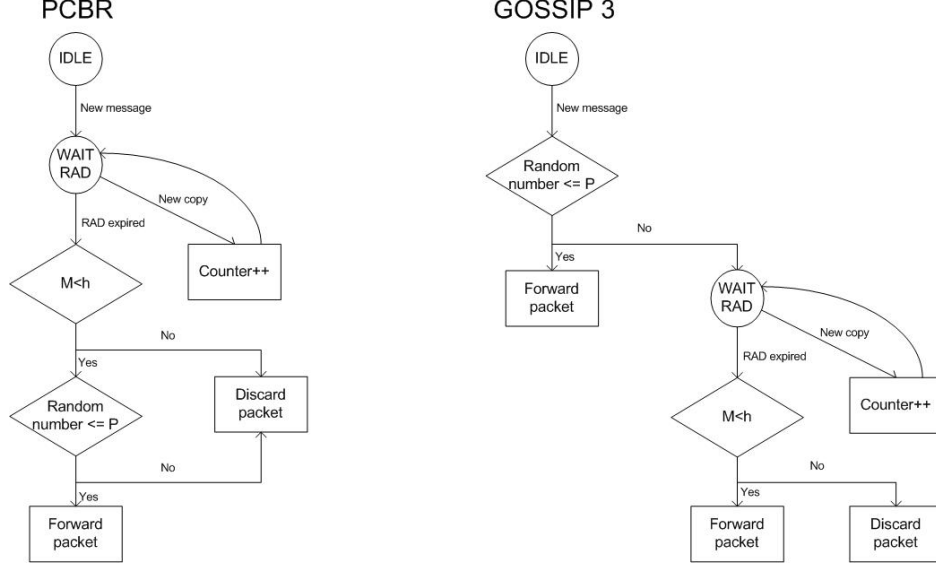
31

Figure 13: Difference between GOSSIP3 and PCBR

$$p_j = min(\frac{p_i S_c}{S_c - 1}(1 - \frac{h_j}{\sum_{j=1}^{S_c} h_j}), 1) \tag{56}$$

Where S_c is the number of sectors, $j = 1, ..., S_c$, and p_i is the initial forwarding probability as defined in GOSSIP3 [42].

b) Node's degree:

The following schemes combine the counter-based mechanism with the node's number of neighbors in order to adjust the forwarding probability.

In AGAR scheme [105] a node forwards the incoming packet with a probability given by (57) whenever its receives fewer than h messages. So instead of using $p = 1$, the nodes will forward the packet with a probability,

$$p = \frac{p_i}{n_b + 1} \tag{57}$$

As a result, the probability will depend on the node's neighbors resulting in a reduction in the number of broadcast messages.

In A_GSP scheme [63], the authors proposed a very similar version of AGAR [105], where they proposed to use the following expression (58) instead of (57),

$$p = \frac{p_i}{n_b} \tag{58}$$

In GOSSIP5[23], the authors proposed a similar scheme to GOSSIP3. But, GOSSIP5 exhibits two basic differences from GOSSP3. On one hand, the counter threshold is fixed

to the node's number of neighbors so $h = n_b$. On the other hand, nodes always wait a fixed RAD before trying to retransmit the incoming packet as in PCBR.

In [54] (message delivery), the authors categorized the nodes into two categories according to the number of neighbors. If a node has fewer than n_c neighbors it is considered as a β node, otherwise as an α node. At the same time the broadcast packets are also categorized as α and β packets. A packet sent by an α node is categorized as an α packet. If the packet is sent by a β node it is considered as a β packet. Whenever a β node receives a β packet, it will be always forwarded with $p = 1$. Otherwise, the nodes wait for a time t_1 before broadcasting the packet with a probability,

$$p = \frac{1}{mn_c} \tag{59}$$

In [85](DAPF), the authors presented a multi phase approach. At each $\triangle t$ (the time interval between phases) the nodes adjust their forwarding probability for the next phase using the following expression:

$$p_j = \frac{1}{(n_b + 1) - \frac{j}{3}n_b} \tag{60}$$

Where $j = 0, 1, 2, 3$ is the node's phase, so up to four phases are defined. Initially, each node tries to forward the incoming packet. If the node does not forward the packet, it will start to count the number of received duplicated packets m and it will wait for a RAD time. After the expiry of RAD, the node passes to the next phase and adjusts its forwarding probability according to (60). In each phase $h = 2$ to decide whether the node must try to transmit or not. In phase 3, the nodes always forward with $p = 1$ to ensure higher reachability.

In RAPID scheme [36, 37], deterministic and probabilistic broadcast are combined to ensure successful delivery of messages in ad hoc networks [36, 37]. First, the authors proposed that the forwarding probability in probabilistic schemes should be inversely proportional to the number of neighbors of a given node. They derived the following expression;

$$p = min(1, \frac{\beta}{n_b}) \tag{61}$$

Where β is a parameter called the reliability factor. The authors stated that $\beta = 3.5$ is a good tradeoff between the number of retransmissions and the reliability level. Moreover, the authors implemented a counter-based version of their original scheme in order to reduce the number of redundant packets. In addition, nodes periodically broadcast to their neighbors the header of messages received from other nodes in order to avoid nodes missing packets. This technique is called Lazy gossip [52] and is deterministic. it has some shortcomings such as an increment of overhead and latency. However, the authors stated that this is the only way to guarantee 100 % reliability. Finally, RAPID also uses jitter to avoid collisions so nodes rebroadcast after waiting RAD time.

c) Density thresholds:

As with non-counter based schemes, density thresholds are also used in counter-based schemes. Notice that in this case the density thresholds are based on the number of received copies instead of the number of neighbors as in non counter-based schemes.

In ACBS scheme [74], the forwarding operation is not suppressed when a density threshold value of h is reached, instead a low value of forwarding probability is used. The forwarding operation is then controlled by the following expression:

$$p = p_h \quad if \quad m < h$$
$$else \quad p = p_l \tag{62}$$

In ProbA scheme [66] multiple density thresholds is proposed. The retransmission probability is calculated as follows:

$$
\begin{aligned}
p &= p_1 \quad if \quad m < h_1 \\
p &= p_2 \quad if \quad h_1 < m < h_2 \\
p &= p3 \quad if \quad h_2 < m < h_3 \\
&\quad ... \qquad ... \qquad ... \\
p &= p_n \quad if \quad h_{n-1} < m < h_n
\end{aligned}
\tag{63}
$$

Where $p_1, p_2, p_3, ..., p_n$ are the forwarding probabilities, and $h_1, h_2, h_3, ..., h_n$ are the counter-based thresholds. The authors evaluated this scheme with three threshold values $h_1 = 1, h_2 = 2$, and $h_3 = 3$ and the forwarding probabilities were $p_1 = 0.9, p_2 = 0.5, and\, p_3 = 0.1$.

In [128](hop by hop), the authors proposed a probabilistic scheme that adapts the forwarding probability hop by hop as a broadcast packet goes through the nodes in a network. If the number of copies is lower than h, the value of p is incremented by a fixed amount $p_{\triangle-}$. In contrast, if the number of copies is higher than h, the value of p is decremented by $p_{\triangle+}$. The authors also defined two limits for the value of p, these values are p_l and p_h, where $p_h > p_l$. So the forwarding probability is calculated at each node as follows:

$$
\begin{aligned}
p &= p_i - p_{\triangle+} \quad if \quad m < h \\
p &= p_i + p_{\triangle-} \quad if \quad m > h \\
p &= p_l \qquad\quad if \quad p < p_l \\
p &= p_h \qquad\quad if \quad p > p_h
\end{aligned}
\tag{64}
$$

At every interval t, the nodes compute m in order to determine the retransmission probability. Unlike the classical counter based implementation, here the nodes evaluate m at each interval t and the nodes make the decision of forwarding the incoming packet immediately after receiving a packet. Therefore the broadcast latency is lower than that of the classical counter based schemes. However, the authors did not describe how they arrived at the optimum value of t. They used the results shown in [108] to select $h = 6$ as the threshold value in order to save rebroadcast packets. Another important parameter to be adjusted is the initial probability p_i, a low value of p_i may result in a low reachability. While a high value of p_i may increase the number of redundant packets. The authors determined the initial probability on the basis of average number of neighbors of a given node n_{avg} and it can be calculated using (6). The initial forwarding probability is determined as follows:

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$$
\begin{array}{lll}
p_i = 1 & if & \frac{6}{n_{avg}} \geq 1 \\
p_i = \frac{6}{n_{avg}} & if & 0 < \frac{6}{n_{avg}} < 1 \\
p_i = 0 & if & \frac{6}{n_{avg}} \leq 0
\end{array}
\tag{65}
$$

In [75](DPCBS), the authors proposed a counter-based scheme with a piecewise probability function based on the number of copies received. The main difference from previous schemes is that DPCBS uses an exponential probability function that is defined as follows:

$$
\begin{array}{ll}
p_1 = e^{-\left(\frac{m}{h}\right)} & if \qquad m < h \\
p_2 = e^{-\left(\frac{m+1}{h}\right)} & Otherwise
\end{array}
$$

Nodes in DPCBS perform as in PCBR so they always wait RAD. The authors used a threshold $h = 3$ to evaluate the performance of DPCBS.

d) Color-based:

A variation counter-based scheme is proposed in [55] (color-based broadcasting). In this scheme, every broadcast message has a color-field [55]. The condition to be satisfied at the expiration time is similar to the original counter-based scheme so the number of *colors* of broadcast messages overhead must be less than a threshold. If this condition is satisfied the message will be retransmitted with a new color assigned to its color-field. The authors argue that the color-based schemes create backbones richer than the counter-based schemes in terms of robustness against node's failures since color-based schemes create mesh-like backbones. In fact, the authors proved that for any backbone generated by a counter-based scheme there exits a backbone that can result from the color-based scheme with the same threshold m, which contains the counter-based backbone as a subset. The authors analyzed and compared the $m = 2$ case, called Red-Blue broadcast, with the same counter-based approach. The simulation results showed that both approaches perform similarly in terms of reachability, while color-based scheme produces less number of rebroadcasts.

Tables 8 and 9 include the main parameters of the reviewed density-based schemes.

Table 8: Adaptive Counter Based and Density Based Probabilistic Schemes I

Scheme	Subtype	Forwarding Probability	Collected Data	Adjusted Parameters	Application
GOSSIP3 [42]	Pure	$p = p_i$ if $t < \tau$ $else$ $p = 1$ if $m < h$ $else$ $p = 0$	m	RAD, h, p_i and k	MANET
PCBR [76]	Pure	$p = p_i$ if $m < h$ $else$ $p = 0$	m	RAD, h, p_i and k	MANET
CCPF [69]	Pure	$p = p_i \cdot e^{-km}$ $t = \tau$	m	RAD, p_i and k	MANET
GOSSIP _DIR3 [104]	Pure	$p_j = min(\frac{p_i S_c}{S_c - 1}(1 - \frac{h_j}{\sum_{j=1}^{S_c} h_j}), 1)$	m	p_i and h_j	MANET
AGAR [105]	Degree	$p = p_i$ if $t < \tau$ $else$ $p = \frac{p_i}{n_b + 1}$ if $m < h$ $else$ $p = 0$	m and n_b	RAD, h, p_i and k	MANET
A_GSP [63]	Degree	$p = p_i$ if $t < \tau$ $else$ $p = \frac{p_i}{n_b}$ if $m < h$ $else$ $p = 0$	m and n_b	RAD, h, p_i and k	WSN
Rapid	Degree	$p = min(1, \frac{\beta}{n_b})$	m and n_b	RAD and β	MANET
Message Delivery [54]	Degree	$p = \frac{1}{m n_c}$ at $t = \tau$ if current node and previous node both are α, otherwise $p = 1$	m and n_b	RAD and n_c	MANET
DAPF [85]	Degree	$p_j = \dfrac{1}{(n_b + 1) - \frac{j}{3} n_b}$	m and n_b	RAD	MANET

Table 9: Adaptive Counter Based and Density Based Probabilistic Schemes II

Scheme	Subtype	Forwarding Probability	Collected Data	Adjusted Parameters	Application
ACBS [74]	Thresholds	$$p = p_h \quad if \quad m < h$$ $$else \quad p = \quad p_l$$	m	$RAD, h,$ p_l, p_h and k	MANET
ProbA [67]	Thresholds	(63)	m	$RAD,$ $p_1, ..., p_n$ and $h_1, ..., h_n$	MANET
Hop by Hop [128]	Thresholds	(64)		$RAD, p_i, p_{\triangle+}, p_h$, $p_u,$ and $p_{\triangle-}$	MANET
DPCBS [75]	Thresholds	$$p_1 = e^{-\left(\frac{m}{h}\right)} \quad if \quad m < h$$ $$p_2 = e^{-\left(\frac{m+1}{h}\right)} \quad Otherwise$$	m	h	MANET

Distance-based Schemes

In distance-based schemes, nodes combine the counter-based mechanism with the relative distance between two nodes in order to determine the forwarding probability. Notice that although in counter-based schemes we have not made the same classification of distance-based schemes as it is done in the non counter-based case, the same approximations used in the non counter-based case are also applicable to the counter-based case.

In [56] (DDAPF), the authors proposed calculating the relative distance between two nodes as follows:

$$d_r = \frac{d_{T,R}}{r_R}$$

.

Where, r_T is the transmitter respectively and $d_{T,R}$ is the Euclidean distance between the transmitter and the receiver. Notice that this is a relative measurement. The authors also proposed to use the received power to estimate the Euclidean distance. In DDAPF, the forwarding probability is calculated as follows:

$$p = p_h \quad if \quad m = 1$$
$$otherwise \quad p = min(\quad p_l, \left(\frac{e - e^{(1-\frac{d_r}{d_{max}})}}{e - 1}\right)^k)$$ (66)

Where d_{max} is the maximum distance, k a shaping parameter, and p_h and p_l are the

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maximum and minimum forwarding probabilities. In addition, a back off delay time based on distance is also proposed. The back off delay is calculated as follows:

$$Delay = delay_{max} \left(\frac{e - e^{(\frac{d_r}{d_{max}})}}{e - 1} \right)^k \tag{67}$$

Where $delay_{max}$ is the maximum delay a packet can experience at each node.

In ACCPF scheme [69], the authors combined the features of ACPF (non counter-based that uses distance) and CCPF (pure counter-based) in order to get benefits from both schemes. In ACCPF, nodes take into account both the Euclidean distance and the number of copies received in order to compute the forwarding probability (68). In this scheme, each node maintains the number of copies m, and the smallest additional coverage area S_{min} for each broadcast packet m. After a waiting period of time RAD, the nodes retransmit with a probability,

$$p = p_i e^{k_1 \frac{Smin(m) - S_{max}}{\pi r^2}} e^{-k_2 m} \tag{68}$$

Where $S_{max} = 0.61\pi r^2$, r is the node's transmission range, k_1 and k_2 are two constants used to control the forwarding probability, and S_{min} is updated every time a node receives a new copy of m.

In Discount scheme [49], the perimeter nodes are preferred. A distance threshold D_{th} determines which nodes are perimeter nodes and which are inner nodes. If a given node is located in the area defined by D_{th} it is considered as an inner node, for instance, node j in Fig. 14. Otherwise, the node will be considered as a perimeter node, see node k in Fig. 14. An inner counter threshold IC_{th} is defined in order to limit the forwarding operation of inner nodes. If the number of copies m is higher than IC_{th}, the inner node will not forward the incoming packet. In summary, the objective consists of reducing the number of rebroadcasts made by the inner nodes.
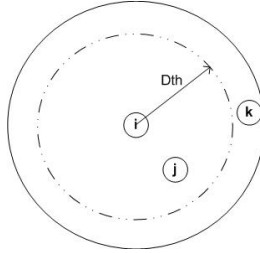

Figure 14: Distance threshold in Discount scheme

An extension of Discount scheme is presented in [49](Discount-RS). The authors identified that discount scheme could lead to a large number of redundant packets if the source node has many border nodes. In order to avoid such redundancy, the authors incorporated counter-based operation to the border nodes. If a border node receives a copy of a packet from another border node, it will not forward the incoming packet.

Table 10 includes the main parameters of the reviewed distance-based schemes.

Table 10: Adaptive counter-based distance-based probabilistic schemes

Scheme	Forwarding Probability	Collected Data	Adjusted Parameters	Application
DDAPF [56]	(66)	d_r and m	k, p_h, and p_l	MANET
ACCPF [69]	$p = p_i e^{k_1 \frac{S_{min}(m) - S_{max}}{\pi r^2}} e^{-k_2 m}$	d and m	p_i, k_1, and k_2	MANET
Discount [49]	Inner nodes $d < D_{th}$ $p = p_i \quad if \quad m < IC_{th}$ $else \quad p = 0$ Perimeter nodes $d > D_{th}$ $p = p_i$	d and m	D_{th}, and IC_{th}	MANET
Discount RS [49]	Inner nodes $d < D_{th}$ $p = p_i \quad if \quad m < IC_{th}$ $else \quad p = 0$ Perimeter nodes $d > D_{th}$ $p = p_i \quad if \quad m < 1$ $else \quad p = 0$	d and m	D_{th}, and IC_{th}	MANET

Self-pruning based Schemes

In NCPF a self-pruning mechanism is added to ACCPF (counter-based scheme that uses relative distance) algorithm [69]. Nodes do not rebroadcast if their entire transmission areas have already been covered by other nodes. To insert this self-pruning mechanism in ACCPF, the broadcast messages have to include the nodes that have already been covered. During the waiting time RAD, nodes can receive multiple broadcast packets from their neighbors. The nodes collect which neighbors have already been covered in order to make the decision of retransmitting the broadcast packet again. If all of a node's neighbors are covered during the waiting time, the node will not forward the broadcast packet. Otherwise, the retransmission probability will be:

$$p = p_i e^{-km} \tag{69}$$

Where k is a constant to control the forwarding probability.

Energy-based Schemes

GEM scheme combines counter-based, energybased and distance-based mechanisms to adjust the forwarding probability [71]. On receiving a broadcast packet a node checks

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its remaining energy (energy-based mechanism), if it is lower than the threshold energy (cut-off energy), it will discard the packet. Otherwise, the node will calculate the relaying probability as a function of the Euclidean distance (distance-based mechanism) between the sender and the receiver as,

$$p = \frac{d}{r} p_h \tag{70}$$

Where p_h is the maximum forwarding probability. If a node has an energy level higher than the cut-off energy but it does not relay the incoming packet x because its coin toss landed "tails", the node will wait for a period of time RAD in order to receive a copy of x from one of its neighbors. If after the waiting time the node does not receive any copy of x it will try to broadcast x using (70) (counter-based mechanims). One important task of this scheme is how to set the cut-off energy. The cut-off energy is a threshold used by each node to determine whether it is localized inside a low energy region. When a given node is located in a low energy region, it should not rebroadcast. The authors used the average energy level of nodes covering a certain region. A region is considered a low energy region when the mean energy of all nodes that cover this region is smaller than the network's mean energy E_{avg} minus its standard deviation σ. A given node I can monitor its energy coefficient E_{c_i} using the following expression:

$$E_{c_i} = \sum_{j=1}^{j=N_{b_I}} \frac{E_j}{n_{b+1}} + \frac{E_I}{n_b + 1} \tag{71}$$

Where E is the node's energy level and N_{b_I} is the set of I's neighbors. Using E_{avg}, σ, and E_{c_i}, the cut-off energy is determined as the highest coefficient that is smaller than $E_{avg} - \sigma$. Notice that when this coefficient does not exist, the network does not have low energy regions so the cut-off energy is zero.

4. Evaluation of Probabilistic Schemes

This section is aimed to describe the methodology used to evaluate the performance of probabilistic broadcast in wireless ad hoc networks. This methodology includes network simulators, performance metrics, and real implementations.

4.1. Simulators

So far, simulation results seem to be the only means to evaluate the performance of probabilistic broadcast schemes. Because of the complexity of developing real testbeds, the simulation results have served as the main benchmark for ad hoc networks wireless networks such as WSNs, MANETs, VANETs. Although it has been observed that different simulators can produce different results for flooding algorithms [100], network simulators are still the main evaluation method for assessing broadcast schemes. The Network Simulator 2 (NS-2) [38] is so far the most used simulator for evaluating broadcast and routing algorithms in wireless ad hoc networks. However, other network simulators have also been used to evaluate broadcast schemes such as GlomoSim [124], QualNet , OPNET, and JiST/SWANS [14, 15]. On the other hand, a few experimental results have been provided in the last few years. Experimental results are important to corroborate and validate the analytical models and the simulation results.

4.2. Performance metrics

The objective of this subsection is to present a detailed list of metrics widely used for the evaluation of broadcast schemes. Notice that although the following metrics have been used to evaluate probabilistic broadcast schemes, they can also be used to evaluate other types of broadcast schemes. We have divided the evaluation metrics into four groups, see Fig. 15, 1) Broadcast efficiency, 2) Discovery process, 3) Routing protocols, and 4) MAC layer. The broadcast efficiency metrics evaluate the broadcast schemes as a stand-alone dissemination technique. These metrics are especially useful for the cases when broadcast schemes are used to disseminate warning messages. We have classified the broadcast efficiency metrics into four categories, 1) Reachability, 2) Redundancy, 3) delay, and 4) energy. The reachability metrics measure the outreach of the broadcast process. The redundancy metrics determine the overhead caused by the broadcast schemes. In general, low redundancy is a basic requirement for broadcast schemes. Delay metrics calculate the time elapsed during the broadcast process. Delay needs to be small when broadcast schemes are used to disseminate warning messages. Finally, energy metrics evaluate the broadcast schemes in terms of energy consumption, which is of paramount importance in wireless ad hoc networks.

The discovery process metrics evaluate the broadcast schemes when they are used in the discovery process of routing protocols. In this case, the objective is to find a communication path between a source node and a destination node in the network. Notice that it is different from the objective of stand-alone broadcast schemes whose main objective is to reach as many nodes as possible.

The routing protocols metrics are normally used to evaluate the routing protocols in wireless ad hoc networks [62]. Since broadcast schemes are an important part of routing protocols, they impact on the general performance of routing protocols. MAC layer metrics evaluate the broadcast schemes in terms of number of collisions. As mentioned earlier, simple flooding causes the well-known broadcast storm problem [109, 108] so MAC layer metrics give an idea on how the broadcast problem is alleviated when probabilistic broadcast schemes are employed.

The metrics included in Fig. 15 are defined as follow:

Broadcast efficiency metrics

Reachability

The objective of this metrics consists of evaluating the dissemination of the broadcast message throughout the network, so high values of the following metrics are always desired in a broadcast scheme.

- **Reachability** (*Re*)**:** is defined as the ratio of nodes that received the broadcast packets to the total number of nodes in the network. When the network is not fully connected, the reachability metric is defined as the ratio of nodes that received the broadcast packets to the total number of nodes that can be reached by the source node directly or through a multi-hop path. This metric is also referred to as the fraction of nodes, Broadcast Delivery Ratio (BDR), and Broadcast Coverage Ratio (BCR) or Coverage.

- **Average Reachability per broadcasting** (*Re*$_{avg}$)**:** Average reachability of the broadcast processes executed.
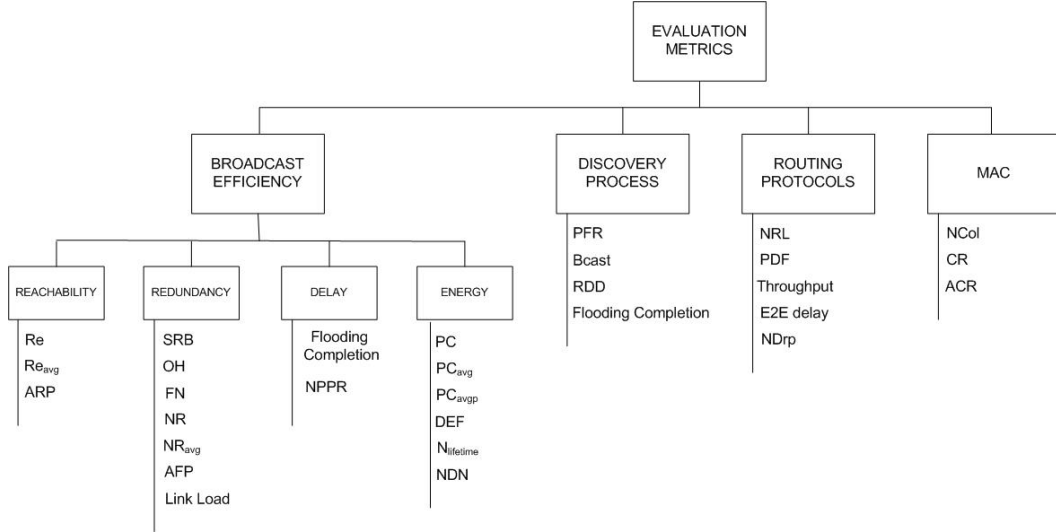
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Figure 15: Classification of the evaluation metrics

- **Average Reception Percentage** (ARP)**:** Reception percentage of a given node with respect to the source node, is the percentage of messages originated at the source node and received at the destination node. The ARP is the reception percentage, averaged over all nodes.

Redundancy

The following metrics evaluate broadcast schemes in terms of redundancy. In general, redundancy should be maintained as low as possible in broadcast schemes. The ideal scenario is one where nodes only receive a broadcast packet once.

- **Saved ReBroadcast** (SRB)**:** Let N_r be the number of nodes that received the broadcast message and let N_t be the number of nodes that actually transmitted the message. The saved rebroadcast is then defined by $\frac{N_r - N_t}{N_r}$.

- **Redundancy Overhead** (OH)**:** The number of duplicated packets received at each node divided by the total number of nodes in the network.

- **Number of forwarding nodes** (FN)**:** The number of duplicated packets received at each node divided by the total number of nodes in the network.

- **Number of retransmissions** (NR)**:** The total number of retransmissions. This metric is also referred to as number of rebroadcasts.

- **Average retransmissions per broadcasting** (NR_{avg})**:** The average number of retransmissions per broadcasting. This is very similar to the previous term, but it also considers the number of broadcast process.

- **Average Forwarding Percentage** (AFP)**:** Forwarding percentage of a given node with respect to the source node, is the percentage of messages originated at

the source node and forwarded by the node. The AFP is the reception percentage, averaged over all nodes.

- **Efficiency Rate** (ER)**:** This metric is defined as the forwarding rate divided by the reception rate.

- **Link Load:** The link load measures the amount of broadcast traffic received at each node over a unit time.

Delay

Delay metrics are related to the time spent by a broadcast message to cross the network. As a rule, low delay is always a good feature of a broadcast scheme specially when the broadcast scheme is used to disseminate emergency messages.

- **Normalized Packet Penetration Rate** ($NPPR$)**:** This metric represents how fast the broadcast packets travel across the network.

- **Flooding Completion Time or Broadcast end to end delay:** The time elapsed between the first broadcast of a broadcast packet and the received route reply.

Energy

The following metrics are used to measure the power consumption of broadcast schemes. These metrics are specially relevant in WSNs where nodes are normally fed by batteries. In general, low power consumption is always desirable.

- **Power Consumption** (PC)**:** The total power consumption of the nodes forming the network.

- **Average Power Consumption** (PC_{avg})**:** The average power consumption of the broadcast processes executed.

- **Average Power Consumption per Broadcasting** (PC_{avg_p})**:** The average power consumption of the broadcast processes executed.

- **Directional Energy Efficiency** (DEF)**:** The ratio of the number of non duplicate packets to the number of sectors used for forwarding broadcast packets (this metric is only used in directional broadcast [104]).

- **Network Lifetime** ($N_{lifetime}$)**:** The network lifetime is defined as the time it takes for the first node to deplete its energy. Notice that this metric sometime is defined as the the time it takes for a percentage of the network to deplete its energy.

- **Number of Dead Nodes** (NDN)**:** The total number of dead nodes in the network. A node is dead when its battery level has depleted.

Discovery process

The following metrics are used to evaluate broadcast schemes as part of the discovery phase of routing protocols. The objective consists of finding a communication path between a source node and a destination node or several destination nodes. The basic requirements are: finding a communication path as fast as possible, using the lowest possible resources (messages) and with a high rate of success.

- **Path Found Ratio** (PFR): The ratio of the number of paths found to the number of path requests. This metric is also defined as Discovery Rate and Connectivity Success Ratio.

- **Route Discovery Delay** (RDD): The time elapsed between the first broadcast of a request packet and the received route reply.

- **Bcast:** The average number of broadcast packets sent by a node per path discovered.

Routing protocols

The following metrics are normally used to evaluate routing protocols in ad hoc networks. Consequently, they can also be used to evaluate broadcast schemes since they are an important part in the performance of routing protocols.

- **Number of hops:** The total number of hops from the source node to the destination node.

- **Packet Delivery Fraction** (PDF): The ratio of packets received successfully by the source node.

- **End-to-End Delay** ($E2E$) **or Latency:** The delay experienced by a packet from the time it is sent by the source until the time it reached the destination.

- **Normalized Routing Load** (NRL): The number of routing packets transmitted for every data packet sent. This metric is also referred to as routing overhead.

- **Throughput:** Total data successfully received by their destinations divided by the simulation time.

- **Number of Dropped Packets** ($NDrp$): The total number of dropped packets.

MAC layer

The following metrics are normally used to evaluate MAC protocols, but they can also evaluate the performance of broadcast schemes since the number of collisions will be influenced by the broadcast scheme used. As a rule, low number of collisions is a requirement for a broadcast scheme.

- **Number of Collisions** ($NCol$): The total number of collisions.

- **Collision Rate** (CR): The total number of broadcast packets dropped by the MAC layer as a result of collisions per unit simulation time.

- **Average Collision Rate** (ACR): The average number of broadcast packets dropped by the MAC layer as a result of collisions per unit simulation time.

4.3. Comparison

In this subsection, we present the most relevant information that we have obtained from the analysis of the result sections of the papers reviewed in this survey, considering how the comparison among different broadcast schemes have been carried out. The main findings are:

- Most of the proposed broadcast schemes in the literature are only compared to simple flooding and GOSSIP1 [41, 42],see Fig. 16. Consequently, there is a lack of a complete comparison among different probabilistic broadcast schemes proposed in the literature. When other schemes are used in the evaluation they are normally proposed by the same authors so there is little comparison among schemes proposed by different authors.
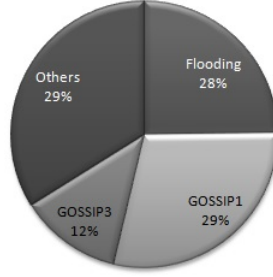

Figure 16: Comparison schemes

- Most of the proposed broadcast schemes have been proposed for MANETs as can be observed in Fig. 17. However, it would be useful to evaluate the proposed schemes for different target scenarios since the goals of broadcast schemes different types of ad hoc networks are very similar.
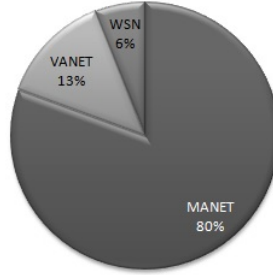

Figure 17: Target network

- As for the performance metrics, Re, SRB, E2E are the most used metrics to evaluate broadcast schemes whenever they are proposed as standalone dissemination mechanisms. On the other hand, if the broadcast schemes are evaluated as part of the

discovery phase of routing protocols, NRL and PDF are the preferred performance metrics.

- When mobility of nodes is considered, for instance in MANETs, the RWP[30] model is so far the most used mobility model. Although this mobility model has been criticized for being unrealistic [123], it is still widely used to evaluate the routing and broadcast algorithms. Moreover, the steady-state version of RWP [81] solves the issues observed in the traditional version of RWP [123]. In VANET scenarios, the mobility models simulate vehicles in a highway with different lanes. On the other hand, static scenarios are normally employed in WSNs. The use of real trace-based mobility model would be useful to evaluate the performance of probabilistic broadcast schemes in real scenarios [78, 10].

- As mentioned earlier, the network simulator NS-2 [38] is the de facto simulator for evaluating probabilistic broadcast schemes in wireless networks. The usage of networks simulators is illustrated in Fig. 18.
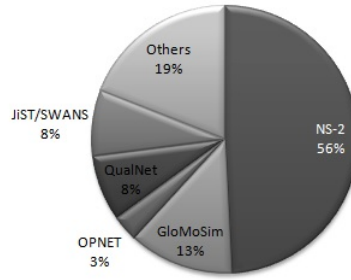

Figure 18: Network simulators

- In general, the use of hello packets is widely applied to probabilistic broadcast schemes. The period of hello packets should be adjusted carefully since it impacts on the congestion of the network [122]. In addition, when neighboring information is included in the hello packets, it increases the payload that in turns affect the time duration for which the packets occupy the wireless medium.

- AODV routing protocol [91] is the most used routing protocol to evaluate the performance of the proposed probabilistic broadcast schemes when they are implemented on a routing protocol as part of the discovery process.

- The IEEE 802.11 Distributed Coordination Function (DCF) [1] is the standard MAC layer employed in majority of the proposed broadcast schemes found in the literature. However, there are many other proposed schemes that are evaluated under an ideal MAC layer. It means that packet collisions are not taken into consideration. Although considering an ideal MAC layer can be useful for evaluating the efficiency of the proposed algorithms, a realistic MAC layer is necessary to emulate real-life scenarios. Moreover, the broadcast schemes impact on the congestion and contention of the network so a real MAC layer is necessary to model and assess the efficiency of a broadcast scheme.

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4.4. Real implementations

Little work has been focused on the evaluation of broadcast schemes in general and probabilistic broadcast schemes in particular. Flooding is studied in detail by Ganesan et al [39] in a grid scenario (a grid with 150 nodes), and the results showed that even in dense scenarios the reachability is not 100%. In [20, 23] the Testbed (DES-Testbed) [22] is used to evaluate several probabilistic schemes. In [20, 23], the DES-Testbed is composed of 59 mesh wireless routers located in two adjacent buildings. In [23] where the probabilistic schemes used are GOSSIP1, two thresholds scheme (GOSSIP2), GPSSIP3, and GOSSIP5, the main findings are:

- The bimodal behavior is observed in GOSSIP1 for a forwarding probability about 0.7. These results corroborate the results included in [41, 42]. However, the results in [23] indicate that such behavior depends on the position of the source node.

- The authors observed that even when a forwarding probability equal to 1 is used the maximum reachability of 100% is not achieved.

- The results obtained by GOSSIP2 showed that this scheme has problems in nodes with a low degree so it can cause network partitioning.

- GOSSIP3 is the probabilistic scheme that achieved the best results in terms of reachability.

- GOSSIP5, it exhibited a behavior strongly dependent on the source node's position so the authors stated that this scheme needed further research.

On the other hand, in [20] when the probabilistic schemes (adapted to the target scenario conditions) used are GOSSIP3 [42, 41], AGAR [105], the dynamic probabilistic scheme based on self-pruning [3], PCBR [76], and APF [44, 45], the main findings are:

- The experimental results showed that GOSSIP3 achieved the best results. GOSSIP3 exhibits independence of the forwarding probability. Moreover, it does not need to exchange hello packets periodically.

- The rest of the probabilistic schemes showed some problems to adapt the adjusting parameters to the deployed scenario. The authors observed that the adjusting parameter should be chosen carefully in order to achieve satisfactory results.

- The authors noticed the importance of the position of the source node.

- According to the results included in [20], none of the probabilistic schemes achieved reachability higher than 80% and the saved rebroadcast compared to flooding is up to 30%.

- The authors also corroborated $h = 1$ as a suitable value for the counter-based scheme's threshold, which is previously demonstrated by simulations [42].

- Finally, the authors pointed out that the most important issue in probabilistic schemes is to identify which nodes are vital for the connectivity of the network.

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In a later work Blywis et al [21], analyzed the limits of some probabilistic schemes experimentally. They used again DES-Testbed, but in this case 105 nodes are used. In particular, they focused their work on GOSSIP1 and GOSSIP3. They studied how some traffic characteristics, such as congestion and payload impact on the performance of GOSSIP1 and GOSSIP3 schemes. The main finding of this study are:

- In GOSSIP1 reachability increases with the forwarding probability and decreases with the congestion (number of sources) and the payload.

- The performance of GOSSIP3 worsens with probability, congestion, and payload. If the forwarding probability is increased in GOSSIP3, the network would behave similar to the situation when flooding is used.

- The authors indicated that the suitable value of the forwarding probability for GOSSIP3 is within the interval [0.2,0.3].

In recent works [24, 25], the authors corroborated that real wireless ad hoc networks do not percolate due to collisions and noisy links, which is previously demonstrated by simulations in [102]. The authors proposed a suppressed bond-site model [82] for modeling the effects of collisions and noisy links in the percolation model.

Other studies that are not focused on probabilistic schemes also use probabilistic schemes for comparison purposes. In [68] the schemes adaptation hop by hop [128] and ECS [73] are compared to other deterministic broadcasting schemes.

5. Lessons learned and open challenges

5.1. Lessons learned

In this subsection we indicate the lessons learned in this survey. The main lessons are:

- Probabilistic broadcasting in ad hoc networks (as a dissemination technique and as part of routing protocols) is an important active research area in MANETs, VANETs, and WSNs.

- The optimal probability is not universal and it depends on many topological parameters such as density, mobility, scenario, etc.

- According to a number of approaches presented in this survey, density metrics are the most used to adjust the forwarding probability in adaptive schemes. In non counter-based schemes, the number of neighbors is the most used density metric. On the other hand, in counter-based schemes, the key metric is the number of duplicated packets received. Although global metrics are used, they should be avoided since global information is difficult to be collected in ad hoc networks.

- Many probabilistic schemes are based on thresholds like density thresholds. However, the optimal value of such thresholds is difficult to obtain in ad hoc networks since these may depend on numerous parameters.

- Many distance-based schemes use the node's transmission range in the expressions to calculate the forwarding probability. However, this parameter can be very different from the nominal value defined by the manufacturer. Several external factors can impact on the real value of a node's transmission range such as external noise and interferences.

- With regard to the evaluation of probabislitc broadcast schemes, most proposed schemes are evaluated under MANETs scenarios with 802.11 MAC layer using the random waypoint mobility model in NS-2 simulator. When a routing protocol is used, AODV is normally the chosen routing protocol. As for the evaluation metrics, Re and SRB are the most used evaluation metric when probabilistic broadcast is used as a stand-alone dissemination technique. On the other hand, PDF, NRL and E2E delay are the most used when probabilistic broadcast is used as part of the discovery phase of routing protocols.

- There are differences between the simulation results obtained and the real experiments carried out. The main problem with some schemes is related to how the defined thresholds are configured in the real experiments.

5.2. Open challenges

In this subsection we indicate the open challenges that have not been covered yet or little work has been focused on them. In addition, we comment briefly how these open challenges can be addressed. The main challenges in probabilistic broadcast schemes are:

- More analytical models that predict the behavior of probabilistic broadcast schemes are needed. Although some analytical models have been presented for broadcasting schemes in wireless ad hoc networks, such as flooding [110, 113], fixed probabilistic scheme [110, 113], distance-based [126, 113, 125], counter-based [126, 113, 125], location-based [113], further work is needed to model the different types of probabilistic schemes presented in this survey. Only a few papers include analytical models for the proposed schemes such as [70] and [37]. Most of the proposed schemes are based on heuristics. In [27] a framework is proposed to evaluate some probabilistic broadcast schemes (IF and NPPB schemes), however, the authors stated that it can be easily extended to evaluate other probabilistic and deterministic broadcast schemes.

- The definition of standard evaluation scenarios and their features such as density, path length (number of hops) , congestion, mobility models, etc. Throughout the papers reviewed in this survey, the authors have used different values of density, and mobility models need to be standardized. Consequently, it is difficult to compare the simulation results presented in different papers. Standard scenarios are needed for a fair comparison of the probabilistic schemes. Kurkowski et al [59, 58], presented some works focused on constructing standard scenarios for MANETs. With regard to mobility conditions, most schemes have been evaluated using the random Waypoint mobility model. However, there are many other synthetic mobility models that can be used to evaluate probabilistic broadcast schemes [30, 78]. There exist mobility generators, such as BonnMotion [9] and VanetMobiSim [47], that can be

used to evaluate the probabilistic schemes under different mobility models. Moreover, we think that the use of real-life trace-based mobility [10, 78] models would be useful to evaluate the performance of probabilistic schemes in real-life scenarios. The Community Resource for Archiving Wireless Data at Dartmouth (CRAWDAD) [120] is an open project aimed to archive data collected from real-life experimentation. This data is freely available and can be used to evaluate broadcast schemes in real scenarios.

- As for the evaluation metrics, it would be useful to define a standard metric for evaluation of probabilistic schemes. In [87] the authors suggested a standard metric to evaluate broadcasting schemes in VANETs. This metric, namely Dissemination Efficiency (DE), combines redundancy, delay, reachability, and success rate. Although it is proposed for VANET scenarios, it can be used for other types of ad hoc networks.

- There is lack of a complete comparison of probabilistic schemes. According to the comparison presented in section 4.3, most probabilistic schemes have only been compared to simple flooding and fixed probabilistic schemes. We hope that this survey will help to improve the understanding of probabilistic schemes and encourage the research community to address the areas where there is lack of effort. There are some examples of good comparisons among broadcast schemes such as [31] and [34].

- Regarding adaptive counter-based schemes, there is no a clear evaluation of the role played by RAD. There is not evaluation on the optimal value of RAD in counter-based schemes.

- In all the reviewed schemes, nodes cooperate in the broadcast process, however, it may be interesting to evaluate the broadcast schemes considering selfish nodes. That is, nodes that do not want to cooperate in the broadcast process and also malicious nodes.

- More experimental results are needed to validate the simulation results. The experimental results should corroborate the simulation results achieved. According to the experimental results presented in [20, 23], it is obvious that the adjusting parameters of probabilistic scheme must be carefully selected.

- Although many probabilistic schemes have been proposed, more adaptive probabilistic schemes are needed. Many proposed schemes use global parameters like global density values. It is unfeasible that nodes could collect such global information in real life scenarios. The forwarding probability should only be adapted using local parameters of nodes like local density.

6. Summary

In this paper, we have highlighted the importance of broadcasting techniques in the performance of wireless ad hoc networks, showing that probabilistic broadcast methods exhibit suitable performance in mobile conditions, emergency situations, and in scenarios with limited resources. Then, we have proposed a classification for probabilistic broadcast schemes according to the reviewed literature, Fig. 1 and Fig. 2. Using the proposed

classification, we have presented a comprehensive review of the probabilistic broadcast found in the literature that fall into the proposed classification. The review points out the main features and shortcomings of each specific scheme. These details can be found in the set of tables included in the section 3 (Table 2 - Table 10). In addition, we analyzed the methodology followed by researchers to evaluate the probabilistic broadcast techniques, considering factors like networks simulators, performance metrics, and real implementations. According to the reviewed literature, simulation is still the main method for evaluating broadcast schemes in ad hoc networks, only some works presented experimental results that indicate the existence of some differences from the simulation results with respect to the experimental results. Regarding the reviewed literature, it is evident that there is lack of a complete comparison of probabilistic broadcast schemes. According to the information included in the comparison section, most probabilistic schemes are only compared to GOSSIP1 and flooding schemes. We hope that this survey helps to encourage the research community to address this issue. Finally, some guidelines are given on the open challenges that have not been addressed or where more research is needed.

Acknowledgments

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