DiSIF: A Distance-Based Silencing Technique for Multi-Hop Broadcast Communications in Pedestrian Ad-Hoc Networks

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Abstract—In this paper, we focus on a particular type of opportunistic ad-hoc networks, namely Pedestrian Ad-hoc NETworks (PANETs). In PANETs, nodes are densely distributed and each node may transmit information to all other nodes in the network via multi-hop broadcasting. Even though flooding is the simplest technique to broadcast information with multi-hop communications, it can be very inefficient because of redundant transmissions which may induce collisions. This problem is known, in the literature, as the "broadcast storm problem." In this work, we present a novel probabilistic forwarding technique, denoted as Distance-based Silencing IF (DiSIF), which is derived from the probabilistic broadcasting protocol Irresponsible Forwarding (IF) and one of its extensions, denotes Silencing IF (SIF). The performance of the DiSIF protocol is analyzed and compared with those of other existing protocols, investigating the impact of fundamental network parameters. Lower bounds (exact and approximate) on the average number of hops, expedient to evaluate the propagation efficiency of DiSIF, are also derived. Finally, under the assumption that each node (e.g., a smartphone) relies on Global Positioning System (GPS) to estimate its position, the robustness of DiSIF against a GPS positioning error is investigated.

Index Terms—Opportunistic mobile networks, broadcasting, multi-hop communications, pedestrian ad-hoc networks, network simulations

1 Introduction

Ad-hoc networks are infrastructureless networks in which a node can act as source, relay, and destination of multi-hop communications. In Pedestrian Ad-hoc NETworks (PANETs), all nodes in the network (namely, devices carried by pedestrians such as hand-held smartphones or wearable devices) may act as information sources and/or destinations. The main characteristics of PANETs are: (i) presence of many information sources; (ii) high node spatial density; and (iii) low node speed (almost static). In particular, we focus on applications where nodes send very small amounts of information data (e.g., geographical coordinates or alert messages) to all other nodes via multi-hop transmissions. This is meaningful, for example, for proximity-based social networking applications.

The simplest broadcast propagation technique is flooding, according to which each node is required to retransmit packets when received for the first time. The flooding strategy, because of highly redundant transmissions, can lead to serious inefficiencies related to the high channel contention level, which results in collisions and interference. This problem, denoted as broadcast storm problem in the literature, has been largely studied by the research community in the last years and several methods have been proposed in order to mitigate it [1]. One possible approach relies on the use of *probabilistic* broadcast techniques. In simple terms, when a node receives a packet, it rebroadcasts it with probability p and takes no action with probability $1-p$. Obviously, the selection of the value of p is crucial.

In this work, we propose a probabilistic broadcasting strategy denoted as Distance-based Silencing Irresponsible Forwarding (DiSIF). This strategy "stems" from two existing probabilistic broadcast strategies: Irresponsible Forwarding (IF) [2] and its extension denoted as Silencing Irresponsible Forwarding (SIF) [3]. IF and SIF have proved to be very efficient for information dissemination in *monodimensional* single-source Vehicular Ad-hoc NETworks (VANETs) [2], [3], [4]. In [5], the performances of IF and SIF have also been analyzed in *bidimensional* multi-source PANET scenarios. While for low values of the network traffic load the performance is good, for medium-high values of the network traffic load some inefficiencies arise, mostly related to the increasing number of collisions. The DiSIF protocol addresses these inefficiencies by introducing a novel silencing mechanism which effectively selects rebroadcasters by introducing an initial contention phase. In order to have a comparison benchmark for the performance of the considered protocols, we derive a lower bound for the average number of hops performed in a single multi hop communication route. The obtained results show that DiSIF can outperform, in terms of packet delivery ratio (PDR), IF and SIF, especially for large values of the node spatial density and/or of the number of source nodes. Moreover, DiSIF minimizes the number of hops and this further lowers energy consumption and channel contention. Since DiSIF relies on the knowledge, by each node, of its position (e.g., through the use of Global Positioning System, GPS), we highlight the robustness of DiSIF against positioning inaccuracy (i.e., GPS positioning estimation errors).

The remainder of this paper is organized as follows. In Section 2, related works are discussed. In Section 3, the IF and SIF protocols are briefly recalled. In Section 4 the DiSIF

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protocol, with its novel embedded silencing mechanism, is presented. In Section 5, a lower bound on the average number of hops along a single communication route, together with a simpler approximation, is provided. In Section 6, the system performance is investigated. Finally, Section 7 concludes the work.

2 Related Work

In [6], the authors present a family of adaptive protocols, denoted as Sensor Protocols for Information via Negotiation (SPIN). These protocols are designed to disseminate individual sensor observations to all sensors in energy-constrained Wireless Sensors Networks (WSNs). Using an initial negotiation phase, SPIN protocols ensure that only useful information will be transferred. Various wireless network models are studied.

In [7], [8], the authors propose a multi-hop forwarding technique denoted as Geographic Random Forwarding (GeRaF). According to GeRaF, a node, which wants to transmit a packet, broadcasts a message which is received by all its neighbors. Each receiving node then determines its distance from the final destination and evaluates its own suitability as a relay. This is done by first dividing the coverage area in two regions: (i) the relay region, which contains all points closer to the final destination than to the transmitting node; and (ii) the non-relay region, which contains all other points. Nodes in the non-relay region are never selected as relays. The relay region is then sliced into "priority regions," on the basis of the distance from the destination. It can be observed that GeRaF is oriented to unicast communications and require the knowledge, by each node, of the position of the final destination of each communication route it may belong to. This is realistic for a static wireless network.

In [9], an optimized Broadcast Protocol for Sensor network (BPS) is proposed. In order to broadcast a packet over a network, BPS allows only a few strategically selected nodes to rebroadcast. First of all, the area to be covered is partitioned into hexagons, the source node being at the center of one of these hexagons. The vertices of an hexagon are denoted as "strategic locations." When a node receives a packet, it computes its distance l from the nearest strategic location and delays the packet rebroadcast by $d = l/R$, where R is the node transmission range. The nodes closer to the strategic position will rebroadcast first and silence the other nodes (potential rebroadcasters) in their vicinity.

In [10], the authors propose a static probabilistic forwarding mechanism denoted as GOSSIP. The so-called "phase transition" phenomenon is considered as the basis to define probabilistic forwarding. More precisely, in a probabilistic forwarding scheme a phase transition occurs when the transmission probability p exceeds a certain threshold value p_{th}, denoted as critical probability, radically changing the overall behavior of the network. In order to characterize this phase transition, the concept of percolation [11] is exploited. GOSSIP can be considered a reference probabilistic multi-hop forwarding protocol and, for this reason, in the performance analysis presented in Section 6.2 it will be considered as performance benchmark for DiSIF. The concept of percolation is also exploited in [12] in order to set the retransmission probability of the proposed probabilistic forwarding approach in VANETs. In particular, the authors propose a multi-hop probabilistic scheme in which Road Side Units (RSUs) are exploited in order to reduce the number of superfluous retransmissions by vehicles.

In [13], a multi-hop broadcast protocol, denoted as RObust and Fast Forwarding (ROFF), is proposed. This protocol tries to avoid collisions due to redundant rebroadcasts in VANETs by assigning to each candidate forwarder a waiting time (before packet retransmission) which is inversely proportional to its forwarding priority. The forwarding priority is assigned to forwarders depending on the distribution of empty spaces between vehicles. Through extensive simulations, ROFF is shown to make broadcasting faster and more reliable than other existing protocols.

In [14], the authors propose a protocol that provides reliable data dissemination in VANETs. With this protocol, a dynamically generated backbone of vehicles is first created and, then, used to disseminate broadcast packets. The backbone is created taking into account vehicle movement dynamics and link quality. Network coding is also exploited to reduce the protocol overhead and to improve the packet reception probability. Both theoretical analysis and simulations are used to compare the proposed protocol with other alternatives.

In [15], the authors consider the problem of broadcasting in cognitive radio ad-hoc networks. In this kind of networks, different unlicensed users (often denoted as secondary users, SUs) exploit available channels which are not used by the licensed users (i.e., primary users, PUs) which have prioritized channel access. For the SUs, the channel availability is not homogeneous across the network, since it strongly depends on the particular positions of PUs: this makes the broadcasting a complicated task for SUs. In this kind of scenario, in [15] an analytical framework, able to predict the performance of different types of protocols, is proposed. This analytical framework is then validated with both real implementations and simulations.

In [16], an analytical model to evaluate different performance metrics of multi-hop message broadcasting in Vehicle-to-Vehicle (V2V) communications is proposed. Several parameters, such as one-hop transmission range, distribution of vehicles, and vehicle density, are taken into account. The proposed scheme is validated by simulations using realistic vehicular traces.

In [17], the authors present an analytical framework which models the one-hop broadcast traffic generated by the 802.11p/WAVE protocol (vehicular networking) [18]. In particular, the periodic transmission of beacon packets and WAVE Service Advertisement (WSA) packets on the Common CHannel (CCH), used for signaling and safety-critical data exchange, is analytically modeled and the performance of the considered protocol, in terms of successful frame delivery probability, is evaluated. The proposed model is particularly accurate and takes into account several aspects related to 802.11p/WAVE networks such as the access priorities assigned to different packet types, as suggested by the Enhanced Distributed Channel Access (EDCA). The proposed model is validated through extensive simulations and the impact of the protocol's parameters on the obtained performance is investigated. An important result in [17] is related to the fact that, even considering the best protocol

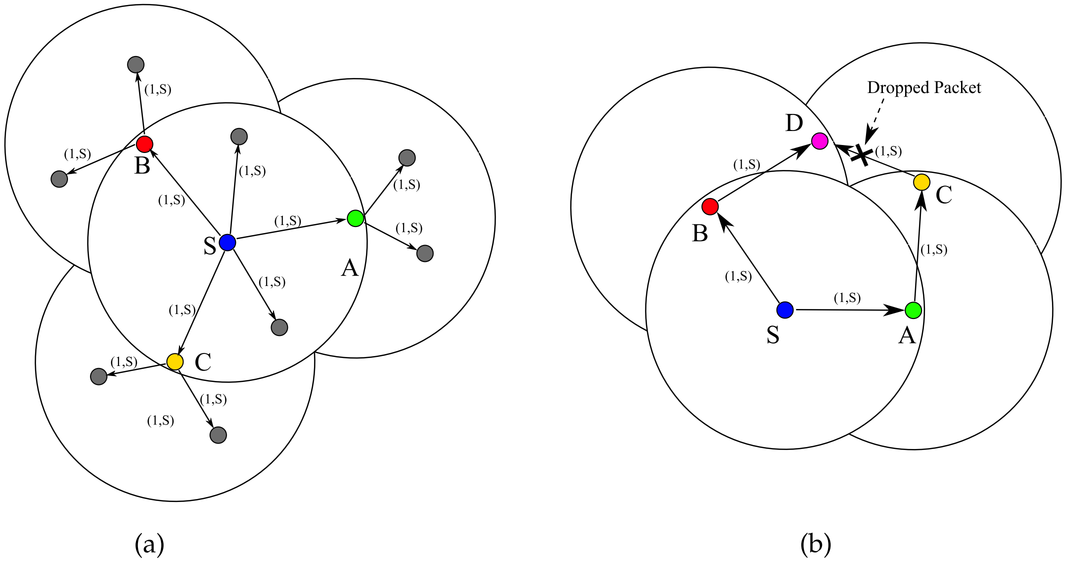

Fig. 1. Representative examples of a single packet propagation with the IF technique.

settings suggested by the model, the performance of the IEEE 802.11 p protocol has a rapid decay for increasing values of the number of nodes in the network.

It is worth noting that the majority of related works do not encompass the presence of multiple sources of information and, often, single unicast multi-hop transmissions are considered. In this sense, DiSIF cannot be directly compared with unicast protocols, as the communication goals are different. In Section 6, we will show that the DiSIF strategy is suitable to be used in *dense multi-source broadcast networking scenarios*.

3 IF AND SIF

3.1 Irresponsible Forwarding (IF)

IF is a probabilistic forwarding protocol according to which every node, upon reception of a packet to forward, computes (in a per-packet manner) its own retransmission probability. Since IF is based on the assumption of the knowledge of some topological network parameters, such as internode distance and node spatial density, in this work we assume that each node is equipped with a GPS transceiver—this is realistic in a PANET scenario where nodes are likely to be smartphones, tablets, or wearable devices.

In a single source scenario, the broadcast forwarding process of a single packet with IF is illustrated in Fig. 1a. The source node S transmits a packet inserting in the header: (i) its position, denoted as $POS_{\rm s}$; (ii) its IP address denoted as $ADDR_{\rm s}$; and (iii) a packet Sequence Number, denoted as SN (this is expedient for the transmission of streams of packets). Note that the combination $(SN, ADDR_{\rm s})$ allows to uniquely identify the packet within the network and, thus, is denoted as Unique ID (UID). In the example of Fig. 1a, node S transmits a packet with UID = (1, S). Each receiver of this packet is a neighbor of S and rebroadcasts independently with a probability computed according to a proper Probability Assignment Function (PAF). In particular, in the example of Fig. 1a, nodes A, B, and C retransmit the packet inserting, in the headers of the retransmitted packets, their positions (i.e., $POS_{\rm A}$, $POS_{\rm B}$, and $POS_{\rm C}$) but keeping unaltered the UID (1,S). Each node which receives a packet from node A, checks the UID: the packet is dropped if already received earlier; otherwise, the node decides whether to retransmit or not according to the PAF previously mentioned. The process is similar for nodes B and C and repeats recursively during packet broadcasting. In Fig. 1b, we show an example in which, due to multi path propagation, the packet with UID = (1, S) is transmitted to node D by both nodes B and C. In this case, since node B transmits before node C, the packet coming from node C is dropped by node D.

The choice of the PAF of IF is based on the intuitive observation that the farther the potential rebroadcaster is from the transmitter, the higher its associated rebroadcast probability should be, as this would yield the highest forward progress—this is reminiscent of the approach in [9]. Based on this idea, in [2] the PAF of IF is introduced for a monodimensional scenario (e.g., a narrow street). In a bidimensional scenario, the PAF proposed in [2] can be generalized as follows:

$$p = \exp\left\{ -\frac{\sqrt{\rho}(z-d)}{c} \right\}, \tag{1}$$

where: d (dimension: [m]) is the distance between a transmitting node and a potential rebroadcaster; z (dimension: [m]) is the transmission range; c is a shaping coefficient (adimensional), which can be used in order to tune the retransmission probability [4]; ρ (dimension: [nodes/km^2]) is the bidimensional node spatial density. Thanks to the POS parameter inserted in the packet header, a receiving node can directly compute its distance d from the transmitter. Moreover, each node can estimate its local node spatial density ρ by evaluating the distances from its (direct) neighbors (e.g., through the exchange of hello messages[1]). According to the PAF in (1), if the network is sparse, the overall retransmission probability is high in order to ensure complete connectivity. On the other hand, if the network is dense the

1. A node simply estimate its local node spatial density as the ratio between number of nodes which reply to its hellos and πz^2, i.e., the area within its transmission range.

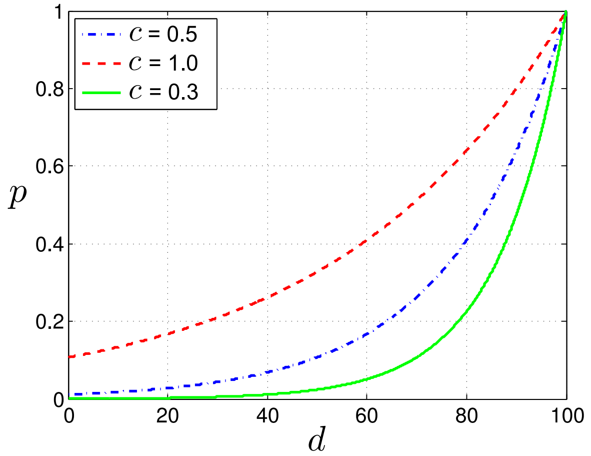

Fig. 2. PAF (1) of IF, as a function of the internode distance, for various values of the shaping parameter c. In all cases, $\rho = 900$ nodes/km^2 and $z = 100$ m.

overall retransmission probability is low in order to reduce useless redundant transmissions and, thus, collisions.

The idea behind the IF rebroadcast paradigm is that once a node receives a packet, it evaluates, in an average statistical sense, the presence of other nodes in its proximity. If the probability that another node can rebroadcast the packet is sufficiently high, then the node of interest "irresponsibly" chooses not to rebroadcast. In Fig. 2, the IF PAF (1) is shown, as a function of the internode distance d, for three different values of c. In all cases, $\rho = 900$ nodes/km^2 and $z = 100$ m. It can be observed that the shaping parameter c allows to "modulate" the behavior of the PAF.

We finally observe that assuming the presence of a GPS transceiver on each device may not be realistic in scenarios in which nodes are energy-constrained. However, in Section 6.3 we show that the IF technique is robust to moderate errors in node's position estimation. This means that the GPS transceiver can be replaced with less accurate positioning estimation techniques—for example, the inter-node distance d could be estimated using the Received Signal Strength Indicator (RSSI) [19], [20].

3.2 Silencing Irresponsible Forwarding (SIF)

SIF derives from IF by applying the concept of silencing. According to the silencing mechanism, when a rebrocaster node (say node r) receives a packet with a certain UID (say u) it first checks its transmission queue: if a packet with UID u is found (i.e., it has already been received but has not been retransmitted, yet), it is removed from the queue, as another neighbor node has already transmitted the same packet. In this way, node r is silenced for the transmission of the packet with UID u. The use of silencing corresponds to the fact that the "fastest" retransmitter (among the set of those which have decided to retransmit) silences the others. In other words, even if a node decides to retransmit a packet, it may refrain from doing so if the same packet has already been retransmitted by another node.

The rationale behind the "fast" silencing technique used by SIF is to limit the potentially large number of rebroadcasts brought by IF. As will be show in the next section, this problem is more critical in a dense, multi-source, bidimensional network.

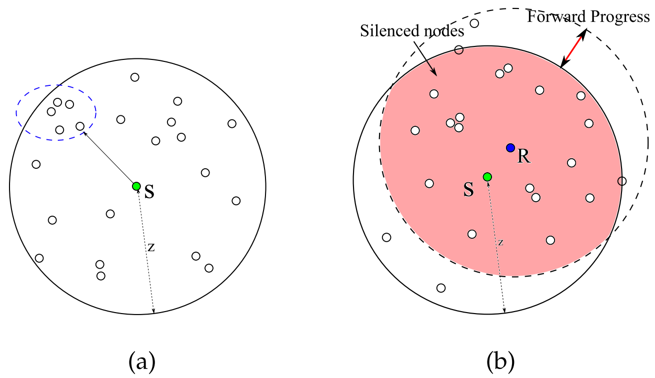

Fig. 3. Representative examples of inefficiencies of (a) IF and (b) SIF.

4 Distance-Based Silencing Irresponsible Forwarding (DiSIF)

4.1 The Dark Force: Shortcomings of IF and SIF

As already mentioned in Section 1, IF and SIF have been originally developed to be applied in highway-like VANETs, i.e., monodimensional networks with a single information source at a time [2], [3], [4]. Although IF and SIF may perform well also in bidimensional PANET scenarios—as shown in [5]—they suffer from intrinsic inefficiencies.

With the IF PAF given in (1), two nodes at the same distance from the source have the same retransmission probability. Therefore, it is possible that a group of neighboring nodes, located at the boundary of the coverage area of the source, simultaneously rebroadcast the packet, possibly colliding. A representative example of this situation, which is likely to appear in dense PANET scenarios, is shown in Fig. 3a.

SIF does not incur IF's collision risk described in the previous paragraph, as the silencing technique guarantees that only the fastest rebroadcaster retransmits the packet. However, the fastest rebroadcaster may not be the "best" rebroadcaster: since SIF is a probabilistic forwarding protocol, a node close to the source may choose to retransmit the packet silencing many potential rebroadcasters farther from the source. This, in turn, results in a low forward progress and may prevent the originally transmitted packet from propagating in some directions. A representative example, in which almost all potential rebroadcasters are silenced by a node close to the source, is shown in Fig. 3b, where S is the source and R is the rebroadcaster.

4.2 A New Hope: DiSIF

The DiSIF protocol implements, through an initial contention phase, a novel silencing technique which is more efficient, in bidimensional multi-source networks, than the silencing technique embedded into SIF. More specifically, this new silencing mechanism guarantees that the "farthest" (instead of the "fastest") rebroadcaster silences the others.

Two types of packets are defined in the DiSIF protocol: (i) DATA packets, which contain the information to propagate; and (ii) Probe Packets (PPs), which are short control packets used by the DiSIF silencing mechanism. In a single source scenario, the forwarding process of DiSIF can be summarized as follows. At a generic instant t_0, the source node s transmits a DATA packet. As already seen for the IF protocol, node s puts in the packet header its own position

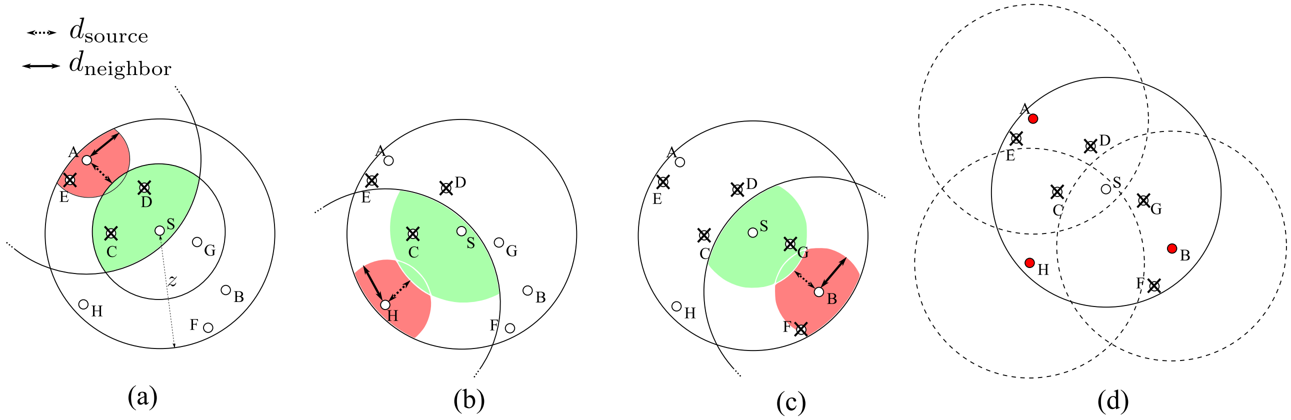

Fig. 4. Representative example of the situation, in the first hop, due to the DiSIF propagation process.

POS_s and the UID pair given by $(SN, ADDR_s)$. The packet is then received by the source neighbors at a time $t_1 = t_0 + \varepsilon$, where ε is the (average) propagation time.[2] Upon reception of the DATA packet, a source neighbor, after checking the UID of the packet, has two options: the packet is dropped if already received earlier; otherwise, the neighbor starts "competing" with the other neighbors to designate a set of rebroadcasters. In particular, each neighbor node elects itself as a *candidate rebroadcaster* with a probability given by (1). We denote as n_{cand} the number of candidate rebroadcasters. A candidate rebroadcaster node k ($k \in \{1, \ldots, n_{\text{cand}}\}$) schedules a transmission of a PP bearing its distance, denoted as d_{ks}, from the source together with the same UID $(SN, ADDR_s)$ of the received DATA packet). The transmission of the PP is scheduled by each candidate rebroadcaster at a time randomly distributed between t_1 and $t_1 + t_{\text{wait}}/2$, where t_{wait} is a DiSIF parameter to be properly optimized. Another candidate rebroadcaster, say node j ($j \in \{1, \ldots, n_{\text{cand}}\} \setminus \{k\}$), which receives the PP sent from node k, silences itself if at least one of the two following conditions apply:

$$d_{js} + d_{\text{source}} < d_{ks} \tag{2a}$$

$$d_{kj} < d_{\text{neighbor}}, \tag{2b}$$

where d_{source} (dimension: [m]) and d_{neighbor} (dimension: [m]) are parameters of the DiSIF protocol. The rationale behind condition (2a) is that if a candidate rebroadcaster is sufficiently closer, with respect to another candidate rebroadcaster, to the source it should silence itself because its retransmission will be redundant. Condition (2b) guarantees that two candidate rebroadcasters, which are sufficiently close to each other, do not simultaneously rebroadcast the packet, thus decreasing the collision probability.

When a candidate rebroadcaster silences itself, it removes the transmission of its PP (if still to be sent) and ignores all other future received PPs with the same UID. At time $t_1 + t_{\text{wait}}$, each unsilenced candidate rebroadcaster retransmits the DATA packet and the process repeats recursively.

2. Note that ε may vary from neighbor to neighbor but, for the sake of simplicity, we assume that is equal for all neighbors. This corresponds to considering an equivalent average propagation time and is reasonable in dense PANETs (e.g., set of hand-held smartphones in a crowd).

In Fig. 4, an illustrative example of the first hop in the DiSIF propagation process with single source is given. All nodes are assumed to have the same transmission range z. Even though the DATA packet transmitted by the source, denoted as S, is received by all neighbors, for the sake of graphical clarity only the candidate rebroadcasters are shown. Moreover, since we are in a single-source, single-packet propagation case, we omit the UID of DATA and PP packets, as it is always equal to $(1, \text{S})$. In Fig. 4a, node A is the first candidate rebroadcaster which transmits a PP—note that condition (2a) leads to silencing all candidate rebroadcasters in the green area, while condition (2b) corresponds to silencing all candidate rebroadcasters in the red area. Node A is far from the source and silences nodes C and D as $d_{\text{CS}} + d_{\text{source}} < d_{\text{AS}}$ and $d_{\text{DS}} + d_{\text{source}} < d_{\text{AS}}$. Node E is also silenced because $d_{\text{AE}} < d_{\text{neighbor}}$. In Fig. 4b, since node H transmits its PP, node C would be silenced once more, as $d_{\text{CS}} + d_{\text{source}} < d_{\text{HS}}$: however, since node C had already been silenced by node A, it drops the PP received from node H. Finally, in Fig. 4c node B transmits its PP and silences nodes G and F. As shown in Fig. 4d, at the end of the contention phase only nodes A, B, and H are still unsilenced, so that they proceed to rebroadcast the DATA packet. The process then repeats recursively. In this example, for the sake of simplicity, the farthest nodes from the source (i.e., A, H, and B) first transmit the PP silencing the nearest nodes (i.e., C, D, G, and E). However, we remark that even if one of the nearest (to the source) nodes, decides to first transmit the PP, the farthest nodes would not be silenced because condition (2a) would not be fulfilled and, even in this case, the nearest node will be silenced by a subsequent PP transmission by one of the farthest node.

Considering a more general multi-source scenario, we point out that, since both DATA and PP packets can be uniquely identified, each packet dissemination process is independent of the others. For example, in Fig. 5 we have two source nodes, denoted as S_1 and S_2, which both transmit DATA packets to the same node A: the transmitted DATA packets have UIDs $(1, \text{S}_1)$ and $(1, \text{S}_2)$, respectively. When node A receives the packet from node S_1, it becomes a candidate rebroacaster for the packet with UID $(1, \text{S}_1)$ and enters in the contention phase, scheduling the transmission of a PP bearing its

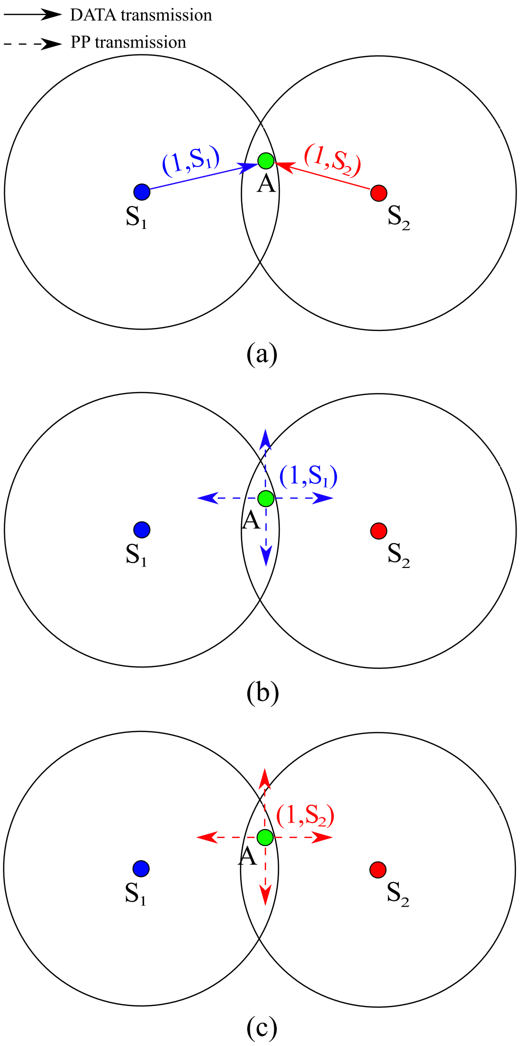

Fig. 5. Representative example of DiSIF propagation with two sources of information: (a) nodes S_1 and S_2 send DATA packet to A, (b) node A first rebroadcasts the PP with UID (1,S_1), and (c) node A rebroadcasts the PP with UID (1,S_2).

distance from S_1 and with UID equal to $(1, \mathrm{S}_1)$. When node A receives the packet coming from node S_2, it becomes a candidate rebroadcaster also for the packet with UID $(1, \mathrm{S}_2)$ and puts in its transmission queue a PP bearing its distance from S_2 and with UID equal to $(1, \mathrm{S}_2)$. After transmitting both PPs, if A has not been silenced by other nodes, it rebroadcasts both the DATA packet with UID $(1, \mathrm{S}_1)$ and the DATA packet with UID $(1, \mathrm{S}_2)$.

The main goal of DiSIF's forwarding strategy is to reduce the number of performed hops during broadcast propagation. This, in turn, increases the propagation efficiency by decreasing the channel contention level and, therefore, collisions. This policy is used in other existing multi-hop forwarding strategies: for example, while DiSIF tries to maximize the distance between transmitting node and rebroadcaster, the GeRaF protocol tries to minimize the distance between rebroadcaster and final destination [7]. In order to quantify the propagation efficiency of DiSIF, in the following Section 5 we derive analytical lower bounds on the average number of hops in a point-to-point (i.e., unicast) communication route.

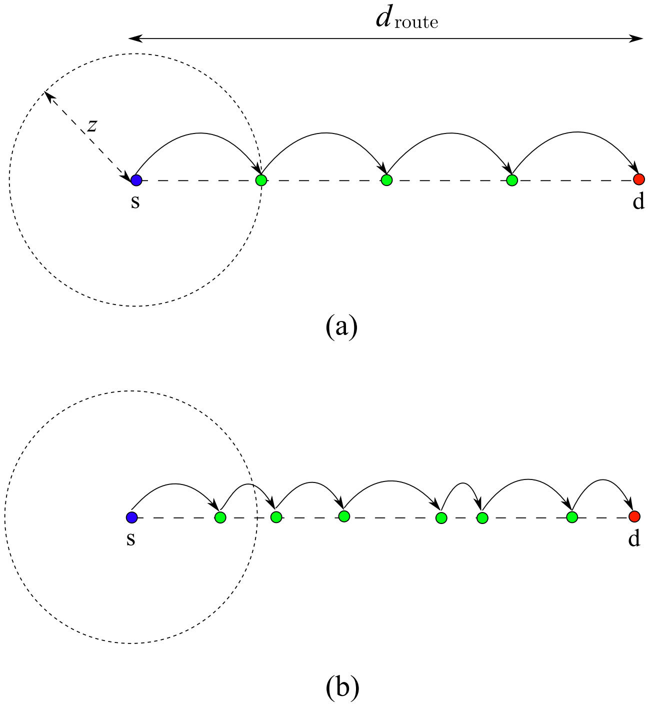

Fig. 6. Representative example of ideal multi hop communications: (a) relay nodes on the boundary of the node range of the previous relay node and (b) relay nodes randomly deployed between source and destination.

5 Lower Bounding the Average Number of Hops in a Unicast Communication Route

5.1 An Exact Lower Bound

In a unicast multi-hop communication, the number of hops is given by the number of relay nodes between source and destination plus one. In the PANET scenario of interest, denoting with n the number (fixed) of nodes in the network, a single broadcast from one of the n nodes can be modeled as $n-1$ multi-hop unicast transmissions. Defining as N_{hop} (random variable)[3] the number of hops of one of these unicast multi-hop communication routes, its expected value $\mathbb{E}\{N_{\text{hop}}\}$ is a relevant metric to evaluate the propagation efficiency of a multi-hop broadcasting protocol.

In order to derive a lower bound on $\mathbb{E}\{N_{\text{hop}}\}$, we consider an "ideal" unicast multi-hop communication route in which: (i) relay nodes lay on the straight line between source and destination; and (ii) a relay node i is on the boundary of the node range of the previous relay node $i-1$ ($i \in \{2, \ldots, N_{\text{hop}}\}$) or the source ($i=1$). In this scenario, which is shown in Fig. 6a, the number of hops is minimized and can be expressed as d_{route}/z, where d_{route} (dimension: [m]) is the distance between source and destination and z (dimension: [m]) is the already introduced *fixed* transmission range.

Therefore, one can write:

$$\mathbb{E}\{N_{\text{hop}}\} \geq \frac{\mathbb{E}\{D\}}{z} \tag{3}$$

where D is the distance (random variable) between node pairs (i.e., the source-destination pairs) in the PANET—in particular, d_{route} in Fig. 6a corresponds to a realization of D.

3. In the following, all random variables are denoted with uppercase letters while other variables are denoted with lowercase letters.

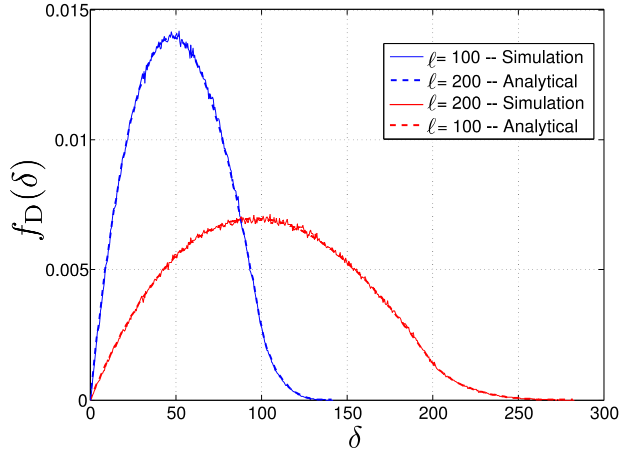

Fig. 7. (a) PDF of D for $\ell = 100$ m and $\ell = 200$ m. Analytical and simulation-based curves are compared.

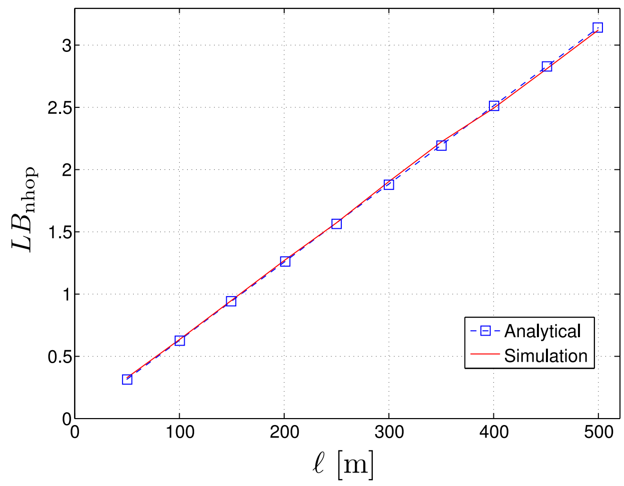

Fig. 8. LB_{nhop}, as a function of ℓ, with $z = 83$ m.

The lower bound at the right-hand side of (3) depends on the statistical distribution of D. Assuming that nodes are randomly deployed over a square region with side ℓ, the corresponding Cumulative Distribution Function (CDF) of D is derived in [21], from which the following Probability Density Function (PDF) follows:

$$f_D(\delta) = \begin{cases} 0 & \delta < 0 \\ \frac{2\pi\delta}{\ell^2} - \frac{8\delta^2}{\ell^3} + \frac{2\delta^3}{\ell^4} & 0 \leq \delta < \ell \\ \frac{\delta}{\ell^4}\Big[4\ell^2\sqrt{b-1} + \frac{2\ell^2}{\sqrt{b-1}} & \\ + \frac{2\delta^2}{\sqrt{b-1}} + \frac{2(l^2-\delta^2)^2}{\ell^2\sqrt{(b-1)^3}} + & \\ - 4\ell^2 \arcsin(\frac{b-2}{b}) - 4\ell^2 + & \\ - \frac{4\ell^4}{\sqrt{\ell^2(\delta^2-\ell^2)}} - 2\delta^2\Big] & \ell \leq \delta < \sqrt{2}\ell \\ 0 & \delta \geq \sqrt{2}\ell, \end{cases} \tag{4}$$

where $b \triangleq \delta^2/\ell^2$. In Fig. 7a, the PDF $f_{\mathrm{D}}(\delta)$ is shown for two different values of ℓ: 100 and 200 m. In both cases, the analytical PDF is compared with the PDF obtained through Matlab simulations. As can be observed, analytical and simulated PDFs almost overlap, thus validating the expression (4) for $f_D(\delta)$. The maximum value of the internode distance is obviously $\sqrt{2}\ell$, which corresponds to the length of the diagonal of the square region. After reaching a maximum value, the PDF rapidly decreases and the probability that two nodes lie more than ℓ meters apart is very low (lower than 0.029 and 0.024 when ℓ is equal to 100 and 200 m respectively).

The average value of D follows directly from (4):

$$\begin{aligned} \mathbb{E}\{D\} &= \int_0^{\ell\sqrt{2}} \delta f_{\mathrm{D}}(\delta)\, \mathrm{d}\delta \\ &= \frac{4 + 2\sqrt{2} + 10\ln(1+\sqrt{2})}{30}\ \ell. \end{aligned} \tag{5}$$

By replacing (5) at the right-hand side of (3), the following lower bound for $\mathbb{E}\{N_{\mathrm{hop}}\}$ is obtained:

$$\begin{aligned} LB_{\mathrm{nhop}} \triangleq \frac{\mathbb{E}\{D\}}{z} &= \frac{4 + 2\sqrt{2} + 10\ln(1+\sqrt{2})}{30}\ \frac{\ell}{z} \\ &\simeq \frac{\ell}{2z}. \end{aligned} \tag{6}$$

In Fig. 8, the lower bound LB_{nhop} is shown, as a function of ℓ, for $z = 83$ m. Analytical and simulation results are compared. As predicted by (6), LB_{nhop} is a linearly increasing function of ℓ.

5.2 An Approximate Lower Bound

One of the assumptions behind the ideal multi-hop communication route considered in Section 5.1 is that two consecutive relay nodes are z meters apart from each other, i.e., at the maximum possible distance. This is a strong assumption for probabilistic forwarding protocols, as even a node which is close to the source may decide to rebroadcast the packet as shown in Fig. 6b. Therefore, we now relax this assumption. When a rebroadcaster, say the ith with coordinates (x_i, y_i), transmits a packet, all nodes in the circle centered in (x_i, y_i) with radius z receive the packet: each of these nodes is a potential rebroadcaster for the next hop. In order to realistically evaluate the distance between relay nodes, the expected value of the random variable given by the distance between i and one of its neighbor, denoted as R, can be derived. Then, by replacing z with $\mathbb{E}\{R\}$ in (3), an approximate lower bound for $\mathbb{E}\{N_{\mathrm{hop}}\}$ can be derived—this approximation is no longer an "exact" lower bound. For analytical tractability, it is convenient to define a coordinate system with its origin at (x_i, y_i) (which thus become $(0,0)$) so that the set of coordinates $\mathcal{C} = \{(x,y) : x^2 + y^2 \leq z^2\}$ represents the coverage area of node i. The CDF of R, denoted as $F_R(r) = P\{R \leq r\}$, can thus be computed as the probability that a node lies in the area $\mathcal{E} = \{(x,y) : x^2 + y^2 \leq r^2\}$, so that one can write:[4]

$$F_R(r) = \frac{\mathrm{Area}(\mathcal{E})}{\mathrm{Coverage\ Area}} = \frac{\pi r^2}{\pi z^2} = \left(\frac{r}{z}\right)^2 \tag{7}$$

and, consequently:

$$f_R(r) = \frac{\mathrm{d}F_R(r)}{\mathrm{d}r} = \frac{2r}{z^2}. \tag{8}$$

4. Expression (7) underlies the implicit assumption that within the coverage area of a node there is at least one other node, i.e., there is no disconnected node.

The expected value of R is:

$$\begin{aligned}\mathbb{E}\{R\} &= \int_{-\infty}^{\infty} r f_R(r)\,\mathrm{d}r \\ &= \int_0^z r f_R(r)\,\mathrm{d}r = \frac{2}{3}z.\end{aligned} \tag{9}$$

Finally, by replacing z (maximum hop length) with $\mathbb{E}\{R\}$ in (3), the following approximate bound is obtained:

$$\mathbb{E}\{N_{\text{hop}}\} \gtrsim \frac{\mathbb{E}\{D\}}{\mathbb{E}\{R\}} = \frac{3\mathbb{E}\{D\}}{2z} \triangleq LB_{\text{approx}}, \tag{10}$$

where $\gtrsim$ stands for "on the order of 1 or greater than" and its use can be motivated as follows. It cannot be claimed that (10) is an exact lower bound, as $\mathbb{E}\{D\}/\mathbb{E}\{R\}$ is not necessarily smaller than the average value of the number of hops. Intuitively, however, the larger is the average number of hops in a multi-hop route, the more accurate is the use of $\mathbb{E}\{R\}$ to estimate the average length of every hop (statistical regularity). This motivates one to consider the approximation sign "$\approx$" in (10). Moreover, the fact that in all scenarios considered in Section 6, (6) will be a loose lower bound (it is very idealistic), whereas (10) will be almost always a tighter lower bound, motivates the use of the strict inequality sign "$>$" in (10). Overall, the choice of the approximate inequality notation $\gtrsim$ in (10) seems the most appropriate.

Owing to (6), the approximate lower bound in (10) can be further expressed as follows:

$$\begin{aligned}LB_{\text{approx}} &= \frac{3}{2}LB_{\text{nhop}} \\ &= \frac{12+6\sqrt{2}+30\ln\left(1+\sqrt{2}\right)}{60}\,\frac{\ell}{z} \\ &\simeq \frac{3\ell}{4z}.\end{aligned} \tag{11}$$

In order to keep the terminology simple, in the next section we will refer to (11) as approximate lower bound.

6 Performance Analysis

6.1 Simulation Setup

All simulations are carried out with the well known discrete-event network simulator ns-3 (ns-3.19) [22]. In all simulated scenarios, the following assumptions hold. As already anticipated in Section 5.1, we recall that nodes are assumed to be randomly deployed over a square region of side $\ell = \sqrt{n/\rho}$.

All nodes move according to the random way point mobility model, available in the ns-3 simulator, with average speed s_p (dimension: [m/s]). Each node has the same transmission range z. Regarding the DiSIF protocol parameters, in all simulations: $t_\text{wait} = 5$ ms, $d_\text{neighbor} = z/3$, $d_\text{source} = z/10$, and $c = 1$. The number of source nodes in the network is n_tx and each of them transmits a burst of n_p DATA packets of fixed size p_s (dimension: [byte/pkt]). Packets are generated at a fixed rate λ (dimension: [pkt/sec]) and transmitted at a fixed data rate (on the wireless channel) equal to 1 Mbps. The performance of the proposed broadcasting protocol DiSIF is compared with those of flooding [1], GOSSIP [10], IF [2], and SIF [3]. For the MAC and physical layers, the wireless communication protocol stack defined by the ad-hoc IEEE 802.11 b standard is used [23].

TABLE 1
Considered Performance Metrics

Metric	Symbol	Dimension
Packet Delivery Ratio	PDR	[adimensional]
Average number of hops	$\mathbb{E}\{N_\text{hop}\}$	[hop]
Average number of retransmissions per generated packet	$n_\text{broad/pck}$	[pck]
Average end-to-end delay	DEL	[sec]

The considered performance metrics are listed in Table 1 and are shortly described in the following. The Packet Delivery Ratio is defined as the global percentage (with respect to the total number of transmitted packets) of correctly received DATA packets. The average number of hops $\mathbb{E}\{N_\text{hop}\}$ in a communication route, already introduced analytically in Section 5, is obtained by averaging over all communication routes in network. The average number $n_\text{broad/pck}$ of retransmissions triggered by a single packet generation (at its source) is given by the ratio between the total number of broadcast transmission acts in the network and the total number of generated packets $n_\text{p}n_\text{tx}$. The *per-packet* end-to-end delay is defined as the time during which a single DATA packet stays in the network, from the generation instant at its source till the reception instant at its destination. The *average* end-to-end delay (DEL) is obtained as the arithmetic average of the end-to-end delays of all correctly received DATA packets.

6.2 Simulation Results

Before starting with a comparative performance evaluation of the DiSIF protocol with other existing broadcast protocols, we first analyze the impact of the parameter c on its performance. In Fig. 9, the performance of DiSIF, in terms of (a) PDR and (b) DEL, is shown as a function of the packet generation rate λ, considering various values of the parameter c. The main network parameters are set as follows: $p_\text{s} = 128$ byte/pkt, $\rho = 2{,}000$ nodes/km^2, $n = 150$ nodes, $n_\text{tx} = 30$ nodes, and $s_\text{p} = 1.5$ m/s. Focusing on Fig. 9a, it can be observed that, for low values of λ, DiSIF has a high PDR and low DEL. Increasing the packet generation rate leads to an increase of the overall channel contention level, which, in turn, decreases the PDR. In Fig. 9b, a performance degradation, in terms of DEL, can be observed for increasing values of λ. In particular, after a "threshold" value of λ (approximately, 15 pck/sec), the network enters into a "saturation" regime: this happens when the transmission queue of each node in the network is full. In these settings, increasing further λ leads the nodes to drop generated packets and does not change the protocol performance in terms of DEL (we remark that only the correctly received DATA packets are considered in order to compute DEL).

Since the results in Figs. 9a and 9b show that the best performance is obtained for $c = 1$, this value will be used in the following simulations. Note that values of c lower than 1 have not been considered because, in this case, even if the protocol obtains a slight performance improvement for large values of λ, the small number of rebroadcasters

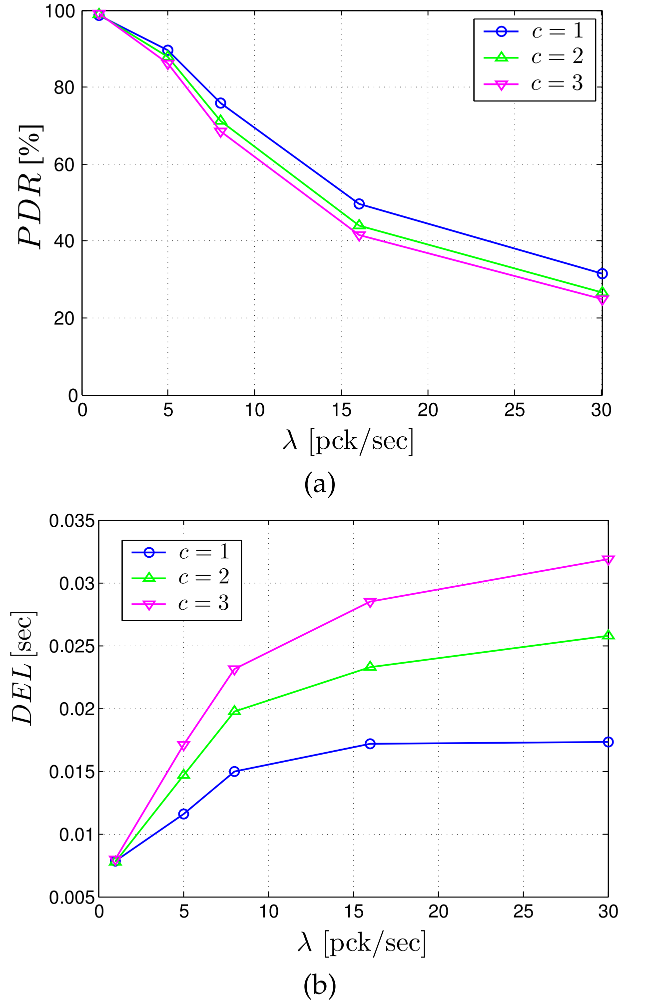

Fig. 9. (a) PDR and (b) DEL as functions of the packet generation rate. The performances of the DiSIF protocol with various values of the parameter c are considered. The network parameters are set as follows: $p_s = 128$ byte/pkt, $\rho = 2{,}000$ nodes/km^2, $n = 150$ nodes, $n_{tx} = 30$ nodes, and $s_p = 1.5$ m/s.

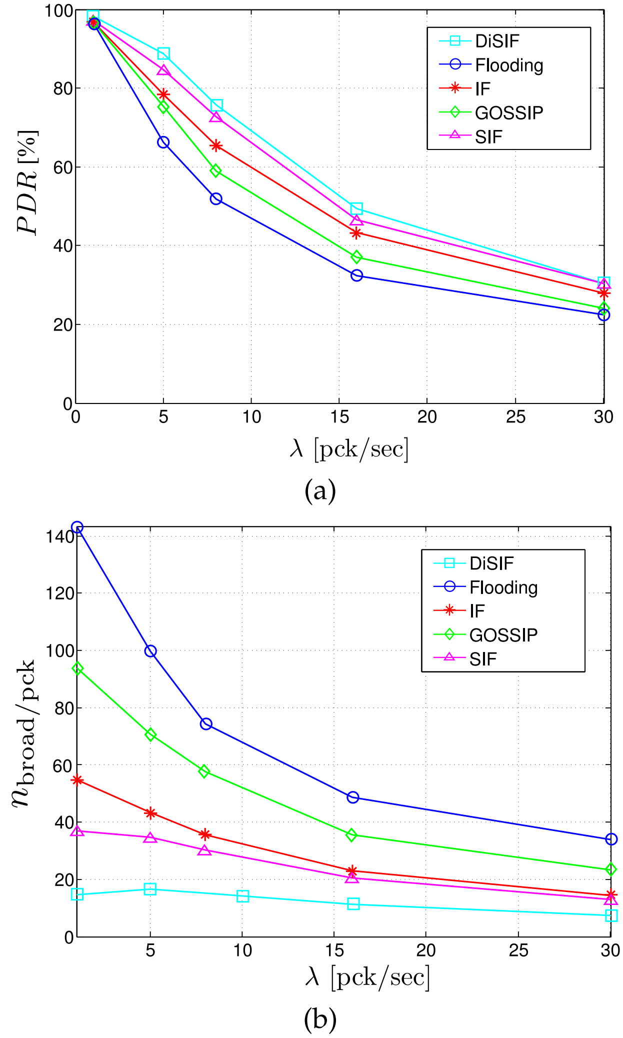

Fig. 10. (a) PDR and (b) $n_{broad/pck}$ as functions of the packet generation rate. The performances of various broadcasting protocols are directly compared. The network parameters are set as follows: $p_s = 128$ byte/pkt, $\rho = 2{,}000$ nodes/km^2, $n = 150$ nodes, $n_{tx} = 30$ nodes, and $s_p = 1.5$ m/s.

prevents the packets to reach all nodes even for low values of the packet generation rate.

In Fig. 10, (a) PDR and (b) $n_{broad/pck}$ are shown as functions of the packet generation rate λ. The performances of all considered protocols are directly compared and the main network parameters are set as in Fig. 9. First of all, it can be observed that DiSIF performs better than all other considered broadcasting protocols for all the values of the packet generation rate. Similarly to what has been observed in Fig. 9a, the results in Fig. 10a show that for very small values of λ the PDR is almost 100 percent for all simulated protocols. In these settings, where nodes can transmit one at a time and there are no concurrent transmissions, even flooding performs well. However, for increasing values of λ, the inefficient use, by flooding, of the radio channel rapidly degrades the performance because of highly redundant transmissions, which lead to collisions. Conversely, the DiSIF protocol guarantees a PDR over 80 percent for $\lambda \leq 7$ pkt/sec, owing to its limited redundancy, which corresponds to a better occupation of the radio channel. For high values of λ, transmissions are highly overlapped and interference and collisions become critical for all protocols.

The results in Fig. 10b show that, increasing the overall network load, each packet generation (at its source) corresponds to a progressively smaller number of rebroadcasts. This is due to the fact that, because of collisions, generated packets are not delivered to all nodes in the network, so that the nodes act as rebroadcasters less frequently. In other words, the multi-hop propagation is limited by collisions and this is confirmed by the PDR results in Fig. 10a. By comparing Fig. 10a with Fig. 10b, it can be observed that for medium-low values of λ, i.e., in the operative conditions of PANETs, the DiSIF protocol guarantees higher values of PDR by performing a consistently smaller number of rebroadcasts. This confirms the effectiveness of the new silencing mechanism, which selects the best rebroadcasters among all neighbors, reducing the channel contention level. It is worth noting that DiSIF, by reducing the number of rebroadcasts, also reduces the overall energy consumption, which is an important issue, in particular when nodes are energy-constrained [24], [25].

The presence of many information sources is a crucial aspect in PANETs, because large values of n_{tx} can drastically increase the overall network load. In order to study

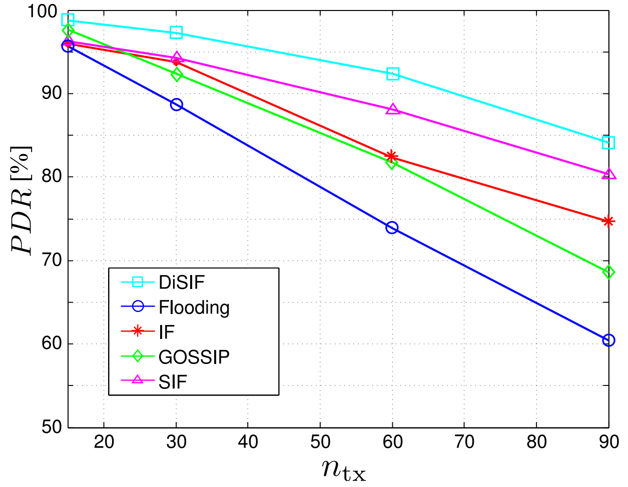

Fig. 11. PDR as a function of $n_{\rm tx}$. Network parameters are set as follows: $p_{\rm s} = 128$ byte/pkt, $\rho = 2{,}000$ nodes/km^2, $n = 150$ nodes, $\lambda = 0.5$ pkt/s, $s_{\rm p} = 1.5$ m/s, and $c = 1$. Various broadcasting protocols are directly compared.

the impact of the number of sources on the system performance, in Fig. 11 the PDR is shown as a function of $n_{\rm tx}$. The main network parameters are set as in Fig. 9, in particular, the value of the packet generation rate is set to $\lambda = 0.5$ pkt/s. It can be observed that, for all the considered values of $n_{\rm tx}$, DiSIF outperforms all other protocols. Note that the performance of flooding degrades for large values of $n_{\rm tx}$, regardless of the relatively small value of λ ($\lambda = 0.5$ pkt/s). This underlines that a large number of source nodes (typical of PANETs) may lead to a high network load even for low values of the per-node packet generation rate. Therefore, efficient (non-redundant) management of the radio channel is crucial in PANETs.

As mentioned in Section 3, the IF strategy takes into account the node spatial density ρ. This feature allows IF to adapt itself to the network conditions and is inherited by DiSIF. In order to get more insights about this adaptivity, in Fig. 12 the PDR is shown as a function of the node spatial density. The main network parameters are set as follows:

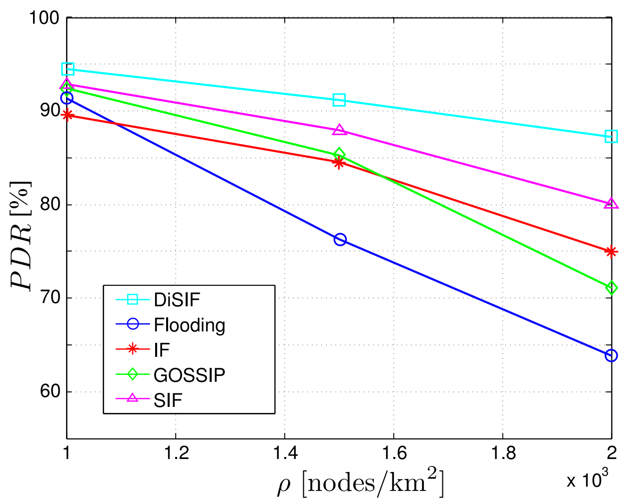

Fig. 12. PDR as a function of the nodes spatial density. Network parameters are set as follows: $p_{\rm s} = 128$ byte/pkt, $n_{\rm tx} = 80$ nodes, $n = 200$ nodes, $\lambda = 0.5$ pkt/s, $s_{\rm p} = 1.5$ m/s, and $c = 1$. Various broadcasting protocols are directly compared.

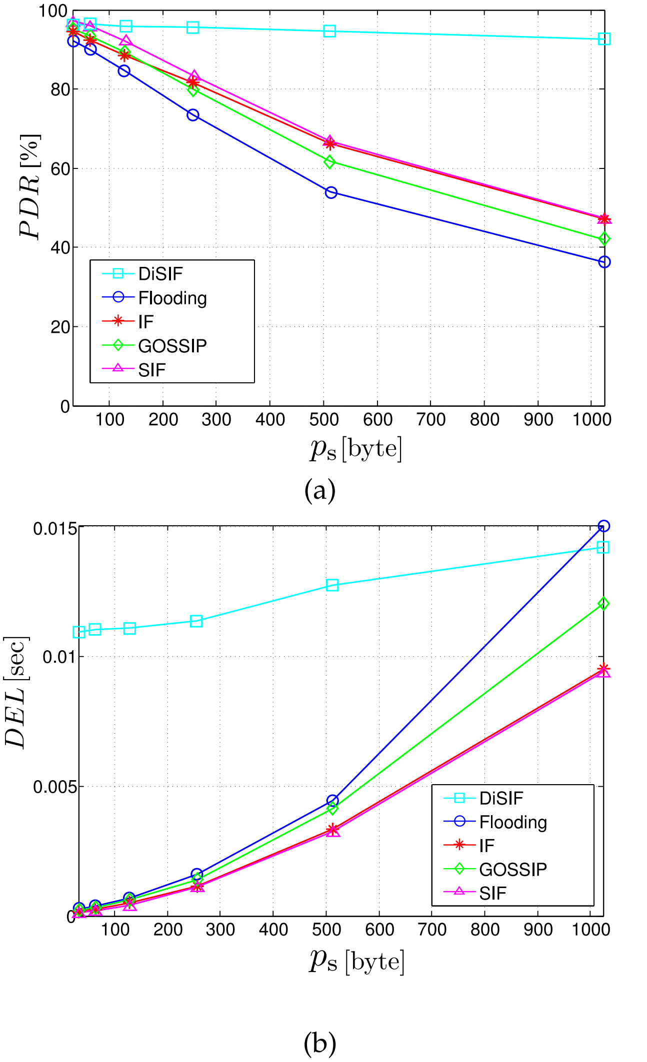

Fig. 13. (a) PDR and (b) DEL as a function of $p_{\rm s}$. The main network parameters are set as follows: $\rho = 2{,}000$ nodes/km^2, $n = 200$ nodes, $\lambda = 1$ pkt/s, $s_{\rm p} = 1.5$ m/s, $n_{\rm tx} = 80$ nodes, and $c = 1$. Various broadcasting protocols are directly compared.

$p_{\rm s} = 128$ byte/pkt, $n_{\rm tx} = 80$ nodes, $\lambda = 0.5$ pkt/s, and $s_{\rm p} = 1.5$ m/s. The node spatial density ρ is varied by keeping constant the side length ℓ of the square network region and varying the number n of nodes in the network. Increasing ρ increases the channel contention level, as more and more nodes are within the transmission range of each other. This directly results in a higher collision probability with flooding and the performance degrades rapidly. Conversely, it can be observed that DiSIF can adapt effectively its behavior to the network conditions.

In addition to packet generation rate and node spatial density, another important network parameter is the packet size $p_{\rm s}$. This parameter is critical because longer packets correspond to longer transmission times, which increase the collision probability. In order to study the impact of increasing values of $p_{\rm s}$, in Figs. 13a PDR and b DEL are shown as functions of the packet size. The main network parameters are set as follows: $\rho = 2{,}000$ nodes/km^2, $n = 200$ nodes, $\lambda = 1$ pkt/s, $s_{\rm p} = 1.5$ m/s, $n_{\rm tx} = 80$ nodes, and $c = 1$. In Fig. 13a, it can be observed that increasing values of $p_{\rm s}$ lead to a rapid performance degradation of IF, SIF, flooding, and

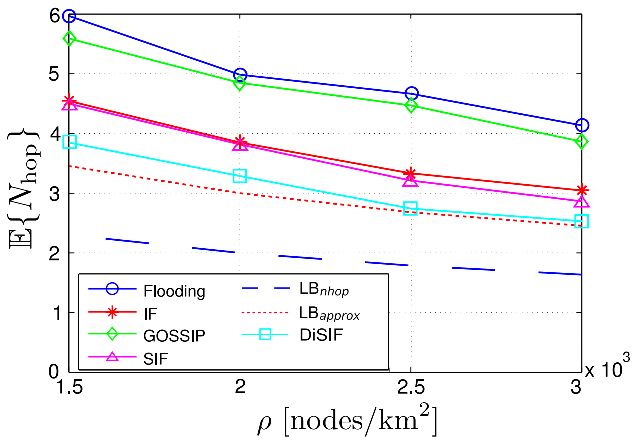

Fig. 14. $\mathbb{E}\{N_{\rm hop}\}$ as a function of ρ. The performances of the considered broadcasting protocols are directly compared with the bounds $LB_{\rm nhop}$ (Eq. (6)) and $LB_{\rm approx}$ (Eq. (11)).

GOSSIP. This is due to the fact that, with longer packets, a transmission act "captures" the channel for a longer time, resulting in a higher collision probability. Conversely, the performance of DiSIF is not affected by the increase of the packet dimension. This result is mostly related to the silencing mechanism of DiSIF which, in its first (contention) phase, allows the transmission of only PPs in order to select the actual rebroadcasters. These packets are very short, so that they "capture" the channel for a short time and collisions among them are unlikely. Then, after $t_{\rm wait}$, only the actual rebroadcasters transmit (longer) DATA packets. These nodes, owing to the silencing mechanism of DiSIF, are typically far away from each other (see Fig. 4), so even long DATA packets do not generate interference and the performance of DiSIF remains roughly the same for increasing values of $p_{\rm s}$. It is worth noting that, since the contention phase of DiSIF slows down rebroadcasting of DATA packets, the drawback of this strategy is an overall increase of the end-to-end delay DEL. This aspect is confirmed by the results in Fig. 13b, which show that the delay of DiSIF is higher that those of the other protocols. However, at high values of $p_{\rm s}$, DiSIF outperforms flooding. In general, the delay of DiSIF is acceptable (e.g., below 5 ms) for PANET-based "social" applications.

In Fig. 14, the average number of hops is shown as a function of the node spatial density ρ. The simulation-based performances of the considered protocols are directly compared with $LB_{\rm nhop}$ and $LB_{\rm approx}$. The main network parameters are set as in Fig. 12, but for the node spatial density ρ, which is varied by varying the side length ℓ of the square network region and keeping the number n of network nodes fixed to 200. In these settings, increasing values of ρ reduce the average number of hops since nodes get closer to each other. From the results in Fig. 14, it can be observed that flooding and GOSSIP require, on average, large numbers of hops. This is due to the fact that the rebroadcaster selection strategy of these protocols does not take into account the internode distance, so that even a node close to the source may rebroadcast a packet, resulting in a low forward progress and increasing the collision probability. Conversely, the IF and SIF rebroadcaster selection strategies favor nodes which are far away from the source and this results in a smaller average number of hops and a lower collision probability. DiSIF guarantees the smallest average number of hops among all simulated protocols for all the considered values of ρ. These results underline, once more, the effectiveness of the new silencing strategy embedded in DiSIF. By comparing the protocols' performances with the proposed bounds, it can be observed that the performance of DiSIF is very close to $LB_{\rm approx}$.

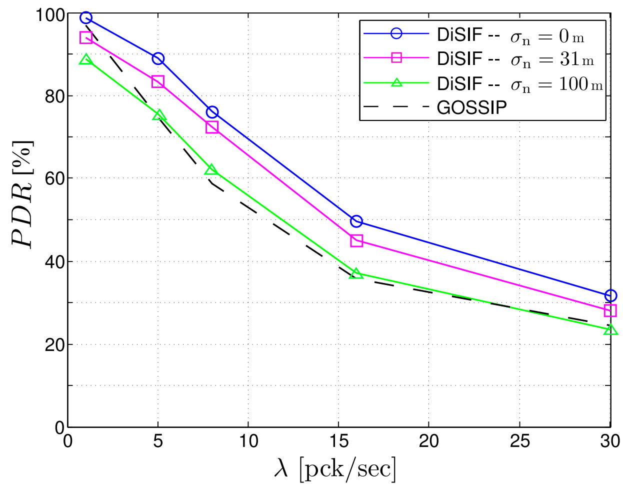

Fig. 15. DiSIF performance, considering the GPS positioning error, in term of PDR as function of λ. Three different values of $\sigma_{\rm n}$ are considered: 0, 31, and 100 m. For comparison purposes the performance of GOSSIP is also shown. The main network parameters are set as in Fig. 10.

6.3 Impact of Positioning Error

As described in Section 4, DiSIF requires the knowledge of some topological network parameters, such as internode distance and node spatial density—note that these two parameters are related [26]. For this reason, each node has been assumed to be equipped with a GPS transceiver. The GPS, deployed in diverse networking settings and increasingly common (e.g., in the majority of smartphones), is often exploited in many existing broadcasting techniques [9], [27]. However, a GPS system can be affected by an error in many ways: propagation errors, signal multipath, receiver clock errors, GPS satellite orbit errors, and others—the interested reader is referred to [28] for a more accurate description. The GPS positioning error, which is rarely taken into account in the communication protocols literature, can severely damage the performance of a topology-based broadcast forwarding technique. For this reason, we now investigate the impact of the positioning error on the performance of DiSIF.

Denoting as $(x_{\rm t}; y_{\rm t})$ the true coordinates of a node, the GPS positioning error can be modeled as follows:

$$\begin{cases} x = x_{\rm t} + n_{\rm x} \\ y = y_{\rm t} + n_{\rm y}, \end{cases}$$

where $n_{\rm x}$ and $n_{\rm y}$ are independent zero-mean Gaussian random variables with standard deviation $\sigma_{\rm n}$ (dimension: [m]). In Fig. 15, the performance of DiSIF, in the presence of GPS positioning error, is investigated in terms of PDR as a function of the packet generation rate λ. Three different values of $\sigma_{\rm n}$ are considered: 0 m (corresponding to perfect localization), 31, and 100 m. Moreover, in order to have a performance reference benchmark, the PDR of GOSSIP is also shown. The main network parameters are set as in Fig. 9. It can be observed that the performances with $\sigma = 31$ m and $\sigma = 0$ m are quite similar: this means that DiSIF is robust to moderate localization errors. The reason behind this robustness is the probabilistic forwarding strategy of DiSIF inherited from IF. In the first contention phase, according to the IF strategy, each node uses the node spatial density and the distance from the source in order to evaluate the presence of other nodes in its proximity and to elect candidate rebroadcasters. However, this is done only in an average statistical sense, so that a moderate position estimation inaccuracy does not affect the performance. Conversely, in the actual rebroadcasters' selection phase, localization errors can lead to silencing nodes which should retransmit the packets and, thus, some inefficiencies may arise. However, the observed results show that these inefficiencies induce a limited performance loss. Focusing on the case with $\sigma_{\rm n} = 100$ m, it can be noted that the performance of DiSIF converges to that of GOSSIP. This is due to the fact that, in our simulations, the node range z is set to 83 m, so that an error of ± 100 m is equivalent to a random selection of the rebroadcasters. The main implication of the robustness of DiSIF to the localization error is that the GPS system can be replaced with less accurate positioning estimation techniques. For example, internode distance estimation could be based on the RSSI [19], [20]. This aspect is attractive in energy-constrained scenarios such as WSNs or LPLNs, where the use of GPS may not be a viable option.

7 Conclusions

In this paper, we have proposed a novel broadcast forwarding strategy, denoted as DiSIF, which improves the previously proposed IF and SIF protocols. For almost all the considered values of the network parameters and for all the considered performance metrics, our results show that DiSIF outperforms, besides IF and SIF, other existing static probabilistic forwarding protocols such as GOSSIP and flooding. This is mainly due to the new silencing mechanism of the DiSIF protocol, which limits the number of retransmissions and effectively selects the best rebroadcasters, making the channel utilization more efficient. By comparing simulation results with theoretical findings, we found that DiSIF is close to be the optimal rebroadcast strategy in terms of minimization of the number of hops per communication route. Finally, the performance in the presence of a GPS positioning error shows that DiSIF is robust to moderate GPS error inaccuracy. This suggests that less accurate positioning estimation techniques could be successfully combined with DiSIF.

Acknowledgments

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