We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900
Open access books available

185,000
International authors and editors

200M
Downloads

154
Countries delivered to

Our authors are among the

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

CLARIVATE ANALYTICS
BOOK CITATION INDEX
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Wired/Wireless Compound Networking

Juan Antonio Cordero[1], Emmanuel Baccelli[1],
Philippe Jacquet[1] and Thomas Clausen[2]
[1]*INRIA Saclay*
[2]*École Polytechnique*
France

1. Introduction

Routing, and more precisely routing within an Autonomous System (AS), is the most basic and still outstanding wireless ad hoc networking challenge. As the properties of ad hoc networks are *a priori* unpredictable and may change dynamically during the lifetime of the network, no assumptions can be made in general concerning topology, link reliability, routers positions, capabilities, and other such aspects. Routing protocols operating within an AS – *i.e.* interior gateway protocols (IGP) – must enable each router to acquire and maintain the information necessary to forward packets towards an arbitrary destination in the routing domain. Currently, the dominant IGP technology is link state routing, as acknowledged by reports of Cisco Systems, Inc. such as Halabi (2000).

Routing protocols that were designed for wired, static environments do not perform well in ad hoc networks: even for small networks, as Henderson *et al.* (2003) points out, control traffic explodes in a wireless, dynamic context. Many efforts have been deployed over the last decade, aiming at providing routing protocols suitable for ad hoc networks. In such context, information acquisition and maintenance has to be provided by distributed mechanisms, since neither hierarchy nor centralized authority can be assumed to exist. Moreover, the typical bandwidth scarcity experienced in wireless ad hoc networks calls for mechanisms that are extremely efficient in terms of communication channel utilization. In the realm of link-state routing two main strategies have been explored: (i) the design of ad hoc specific routing protocols; and (ii) the reuse and adaptation of existing generic routing protocols so that they can handle ad hoc conditions. The first strategy has mainly led to the emergence of the Optimized Link State Routing protocol, OLSR, standardized as RFC 3626 (2003). The second approach has led to protocol extensions such as RFC 5449 (2009), which enable the operation of Open Shortest Path First (OSPF) on ad hoc networks.

This chapter focuses on scenarios where the AS consists in *compound networks*: networks gathering both potentially mobile ad hoc routers, and fixed wired routers. Such scenarios may become frequent in a near future where wireless ad hoc and sensor networks play an increasing role in pervasive computing. Obviously, it is possible to employ multiple routing protocols within a compound network (*e.g.* one for wireless ad hoc parts of the network, and another for the wired parts of the network). However, a single routing protocol makes more economical sense for the industry, and furthermore avoids the potential sub-optimality of having to route through mandatory gateways between different routing domains. Thus a single protocol is desired to route in compound networks, and (ii) is deemed the best strategy

to do so. The main reason for this is, that (ii) takes advantage of wide-spread, generic protocols which on one hand already provide very elaborate modules for various categories of wired networks, and on the other hand can easily accommodate a new module for efficient operation on ad hoc networks.

This chapter thus explores techniques that enable efficient link state routing on compound networks. These techniques rely on the selection and maintenance of a subset of links in the network (i.e. an *overlay*) along which the different operations of link-state routing can be performed more efficiently. The following provides a formal analysis of such techniques, a qualitative evaluation of their specific properties and example applications of such techniques with a standard routing protocol.

1.1 Terminology

In this chapter, the following notation is used:

– The 1-hop and 2-hop (bidirectional) neighborhoods of a router x are denoted by $N(x)$ and $N_2(x)$, respectively.

– The usual notation of graph theory is assumed: $G = (V, E)$ stands for a (connected) network graph, in which the set of vertices is $V = V(G)$ and the set of edges is $E = E(G)$. Overlay subgraphs are denoted accordingly, as subsets of G.

– Given two vertices (routers) $x, y \in V$, $dist(x, y)$ is the cost of the optimal path between x and y. Similarly, given two vertices $x, y \in V$ reachable in 2 hops, it will be denoted by $dist_2(x, y)$ the cost of the optimal path between x and y in 2 hops or less (*local shortest path*). For two neighbors x and y, $m(x, y) = m(\overline{xy})$ denotes the cost of the direct link from x to y.

1.2 Chapter outline

The chapter is organized as follows. Section 2 describes the key operations providing link-state routing. Section 3 elaborates on the constraints that ad hoc networking imposes on link-state routing, with a specific focus on compound networks. Section 4 introduces to the notion of overlay for performing these key operations, analyzes the properties of several overlay-based techniques and discusses their advantages and drawbacks of their use in the context of a concrete routing protocol. Section 5 applies and evaluates the performance of such techniques as ad hoc OSPF extensions. Finally, section 6 concludes this chapter.

2. Communication aspects in link-state routing

This section provides a structural high-level description of the operations of link-state routing. Section 2.1 presents a short summary of link-state routing. Sections 2.2, 2.3 and 2.4 describe in more detail the main tasks associated to such operation: neighbor discovery, network topology dissemination and route selection for data traffic, respectively.

2.1 Link-state routing overview

Link-state routing requires that every router learns and maintains a view of the network topology that is sufficiently accurate to compute valid routes to every possible destination. This, typically (as for OSPF or IS-IS[1]), in form of shortest paths w.r.t. the metrics used. Such shortest paths are computed among the available (advertised) set of links by means

---

[1]Intermediate-System-to-Intermediate-System, specified in ISO 8473 (2002).

of well-known algorithms such as Dijkstra (1959), and will provide effectively optimal routes when the view of the topology is up to date.

These objectives require that every router in the network performs two operations, other than the shortest path computation: first, take efficient flooding decisions for the forwarding of topology information messages; and second, describe accurately its links in order to advertise them to the rest of the network. Three tasks emerge thus as necessary for the performance of link-state routing operation:

1. participation in the flooding of topology information (both of self-originated messages and of messages from other routers),

2. selection of links to advertise to enable shortest route construction and,

3. discovery and maintenance of the neighborhood, as a pre-requisite for the two previous tasks.

2.2 Neighbor discovery and maintenance

The discovery and maintenance of neighbors is a prerequisite for performing efficient link-state routing. Without neighborhood knowledge, link-state routing can only be deployed by means of pure flooding, which has been proven by Ni *et al.* (1999) to be dramatically inefficient when dealing with ad hoc networks (the *broadcast storm* problem); or with counter-based or similar approaches, which have severe performance limitations, as shown in Tseng *et al.* (2003). The most widespread and basic mechanism for neighbor sensing consists of the periodic transmission of Hello packets by every router in the network (Hello protocol). Exchange of such Hello packets enable routers to learn their neighborhoods and establish bidirectional communication, if possible, with neighbors within its coverage range. Aside from this use, Hello exchange may be useful for acquiring additional information about the neighbors (geographic position, remaining battery power, willingness to accept responsibilities in communication), the links to them (link quality measures) or the neighbors of such neighbors (2-hop neighborhood acquisition).

2.3 Topology information dissemination

Consistency of the distributed LSDB and correctness of routing decisions require that every router maintains an updated view of the network topology. When a router detects a relevant change in its neighborhood, it needs to advertise it by flooding a topology update message, so that any other router can modify accordingly its link-state database and, if necessary, recalculate optimal routes.

In ideal conditions [2], such mechanism would be sufficient for keeping identical LSDBs in every router in the network. Since these conditions are not found in wireless ad hoc scenarios, additional mechanisms might be considered:

– **Reliable flooding of topology messages.** Reception of such messages is acknowledged by the receiver, or retransmitted by the sender/forwarder in the absence of such acknowledgment, in a hop by hop fashion. Reliable flooding is provided by the main wired routing protocols (OSPF, IS-IS), but its cost in mobile ad hoc networks discourages its use in MANET-specific solutions such as OLSR.

– **Periodic re-flooding of messages.** After a certain interval, even if no changes have been registered in the neighborhood, the routers reflood to the network an advertisement

---

[2]That is, static, always-connected networks in stationary state with error-free links.

containing the current state of the links between themselves and their neighbors. The length of the interval is typically related to the mobility pattern of the network: the faster nodes in the network move, the shorter the interval between consecutive topology messages from the same source needs to be.

– **Point-to-point link-state database synchronization.** A link between two routers is said to be *synchronized* when the routers have completed a synchronization process of their respective LSDB. This involves the exchange of the database contents and the installation of the most updated topology information in each of them. This mechanism is implemented in the major wired routing protocols (OSPF, IS-IS), but the conditions in which such synchronization is performed are not completely adapted to mobile ad hoc operation. Therefore, the mechanism as-is is not considered in specific protocols such as OLSR, and its use is widely restricted, for instance, in the different OSPF MANET extensions.

These mechanisms handle different issues concerning topology dissemination. Reliable transmission permits overcoming phenomena such as wireless channel failures or collisions. Periodic re-flooding and point-to-point synchronization provide up-to-date topology information to routers appearing in the network after some of the disseminated messages were flooded across the network. Periodic reflooding by itself enables every router to acquire the latest topology information (maybe with a non-negligible delay, depending on the re-flooding interval). In contrast, full synchronization is not capable on its own to assure database convergence from all routers in link-state routing[3]. Point-to-point synchronization is, at best, a complementary mechanism to periodic re-flooding that allows a router that has not received all the topology updates to get within a shorter delay the last topology information from an updated neighbor.

Synchronization techniques implicitly introduce the concept of a *synchronized overlay*. A router is *included* into the synchronized overlay if it is aware of the last topology update messages that were flooded across the network, and, correspondingly, it is *removed* from the overlay when it does not receive one of more topology information messages. In that context, the periodic re-flooding of topology messages permits including every reachable router into the network within a maximum delay equal to the interval between two consecutive refloods. Point-to-point LSDB synchronization between a router and a synchronized neighbor permits, in turn, including routers immediately into the overlay (by means of the database exchange process), *i.e.*, to restore or establish for the first time the router's synchronism with the rest of the network.

In wired networks, the synchronized overlay is expected to grow monotonically until it contains all routers – then the network is said to converge. Router removals from the synchronized overlay are rare events mostly caused by physical link disconnections or router shut-downs. In ad hoc networks, the nature of the synchronized overlay is far more unstable. Alternative inclusion and removal events may thus occur due to router mobility or wireless link quality variations, preventing the network to converge in the usual sense.

2.4 Route selection for directed communication

The final goal of any routing protocol is that every router is able to route traffic to any other router (and any destination provided by such router) in the network. For a link-state routing

---

[3]This is different, for instance, in proactive distance-vector routing, in which the network is expected to converge through *repeated* database synchronization processes. In the considered link-state context, synchronization occurs *once* in a link lifetime, which is not sufficient for assuring convergence.

protocol, such ability is provided by disseminating the topology updates of all routers across the network. Such dissemination permits every router to construct and maintain updated routing tables, as Figure 1 describes schematically.
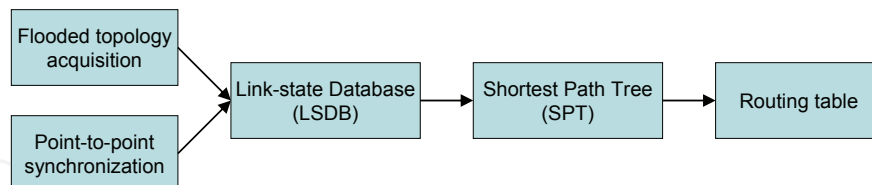

Fig. 1. Construction of the routing table for a link-state routing protocol.

The tree of the optimal routes to every destination (Shortest Path Tree) is then computed by means of well-known minimum paths algorithms. Typically, link-state routing protocols (OSPF, IS-IS, OLSR) use Dijkstra (1959), while distance-vector protocols (RIP[4], EIGRP[5]) rely on Bellman-Ford [Bellman (1958); Ford & Fulkerson (1962)]. These algorithms operate over a graph in which vertices correspond to routers in the network and edges mostly correspond to links advertised by the received topology update messages[6]. The routing table is thus extracted from the next hop, according to the Shortest Path Tree, to every possible destination. In general, the reconstructed link-state database should bring every router exactly the same perspective of the network topology, which would require that all links are advertised. In practice, the set of links that a router advertises to the rest of the network can be restricted as far as it does not prevent the shortest path algorithm to select network-wise optimal routes.

3. Link-state routing with ad hoc constraints

This section exposes the main challenges for link-state routing in ad hoc networks. These are mainly related to (i) the efficient dissemination of topology information across the network, in presence of lossy channels and dynamic topologies as is typical in these networks, and (ii) the ability of the network to acknowledge and react quickly to topology changes. Section 3.1 presents the most relevant implications of the ad hoc nature in the performance of link-state routing, while section 3.2 focuses on the specific case of compound networks integrated by wired and wireless groups of routers.

3.1 General issues of ad hoc link-state routing

Wireless ad hoc networking presents a certain number of unique communication conditions that link-state routing needs to accommodate:

– **Unreliability of wireless links.** Wireless links are inherently unreliable: channel failures and collisions are more frequent than in wired links. Wireless link quality can be also highly dynamic. Both circumstances make necessary continuous monitoring of the state and characteristics of links.

---

[4]Routing Information Protocol, specified in RFC 1058 (RIPv1), RFC 1723 and RFC 2453 (RIPv2) and RFC 2080 (RIPng, designed for IPv6).

[5]Enhanced Interior Gateway Protocol, Cisco proprietary routing protocol that improves Cisco's previous IGRP.

[6]Not necessarily all edges have been acquired by means of topology update messages. Section 4 explores some techniques in which some additional edges, not advertised in such messages, might be included as well.

– **Semibroadcast nature of wireless multi-hop communication.** Wireless communication entails shared bandwidth among not only the routers participating in the communication, but also those within the radio range of the transmitting routers. This reduces drastically the available bandwidth for a router, since it is affected by the channel utilization of its neighbors. Applications may take advantage of such bandwidth sharing phenomenon by privileging, when possible, multicast transmissions in place of a unicast (point-to-point) approach that no longer corresponds to the physical conditions of communication.

– **Asymmetry and non-transitivity of links.** Semibroadcast communication also implies that the set of nodes receiving a transmission if not (necessarily) the whole network. Moreover, the set of nodes receiving a transmission may be different for two routers, even when such routers are neighbors. This means that wireless links in a multi-hop ad hoc network cannot be expected to be transitive: the fact that a router x can directly communicate with routers y and z does not imply that routers y and z can also communicate directly ($x \leftrightarrow y, y \leftrightarrow z \nRightarrow x \leftrightarrow z$). Asymmetric links (*i.e.*, links in which a router can hear the other's transmissions, but not the other way around) are also possible due to specific channel conditions or different router capabilities.

– **Topology acquisition and maintenance.** Neither hierarchy nor specific routers relationships can be *a priori* assumed in an ad hoc network. Dynamic configuration of hierarchical schemes becomes unfeasible due to difficulties on electing top-level routers (related to non-transitivity of links) and cost of performing hierarchy recompositions (caused by node failures, node mobility or channel quality variations). Distributed approaches are thus encouraged in place of hierarchical ones. Moreover, unreliability of wireless links makes necessary to complement topology dissemination with a periodic and frequent reflooding of topology messages that ensures that nodes acquires the last updates with a relatively short delay.

3.2 Dissemination in compound networks

In addition to wireless ad hoc routers, compound networks also contain wired static components, for which the typical link lifetime is much higher than for standard ad hoc communications. The coexistence of wired and wireless ad hoc components poses some additional constraints to those presented in the previous section 3.1. Frequent flooding updates from the wired components lead to inefficient use of the available bandwidth, as the information about wired links carried by consecutive messages would be unchanged. Low update frequencies (with intervals in the order of wired networks) may however be insufficient to accommodate communication failures in the wireless and/or mobile components of the network.

Link synchronization between selected pairs of neighboring routers (in addition to topology changes flooding and periodic topology reflooding) helps to alleviate this issue. Point-to-point link synchronization enables highly dynamic routers to acquire updated topology information from wired links even long time after its origination, without requiring frequent refloods of the same link-state description by the corresponding wired (stable) source.

Consider Figure 2, where fixed routers (1 and 2) can handle changes in their wired (stable) links by transmitting topology updates at relatively low rate (with the time interval between updates in the order of minutes). Mobile routers (such as 5, 6 and 7) and, more in general, routers maintaining wireless links (also the hybrid routers 3 and 4) should use significantly lower time intervals (in the order of seconds, depending on their mobility pattern). If, for any reason, a mobile router (such as 5, 6 or 7) did not receive a topology update from a wired one

as router 1, it will be unable to update its LSDB until the next flooding from the wired router, failing at computing valid routes that involve that router in the meanwhile.
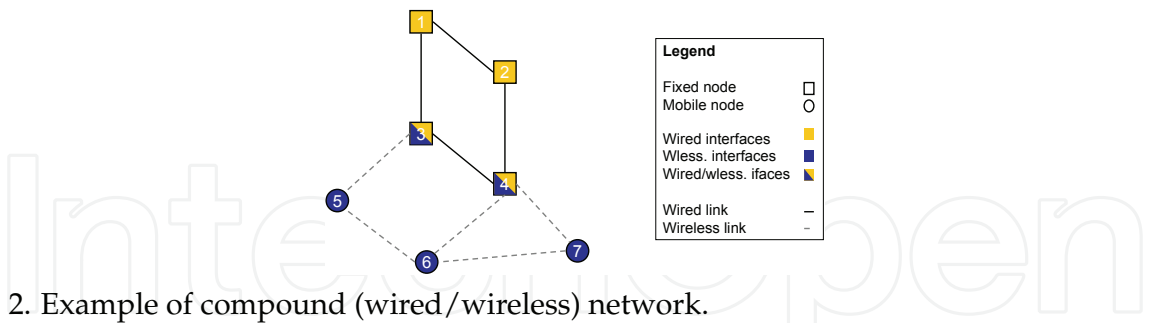

Fig. 2. Example of compound (wired/wireless) network.

The inclusion of a LSDB synchronization mechanism addresses the coexistence of wired and wireless components without having to reflood unnecessary topology updates from wired routers nor compromising the accuracy of network topology view of ad hoc (mobile) routers. This, at the expense of an additional dissemination mechanism (in addition to regular flooding of topology changes and periodic topology reflooding) and the corresponding additional complexity in the flooding operation.

4. Overlay techniques for compound networks

This section proposes and analyzes various techniques for performing link-state routing in ad hoc compound networks. Section 4.1 introduces the notion of overlay and reformulates the main operations of link-state routing in terms of overlays. Subsequent sections 4.2, 4.3 and 4.4 describe three overlay-based techniques (Multi-Point Relays, Synchronized Link Overlay and Smart Peering, respectively) and analyze their most relevant properties, both from theoretical and experimental (simulation-based) perspectives.

4.1 The notion of overlay

The three main operations of link-state routing in ad hoc networks can be reduced to overlay definition problems. Intuitively, an *overlay* of an ad hoc network is a restricted subset of routers and links of the network in which a certain operation is performed. More formally, the overlay of a network graph $G = (V, E)$ corresponds to a subgraph $S \subseteq G$ containing a subset of vertices $V(S) \subseteq V(G) = V$ and a subset of links $E(S) \subseteq E(G) = E$ of the underlying network graph G. In an ad hoc network, link-state routing operations are performed locally (independently by every router in the network) and thus, the corresponding overlays are built in a distributed fashion and may change dynamically during the network lifetime. Three different types of overlays can be identified, one for each of the following operations:

– **Topology update flooding.** The flooding overlay has to be dense (in the mathematical sense) in every of its connected components – meaning that, in case the overlay is not connected, each of its *pieces* is at distance ≤ 1 (number of hops) of every router in the network. This condition guarantees that a topology update generated in any of such components reaches all routers. Due to the impact of any additional router in the flooding overlay (an additional transmission, and the corresponding utilization of the channel of all its neighbors for every topology update generated in the network), the size of such overlay should be minimized.

– **Point-to-point synchronization.** The synchronized overlay contains links between those routers having exchanged their LSDBs. Formally, such overlay needs to form a spanning

connected subgraph of the general network graph[7], in order to facilitate the distribution of the LSDB over the whole network. The number of LSDB synchronization processes induced by a synchronized overlay is related to the overlay density (the number of links in the overlay), and also depends on the lifetime of the synchronized links (given that synchronization is performed once during the existence of the link). Therefore, minimization of overhead caused by LSDB synchronization requires a low density overlay with stable links.

– **Topology selection.** In wired deployments, all links are typically advertised to ensure that all routers in the network have an identical view of the network topology. In wireless ad hoc networks, this condition is often relaxed, and every router is only expected to acquire a consistent topological view of the network accurate enough to perform correct route computation. Hence, selection of advertised links trades-off the size of the topology update messages and the accuracy of the topological view of the network in all routers. A topology selection rule must, however, produce a connected and spanning subgraph (otherwise there would be non-reachable destinations) and whose set of edges contains all network-wide shortest paths – otherwise the computation would be asymptotically suboptimal[8].

Table 1 summarizes the requirements of each operation to the corresponding overlay.

	Graph / Overlay	Topology requirements	Minimization targets
Full Network	$G = (V, E)$	Connected	-
Flooding	$G_F = (V_F \subseteq V, E_F \subseteq E)$	Dense for every conn. cp.	Number of links
Link-State DB Synchronization	$G_S = (V, E_S \subseteq E)$	Connected and spanning	Number of links & link change rate
Advertised Links (topology selection)	$G_R = (V, E_R \subseteq E)$	Connected and spanning Includes sh.-paths of G	Link change rate

Table 1. Summary of overlay requirements.

4.2 Multi-point relays – MPR

Multi-Point Relaying (MPR) is primarily a technique for efficient flooding. It reduces the number of required transmissions for flooding a message to every 2-hop neighbor of the source by allowing a restricted subset of 1-hop neighbors (*multi-point relays* of the source) to forward it. Figure 3 illustrates that a clever election of 1-hop neighbors as relays can achieve the same coverage as allowing every 1-hop neighbor to transmit (pure flooding, see Fig. 3.a) while reducing significantly the number of redundant transmissions.

The subset of selected relays must satisfy the condition of full 2-hop coverage:

MPR coverage criterion Every 2-hop neighbor of the computing router must be reachable by (at least) one of the selected multi-point relays.

Therefore, an MPR set of a router x can be formally defined as follows:

$$R(x) \subseteq N(x) \text{ is an MPR set of } x \iff \forall z \in N_2(x), \exists y \in R(x) : z \in N(y) \tag{1}$$

---

[7]*I.e.,* has to include every vertex (router) in the network.

[8]In real conditions, the computation may be suboptimal due to stale topology information, transmission failures and such. *Asymptotic suboptimality* implies that even in ideal conditions (message transmission delay $\longrightarrow 0$, collision probability $\longrightarrow 0$, channel failure probability $\longrightarrow 0$) the computation would be suboptimal.
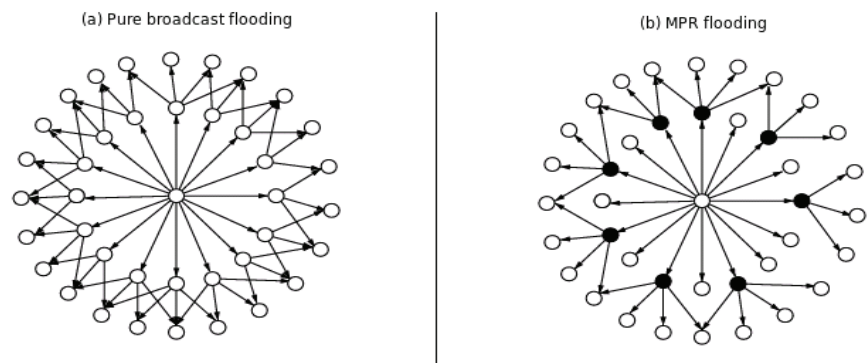
Fig. 3. **(a)** Pure flooding *vs.* **(b)** flooding based on the Multi-Point Relays (MPR) principle. *Solid dots in (b) represent multi-point relays.*

Different heuristics can be used for selecting multi-point relays, all valid as long as they satisfy the MPR coverage criterion. This chapter uses the heuristic in Figure 4, presented and analyzed in Qayyum *et al.* (2002).

$$\begin{cases} MPR(x) = \{\varnothing\} \\ MPR(x) \longleftarrow \{y_{excl} \in N(x) : y_{excl} \text{ provides exclusive coverage to one or more 2-hop neighbor(s) of } x\} \\ while(\exists \text{ uncovered 2-hop neighbors of } x), \\ MPR(x) \longleftarrow y \in N(x) : y \text{ covers the maximum } \# \text{ of uncovered 2-hop neighbors of } x \end{cases}$$

Fig. 4. Summary of the MPR heuristic.

This heuristic assumes that the source is aware of its 2-hop neighbors. Acquisition of the 2-hop neighborhood is thus required. Dependence on 2-hop neighbors has yet another side effect on the MPR properties: given that an MPR selection may become obsolete due to a change in the 2-hop neighborhood of the computing source, stability of the MPR set is not only affected by conditions in MPR links[9], but also by the MPR recalculations due to changes within the 2-hop neighbors or they way in which they are connected to the 1-hop neighbors of the source (see Figure 5). Such sensitiveness of the MPR set of a router to variations in its 2-hop neighborhood has further implications for the MPR overlay that will be further detailed in section 5.
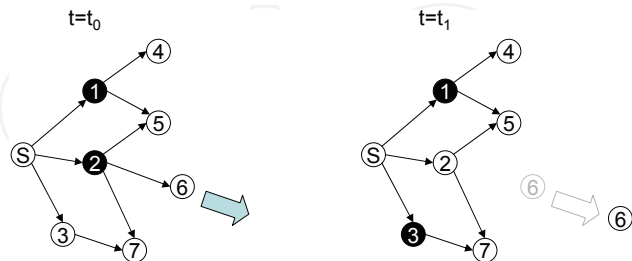

Fig. 5. MPR recalculation due to changes in the 2-hop neighborhood. *Solid dots represent relays of router S.*

4.2.1 MPR as a flooding overlay principle
MPR flooding introduces a directed overlay for every flooded message, by allowing a router to forward such message if and only if the following two conditions are satisfied:

---

[9]An *MPR link* is a link connecting a router to one of its multi-point relays.

1. the message comes from a MPR selector (that is, a neighbor that has selected that router as multi-point relay), and

2. it is the first time the message is received in that router.

Note that condition (2) ensures that the flooding process terminates in a finite number of steps. The (re)transmission of a message by a router triggers a number of retransmissions for which an upper bound is the number of multi-point relays (MPRs) of such router (see Fig. 12), and the process iterates recursively. The number of retransmissions triggered by a single transmission is close to the size of the MPR set in the first steps of MPR flooding. As the flooding advances over the network, an increasing part of the MPR links of the transmitting routers have already received the message and thus do not forward it again (condition (2)), until the message reaches routers for which every neighbor has received a copy, and the flooding terminates.

The flooding overlay formed by the MPR links of every router in an ad hoc network does not need to be connected. *Lemma 1* shows that each of its connected components (in case there are several) are dense in the network. For proofs of the results presented in this section, as well as for examples of disconnected MPR overlays, see Cordero (2010).

Lemma 1 *Let $G = (V, E)$ be a network connected graph, and $H \subseteq G$ the subgraph of G containing the links from every vertex in the graph to all its MPRs. Then, every connected component of H is dense over G.*

Note that this lemma addresses an asymptotic topological property of the overlay generated by condition (1), depending only on the ad hoc network topology. Condition (2) is not contradictory with this property by its own nature, since it removes from the overlay those links which produce no additional coverage. Thus, the conclusion is valid also for the overlay resulting from conditions (1) and (2).

4.2.2 MPR as a synchronized overlay

Multi-Point Relays can also be used for synchronization purposes. A link between two neighbors becomes synchronized if any of its endpoints has selected the other as multi-point relay. The overlay derived from this contains the same links as those described by condition (1) of section 4.2.1. Unlike the flooding overlay, the MPR synchronized overlay is undirected. This is due to the symmetric nature of the LSDB synchronization operation (see section 2.3), and leads to a denser overlay (that is, with more links per router) than the MPR flooding one, as it can be observed in Figure 12.

A synchronized overlay needs to be asymptotically connected[10]. This is not necessarily the case for an overlay containing MPR links of all routers in the network, as it was pointed out in section 4.2.1. *Lemma 2* provides a sufficient condition for *connecting* the MPR overlay.

Lemma 2 *Let $G = (V, E)$ be a network connected graph, and $H \subseteq G$ the subgraph of G consisting of:*

1. *$H_1 \subseteq G$: For every vertex $x \in V$, the edges from x to the neighbor vertices selected by x as MPRs.*

2. *$H_2 \subseteq G$: For a certain $s \in V$, the edges from s to every neighbor of s.*

Then, H is connected.

---

[10]An overlay defined over a network is *asymptotically connected* if its definition ensures connection in conditions of instantaneous transmission (delay $\longrightarrow 0$), error-free and collision-free links (probability of error/collision $\longrightarrow 0$). Note that an overlay may be asymptotically connected, but not connected in practice due to stale information stored in routers, loss of messages and such.

Under these conditions, the MPR-based overlay G_S defined in (2) is asymptotically connected. Despite fulfilling which topological condition, Multi-Point Relaying does not fill well in the requirements for a synchronized overlay, as they were defined in section 4.1. The link density (average number of links per node) of the MPR synchronized overlay, even without considering any additional router s, is significantly higher than the MPR flooding overlay (see Figure 12, below). The reduction with respect to the full network overlay (bidirectional links) is less than a 60%, even for dense networks. In following sections there are presented techniques able to minimize in a higher degree the synchronized overlay.

$$\begin{cases} V(G_S) = V(G) \\ E(G_S) = \{\overline{xy} \in E(G) : x \in MPR(y) \vee y \in MPR(x) \vee (x \equiv s) \vee (y \equiv s)\} \end{cases} \quad (2)$$

In addition to the high overlay density, the MPR synchronized overlay also presents a high overlay link change rate. Changes in the 1-hop of 2-hop neighborhood of a router may cause changes in the MPR set of such router (see Figure 5). This turns useless part of the synchronized links (those connecting with neighbors that are no longer MPRs) and increases the amount of synchronizations to perform (to newly elected MPRs), thus increasing the overhead dedicated to maintain the synchronized overlay.

The *persistent* MPR synchronized overlay overcomes partially these issues. This overlay includes, for each router, existing links to all neighbors that were elected as MPR by this router, even if they were later removed from the MPR set. The persistent mechanism produces significantly larger synchronized overlays (see Figure 13), but these persistent overlays are more stable than the non-persistent ones. Section 5 empirically evaluates the impact of the persistent mechanism in the size and stability of the MPR synchronized overlay (see Figs. 13 and 14).

4.2.3 MPR as a topology selection rule – Path MPR

Section 4.1 points out that the main requirement for an overlay of advertised links (topology selection overlay) is that it is a spanning subgraphs that contains the network-wide shortest paths to all destinations.

Computation of shortest paths involves a metric, that is, a link cost function which gives sense to the notion of *shortest*. But the MPR mechanism is defined in terms of coverage requirements, rather than cost minimization objectives. It becomes thus necessary to translate the cost-based optimality considerations in terms of optimal coverage, in order to reuse and extend MPR as efficient topology selection mechanism.

This section elaborates on the *Path MPR* mechanism, based on the previously stated conditions. Figure 6 displays the input/output block diagram of such approach.
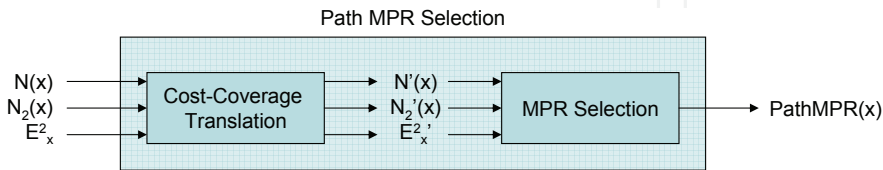

Fig. 6. Block diagram for an MPR-based topology selection algorithm. $E_x^2 \subset E(G)$ *stands for the set of edges connecting vertices within* $x \cup N(x) \cup N_2(x)$.

The cost-coverage translation block (see Fig. 6) extracts the subgraph of (local) shortest paths from the 2-hop and 1-hop neighbors of x to x. Vertices of this subgraph include x, $N'(x)$ and $N_2'(x)$, while the edges are represented by $(E_x^2)'$. $N'(x)$ extracts from $N(x)$ those neighbors

for which the direct link from x is also the optimal (shortest) one; and correspondingly, $N_2'(x)$ extracts from $N_2(x)$ those neighbors for which the optimal path from x has 2 hops. Finally, $(E_x^2)'$ contains those edges (links) of E_x^2 that participate in at least one shortest path from a 1-hop or 2-hop neighbor of x to x. The formal definition of the translation block's output is as follows:

$$\left\{ \begin{array}{ll} N'(x) = & \{n \in N(x) | m(x,n) = dist_2(x,n)\} \subseteq N(x) \\ N_2'(x) = & \{n \in N(x) \cup N_2(x) | n \notin N'(x), \exists m \in N'(x) : m(n,m) + m(m,x) = dist_2(n,x)\} \subseteq N(x) \cup N_2(x) \\ (E_x^2)' = & \{\overline{nm} \in E(G) : n \in N'(x), m \in N_2'(x), m(x,n) + m(n,m) = dist_2(x,m)\} \cup \\ & \cup \{\overline{xn} \in E(G) : n \in N'(x)\} \subseteq E_x^2 \end{array} \right.$$

From these definitions, it is immediate that the Path MPR mechanism, as defined in Figure 6, returns a set of relays that provide (local) shortest paths from every 2-hop neighbor of x to x: if a path $p_{zy} = \{\overline{zy}, \overline{yx}\}$ is not optimal, with $y \in N'(x)$ and $z \in N_2'(x)$, then $\overline{yz}$ will not belong to $E(S_x')$. That ensures that this extension of MPR is able to select the local (2 hops) shortest paths to the computing router x, given that every 2-hop neighbor of x is included in $N_2'(x)$.

A topology selection mechanism based on the advertisement by each router of the Path MPR set, as it has been defined, induces a network-wide overlay that contains, for every router x, the 1-hop neighbors of x that provide shortest paths (in a 2 hop scope) from 2-hop neighbors of x to x. The requirements for topology selection overlays identified in section 4.1 included however:

– Overlay connection.

– Preservation of network-wide (and not only local) shortest paths.

Connection of an MPR overlay can be achieved (*Lemma 2*) by adding to the overlay all the links maintained by a single arbitrary router. *Lemma 3* shows that the overlay that results of adding such additional router (the computing router itself, for Path MPR) contains network-wide shortest paths from every destination of the network to the computing router:

Lemma 3 *Let $G = (V, E)$ be a connected network graph, an edge metrics function $cost(e \in E(G))$, a router $s \in V(G)$ and a subgraph $G_s' = (V, E_s')$ including:*

1. the edges connecting s to its 1-hop neighbors, and

2. for every router x of the network, the edges from x to those 1-hop neighbors of x providing local shortest paths from every 2-hop neighbor of x to x.

Then, the Dijkstra algorithm computed on a source router s over G_s' selects the shortest paths in G from the source to every possible destination.

Note that, as other improvements are possible (such as including not only $N(x)$ but also $N_2(x)$), the previous lemma states a sufficient condition for the asymptotic correctness of an MPR-based topology selection overlay.

4.3 The Synchronized Link Overlay-Triangular – SLO-T

The Synchronized Link Overlay (SLO) is an overlay-based technique inspired by the Relative Neighborhood Graph (RNG), first presented in Toussaint (1980). Given a set of points S in a plane, the relative neighbor graph of S is the graph that results from considering links between points in S, except those connecting points for which there are points *closer*[11] to them than the

---

[11]Even though RNG was originally defined for Euclidean distances (so the notion of close has to be understood under such distance), it can be easily generalized to other metrics.

routers themselves to each other. Included links thus connect pairs of points $\{u,v\}$ for which the intersection of circles centered on u and v, with radius the distance from u to v, contains no other points of S (see Figure 8, the intersection corresponds to the dotted region). More formally, the relative neighbor graph of S is defined as follows:

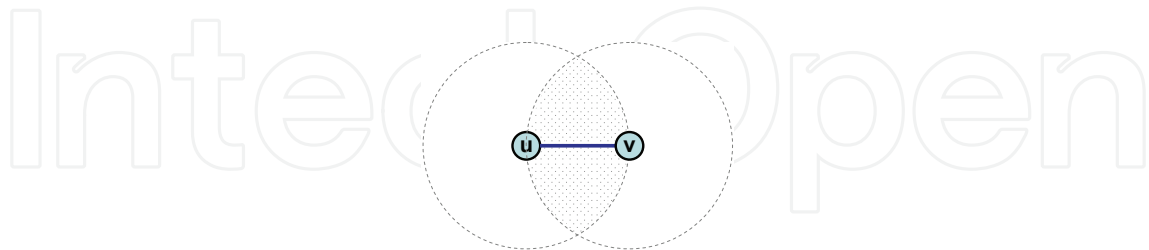$$RNG(S) = \{\overline{xy}, x,y \in S : \nexists z \in S : dist(x,z), dist(z,y) < dist(x,y)\}$$

Fig. 7. Link $\overline{uv}$ belongs to $RNG(S)$ if the dotted region does not contain any other point of S.

where *dist* represents the standard, Euclidean distance in the plane. A similar principle is used in SLO. A link of a network graph $G = (V,E)$ is not synchronized under this rule if there is a chain of common neighbors to both endpoints of the link such that the links in the chain are cheaper (w.r.t. the metrics) than the considered link.

$$\overline{ab}) \notin SLO(G) \Longleftrightarrow \exists c_1, c_2, c_3, ..., c_n : \left\{ \begin{array}{l} \forall i \leq n, c_i \in N(a) \cap N(b) \\ m(a,b) > max\{m(a,c_1), m(c_1,c_2), ..., m(c_n,b)\} \end{array} \right.$$

This section elaborates on a simplified version of the SLO, the Synchronized Link Overlay Triangular (SLO-T). This version restricts the chain of intermediate common neighbors $\{c_1, c_2, ..., c_n\}$ to a single neighbor. It consists of synchronizing a link between two neighbor routers u and v if and only if it does not exist any router w that is common neighbor of u and v and is closer or at the same distance to u and v than they are to each other. Note that this simplification generalizes RNG for arbitrary metrics m. In case of link cost equality (*i.e.*, $m(\overline{uw}) = m(\overline{wv}) = m(\overline{uv})$, m being the metric function), the tie is broken by excluding from synchronization the link connecting the routers with lowest ids.

Different metrics lead to different SLO-T rules. Two variations are considered in this section: the unit link cost (associated to the SLOT-U rule), and the distance-based cost (associated to the SLOT-D rule). Note that the tie breaking applies for the former (as all the link costs are equal to 1), while the main rule is implemented for the latter. Both variations are formally defined as follows:

$$\left\{ \begin{array}{lll} SLOT_U(G) & = & \{\overline{xy} \in E(G) : (\nexists z \in V(G), z \in N(x) \cap N(y) : id_z > max\{id_x, id_y\})\} \\ SLOT_D(G) & = & \{\overline{xy} \in E(G) : (\nexists z \in V(G), z \in N(x) \cap N(y) : m(x,y) \geq max\{m(x,z), m(z,y)\})\} \end{array} \right.$$

SLOT-U can be implemented more easily since it does not require any particular mechanism to monitor and measure the link cost: all the available links are treated equally, with the same uniform metric. For SLOT-D, in contrast, it is needed a mechanism to estimate the distance between two neighbor routers, something that can be achieved by location-based means (such as GPS).
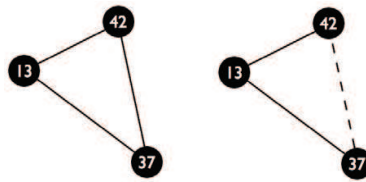
Fig. 8. The SLOT triangular elimination under unit link cost. *The link connecting routers with the highest ids, $\overline{42,37}$ in the picture, is excluded.*

SLOT inherits the properties required for a synchronized overlay (connection and spanning subgraph) from the Relative Neighbor (RNG). For any set of points S of the plane, Toussaint (1980) shows that $RNG(S)$ contains the Minimum Spanning Tree (MST) of G. Hence, SLOT contains it also and, in particular, is connected and a spanning subgraph of G.

Link synchronization and flooding operations require low density overlays that contain the most stable links, as mentioned in section 4.1. The two following sections elaborate on the overlay density and link stability for SLOT-U and SLOT-D from two different perspectives: theoretical analysis on mobile conditions and simulations of static scenarios. Proofs for the results presented in the remaining of the section are detailed in Baccelli *et al.* (2010). Theoretical analysis assumes a unit disk graph model, in which routers are distributed uniformly (approximated by Poisson distribution) over a large enough scenario (area $A \longrightarrow \infty$, not considering border effects) and move following isotropic random walks with an average speed s.

4.3.1 Overlay density

An overlay containing the full network has $M_{full} = \pi\nu$ links per router in average under the unit disk graph model, where ν is the network density. *Theorems 1* and *2* show how the overlay density is reduced when using SLOT with unit cost and distance-based cost, respectively.

Theorem 1 *The average number of SLOT-U links per router satisfies, as a function of the network density ν,*

$$M_u(\nu) = \int_{\frac{\pi}{3}}^{\frac{\pi}{2}} d\theta \, \frac{8\pi}{\nu(A(\theta))^2} sin(2\theta)(\nu A(\theta) + e^{-\nu A(\theta)} - 1)$$

and tends when network density $\nu \longrightarrow \infty$, to

$$M_u = \int_{\frac{\pi}{3}}^{\frac{\pi}{2}} d\theta \, \frac{8\pi sin(2\theta)}{2\theta - sin(2\theta)} + O\left(\frac{1}{\nu}\right) \approx 3.604$$

Theorem 2 *The average number of SLOT-D links per router satisfies, as a function of the network density ν,*

$$M_d(\nu) = \int_0^1 dr \, 2\pi\nu r e^{-r^2 A\left(\frac{\pi}{3}\right)}$$

and tends when network density $\nu \longrightarrow \infty$, to

$$M_d = \frac{\pi}{2\frac{\pi}{3} - \frac{\sqrt{3}}{2}} + O(\nu e^{-\nu(\frac{2\pi}{3} - \frac{\sqrt{3}}{2})}) \approx 2.558$$

where $A(\theta) = 2\theta - sin(2\theta)$. Figure 9.a indicates the evolution of SLOT-U and SLOT-D overlay densities depending on the network density ν. It can be observed that the density reduction, while being relevant for both SLO-T variations, is more significant for the distance-based cost: in this case, routers have more information about the network topology and can thus perform a more accurate synchronized links selection.

Theorems 1 and *2* shows that SLOT overlay (both the unit cost and distance-based cost variations) densities are upper-bounded by finite limits (V_u and V_d) which do not depend on the network density. This is a outstanding advantage of SLOT-like solutions with respect to other overlays for which the size (number of links) grows with the full network density, mainly for very dense networks.

Figure 12 (see below) confirms the previous theoretical analysis with an experiment that measures the average number of synchronized links in static uniformly distributed networks over a finite square scenario, for different network densities. Distance-based costs are implemented by means of a discrete function $m_d(\overline{xy}) = \lceil \frac{K}{r} d(x,y) \rceil \in \mathbb{N}$ ($d(x,y)$ measuring the Euclidean distance between x and y), that quantizes the link length into a number between 1 and K.

It can be observed that SLOT overlays are in general less dense than the MPR overlays studied in section 4.2, in particular with very dense networks. For low densities, however, SLOT-U produces overlays with a very similar asymptotic density to the directed MPR flooding (directed) overlay.

4.3.2 Link stability
Let $\Delta(s)$ be the average relative speed between two routers. Then, the link rate change under the unit disk graph, for an isotropic random walk router mobility, corresponds to $V_{full} = 2\Delta(s)v$. *Theorems 3* and *4* show that links belonging to SLOT variations have a significantly lower change rate. Figure 9.b illustrates such stability for a moderate mobility scenario (constant router speed $s = 5m/s$).

Theorem 3 *The average number of SLOT-U links per router satisfies, as a function of the network density v,*

$$V_u(s,v) = \Delta(s) \int_{\frac{\pi}{3}}^{\frac{\pi}{2}} d\theta \frac{32\theta sin(2\theta)}{v(A(\theta)^3)} (A(\theta)v - 2 + e^{-vA(\theta)}(2 + vA(\theta))) \qquad (3)$$

where $\Delta(s)$ is the average relative speed between routers. For constant speed ($\Delta(s) = \frac{4}{\pi}s$), equation (3) becomes

$$V_u(s,v) = \frac{128s}{\pi} \int_{\frac{\pi}{3}}^{\frac{\pi}{2}} d\theta \frac{\theta sin(2\theta)}{(2\theta - sin(2\theta))^2} \approx 4.146s + O(\frac{4s}{\pi v})$$

Theorem 4 *The average number of SLOT-D links per router satisfies, as a function of the network density v,*

$$V_d(s,v) = \frac{4}{3}\Delta(s) \int_0^1 2\pi v^2 r^2 e^{-r^2 v A(\frac{\pi}{3})} \qquad (4)$$

where $\Delta(s)$ is the average relative speed between routers. For constant speed ($\Delta(s) = \frac{4}{\pi}s$), equation (4) becomes

$$V_d(s,v) \approx 3.471s\sqrt{v}$$

Note that SLOT-U presents a higher stability than SLOT-D, which is caused by the sensitivity of the latter variation to router position (and thus distance to the other link endpoint) changes. Changes in the link cost may lead to new SLOT-D elections, while the unit cost (SLOT-U) ensures that there will be no changes in the synchronization decisions as long as there are no new routers forcing new triangular eliminations (see Fig. 8).

4.3.3 Link characterization depending on distance
The two considered variations of SLOT (SLOT-U and SLOT-D) assume different behaviors with respect to the distance of the links selected for synchronization. Intuitively, the longer
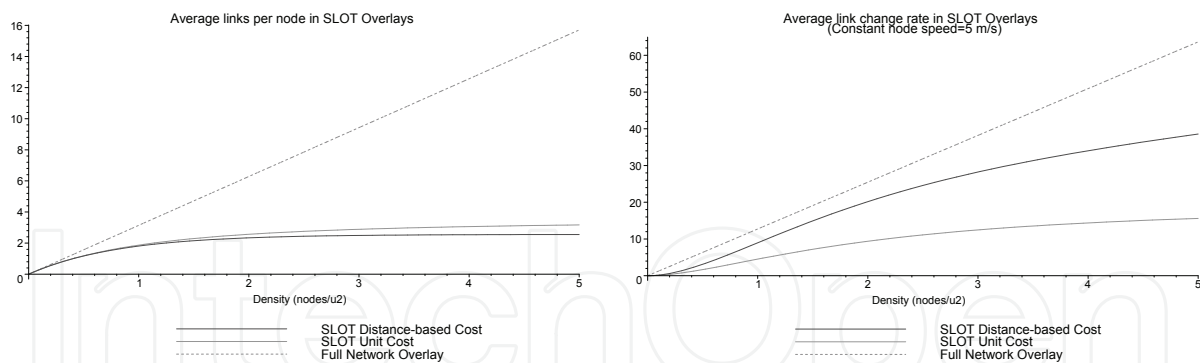
Fig. 9. **(a)** Average SLOT overlay density (links per router), and **(b)** average SLOT links change, for constant speed $s = 5m/s$.

the link is, the less likely is that there is a common neighbor to both endpoints whose identity is higher than those of the involved routers (and thus excludes the link from the synchronized overlay, according to the tie breaking rule of SLOT-D). On the contrary, the more far two neighbor routers are, the easier is that a common neighbor is closer to both endpoints – thus, the more likely is that SLOT-D discards such link.

This intuition can be formalized as follows. Let us denote the synchronization relationship by the symbol $\sim$. Then, the probability that a link $x \longleftrightarrow y$ is synchronized under the SLOT-U rule is:

$$P(x \sim y)_U = \left(\frac{2}{3}\right)^{n_{x,y}} \tag{5}$$

where $n_{x,y}$ is the number of common neighbors of x and y.

In consequence, the probability that a link between two routers x and y at distance $d < r$ is selected as part of the synchronized link can be defined as:

$$
\begin{aligned}
P(x \sim y | m(\overline{xy}) = d)_U &= \sum_{k=0}^{\infty} P(n_{x,y} = k) P(x \sim y | m(\overline{xy}) = d, n_{x,y} = k) = \sum_{k=0}^{\infty} \left(\frac{2}{3}\right)^k e^{-\nu A_r(d)} \frac{(\nu A_r(d))^{k+2}}{(k+2)!} = \\
&= e^{-\nu A_r(d)} \sum_{k=0}^{\infty} \left(\frac{2}{3}\right)^k \frac{(\nu A_r(d))^{k+2}}{(k+2)!} = \frac{3}{2} e^{-\nu A_r(d)} \left(\frac{3}{2} e^{\frac{2}{3}\nu A_r(d)} - \frac{3}{2} - \nu A_r(d)\right)
\end{aligned} \tag{6}
$$

where ν is the router density in the network and $A_r(d)$ is the intersection area between two circles of radius r at a distance d:

$$A_r(d) = 4 \int_{\frac{d}{2}}^{r} \sqrt{r^2 - x^2} dx \tag{7}$$

Figure 10 indicates the probability that a link is selected for synchronization, depending on its length.

The same argument applies for the distance-based cost of SLOT-D: a link between routers at distance d is selected for synchronization if there are no routers which are closer to any of the link endpoints that both endpoints to each other. If the link cost corresponds exactly to its length, this condition leads to:

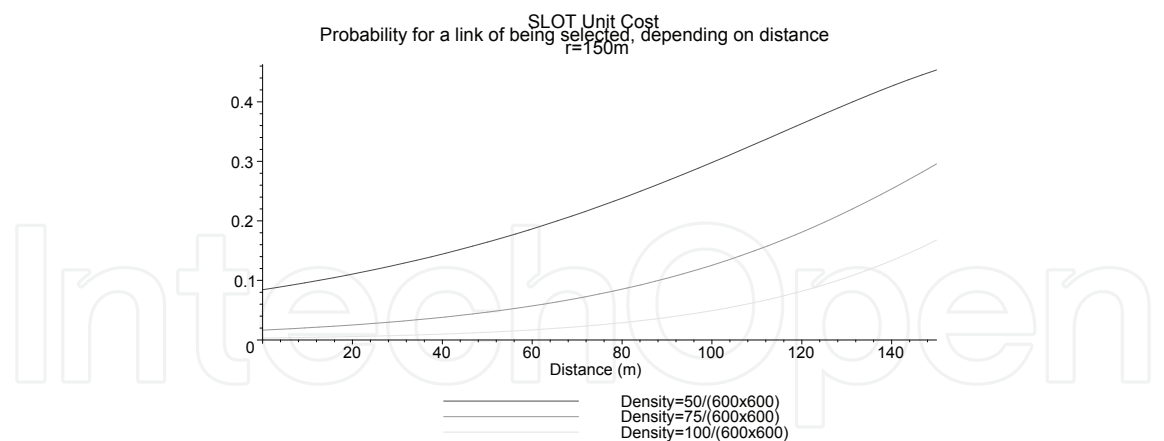$$P(x \sim y | m(\overline{xy}) = d)_D = 1 - e^{-\nu d^2 (2\frac{\pi}{3} - \sin(2\frac{\pi}{3}))} \tag{8}$$

Fig. 10. Probability for a link of being selected, under SLOT (unit cost), for different network densities ν.

With a the more realistic model of link cost (*e.g.*, $cost = \lceil K\frac{d}{r} \rceil$), (8) becomes

$$P(x \sim y | m(\overline{xy}) = d)_D \quad = \quad 1 - e^{-\nu \lceil \frac{K}{r}d \rceil^2 (2\frac{\pi}{3} - sin(2\frac{\pi}{3}))} \tag{9}$$

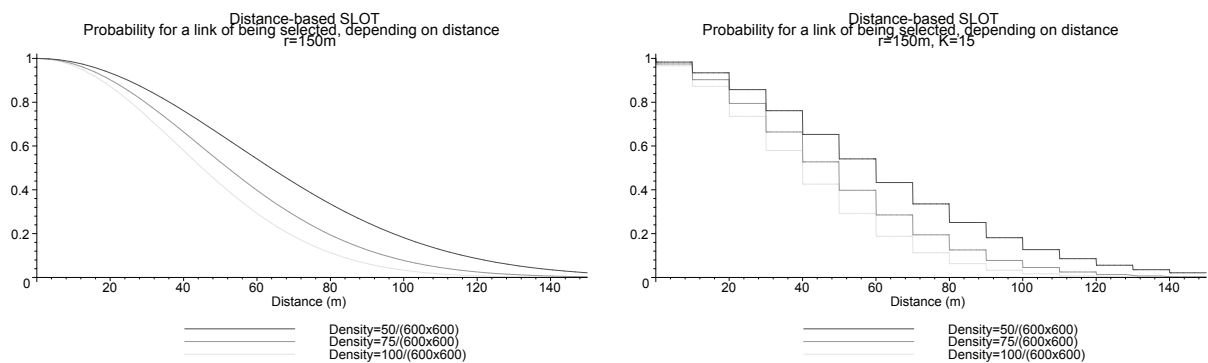where K stands for the number of discrete values for the distance-based quantized cost.

Fig. 11. Probability for a link of being selected, under SLOT based on distance, for different network densities ν.

The upper quantization of the link cost reduces the probability of selecting a router for synchronization. This is consistent with the effect observed in Figures 9.a and 12, in which the theoretical number of links per router achieved by SLOT-D (with an ideal link cost equal to the length) was significantly higher than the average number of links per router obtained in the static simulations (performed with a quantized link cost, $K = 10$).

4.4 The Smart Peering rule – SP

The Smart Peering rule was presented in Roy (2005) as a mechanism for link-state database synchronization and flooding in ad hoc networks ruled by OSPF. Under this rule, a router x synchronizes its link-state database with a bidirectional neighbor y if and only if:

– There are not *enough* available paths from x to y within the synchronized overlay (consisting on links selected through the Smart Peering rule).
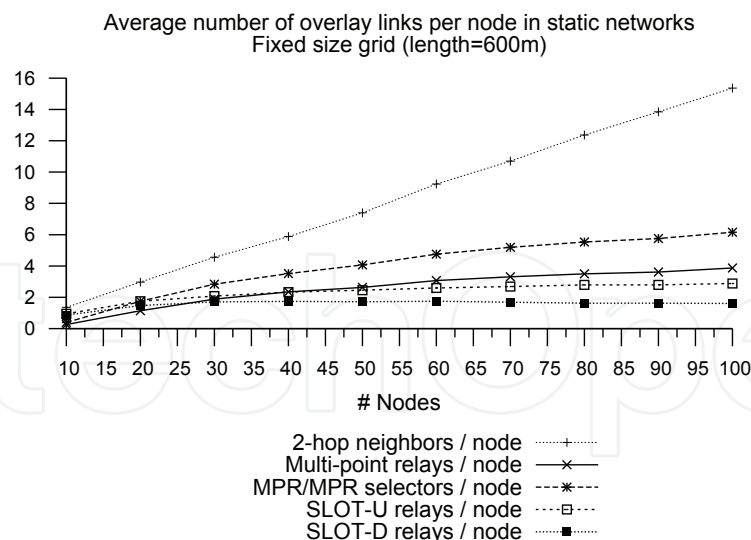
Fig. 12. Density of MPR and SLOT overlays in static networks. *The SLOT-D simulations are computed with the quantized cost: $cost(\overline{xy}) = \lceil K\frac{d(\overline{xy})}{r} \rceil$, with $K = 10$ and $d(\overline{xy})$ being the Euclidean distance between x and y.*

- The link between *x* and *y* provides a *significantly* cheaper path from *x* to *y* than those already present in the synchronized overlay.

The precise meaning of *enough* and *significantly* defines the different possible variations of Smart Peering. This section considers the most basic version: a neighbor is synchronized if and only if there are no paths within the synchronized overlay to it. In all variations a link synchronization is triggered when any of the involved routers (not necessarily both) decides to allow such operation.

Performing SP-based decisions requires that every router determines whether a synchronized path between itself and the router candidate to synchronization exists. When using a link-state routing protocol such as OSPF, such verification can be done by means of the Shortest Path Tree (SPT), if synchronized links are included and can be identified within the SPT. In this sense, Smart Peering needs to rely on a topology selection mechanism that advertises the synchronized links of the routers in the network.

From an asymptotic perspective, the overlay induced by the Smart Peering rule fulfills the topological requirements for a synchronized and a flooding overlay: *Lemma 4* shows that Smart Peering decisions lead to an asymptotically connected overlay. By construction, this overlay includes every router belonging to a connected ad hoc network, which trivially implies the density of the Smart Peering overlay.

Lemma 4 *Using the Smart Peering rule, every pair of routers (x,y) of a connected network are connected through at least one SP-synchronized path.*

Proof: Let d be the minimum distance in bidirectional hops from x to y ($d < \infty$).

- $d = 1$: if x and y are not already connected via an SP-path, the two routers will synchronize their link-state databases, by definition of Smart Peering.

- $d \Rightarrow d + 1$. Let us consider the set of bidirectional neighbors of x, $N(x)$. There exists at least one $z \in N(A)$ for which $d(z,y) = (d + 1) - 1 = d$, and is thus SP-connected to y (induction hypothesis). Calling $\overline{xz}$ the SP-route between x and z (which exists as proved for the case $d = 1$), $\overline{zy}$ the SP-route between z and y, it is clear that the route $\overline{xz} \cup \overline{zy}$ is an SP-route between x and y, and that concludes the proof. $\square$

Unlike the techniques presented in previous sections, Smart Peering decisions are not taken under local (neighborhood) considerations. The overlay produced by the Smart Peering rule for a given ad hoc network cannot thus be deduced from the relations between routers. Rather, it may be significantly affected by aspects such as the order of appearance of the routers in the network, the trajectory of routers or the mobility patterns of the network. This latter is probably one of the most interesting features of the Smart Peering rule for mobile ad hoc networks.

For a static and stable network with error-free links, in which synchronization decisions are taken independently and concurrently, the overlay induced by Smart Peering is roughly equivalent to the full network overlay. When a router first appears in a network, and is discovered by its neighbors, none of them has any trace of it in the link-state database maintained locally. In consequence, all of them initiate synchronization processes with the new router (the argument is also valid from the point of view of such new router).

In wireless ad hoc networks, the characteristics of the Smart Peering relay are more unpredictable. For mobile scenarios, the SP rule filters the less stable links, those between routers with high relative speed. Once the first LSDB synchronization of a router has been completed and advertised to the whole network, no other router will accept a new synchronization with it as long as the trace of the first one remains. Highly mobile routers will therefore have difficulties to establish synchronized links after the completion of the first one, while routers presenting a lower relative speed to their neighbors will have more chances to keep up their synchronized links by means of their initial performed synchronization. This behavior is confirmed empirically (via simulations) in section 5.4.

5. Application: OSPF extensions for ad hoc operation

This section addresses an experimental evaluation of the overlay techniques presented in section 4, implemented as extensions to the modules of flooding, LSDB synchronization and topology selection of OSPF. These extensions are tested in ad hoc networks, both static and mobile, but would coexist with classic OSPF in compound wired/wireless networks. Section 5.1 indicates the parameter set and the implementations used for the simulations. Section 5.2 describes briefly the main elements of OSPF, and section 5.3 presents each of its analyzed ad hoc extensions. Sections 5.4, 5.5, 5.6 and 5.7 discuss the performance of such extensions and their corresponding techniques in the different link-state routing modules.

5.1 Simulation parameters

Implementations of the extensions are publicly available[12], and were simulated with the Georgia Tech Network Simulator (GTNetS, see Riley (2003) for reference). Unless otherwise specified, the set of simulation parameters corresponds to the set described in Baccelli *et al.* (2009), except for the following aspects:

– Node mobility: constant node speeds, $0\frac{m}{s}$ (static scenario) and $5\frac{m}{s}$ (mobile scenario).

– Pause time: $0sec$.

– Time interval between periodic topology refloods (*LSRefreshInterval*): $20sec$.

5.2 Overview of OSPF

The Open Shortest Path First protocol (OSPF) is, together with IS-IS, one of the most widespread protocols for link-state routing within an Autonomous System [Halabi (2000)].

---

[12]INRIA OSPF Extensions for MANET Code: `www.emmanuelbaccelli.org/ospf`

Although it supports a hierachical 2-level structure based on *areas*, this section focuses on a single area scheme[13].

Routers in OSPF maintain an identical Link-State Database (LSDB) and thus share the exact same view of the network topology. The routes are extracted from the Shortest Path Tree (SPT), which is computed over the LSDB by means of the Dijkstra algorithm. Network topology information is disseminated through topology update messages called *Link State Advertisements* (LSA). These LSAs are flooded in a reliable manner (that is, implying hop-by-hop acknowledgements in case of successful transmission and retransmission in case of failure), both periodically and following a topology change event.

In OSPF, the flooding operation depends on the type of interface performing the transmission. For Non-Broadcast Multiple Access (NBMA) interfaces, the flooding is centralized by a *Designated Router* (DR), which is elected by all routers in the link. Such DR synchronizes its LSDB with those of all its neighbors (in OSPF terminology, synchronized links are denominated *adjacencies*), and it is responsible of diffusing topology updates (LSAs) originated in the link to all its synchronized (adjacent) neighbors. Point-to-point synchronization is performed by exchanging *Database Description* (DBD) packets and requesting the most updated LSAs that are missing in a reliable fashion. LSAs originated by the routers (Router-LSAs) advertise the adjacent links of the originator.

Routers annouce their presence in the network and learn the presence of its neighbor through the periodical exchange of *Hello* messages. Typically, such messages advertise the source identity and the list of neighbhors. That allows every router in the network to keep track of its 2-hop neighborhood, as well as to establish symmetric (*bidirectional*) communication with its 1-hop neighbors. Flooding, synchronization and routing decisions are performed over the available bidirectional links in the network.

These properties define implicitly an OSPF link model: adjacencies are selected among the set of bidirectional links; and the Shortest Path Tree is computed over the adjacent overlay. The fact that flooding is performed over adjacent links implies that control traffic (LSAs and database exchange packets) only flows through synchronized links, while data traffic is sent via shortest paths. These two principles constitute the core of the OSPF routing philosophy.

5.3 OSPF-based configurations

This section examines different configurations of OSPF that explore other principles for data and control traffic forwarding than those from classic OSPF. They combine the overlay techniques presented in section 4 to optimize the performance in ad hoc networks of the link-state routing modules (operations). Table 2 summarizes the architecture of such configurations.

	MPR-OSPF	MPR+SP	OR/SP	SLOT-OSPF
Flooding	MPR	MPR	MPR(SP)	MPR
Synchronization	MPR+synch	SP	SP	SLOT-U
Routing	Path MPR	Path MPR	SP	Path MPR

Table 2. OSPF MANET Configurations.

MPR-OSPF and OR/SP are standard extensions for OSPF MANET (RFC 5449 (2009) and RFC 5820 (2010)). The considered configuration of Overlapping Relays (OR) performs flooding, synchronization and topology selection based exclusively in Smart Peering (SP), without considering additional links (denominated *unsynchronized adjacencies* in RFC 5820) in any of

---

[13]For a more detailed description of OSPF and its area-based architecture, see Moy (1998b).

these operations. SLOT-OSPF is a variation of MPR-OSPF which uses SLOT-U for LSDB synchronization, while keeping MPR as a flooding and topology selection overlay (Path MPR). Finally, MPR+SP incorporates Smart Peering as synchronization criterion in the framework of MPR-OSPF, also keeping MPR for flooding and topology selection.

5.4 Overlay properties validation

The simulations validate the main properties of the overlays described in section 4. Figure 13.a displays the average density of the considered overlay techniques, for a static and moderately mobile scenario (constant router speed, 5 m/s). In the static deployment, it can be observed that the Smart Peering rule produces the most dense overlay, showing a linear increase with respect to the full network density. Its size is only comparable to the one achieved by the MPR synchronized overlay for low density networks, but it has to be pointed out that a significant part of such overlay consists of *persistent* sychronized links which are not costly in terms of database exchange. Therefore, the network overlay reduction performed by SP is very low when routers do not move and thus the corresponding router traces cannot be used to reject (a part of the) new synchronizations – this effect disappears in mobile scenarios (see Figure 13.b). The MPR flooding overlay achieves a significantly lower density than the sychronized MPR overlay, and the Synchronized Link Overlay Triangular (SLOT) for unit link costs remains below the theoretical upper bound shown in *Theorem 1*.
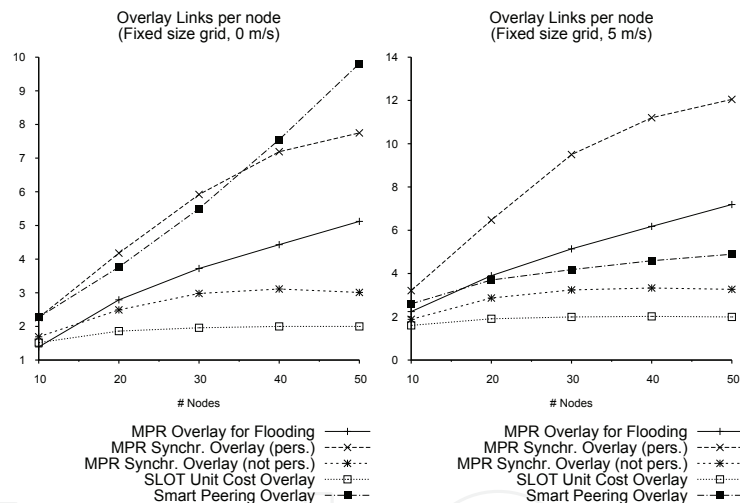
Fig. 13. Overlay link density for **(a)** static scenarios and **(b)** mobile scenarios (5 m/s).

5.5 Link synchronization – adjacencies

The average lifetime of the synchronized links (adjacencies) for each configuration is displayed in Figure 14.a. It confirms that adjacencies selected through the Smart Peering rule (both in configurations MPR+SP and Overlapping Relays) are more stable than those selected by MPR-OSPF. The Smart Peering ability to choose the most stable links for synchronization is also visible in Figure 14.b, where the adjacent set of SP configurations remains stable for a significant range of link quality[14] values. On the contrary, MPR-OSPF keeps increasing the number of adjacencies as α grows (the channel becomes more reliable).

Adjacency stability of MPR+SP and Overlapping Relays present a significant difference, although both configurations rely on the same technique (Smart Peering) for selecting synchronized links. This gap is caused by the neighbor keep-alive mechanism. In OSPF,

---

[14]For more details on the link quality model and the parameter $\alpha \in [0,1]$, see Henderson *et al.* (2005).
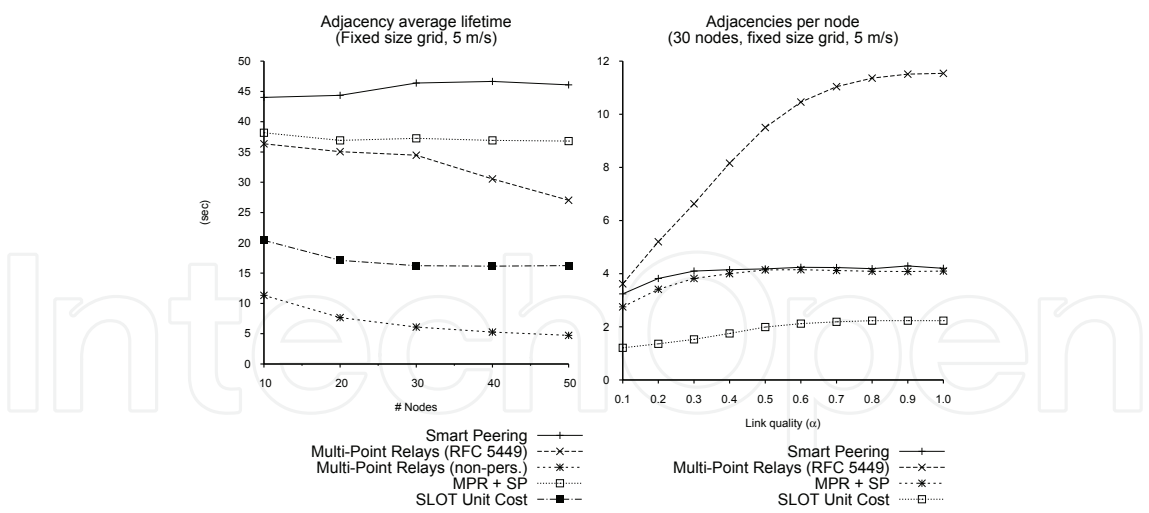
Fig. 14. **(a)** Average adjacency lifetime, depending on the network density, and **(b)** Average number of adjacencies depending of link quality (30 routers, 5 m/s).

a router declares a neighbor *dead* if it has not received a Hello packet from it during a *DeadInterval* period. In the simulated moderately lossy channel ($\alpha = 0.5$), the probability of losing a packet is related to the length of such packet. Since Hello packets of MPR+SP are significantly longer than those of Overlapping Relays (see Figure 15.a), the loss of packets in the former configuration is more relevant, causing the breakup of more links (and, in particular, adjacencies) than for the latter. The impact of such keep-alive mechanism has been measured in Figure 15.b, which shows the variation of the adjacency lifetime achieved for the same MPR+SP configuration when Hellos are the only packets assuming a keep-alive role, and when other packets (Link State Updates) are used as well for the same purpose.
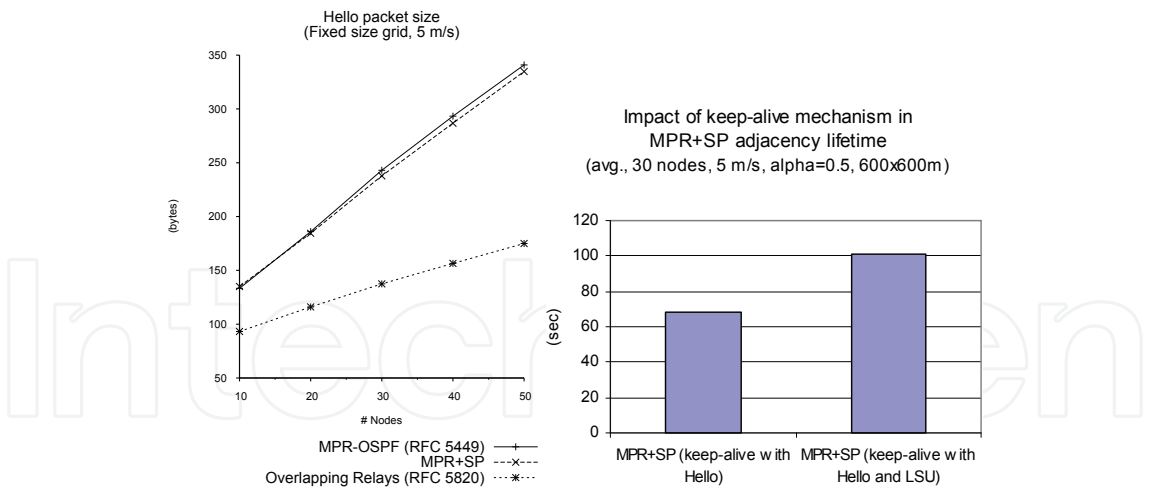
Fig. 15. **(a)** Average size of Hello packets, **(b)** Impact of keep-alive configuration in adjacency lifetime (fixed grid of length $600m$, with speed $5m/s$).

5.6 Route selection and routing quality

From the considered overlay techniques, only Multi-Point Relaying can be used as a basis for an efficient (optimal) topology selection mechanism. In section 4 it was shown that the Path MPR algorithm, which adapts the MPR to the requirements of a topology selection overlay, generates an overlay that contains the network-wide shortest paths. The impact of such property is shown in Figure 16.a, which compares the average path length for data traffic

of configurations using Path MPR, with the path length achieved by a configuration that uses Smart Peering, which does not advertise in general optimal routes – the Overlapping Relays configuration, without *unsynchronized adjacencies*. Suboptimal routing of data traffic may lead to a significant waste of bandwidth dedicated to forward data packets through non-optimal routes – see Figure 16.b for data delivery ratio: the configuration not providing shortest paths performs significantly worse than the others.
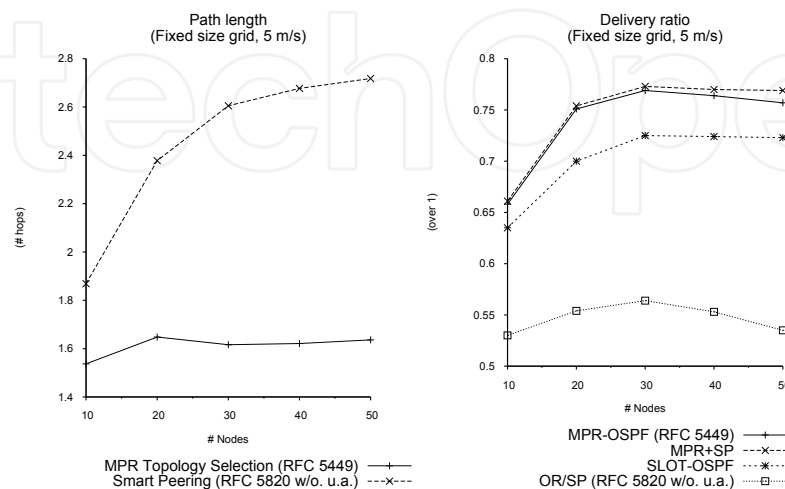
Fig. 16. **(a)** Path length, **(b)** Data delivery ratio, for $5m/s$.

5.7 Flooding and control traffic overhead

MPR and SP are used for reliable flooding in the configurations analyzed in this section. MPR-OSPF relies on (directed) MPR links to flood control traffic, expecting acknowledgement from MPR synchronized (persistent) links. In the Overlapping Relays configuration, the flooding operation is performed in two rounds. The first one involves the MPRs computed among the Smart Peering links, called *active Overlapping Relays*. Absent this acknowledgement, other SP-synchronized neighbors may retransmit the pending packet until it is acknowledged.

Let us first discuss the implications of the MPR election over the SP-synchronized overlay. When compared with the selection of Multi-Point Relays among the bidirectional neighbors of a source, Overlapping Relays presents a lower amount of MPRs per router and a significantly higher stability of such relays, as shown in Figure 17.a and 17.b.

The drawbacks of this approach are however significant. In first term, computing MPRs over a restricted overlay weakens the main advantage of using Multi-Point Relays for flooding, which is the ability of reaching all the 2-hop neighbors of the source while avoiding redundant transmissions. Since the neighborhood topology in which MPR operates is distorted by the Smart Peering selection rule, the set of reachable 2-hop neighbors becomes also affected and the quality of the flooding operation becomes damaged, as Figure 17.c shows.

In second term, MPR selection over the Smart Peering overlay makes the MPR computation nearly irrelevant. If the probability of relaying an MPR flood is close to $\frac{M_r}{M}$ (with M_r being the average number of relays per router and M the average number of bidirectional neighbors), the situation in sparse networks (such as the Smart Peering overlay) is close to $M_r = M$, meaning that almost every SP-synchronized neighbor will become a multi-point relay, thus making wasteful the relay selection process.

The control traffic mobilized by every configuration is displayed in Figure 18, together with the overall traffic. Such overall control traffic has two main components: the traffic dedicated to adjacency-forming processes, which depends on the synchronized overlay, and the reliable
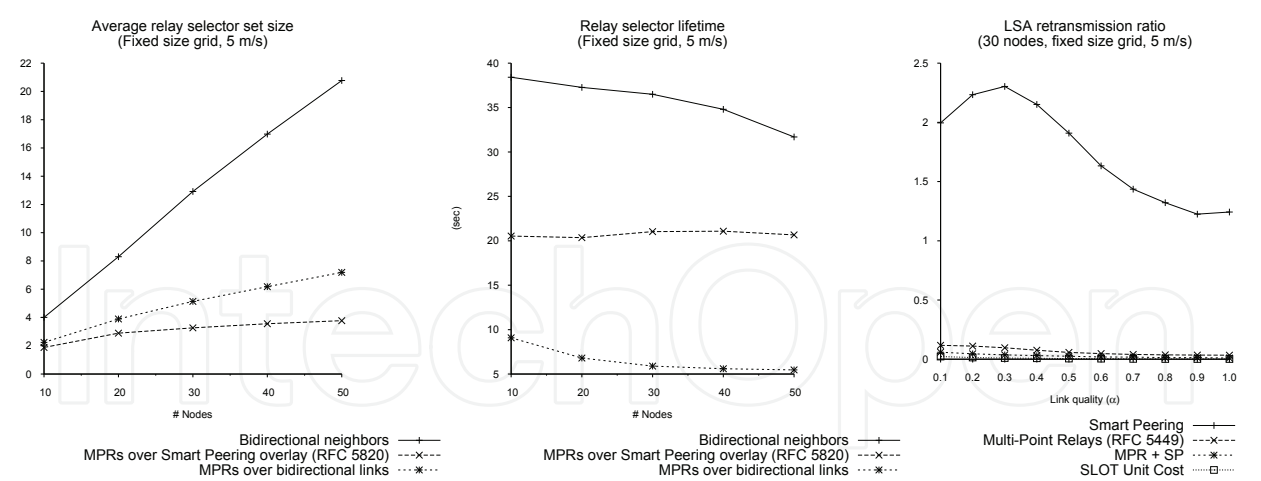
Fig. 17. **(a)** Average size of the MPR set and **(b)** average relay lifetime (5m/s). **(c)** LSA retransmission, depending on the link quality (30 routers, 5m/s. *The LSA retransmission ratio is the number of backup LSA retransmissions over the number of primary LSA transmissions.*

flooding traffic. The figure shows that the analyzed configurations can be grouped in three categories: the one not using MPR at all (Overlapping Relays, with relies on Smart Peering), those using MPR only as a flooding rule (SLOT-OSPF and MPR+SP), and the configuration using MPR both for flooding and synchronization purposes. The results indicate that, while MPR flooding has in general a better performance (in terms of overhead) than other flooding overlays, the use of MPR as a synchronization rule has significant shortcomings in terms of overhead – a conclusion that is consistent with section 4.2. Therefore, configurations exploring less dense overlays for synchronization, while keeping MPR as the reliable flooding overlay, present more balanced trade-offs between flooding quality and control traffic overhead.
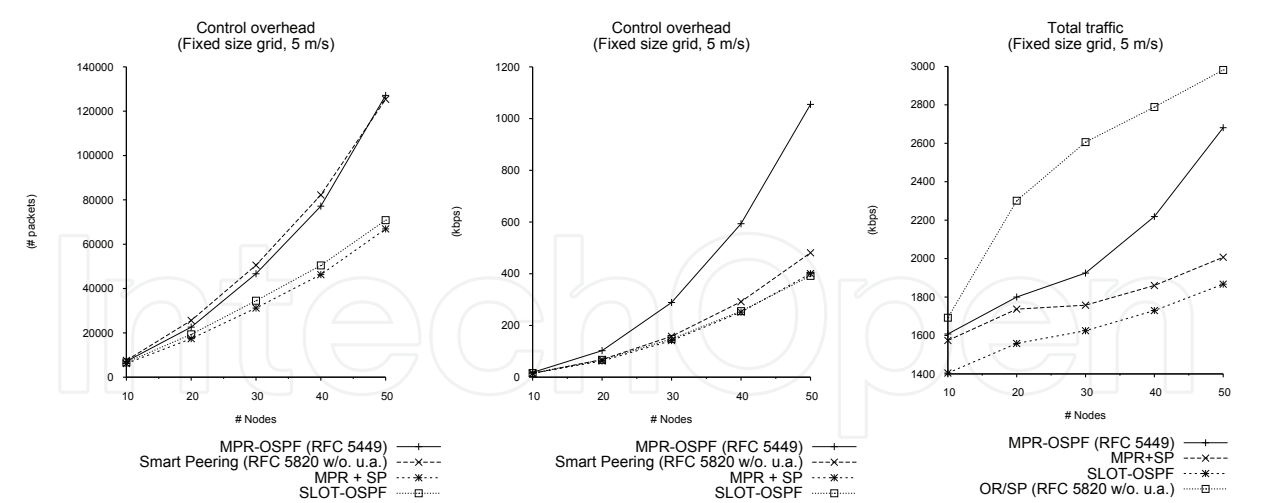
Fig. 18. **(a)** Control traffic overhead, in number of packets, **(b)** in kbps, and **(b)** Total (data+control) traffic, in kbps (5m/s).

6. Conclusion

This chapter has investigated the subject of compound networks, *i.e.* networks comprising of fixed wired routers as well as wireless mobile ad hoc routers. A single protocol is desired to provide routing over such networks in order to avoid sub-optimality due to paths through

gateways between incompatible protocols, and lack of efficient traffic engineering. This chapter has thus reviewed various mechanisms that enable OSPF to fulfill this task. OSPF is indeed a designated candidate for this job, as it is both a popular routing solution for wired IP networks, and quite similar to OLSR, the most deployed MANET routing protocol, also based on a link state algorithm.

This chapter analyzed the specific mechanisms that enable efficient link state routing in compound networks, focusing in particular on different overlay techniques. These techniques were compared via simulations their performance when applied to OSPF. The resulting analysis may be useful in order to design appropriate routing protocols for compound networks.

7. References

Adijh, C.; Baccelli, E.; Clausen, T.; Jacquet, P. & Rodolakis G. (2004). Fish Eye OLSR Scaling Properties. *IEEE Journal on Communications and Networks (JCN)*, Special Issue on Mobile Ad Hoc Wireless Networks, December 2004, pp. 343-351.

Baccelli, E. (2006). *Routing and Mobility in Large Heterogeneous Packet Networks*. PhD Thesis, École Polytechnique, Paris (France).

Baccelli, E.; Jacquet, P.; Nguyen, D. & Clausen, T. (2009). *OSPF Multipoint Relays (MPR) Extension for Ad Hoc Networks*, RFC 5449, IETF, February 2009.

Baccelli, E.; Cordero, J. A. & Jacquet, P. (2009). Multi-Hop Relaying Techniques with OSPF on Ad Hoc Networks, *Proceedings of the 4th IEEE International Conference on Sensor Networks and Communications*, pp. 53-62, IEEE ComSoc, Porto (Portugal), Sept. 2009.

Baccelli, E.; Cordero, J. A. & Jacquet, P. (2010). Using RNG for Reliable Database Synchronization in MANETs, *Proceedings of the 5th IEEE SECON Workshop on Wireless Mesh Networks (WiMESH)*, pp. 13-18, IEEE ComSoc, Boston, MA (United States), June 2010.

Bellman, R. (1958). On a Routing Problem, In: *Quarterly of Applied Mathematics*, No. 16, pp. 87-90.

Clausen, T.; Jacquet, P. (2003). *Optimized Link State Routing Protocol (OLSR)*, RFC 3626, IETF, October 2003.

Coltun, R.; Ferguson, D.; Moy, J. (2008). *OSPF for IPv6*, RFC 5340, IETF, July 2008.

Cordero, J. A. (2010). MPR-based Pruning Techniques for Shortest Path Tree Computation, *Proceedings of the 18th International Conference on Software Telecommunications and Computer Networks*, IEEE ComSoc, Split (Croatia), September 2010. *(to appear)*

Dijkstra, E. W. (1959). A Note on Two Problems in Connection with Graphs, In: *Numerische Mathematik*, No. 1, pp. 269-271.

Ford, L. R. Jr. & Fulkerson, D. R. (1962). *Flows in Networks*, Princeton University Press.

Halabi, S. (2000). *Internet Routing Architectures*, Cisco Press.

Henderson, T.; Spagnolo, P. & Kim, J. H. (2003). A Wireless Interface Type for OSPF, *Proceedings of the IEEE Military Communications Conference (MILCOM)*, pp. 137-145, IEEE ComSoc, Boston, MA (United States), October 2003.

Henderson, T.; Spagnolo, P.; Pei, G. (2005). *Evaluation of OSPF MANET Extensions*, Technical Report, D950-10897-1, Boeing, July 2005.

International Organization for Standardization (2002). *Intermediate System to Intermediate System intra-domain routeing information exchange protocol*, International Standard, Ref. Number ISO/IEC 10589:2002(E), ISO Secretariat, Geneva (Switzerland), 2002.

Jacquet, P. (2006). Control of Mobile Ad hoc Networks, *Proceedings of the IEEE Information*

Theory Workshop, pp. 97-101, IEEE, Punta del Este (Uruguay), March 2006.

Moy, J. (1998a). *OSPF Version 2*, Request For Comments 2328, IETF, April 1998.

Moy, J. (1998b). *OSPF: Anatomy of an Internet Routing Protocol*, Addison-Wesley.

Ni, S.Y.; Tseng, Y.-Ch.; Chen, Y.-S.; Sheu, J.-P. (1999). The Broadcast Storm Problem in a Mobile Ad Hoc Network, *Proceedings of the Annual International Conference on Mobile Computing and Networking*, pp. 151-161, ACM Press, Seattle (United States), August 1999.

Qayyum, A.; Viennot, L. & Laouiti, A. (2002). Multipoint Relaying for Flooding Broadcast Messages in Mobile Wireless Networks, *Proceedings of the 35th Hawaii International Conference on System Sciences*, IEEE ComSoc, Hawaii, HI (United States), January 2002.

Riley, G. F. (2003). The Georgia Tech Network Simulator, *Proceedings of the ACM SIGCOMM Workshop on Models, Methods and Tools for Reproducible Network Research*, pp. 5-12, ACM Press, Karlsruhe (Germany), August 2003.

Roy, A. (2005). *Adjacency Reduction in OSPF using SPT Reachability*, Internet-Draft `draft-roy-ospf-smart-peering-01.txt`, IETF, November 2005. *(obsolete)*

Roy, A. & Chandra, M. (2010). *Extensions to OSPF to Support Mobile Ad Hoc Networking*, RFC 5820, IETF, March 2010.

Toussaint, G. T. (1980). The Relative Neighborhood Graph on a Finite Planar Set, In: *Pattern Recognition*, No. 12, pp. 261-280.

Tseng, Y.-Ch.; Ni, S.-Y. & Shih, E.Y. (2003). Adaptive Approaches to Relieving Broadcast Storms in a Wireless Multihop Mobile Ad Hoc Network. *IEEE Transactions on Computers*, Vol. 52, No. 5, May 2003, pp. 545-557.
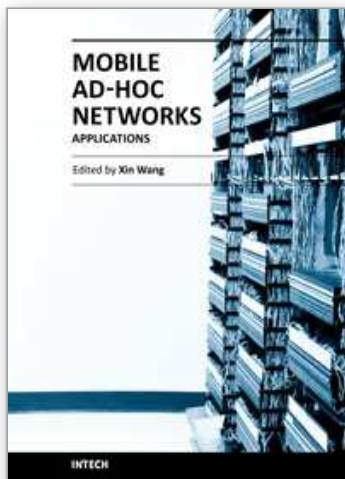
Mobile Ad-Hoc Networks: Applications

Edited by Prof. Xin Wang

ISBN 978-953-307-416-0

Hard cover, 514 pages

Publisher InTech

Published online 30, January, 2011

Published in print edition January, 2011

Being infrastructure-less and without central administration control, wireless ad-hoc networking is playing a more and more important role in extending the coverage of traditional wireless infrastructure (cellular networks, wireless LAN, etc). This book includes state-of the-art techniques and solutions for wireless ad-hoc networks. It focuses on the following topics in ad-hoc networks: vehicular ad-hoc networks, security and caching, TCP in ad-hoc networks and emerging applications. It is targeted to provide network engineers and researchers with design guidelines for large scale wireless ad hoc networks.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

INTECH
open science | open minds