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Abstract: Incorporating multi-hop wireless networks in the IP infrastructure is an effort to which a growing community participates. One instance of such activity is the extension of the routing protocol OSPF, for operation on MANETs. Such extension allows OSPF, the most widely deployed interior gateway routing protocol on the Internet, to work on heterogeneous networks encompassing both wired and wireless routers. The latter may self-organize as multi-hop wireless subnetworks, and may be mobile. Three solutions have been proposed for this extension, among which two based on techniques derived from multi-point relaying (MPR) techniques and OLSR. This paper analyzes these two approaches and identifies some fundamental discussion items that pertain to adapting OSPF mechanisms to multi-hop wireless networking, before concluding with a proposal for a unique, merged solution based on this analysis.

Key-words: Ad hoc, Scalability, IP, OSPF, Routing, Network, Wireless, Multi-hop, Standardization, IETF

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Résumé : Ce rapport étudie différentes solutions proposées récemment pour utiliser OSPF sur les réseaux ad hoc multi-sauts, utilisant des techniques dérivée des multi-points relais (MPR). Les solutions existantes sont analysées et évaluées, permettant d'identifier, en conclusion de ces résultats, une solution hybride optimale en terme de performance.

Mots-clés : Ad hoc, Passage à l'échelle, OSPF, Routage, IP, Réseau, Sans-fils, Multi-saut, Normalisation, IETF

1 Introduction

Link state routing has succeeded to distance vector routing as the dominating technique for interior gateway routing. At the price of having considerably more complex mechanisms than with distance vector, link state algorithms produce protocols that don't diverge, that converge faster and that avoid routing loops. The most typical examples of such protocols are OSPF (Open Shortest Path First [1] [2]) and IS-IS (Intermediate System to Intermediate System [23]), the former being by far the most widely deployed interior gateway routing protocol on the Internet so far.

More recently, multi-hop wireless networks, such as Mobile Ad-hoc NETworks (MANETs), wireless sensor networks [25], or wireless mesh networks, are emerging as new and important networking components. Specific routing protocols have thus been designed to work on this new type of network, which presents harsh characteristics such as higher topology change rates, lower bandwidth, lower transmission quality, more security threats, more scalability issues and as well as novel energy and memory constraints aboard mobile network elements.

OLSR (Optimized Link State Routing [3]) is the most well-known routing protocol for multi-hop wireless networks based on a link state approach, which, incidently, makes it very similar to OSPF. One question then immediately comes to mind: if OSPF and OSLR are so similar, why is OSPF not also used on multi-hop wireless networks? Indeed, operating OSPF also on this new type of network is a seducing idea for at least two reasons (i) OSPFs legacy: it is extremely well deployed, known, and renowned, thus facilitating greatly the integration of multi-hop wireless networking, and (ii) it would allow to seamlessly unify wired and wireless IP networking under a single routing solution, an interesting perspective industry-wise, in terms of maintenance and costs.

There are however multiple issues with the use of OSPF in ad-hoc networks [27] [26]. The main problem is the amount of overhead necessary for OSPF to function, which is too substantial for the low bandwidth available so far on multi-hop wireless networks. However, OSPF has a modular design, using different modules (called interface types) tailored for specific technologies, such as Ethernet (Broadcast interface type), or Frame Relay (Point-to-Multipoint interface type).

An extension of OSPF, namely a new OSPF interface type, would thus be desireable to enable OSPF to work appropriately on multi-hop wireless networks. The goal is to develop an extension that adapts well to the characteristics of multi-hop wireless networks, while letting OSPF run unaltered on usual networks and existing interfaces. This is a must, for obvious reasons including legacy and backward compatibility with wired networks running usual OSPF. Moreover, the targeted devices are assumed to have reasonable CPU, memory, battery and mobility characteristics. In other words, the targeted devices are rather Cisco mobile routers aboard vehicles that move at low or medium speeds, than sensor nodes or high-speed MANET nodes.

Several extension proposals have thus recently emerged, such as [19] [8] [13].

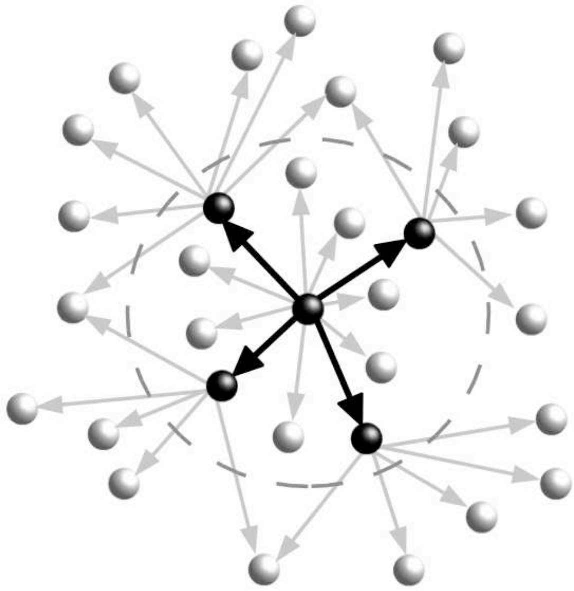

Figure 1: Multi-Point Relaying. The center node selects sufficient relays (in black), to cover every node two hops away. Selected relays are then called called MPRs. The dashed circle is the radio range of the center node.

As explained above, each proposal specifies a new OSPF interface type tailored for MANETs, cashing in on OSPF's modular framework which enables MANET enhancements where necessary, while retaining compatibility with legacy OSPF. Among these proposals, a category can be identified, which relies on the use of multi-point relaying techniques (MPR [3]) that have been developed and used in various ad hoc networking environments over the past decade. The proposals in this category, including [19] [8], essentially propose different configurations of similar concepts based on MPR (see Fig. 1).

The remainder of this paper analyses how these MPR concepts are configurable, then discusses and evaluates the respective merits of each configuration. Simulations are carried out with GTNetS (parameters can be found in appendix). The paper concludes by proposing, based on this analysis, a recommended configuration for MPR-based OSPF operation on MANETs.

2 OSPF on Ad Hoc Networks

As a proactive link-state routing protocol, OSPF [1] [2] employs periodic exchanges of control messages to accomplish topology discovery and maintenance: *Hello*s are exchanged locally between neighbors to establish bidirectional links, while *LSA*s reporting these links are flooded (*i.e.* diffused) throughout the entire network. This signalling results in a topology map, the link state database (*LSDB*), being present in each node in the network, from which a routing table can be constructed. An additional mechanism, particular to OSPF, provides explicit synchronization of the LSDB between neighbors, via additional control signalling (*database description* messages and *acknowledgements*). Such neighbors are then called *adjacent*, while other bidirectional neighbors are called 2-WAY.

In a wireless ad hoc environment, limited bandwidth and interferences between neighbors call for a significant reduction of OSPF control traffic [6]. Moreover, router mobility requires Hello and LSA periods to be drastically shortened in order to be able to track topology changes as they happen. Increased frequencies of LSA and Hello imply heavier control traffic, which brings the need for even more efficient control traffic reduction techniques.

The legacy OSPF mechanism providing control traffic reduction is the *designated router* mechanism OSPF [1]. However, in a wireless ad hoc environment, this mechanism is not functional, due to the fact that wireless neighbors generally do not have the same set of wireless neighbors.

OSPF extensions for MANET thus use alternative mechanisms. Aside of miscellaneous tweaks and tricks such as implicit acknowledgements or control traffic multicasting (instead of unicast), these alternative mechanisms can be classified in the following categories:

- **Flooding Optimization and Backup**. Instead of the usual, naive flooding scheme, use more sophisticated techniques that reduces redundant retransmissions.
- **Adjacency Selection**. Instead of attempting to become adjacent with all its neighbors, a router becomes adjacent with only some selected neighbors.
- **Topology Reduction**. Report only partial topology information in LSAs, instead of full topology information.
- **Hello Redundancy Reduction**. In some Hello messages, report only changes in neighborhood information instead of full neighborhood information.

This paper discusses the respective merits of different configurations (*i.e.* sets of mechanisms or parameters used in each category). The discussion bases itself on the use of MPR techniques which [8] and [19] have in common. The configurations in the remainder of this paper are depicted in table 2. Hello redundancy reduction configuration is discussed independently of configurations 1 and 2.

3 Flooding Optimization

In all considered configurations, MPR flooding (see Fig. 1) is used to reduce the number of forwarders of a given disseminated packet, while still ensuring that

	Configuration 1		Configuration 2	
	1.1	1.2	2.1	2.2
Flooding Optimization	MPR Flooding		MPR Flooding	
Flooding Backup	Overlapping Relays Backup		Adjacency Backup	MPR Backup
Adjacency Selection	Smart Peering Selection		MPR Adj. Selection	SLO-T Selection
Topology Reduction	Unsynchr. adjacencies	Smart Peering Reduction	MPR Topology Reduction	

Table 1: Considered configurations.

this packet is sent to each router in the network. However, in case no acknowledgement is received, different backup retransmissions policies are employed, depending on the configuration in use:

- **Per adjacency**. A router receiving an LSA from an adjacent neighbor must acknowledge its reception to the neighbor. Absent this acknowledgement, the neighbor must retransmit the LSA. This process is the basic OSPF policy. This is the behavior of configuration 2.1, this approach is called Adjacency Backup.
- **Per neighborhood**. Instead of making a single pair of routers responsible for LSA transmission/reception, the whole 1-hop neighborhood is responsible for flooding the LSA. MPR relays ensure primary transmission while other neighbors which overheard the transmission ensure backup retransmissions in case an LSA is not properly acknowledged by some router(s) in the neighborhood. This is the behavior of configurations 1.1 and 1.2, this approach is called Overlapping Relays.
- **Per MPR selector and per adjacency**. A router receiving an LSA from an MPR selector or from an adjacent meighbor must acknowledge its reception to the sender. Absent this acknowledgement, the neighbor must retransmit the LSA. This is the behavior of configuration 2.2, this approach is called MPR Backup.

The Overlapping Relays approach is more complex than the other approaches in terms of synchronization and buffer management. It also implies significantly bigger amounts of retransmitted LSAs, and thus more control traffic overhead. It does not, however, substantially improve routing quality in terms of delivery ratio, or path length, as observed later on in this paper. Fig. 2 compares LSA retransmission ratios with configurations 1.1, 1.2, 2.1 and 2.2, in a moderate mobility scenario, for different link quality scenarios modeled by α. A significant difference can be noticed between the amount of retransmissions required with configurations 1.1 or 1.2 (using Overlapping Relays), compared to the amount of retransmissions required with configurations 2.1 or 2.2. Moreover, configurations 1.1 and 1.2 (using Overlapping Relays) are also quite dependent on link

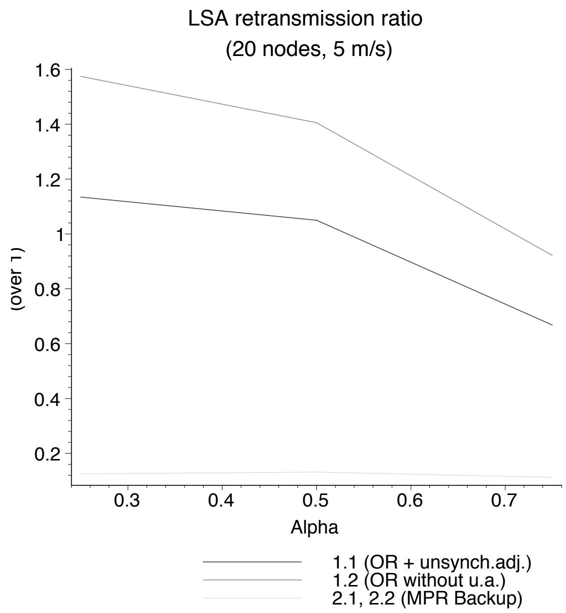

Figure 2: Number of retransmitted and backup LSAs over number of primary LSA transmissions (LSA retransmission ratio) for configurations 1.1, 1.2, 2.1 and 2.2 (speed: 5 m/s).

quality changes, while other configurations are more stable with regards to this parameter.

4 Adjacency Selection

The decision whether to bring up an adjacency with a neighbor can be taken using different criteria, depending on the configuration in use:

- **Per MPR selection**. A router brings up an adjacency with a neighbor if (i) it has selected this neighbor as MPR, or (ii) it is selected as MPR by this router. This is the behavior of configuration 2.1, this approach is called MPR Adjacency Selection.
- **Per SPT selection**. A router brings up an adjacency with a neighbor if this neighbor is not already reachable in the synchronized SPT. This is the behavior of configurations 1.1 and 1.2, this approach is called Smart Peering Selection.
- **Per RNG selection**. A router brings up an adjacency with a neighbor if this neighbor is not pruned by the relative neighbor graph triangular elimination (see Fig. 3). This is the behavior of configuration 2.2, this approach is called Synchronized Link Overlay (SLO-T) Selection [21].

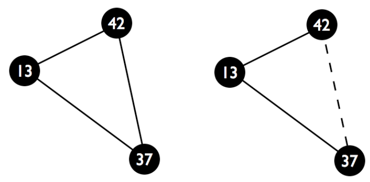

Figure 3: Relative Neighbor Graph (RNG) triangular elimination. In case of a triangular connection A-B-C-A, the edge with the highest ID is pruned. The ID of an edge is defined as the minimum of the IDs of its vertices. In the example shown above on the left, the edge with highest ID is between node 42 and node 37, which is thus pruned, as shown on the right.

MPR Adjacency Selection reduces somewhat the number of adjacencies, but may provide a set of adjacencies that is not connected network-wide. In order to remedy to this, the adjacency set may be completed by one or more *synch routers* (one is sufficient), which become adjacent to all their neighbors, at the expense of slightly more control overhead [19]. However, the provided set of adjacencies are assured to contain the shortest paths, network-wide [3].

Smart Peering Selection reduces more drastically the number of adjacencies while providing a connected set of adjacencies, but these may on the other hand not include all the shortest paths network-wide. SLO-T Selection produces an even smaller set of connected adjacencies, as shown in Fig. 4. However, it can be observed on the other hand in Fig. 5, that Smart Peering tends to identify and choose more stable links as adjacencies.

One could think that it is furthermore a good idea to tie adjacency selection and flooding relay determination. For instance, some implementations of configurations 1.1 and 1.2 (following the specifications in [8]) use such a tie, in that flooding relays are chosen only among adjacent neighbors to cover, in turn, their own adjacent neighbors only. However, if the adjacency subgraph is sparse, it may result in more or less all the nodes in the subgraph being chosen as flooding relays, as the probability of relaying an MPR flood is close to $\frac{M_r}{M}$, where M_r is the average number of relays per node, and M the average number of neighbors per node. In sparse networks we basically get $M_r = M$. Although it is seducing, as shown in Fig. 6, because it seems to result in less relays, it is nevertheless useless for two reasons: (i) since almost every node in the adjacency subgraph is chosen as relay anyways, it is wasteful to use CPU ressources for MPR computation, and (ii) as seen in Fig. 2, it results in many retransmissions.

5 Topology Reduction

LSAs can contain information about different types of links, depending on the configuration in use:

- **All the adjacencies**. The LSAs originated by a router list all the adjacencies (i.e. links with adjacent neighbors, see Section 2) set up by this

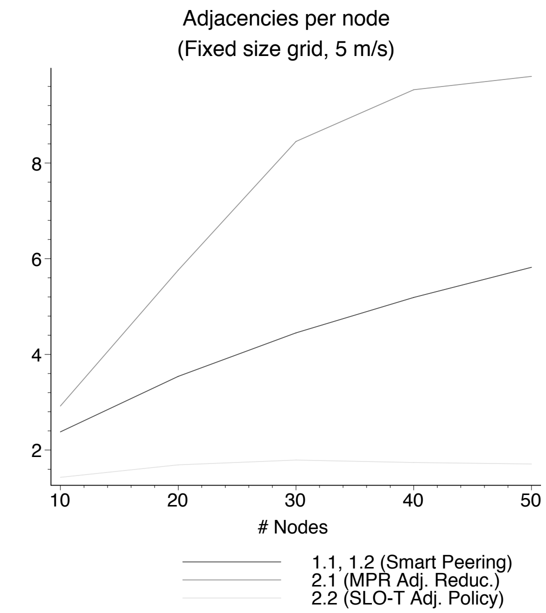

Figure 4: Average number of adjacencies per node in configurations 1.1 and 2 (5 m/s).

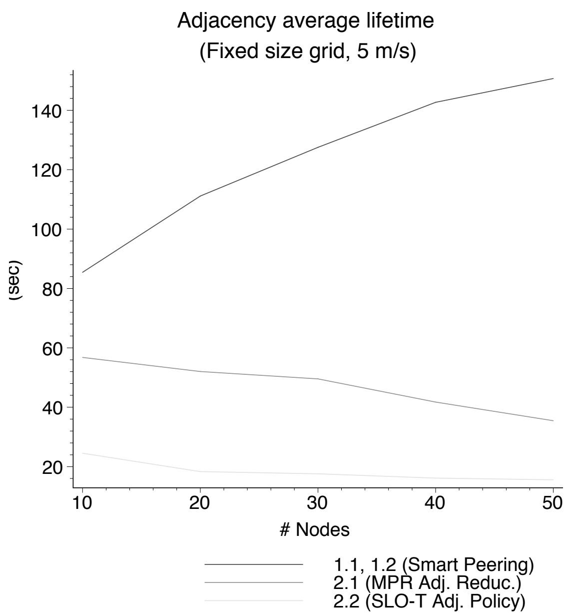

Figure 5: Average adjacency lifetime in configurations 1.1 and 2 (5 m/s).

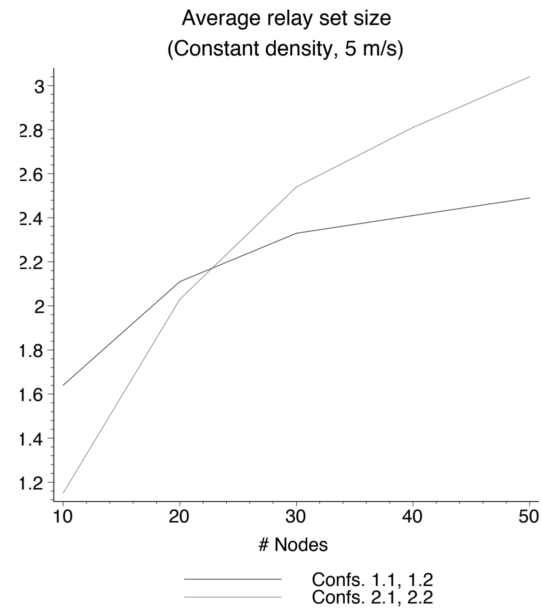

Figure 6: Average relay set size (constant density, 5 m/s).

router. This process is the basic OSPF policy, and this is also the behavior of configuration 1.2 (using Smart Peering).

- **A subset of all the adjacencies**. The LSAs originated by a router list a subset of the adjacencies set up by this router. This is the behavior of configuration 2.1, called MPR topology.
- **Some adjacencies and some TWO-WAY links**. The LSAs originated by a router list some adjacencies and some TWO-WAY links, i.e. links with TWO-WAY neighbors (see Section 2), also called *unsynchronized adjacencies*. This is the behavior of configurations 1.1 (using Smart Peering) and 2.2 (using MPR topology).

Unless an adjacency selection scheme is employed, listing all the adjacencies in LSAs may yield substantial control overhead. Configuration 1.2 thus uses Smart Peering in order to reduce the size of LSAs. However, the impact of reducing the link information in LSAs on data traffic must be evaluated. In particular, if the information is sufficient to compute optimal paths (such as the subset provided by MPR topology in configuration 2.1), there is no impact on data traffic. If on the other hand the information is not sufficient to compute optimal paths, the impact on data traffic may be substantial as paths may be longer than needed (for instance with configuration 1.2).

Fig. 7 shows the path costs provided by each configuration, when the hop-count metric is used. The increase in number of hops provided by Smart Peering in configuration 1.2 can be noticed. No relevant variation is observed in scenarios with different speeds.

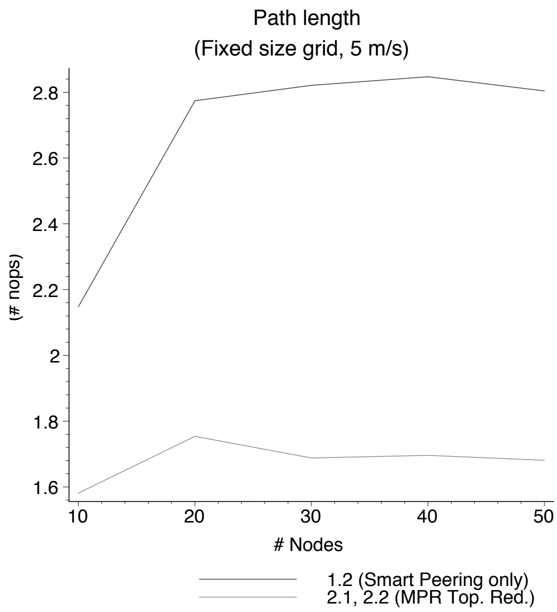

Figure 7: Average path length for data traffic in configurations 1.2 and 2 (5 m/s).

If the adjacency selection scheme in use provides an adjacency set that yields path suboptimality, a modified scheme can enhance the reported adjacency set with enough *unsynchronized adjacencies*, *i.e.* links with 2-WAY neighbors (see Section 2), so that optimal paths can be derived from the LSDB. This is the approach of configurations 1.1 and 2.2, at the expense of more LSA overhead (with respect to configuration 1.2 for instance). This approach also yields a higher risk of routing loops, since links between neighbors, that have not explicitly synchronized their LSDB, will be used for data forwarding.

Fig. 8 shows the impact of path suboptimality on data traffic. With configuration 1.2, which does not provide enough information to derive the optimal paths, data taffic network-wide is much bigger for the same user data input, than with the other configurations, which on the other hand provide optimal paths. This gap can be expected to grow larger with more user data input (results in Fig. 8 report up to 2Mbps).

Note that the same gap is observed taking into account total traffic network-wide (i.e. both data traffic and control traffic), as shown in Fig. 9. This shows that in case of substantial user data input, path optimality is paramount if one is to minimize the traffic overhead. Namely, inconsiderate saving on control overhead may cost a lot in the end, as seen with configuration 1.1. On the other hand, as explained above, configurations 2.1, 2.2, and 1.1 provide path optimality.

Having a tie between adjacency selection and topology reduction is the usual

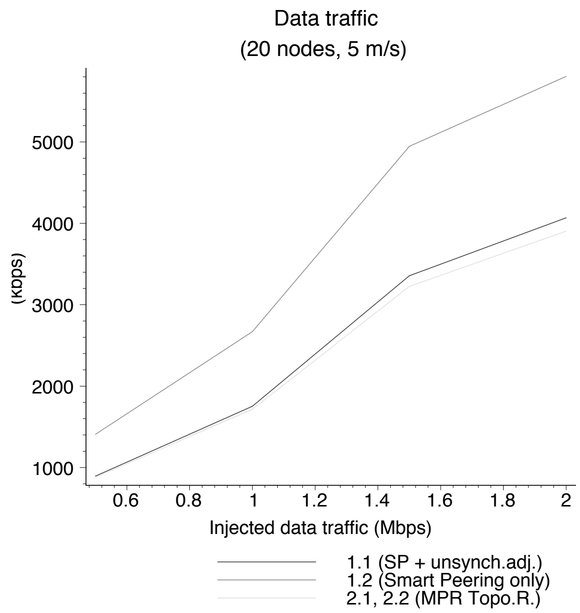

Figure 8: Data traffic in the network for each configuration (20 nodes, 5 m/s).

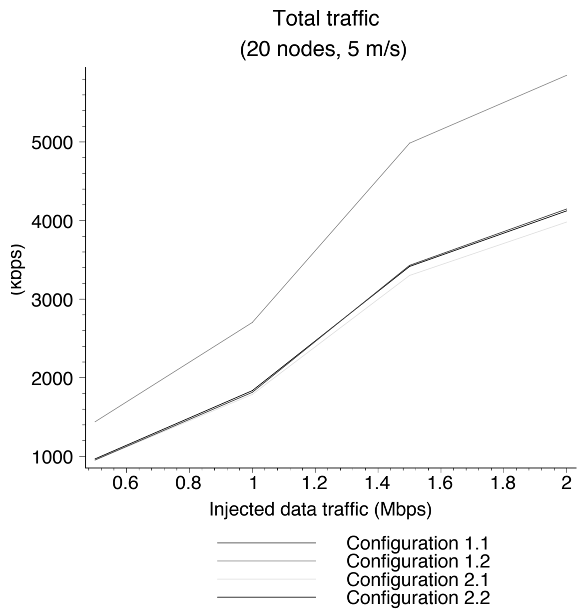

Figure 9: Total traffic (control+data) in the network for each configuration (20 nodes, 5 m/s).

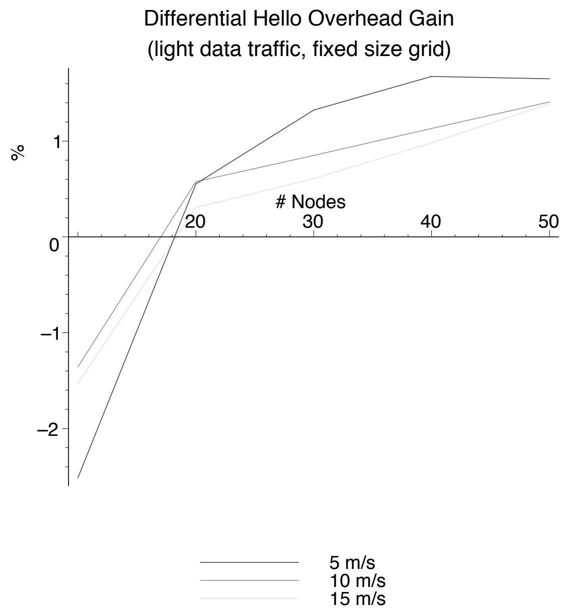

Figure 10: Differential Hellos impact in terms of relative overhead reduction.

OSPF approach, specified in [1] [2]. It is however a seducing idea, in a mobile ad hoc context, to undo this tie. Further discussion on the subject is proposed in Section 7.

6 Other Parameters

A variety of additional parameters may be set differently, with each configurations considered in this paper. The following lists the most important ones.

Hello Redundancy Reduction. *Incremental Hellos* [8] and *Differential Hellos* [13] are two techniques that can report changes noticed in the neighborhood over the last hello period, instead of full neighborhood information every hello period (which is the normal OSPF behavior). However, in doing this, transmission failures may cause hello synchronism loss and may take away nodes' ability to track neighborhood changes properly. In order to detect these cases additional mechanisms check sequence number gaps. Differential hellos use a proactive synchronism recovery mechanism, while incremental hellos make the receiver responsible for synchronism management. Both machanisms can be applied to any configuration discussed in this paper. However, the impact of these hello redundancy reduction mechanisms is limited, as shown in Fig. 11 and Fig. 10. The best reduction ratio stands around 3% with respect to the total amount of control traffic, achieved by the Incremental mechanism for very small networks.

Information Determining Relays. MPR computation may be based on information contained in (i) Hellos originated by neighbor routers, or (ii) LSAs

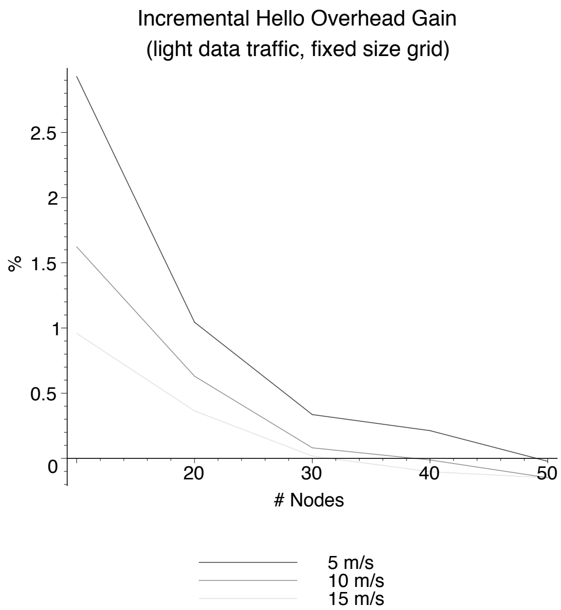

Figure 11: Incremental Hellos impact in terms of relative overhead reduction.

originated by neighbor routers. Both methods can be applied to any configuration discussed in this paper. However, the relay selection and update speed may vary depending on this choice. In a mobile network context, LSAs are usually less frequent than Hello packets, and this would make relays' adjustements to topology changes to slow down when depending on LSA reception instead of Hello reception. The same reaction ability could be achieved if *HelloInterval* and LSA interval values were equivalent, but increading LSA frequency would have a very significant effect network-wide in terms of control overhead.

Relay Population. MPR selection identifies a set of relays in N (the set of neighbors), that covers entirely $N2$, the set of neighbors two hops away. However, N and $N2$ may be populated differently, whether one considers covering (i) adjacent neighbors only, or (ii) both adjacent and 2-WAY neighbors. As shown in Section 4, it is preferable to use both adjacent and 2-WAY neighbors to populate N and $N2$.

Implicit Acknowledgement. Forwarding a flooded packet over the same interface it was received on may serve as implicit acknowledgement, and thus eliminate the need for explicit acknowledging. The use of implicit acknowledgement may reduce the number of transmissions due to control traffic. This can be applied to any configuration discussed in this paper.

Multicasting of Control Traffic. Instead of unicast (this is usual OSPF policy), some protocol packets, such as LSAs, may be multicast. The use of multicast may reduce the number of transmissions due to control traffic. This can be applied to any configuration discussed in this paper.

7 OSPF Adaptation to Multi-Hop Ad Hoc Networking

In the previous sections, we have overviewed the key challenge with routing on multi-wireless networks in the OSPF context: drastic control signalling reduction while keeping track of a topology changing much more often compared to Internet topology so far. Various ways to achieve this were overviewed and evaluated.

One element that is often neglected in a discussion about adapting OSPF to multi-hop wireless networking is the fate of user data. Reports on wireless OSPF usually focus exclusively on control data and do not take into account the consequences of algorithm alteration on user data. However, as shown in Section 5, using suboptimal paths can have drastic consequences in terms of total traffic that the network has to bear. So far, OSPF specifications have had the following built-in principles:

- *Principle 1.* User data is always forwarded over optimal paths.
- *Principle 2.* User data is only forwarded over links between routers with explicitly synchronized link state data-base.

In wired networks, the first principle aims at reducing delays and overhead due to data traffic. The second principle aims at reducing risks of routing loops occurences.

In multi-hop wireless networks, these principles are in question, as shown by the solutions proposed so far [19] [8] [13]. For instance, the shortest path in terms of hops, is not always the best path in terms of bandwidth. The wireless metric must thus be knowingly chosen and defined. However, as shown in this paper with the hop-count metric (the most common metric used to date on multi-hop wireless networks, for better and for worse), an approach that does not provide optimal paths with respect to the chosen metric should be discarded. If for one reason, because user data input can be substantial on networks where OSPF is typically used. Thus, *Principle 1* should be kept, and the question to ask is rather: which link metric should be used on multi-hop wireless networks?

Principle 2 is more debatable. A clear difference could not be identified so far between the use of optimal paths made only with synchronized links (such as configuration 2.1) or the use of optimal paths made both with synchronized and unsynchronized links (such as configuration 2.2). This could be explained by the short life-time of links, compared to wired links: if links are too short-lived, it may be wasteful to use bandwidth to synchronize link state databases.

Thus, we came to the following conclusions. If, for any reason, *Principle 2* must be kept in addition to *Principle 1*, configuration 2.1 (MPR flooding, MPR adjacency selection and MPR topology reduction, see Table I) is the only satisfactory solution known to date. If on the other hand *Principle 2* is not considered mandatory in the MANET context, we can recommand the following configuration for MPR-based OSPF operation on MANETs, based on the results presented in this paper:

- Flooding Optimization: *MPR Flooding.*
- Flooding Backup: *MPR Backup.*
- Adjacency Sel.: *Smart Peering.*
- Topology Red.: *MPR Topology & Smart Peering links.*
- Hello Redundancy Reduction: *None.*
- Relay Selection: *from Hellos. Include 2-WAY neigh.*
- Implicit Acknowledgements: *Yes.*
- Control Traffic Multicast: *Yes.*

This configuration offers a good bargain in terms of performance, *versus* algorithm and implementation complexity. As shown in Fig. 12 and Fig. 13, superior performance is achieved. Using the best of both worlds produces similar route quality with less overhead, as observed in Fig. 14. Compatibility with *Principle 1* is provided using MPR topology, but *Principle 2* is left behind. The backbone of adjacencies is setup using the most stable links (using Smart Peering), where it makes more sense to synchronize databases. Useless control traffic due to incomplete database synchronization attempts is thus avoided, as shown in Fig. 15.

8 Conclusion and Next Steps

As wireless Internet is becoming a reality, we studied in this paper a piece of tomorrow's IP protocol suite: OSPF on multi-hop wireless networks. Extending OSPF to work in such environments will allow new heterogeneous networks to exist, encompassing both wired parts and multi-hop wireless parts in the same routing domain. However, such an extension must overcome several challenges. This paper overviewed the key issued that are faced, and evaluated different solutions that have been proposed. A category of solutions was identified as being different configurations of the same concept, derived from multi-point relaying techniques. The paper then concluded with a recommended configuration for a solution in this category, based on the analysis and the simulations that were carried out. Next steps in this field will include real testbed experimentations on routing-specific hardware, and, hopefully, standardization.

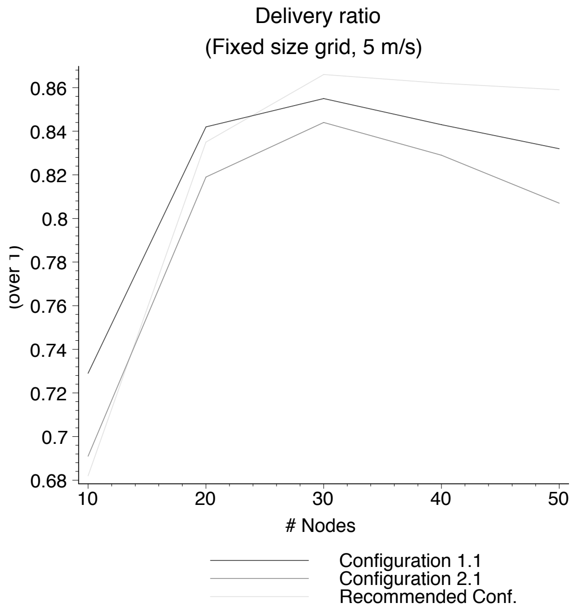

Figure 12: Delivery ratio with the recommended configuration.

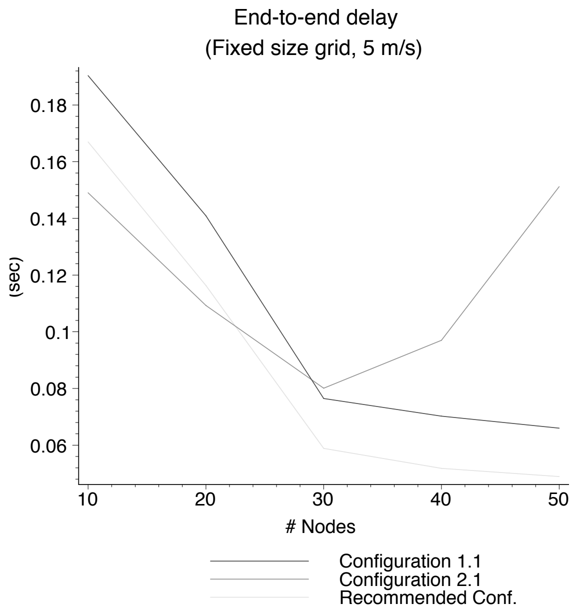

Figure 13: Delay with the recommended configuration.

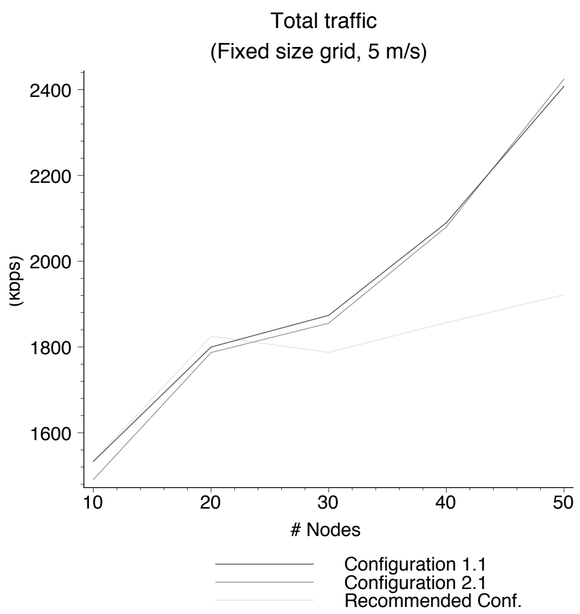

Figure 14: Total traffic (data and control) with the recommended configuration.

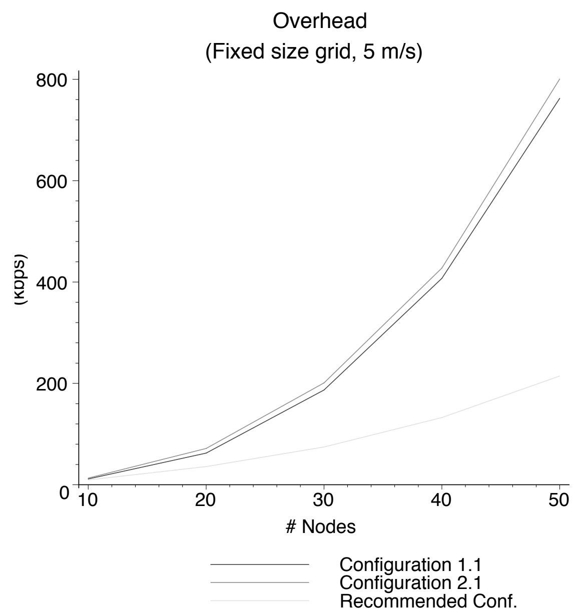

Figure 15: Control traffic with the recommended configuration.

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Appendix

Table 2: General Simulation Parameters.

Name	Value
Experiment statistic parameters	
Seed	72
Number of samples	20 samples/experiment
Traffic pattern	
Type of traffic	CBR UDP
Packet size	1472 bytes
Packet rate	85 packets/sec
Traffic rate	up to 2 Mbps
Scenario	
Radio range	150 m
Wireless α	0.5
Pause time	40 sec
MAC protocol	IEEE 802.11b
OSPF general configuration	
HelloInterval	2 sec
DeadInterval	6 sec
RxmtInterval	5 sec
MinLSInterval	5 sec
MinLSArrival	1 sec

Table 3: OR/SP Specific Parameters.

Name	Value
AckInterval	1800 msec
PushbackInterval	2000 msec
Optimized Flooding?	Yes
Smart Peering?	Yes
Unsynch. adjacencies?	Yes
Surrogate Hellos?	Yes
Incremental Hellos?	No

Table 4: MPR-OSPF Specific Parameters.

Name	Value
AckInterval	1800 msec
PushbackInterval	2000 msec
Flooding MPR?	Yes
Topology Reduction	MPR Topology Reduction
Adjacency Selection	MPR Adjacency Reduction SLO-T Adjacency Policy

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