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Fabrice THEOLEYRE, CNRS Researcher, LIG, Grenoble, France
Eryk SCHILLER, Drs, LIG, Grenoble, France
Andrezj DUDA, Professor, Grenoble-INP, LIG, Grenoble, France

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Fabrice Theoleyre, Eryk Schiller and Andrzej Duda

Grenoble Informatics Laboratory
CNRS and Grenoble-INP
681 rue de la passerelle, BP72
38402 Saint Martin d'Heres, France
Email: {firstname.lastname}@imag.fr

Abstract

We present a novel geographical routing scheme for spontaneous wireless mesh networks. Greedy geographical routing has many advantages, but suffers from packet losses occurring at the border of *voids*. In this paper, we propose a flexible greedy routing scheme that can be adapted to any variant of geographical routing and works for any connectivity graph, not necessarily Unit Disk Graphs. The idea is to reactively detect voids, backtrack packets, and propagate information on blocked sectors to reduce packet loss. We also propose an extrapolating algorithm to reduce the latency of void discovery and to limit route stretch. Performance evaluation via simulation shows that our modified greedy routing avoids most of packet losses.

1 Introduction

We consider wireless mesh networks composed of a large number of wireless routers providing connectivity to mobile nodes. They begin to emerge in some regions to provide cheap network connectivity to a community of end users. Usually they grow in a *spontaneous* way when users or operators add more routers to increase capacity and coverage.

We assume that mesh routers benefit from abundant resources (memory, energy, computation power, GPS devices in some cases), may only move, quit, or join occasionally, so that the topology of a typical mesh networks stays fairly stable. The organization of mesh networks needs to be *autonomic*, because unlike the current Internet, they cannot rely on highly skilled personnel for configuring, connecting, and running mesh routers. Spontaneous growth of such networks may result in a dense and unplanned topology with some uncovered areas.

Unlike traditional approaches, *geographical routing* presents interesting properties for spontaneous wireless mesh networks: it does not require any information on the

global topology since a node choses the next hop among its neighbor routers based of the destination location. Consequently, the routing scheme is scalable, because it only involves local decisions. Geographical routing is simple, because it does not require routing tables so that there is no overhead of their creation and maintenance. Joining the network is also simple, because a new mesh router only needs an address based on its geographical position. Such addresses can be obtained from a dedicated device (e.g. GPS) or with methods for deriving consistent location addresses based on the information from neighboring nodes about radio signal strength [1] or connectivity [2]. The most familiar variant of geographical routing is *greedy forwarding* in which a node forwards a packet to the neighbor closest to the destination [3, 4]. Greedy forwarding guarantees loop-free operation, but packets may be dropped at *blocked nodes* that have only neighbors in the backward direction. Blocked nodes appear at some places near uncovered areas (*voids*) or close to obstacles to radio waves in a given direction.

Our main contribution is to propose a new greedy routing that correctly deals with voids. First, we define a new mechanism to reactively detect voids and surround them, which significantly reduces packet loss. Moreover, the information of detected voids propagates backwards so that subsequent packets to the same direction benefit from this reactive detection. Second, we propose a mechanism in which voids deviate packets and shorten the length of a route compared to classical approaches. Our routing scheme works in any network topology independently of whether it corresponds to a planar graph or not.

We start with the description of the related work on geographical routing in Section 2. Section 3 presents the details of the proposed new greedy routing protocol. Then, we evaluate its performance via simulation in Section 4 and conclude.

2 Related Work

Geographic information can largely reduce complexity of routing in spontaneous mesh networks. The most simple and widely used protocol is greedy geographic routing [3, 5, 6, 7]: when a node receives a packet, it uses the following forwarding rule:

> ”forward the packet to the node with the best improvement”.

Improvement is usually defined with respect to the distance towards the destination. Since improvement is not negative, there is no routing loops. Moreover, routing is scalable, because all routing decisions are local.

Geographical routing requires addresses based on geographical coordinates: a node must obtain its location either with a dedicated physical device (e.g. GPS) or through a more complex algorithm, e.g. by estimating the position with respect to its neighbors. Capkun et al. propose to construct a local coordinate system for each node and determine the coordinates of its neighbors [1]. Then, they aggregate the local coordinate systems into global coordinates. The authors assume the distance to each neighbor known, but usually it is difficult to obtain. Niculescu et al. follow a similar approach, but based on the *angle of arrival* of packets coming from neighbors [8]. A pragmatic approach to this problem is to assume that a subset of mesh routers know their exact

positions via GPS devices and other nodes can compute their positions with respect to its neighbors [9].

The main drawback of greedy geographical routing is packet loss at blocked nodes near voids or obstacles. A node must drop a packet when the improvement associated with any of its neighbors is negative (cf. Figure 1). In *face routing* the *left-hand* rule [4] tries to go around a void, but it requires the connectivity graph of nodes to be planar. Relative Neighborhood Graphs can yield planar graphs for Unit Disk Graphs [10], but in real wireless environments, the conditions for obtaining planar graphs are not satisfied due to asymmetric links and not circular radio coverage [11]. To the best of our knowledge, there is no efficient and localized planarization algorithm proposed for a general connectivity graph. A possible solution to this problem is the following method: a border node initiates local flooding to find the next hop closer to the destination [12]. However, it results in long delays and significant overhead. Fotopoulou et al. [13] propose to adapt this method to establish and maintain a *virtual circuit*. Funke et al. [14] propose an algorithm inspired by topological geometry to discover the void limits, i.e. the *border nodes* by creating isosets. However, this method does not work for non Unit Disk Graphs since isosets are not rings in general connectivity graphs. Very recently, [15] proposed to maintain both virtual and physical coordinates. When a node detects that it is blocked, it changes its virtual position increasing its height to dissuade neighbors to send packets. Greedy routing will use virtual coordinates in order to surround the voids. However, a node is considered blocked only if an empty sector of more than 220 exists, and not all voids can be detected in this manner.

We propose here a generic method to deal with voids by backtracking packets and discovering blocked areas near voids: deflection routing deviate packets outside them. Thus, the algorithm presented here is perfectly supplementary to existing methods: deflection improves greedy routing by trying to surround voids and any other technique presented above can be used when a void is reached.

3 Reactive Deflection

Geographical routing is attractive for mesh networks, but suffers from two main drawbacks: blocked nodes can drop many packets and the route length may drastically increase when a surrounding mechanism tries to deviate a packet around a void (e.g. the left-hand rule in unit disk graphs). In this paper, we assume a general connectivity graph and propose to reactively detect blocked nodes and locally advertise blocked sectors to avoid packet losses. Such a technique is efficient in any type of networks and graphs since it does not assume any particular graph property.

Detection of blocked nodes can be done in a proactive way: locally flood information to detect voids. For example, we can discover the topology of the wireless mesh to detect elementary cycles in which no other node is located inside the ring. The location of nodes helps to surround voids. However, such an approach requires a complete knowledge of the mesh topology and is computationally intensive.

In opposition to this approach, we have chosen a reactive method: a node becomes *blocked* with respect to a given destination when it cannot forward a packet to any neighbor closer to the destination. Hence, the part of the network not concerned by

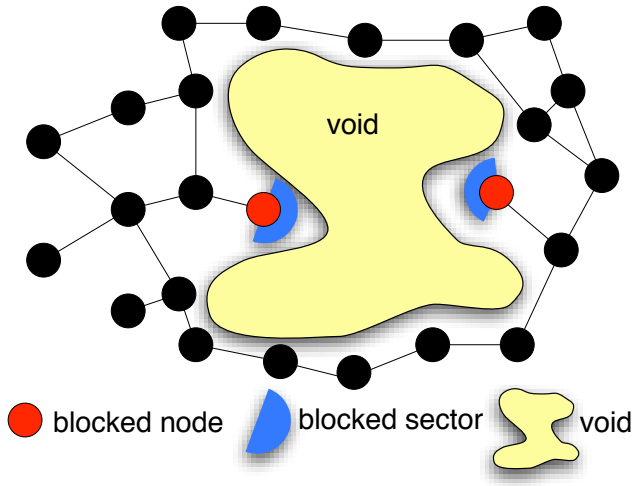


Figure 1: Blocked nodes in greedy geographical routing.

forwarding this packet does not generate any control traffic so that this approach is more scalable.

Let us first adopt the following notation:

- $d(A, B)$: the Euclidean distance between the geographical coordinates of nodes A and B
- $\angle(AB, AC)$: the oriented angle between two coordinates of nodes (A, B) and (A, C) (by convention, we denote by $\angle(AB)$ the normalized angle $\angle(\begin{pmatrix}1\\0\end{pmatrix}, AB)$)
- $\mathbb{S}(S, \alpha, \beta, d_{min})$: the sector of node S composed of all nodes N such that $\alpha \leq \angle(SN) \leq \beta$ and such that $d(S, N) \geq d_{min}$

In our approach, a node chooses a neighbor closer to the destination and not blocked for this direction. If a node fails to forward a packet to a given destination, it will consider itself as blocked for this direction. It will advertise backwards a list of blocked directions so that its neighbors will not choose it as a next hop for these directions. If several non blocked neighbors exist, the forwarder chooses the neighbor closest to the destination, i.e. with the best *improvement*.

For advertising blocked directions, we propose to use the notion of *blocked sectors*: a node N advertises that it is blocked for any destination that falls in sector $\mathbb{S}(N, angle_{min}, angle_{max}, dist_{min})$. Let us consider the topology illustrated in Figure 2. Node n_1 wants to forward a packet to destination d and it discovers that it is blocked for this destination since no neighbor exists in this direction. Thus, it backwards the packet to s with its two blocked sectors. Based on this information, s marks

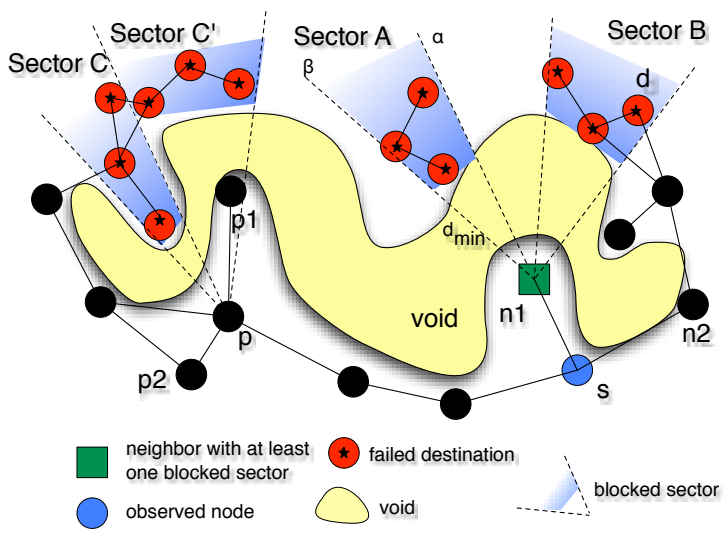


Figure 2: Examples of blocked nodes and blocked sectors.

n_1 as blocked and forwards the packet to another neighbor closer to d (node n_2 in this case).

Algorithm 1 ReactiveDeflection(N→D)

```
next ← ∅
for all n ∈ Neighbors do
    if d(n, D) < d(N, D) and !BLOCKED(n,D) and d(n, D) < d(next, D) then
        next ← n
    end if
end for
if next = ∅ then
    Blocked(N,D) ← true
    next ← previous_hop
end if
return next
```

To limit the overhead, a node tries to merge all its blocked sectors before advertising them. It can only merge overlapping sectors having the same minimal distances (within some tolerance Δ_d). Otherwise, the merged blocked sector may include nodes that are reachable—consider for instance the topology of figure 2: if node p merges sectors C and C', node p_1 may appear in the blocked sector. Thus, it would become unreachable from p_2. Clearly, we must avoid such a merging. Only sectors will the same d_{min} will be merged : tolerance Δ_d allows some merging of sectors with approximately equal minimal distances.

More formally, node N executes Algorithm 1. Procedure $ReactiveDeflection()$

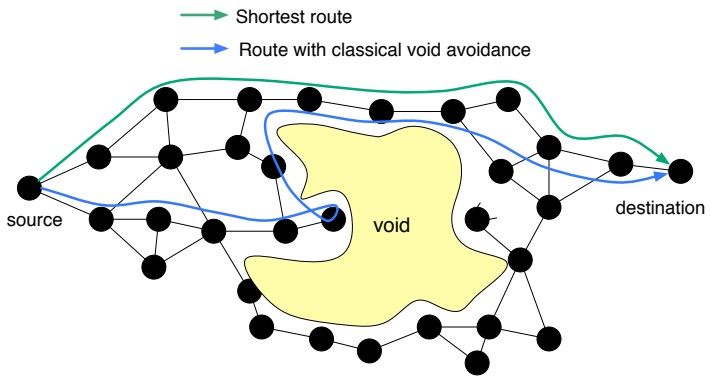


Figure 3: The increase of route length when surrounding a void.

finds the next hop for forwarding a packet to destination D: the next hop must be closer to the destination and must be unblocked for D. If it does not return any node, it means that node N becomes *blocked* for destination D (variable BLOCKED(N,D) becomes true). Thus, node N updates its blocked sectors and sends the packet backwards to the previous hop with its list of blocked sectors piggybacked onto the packet. This scheme is loop-free: when a node sends a packet backwards, the receiver will update its blocked sectors and it cannot choose the same next hop for subsequent packets, because Algorithm 1 does not forward packets to blocked nodes.

In networks with non unit disk graph topology, when a node becomes blocked and there are no other neighbor closer to the destination, the node needs to discover a node in a larger vicinity able to forward the packet to the destination. Usually, it consists of flooding a request in a k-neighborhood of the node, k being a parameter to limit the scope of flooding. In this case, the length of the route may increase, which is illustrated in Figure 3: border nodes need to forward the packet to reach a *virtual* next hop [3, 13]. This increases both the load of the border nodes and the route length. We propose to limit the effect of such a behavior.

Note that when we reduce packet loss with the previously described algorithm, we also reduce in the long term the route length. Indeed, the nodes around the void discover that they have blocked sectors. When they propagate the information about blocked sectors, nodes with all blocked neighbors also become blocked for this destination. Finally, each node discovers a blocked area and forwards packets outside this area. However, we need several useless packet transmissions and backtracking before the network converges, and blocked sectors are correctly constructed. We propose a mechanism to accelerate the convergence of this propagation process by extrapolating the location of a blocked area.

We propose to detect the border of a void based on only local neighborhood knowledge. We will show that even if a node has only local knowledge, i.e. about nodes at a limited distance, voids can be efficiently surrounded. When a node must transmit a packet backwards, it locally floods an `hello` packet containing the list of its neighbors

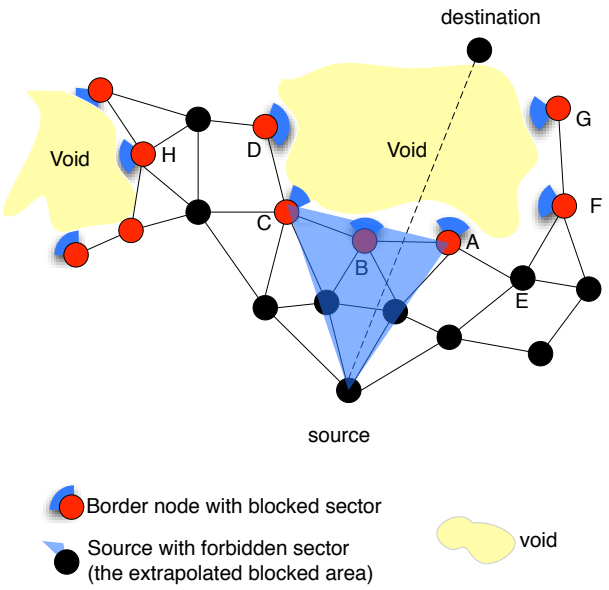


Figure 4: Method for locally detecting the border of a void.

and blocked sectors in a k hop scope.

To detect the border of a void, node N first searches for the blocked k-neighbor closest to the direction of the destination D, i.e. minimizing angle $\angle((N, D), (N, BN))$ for all blocked nodes BN. Then, N constructs the Maximum Connected Set of blocked nodes that contains BN: it adds BN to this set, and recursively adds all its blocked neighbors. Finally, N computes the *forbidden sector* that spans the maximum connected set—it extrapolates the blocked area.

Figure 4 illustrates void detection with the knowledge of the 3-neighborhood topology. First, the source node detects if it knows a node with a blocked direction and takes the closest one to the direction to the destination. In the example the blocked node is B. Then, the source constructs the connected set of blocked nodes that includes node B: it obtains set $\{A, B, C, D\}$. Obviously, node F is not present in the set since it is not connected to A via other blocked nodes. In the same way, border node H is not in set $\{A, B, C, D\}$, because it is 2 hops away: it is border to another void. Finally, we obtain the forbidden sector for the destination. We can note that node E is not blocked since it can choose node F when A is blocked: E will never be blocked for the direction.

Algorithm 2 presents the modified protocol. Function IsInForbiddenSector computes the forbidden sector and returns TRUE, if the node is located inside this sector. Function CloserToSectorLimits(P,Q) returns TRUE, if P is closer than Q to the forbidden sector limits.

In other words, if some next hops exist and do not lie in the computed forbidden sector, we choose the best one. Otherwise, if all possible next hops are in this forbidden sector, we choose the node closest to the limits of the forbidden sector. With this

Algorithm 2 ModifiedReactiveDeflection(D,ForbiddenSector)

```
next ← ∅
for all n ∈ Neighbors do
    if d(n, D) < d(S, D) and !BLOCKED(n,D) then
        if !ISINFORBIDDENSECTOR(n) and { ISINFORBIDDENSECTOR(next) or
        d(n, D) < d(next, D) } then
            next ← n
        else if ISINFORBIDDENSECTOR(next) and ISINFORBIDDENSECTOR(n) and
        CLOSERTOSECTORLIMITS(n,next) then
            next ← n
        end if
    end if
end for
if next = ∅ then
    Blocked(N,D) ← true
    next ← previous_hop
end if
return next
```

Table 1: Route length with deflection routing for different values of the k-neighborhood

k (in hops)	Route length
1	33.6
2	33
3	32.7
4	33.2
5	33.6

modified routing scheme, we forward packets outside the forbidden sector, because a void appears as something repellent to packets by creating forbidden sectors in a distributed manner while keeping routing loop-free.

4 Performance evaluation

We have generated random meshes of 1000 nodes according to two models: Unit Disk Graphs [16] and what we call a *proxi-graph* (a graph based on proximity). In a proxi-graph, each node chooses a *radio range* following a Gaussian distribution centered at 1 with standard deviation Std depending on the radio range (we assume $Std = 25\% \cdot (radio{-}range)$ in our simulations). We consider a proxi-graph with a rectangular void of size two fifth of the simulation disk radius in the center of the simulation area. Besides, we discard disconnected topologies and use a disk simulation area to reduce border effects. Data traffic consists of 1,000 flows of 10 packets each from a random source to a random destination.

At the beginning, to evaluate only the properties of routing itself, we assume ideal radio and MAC layers: packets do not experience any loss due to channel or MAC behavior to only test routing properties. Then, we evaluate the performances of the proposed protocols with the ns2 simulator to take into account more realistic radio conditions. Finally, we assume that nodes advertise the list of blocked sectors to their neighbors and a node is aware of the blocked nodes in its 3-neighborhood (hellos contain the list of neighbors) since it achieves the best tradeoff between the performance and the overhead as shown in the simulations.

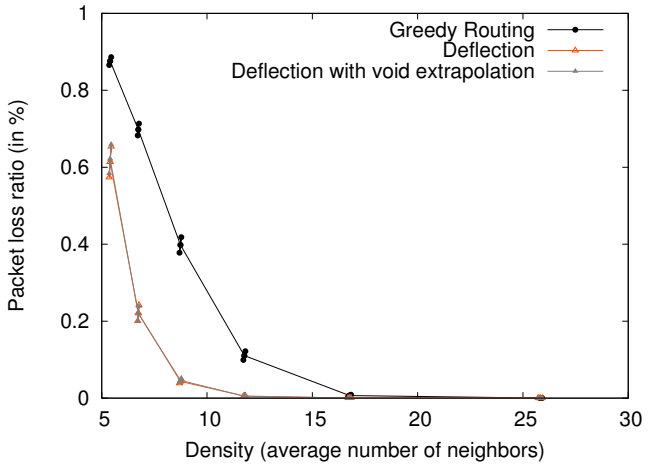
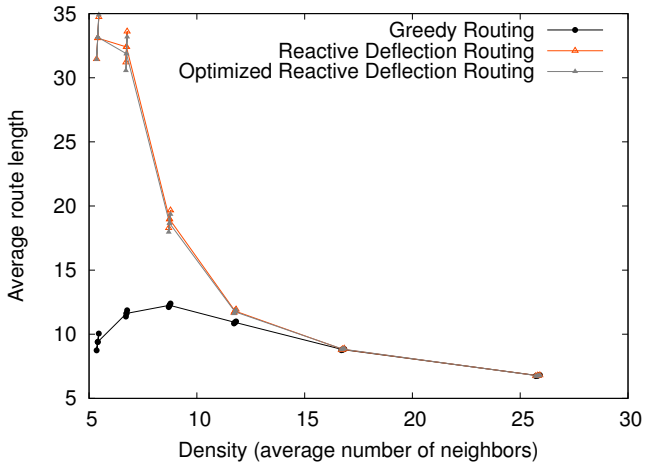


Figure 5: Packet loss under different routing schemes for UDG.

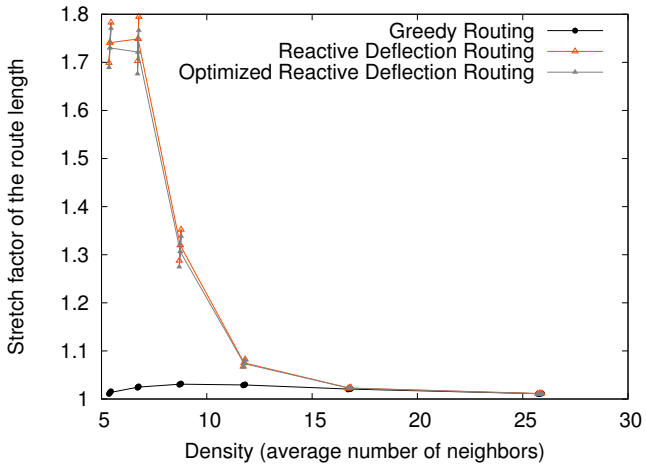
We compare our routing algorithm with greedy geographic routing to quantify the reduction of packet loss. We use the classical version of greedy routing (the neighbor closest to the destination is chosen as next hop) since other versions do not show a significative improvement (smallest angle deviation, closest neighbor that is closer to the destination than myself). We mainly measure packet loss (the proportion of packets sent by a source that never reach the destination), route length (the average route length in hops for the delivered packets), and stretch factor (the average ratio of the route length for a packet and the length of the shortest route for the associated source/destination pair). We evaluated mainly the impact of density (average number of neighbors per node) on the routing performances. We plot the average values and the associated 95% confidence intervals.

4.1 Performance for Unit Disk Graphs

In the first experiment, we have measured the route length obtained for deflection routing with different values of the k-neighborhood with density of 8 neighbors per node in Unit Disk Graphs (cf. Table 1). We can remark that we quickly obtain a shorter route length with $k = 3$. For larger values, deflection routing tends to overestimate the size of voids and increase the route length.



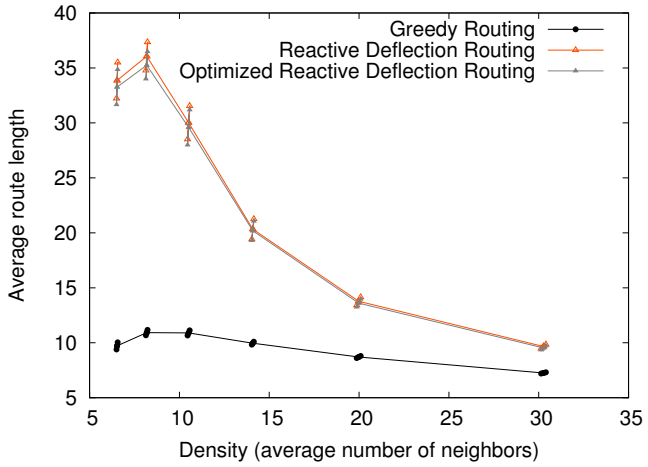
(a) Route length in hops



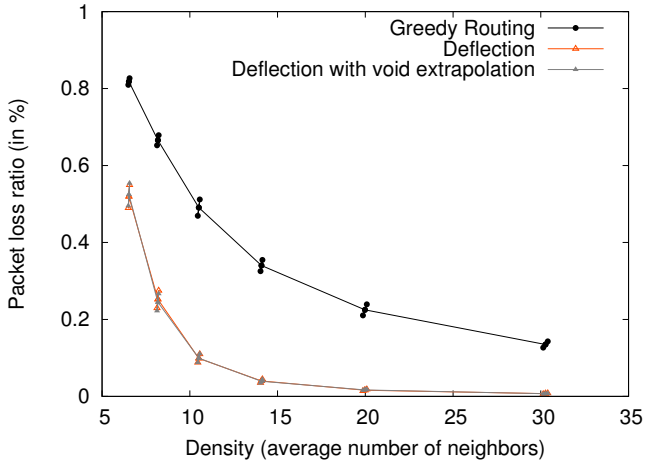
(b) Stretch factor

Figure 6: Route length under different routing schemes for UDG.

Then, the following experiment shows (cf. Figure 5) that packet loss for greedy routing decreases with the increase of density: probability of having a large area without any node decreases so that voids are less probable to appear. However, more than 70% of packets are lost for low density. On the contrary, the proposed routing scheme lowers packet loss: almost no packet is lost (less than 4%) when density exceeds a small threshold (8 neighbors per node). Thus, nodes reroute less packets by means of reactive discovery so that the overhead is lower and delay improved. We can also notice that route length optimization has no impact on delivery ratio.



(a) Route length.



(b) Packet losses.

Figure 7: Performances of different routing schemes for a proxi-graph with one central void.

We have also measured the route length (cf. Figure 6(a)). Greedy routing does not achieve to find routes when voids exist. Thus, the packet drop probability for greedy routing is larger when the destination is farther. Since the route length is only measured for delivered packets, this poor delivery ratio creates mechanically a lower average route length. To characterize its increase, we have measured the stretch factor (cf. Figure 6(b)). We can observe that our optimized algorithm succeeds in slightly reducing the route length. More importantly, route length optimization results in deviating packets from voids and decreasing the load on the void's borders. The stretch factor is larger for low density since more voids are present and packets must be deflected and backtracked more often. The reader can note that greedy routing forwards one packet until it reaches a blocked node: this increases the load on these block nodes, even if they implement a void bypassing. Finally, the route length is reduced only for very low densities with the optimized version of deflection routing since blocked sectors interpolating is working only when voids are sufficiently large. Moreover, we could overestimate the forbidden sector by adding a guarding angle around the blocked nodes: we would reduce the route length, but increase packet drops since we would over-estimate the presence of voids.

4.2 Performance for a proxi-graph with one rectangular void

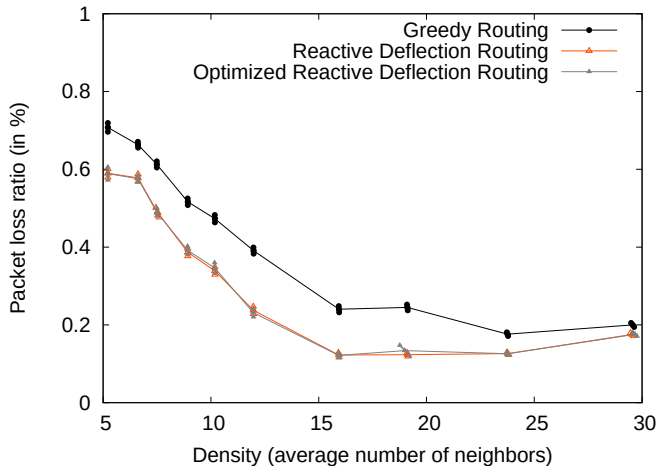
We have evaluated packet loss rate in a proxi-graph with one central void (cf. Figure 7(b)). We can see that packet loss increases compared to unit disk graphs, particularly for high density: dead-ends are more probable. Moreover, since the graph is not UDG, a node may choose a next hop in a greedy way although it does not have any neighbor in the direction of the destination. Thus, to increase density it is not sufficient to surround voids. We can remark that with our algorithms we significantly reduce packet loss ratio.

Finally, we have measured the route length (cf. Figure 7(a)). We can remark the same trend as for UDG and for a proxi-graph with a void. Obviously, the route length is longer, because packets have to surround the rectangular void.

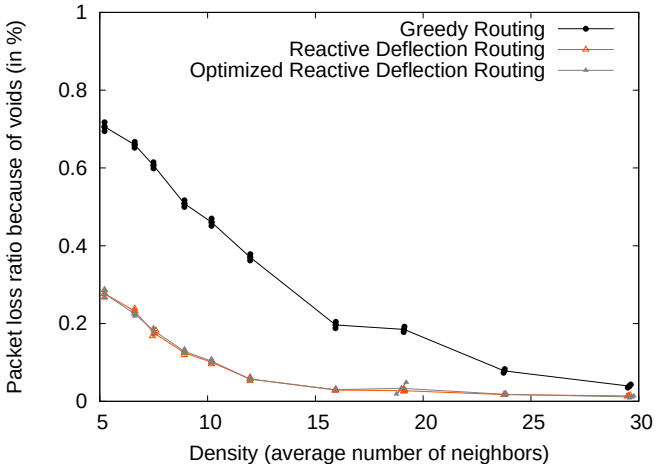
4.3 Performance for more realistic channel conditions

We have implemented greedy and deflection routing in ns (version 2.33) to test a non-ideal MAC and PHY layer. We have only consider 200 nodes, because of scalability limits of ns2. As above, we have placed one rectangular void in the center and all the nodes are placed randomly in the remaining simulation area. We have discarded all disconnected nodes. Finally, we have sequentially activated flows between random pairs of source and destination nodes. A flow sends 10 packets of 512 bytes with an inter-packet interval of 0.25s. In this way, we measure the ability of the routing protocol to discover a route rather than its robustness to the network load.

We first report on the packet loss ratio for greedy and deflection routing (cf. Figure 8). We can remark that deflection routing achieves a lower loss rate than greedy routing: it discovers more routes. However, the MAC layer is now not ideal: packets can be dropped because of collisions or transmission errors, especially if the route is long. This explains the larger packet loss compared to the previous simulations. This



(a) Total packet losses.



(b) Packet losses due to the absence of the next hop.

Figure 8: Packet loss ratio under different routing schemes in ns2.

effect also suggests that IEEE 802.11 needs improvement for wireless mesh networks [17].

Figure 8(b) represents packet losses only due to routing voids (i.e. there is no next hop according to the routing algorithm) that characterize the routing protocol and not the influence of the MAC layer (collisions, errors etc.). We can observe the same trends as for the proxi-graph (cf. Figure 7(b)): greedy routing suffers much more from voids than deflection routing. Finally, we also measure the route length (cf. Figure 9): although the route can be longer than for the ideal MAC and PHY layers, because for instance a node could not discover a neighbor, deflection routing discovers routes that are not much longer than those in greedy routing. Besides, the optimized version of deflection routing becomes efficient in surrounding voids and reducing the route length in very sparse networks.

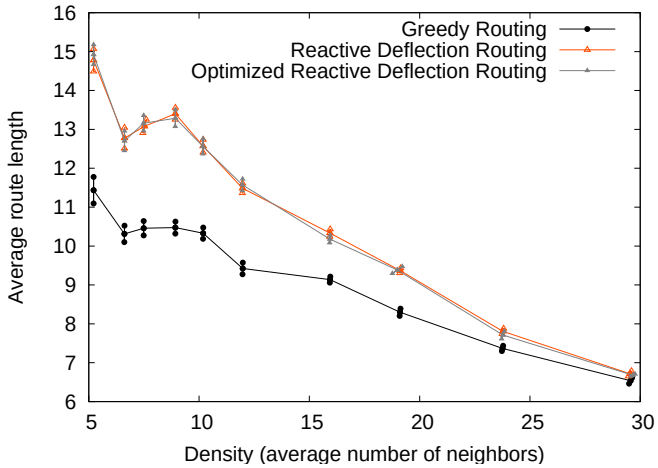


Figure 9: Route length under different routing schemes in ns2.

5 Conclusion

We have proposed a scheme for greedy geographical routing with reactive defect detection. The idea is to reactively detect blocked nodes and propagate the defect information by computing a set of blocked sectors. To reduce the route length and accelerate void detection in dense mesh networks, we have also proposed a method to extrapolate void location. Simulation results show good performance of the proposed methods: packet loss as well as the route length decrease compared to greedy routing.

Acknowledgments

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