MLSD: A Network Topology Discovery Protocol for Infrastructure Wireless Mesh Networks

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***Abstract*—In Infrastructure Wireless Mesh Networks (IWMN), the network topology discovery protocol has an essential role for responding proactively and promptly to topology modifications. It is responsible for disseminating link state updates, managing the tension between update frequency and number of messages, which has strong impact in protocol performance, network resource consumption and scalability. In such a context, this paper proposes the Mesh Network Link State Discovery (MLSD) protocol, which has been specifically designed considering IWMNs features. MLSD adopts a proactive, reliable, incremental, controlled and event-based delivery strategy, which avoids periodic messages and coordinates how information is propagated for enhancing efficiency. Besides, it joins several updates for reducing network resource consumption.**

Keywords-wireless mesh networks; routing protocols; link-state protocols

I. INTRODUCTION

As an evolution of wireless networks, *Infrastructure Wireless Mesh Networks* (IWMNs) have emerged as a key technology for dynamic self-configurable and self-healing networks that provide large-scale, reliable service coverage, allowing devices to automatically reconfiguring, establishing and maintaining connectivity among themselves [1][2]. In essence, an IWMN is a multi-hop wireless network that introduces a hierarchy of devices, called mesh routers and mesh clients [3]. *Mesh Routers* (MRs) are dedicated, stationary and power enabled devices, strategically positioned to provide a multi-hop wireless backbone for stationary or mobile, power constrained *Mesh Clients* (MCs).

In IWMNs, connectivity among non-neighboring nodes is achieved through multi-hop communication in which MRs forward packets hop by hop to other intermediate MRs in direction to the destination node. Note that, in IWMNs, MCs cannot forward packets and besides cannot communicate directly with each other. Thus, MRs have to manage and disseminate routing information, and to do that, a routing protocol must be adopted.

In practice, taking into account shared similarities among IWMNs and *Mobile Ad Hoc Networks* (MANETs), routing protocols designed for MANETs have been applied to IWMN projects [1]. For instance, the VMesh [4] project employs the *Optimized Link State Routing* (OLSR) protocol [5]. As another example, Microsoft mesh networks [6] are built using a modified version of the *Dynamic Source Routing* (DSR) protocol [7].

However, according to Akyildiz [1], ad hoc routing protocols do not scale very well in IWMNs and the throughput drops as the number of nodes increases. Therefore, despite the large availability of ad hoc routing protocols, considerable research efforts are still needed for designing more efficient and effective routing protocols for IWMNs, which can be specifically designed to explore and take advantage of their built-in features.

Taking into account IWMN architectural features, in order to be able to forward packets, MRs ought to support advanced routing capabilities, which need to detect fast topology changes and keep updated routes. In such a context, the link-state routing approach has the advantage of fast convergence when contrasted with the distance-vector routing approach, updating in a faster way routing information in all nodes of the network. Thus, in IWMNs, link-state routing protocols seem to be more adequate than distance-vector routing protocols.

In link-state routing protocols, a key element is the *Network Topology Discovery Protocol* (NTDP), in which network topology updates are propagated using messages called *Link-State Advertisements* (LSAs) [8]. Such protocols can generate LSAs on a periodic basis or can adopt an event-based approach for generating LSAs when detect changes in the state of the wireless links among nodes [9].

In such a context, this paper presents a scalable, robust and reliable network topology discovery protocol, called *Mesh Network Link State Discovery* (MLSD), based on the link-state approach and specifically designed taking into account IWMNs features. In order to reduce the control overhead related to topology update messages, the MLSD protocol adopts a proactive, reliable, incremental, controlled and event-based approach for generating LSAs, making more efficient use of network resources. Simulations show over 60% reduction in the control overhead of topology discovery compared to a periodic-based link-state protocol.

The remainder of this paper is organized as follows. Section 2 examines the strategies adopted in related work for disseminating topology information. Then, Section 3 presents the MLSD protocol, detailing its several strategies for disseminating link state updates. Next, Section 4 presents initial performance evaluation results, and, in conclusion, Section 5 draws final remarks and delineates future work.

ISBN: 978-1-61208-318-6

II. RELATED WORK

In order to contextualize the proposed protocol, this section identifies routing protocols that have been adopted in IWMNs, highlighting their strategies for disseminating topological information. According to Chen [10], IWMNs represent a recent research field, favoring the adoption of ad hoc routing protocols, in special, the strategies employed by *Optimized Link State Routing* (OLSR) [5] and *Ad hoc On-Demand Distance Vector* (AODV) [11] protocols.

OLSR [5] is a proactive, link-state routing protocol that disseminates topological information using a flooding process that consists in choosing a set of *Multipoint Relays* (MPRs), which are responsible for periodically generating and forwarding topology control messages throughout the wireless network. Thus, OLSR simply floods topology data often enough to make sure that the topological database does not remain unsynchronized for extended periods of time.

In OLSR, MPRs are chosen considering the neighborhood of the nodes. Each node discovers 2-hop neighboring information and performs a distributed election of a set of MPRs. Nodes select MPRs such that there exists a path to each of its 2-hop neighbors via a node selected as an MPR. Then, MPR nodes source and forward *Topology Control* (TC) messages that contain the MPR selectors. Note that each node independently selects its own set of MPRs.

In order to build the topology database, each node, which has been selected as MPR, periodically generates and broadcasts TC messages at a regular time interval around 5 seconds by default. Thus, TC messages are broadcasted and retransmitted by MPRs only. Upon receiving a TC message from a neighboring MPR, the receiving MPR must retransmit the message in at most 0.5 seconds.

Given the link state information acquired through periodic TC messages, the routing table for each node can be computed using the shortest path algorithm. In route calculation, the MPRs are used to form the route from a given node to any destination in the network.

OLSR has been largely adopted without modification in IWMNs, and besides, new routing protocols specifically designed for IWMNs, such as *Radio Aware Optimized Link State Routing* (RA-OLSR) [12], *Hybrid Wireless Mesh Protocol* (HWMP) [12] and *Wireless-mesh-network Proactive Routing* (WPR) [13], have adopted OLSR as a basis, including its strategy for disseminating topological information.

Consequently, as a common strategy, OLSR, RA-OLSR, HWMP and WPR propagate link-state information in a periodic basis, since their messages are transmitted without any guarantee of delivery. Thus, such protocols do not bother with reliability. They simply flood link-state information often enough to make sure that the topological databases do not remain unsynchronized for extended periods of time. Indeed, they suppose that, in some moment, all nodes receive updated topological information, and then, their topological databases can become consistent and synchronized.

In contrast, the MLSD protocol proposed herein adopts a reliable, event-based approach. Taking into account that MLSD messages are transmitted with guarantee of delivery, it does not require periodic and repetitive propagation of link-state advertisements, and so, has the potential for reducing the control overhead.

III. THE MLSD PROTOCOL

The protocol proposed herein has been developed to be adopted in the topology layer of a three-layered routing architecture, called *Infrastructure Wireless Mesh Routing Architecture* (IWMRA) [14], specifically designed taking into account IWMNs architectural features. The IWMRA architecture splits routing functionalities into 3 layers: *neighborhood*, *topology* and *routing*. The *neighborhood layer* detects the presence or absence of directly reachable neighbors. Based on a flooding approach, the *topology layer* disseminates neighborhood information all over the network. Then, the *routing layer* builds the best routes for all nodes. Consequently, a specific protocol ought to be developed for dealing with issues and functionalities in each layer.

This section presents the *Mesh Network Link State Discovery* (MLSD) protocol, a link state topology discovery protocol for IWMNs, which takes in account requirements related to scalability, robustness and reliable delivery. In order to become scalable, MLSD tries to reduce the signaling overhead for disseminating link state updates.

In order to reduce the signaling overhead for updating topology information, instead of using a periodic-based signaling strategy, MLSD adopts a *proactive, reliable, incremental, controlled and event-based signaling strategy*. In such an *event-based strategy*, a given node only sources and emits a signaling message in the event that occurs a modification in the network topology, for instance, a given mesh client (MC) establishes a new wireless link by moving within the coverage range of a given mesh router (MR).

However, taking into account the event-based strategy for fast mobile MCs, the number of messages could drastically increase as the number of events related to establishment and disconnection of wireless links among MRs and MCs intensively occurs. To deal with such an issue, MLSD adopts a *controlled strategy* for limiting the time interval between messages, and so, it tries to reduce the transmission of excessive messages in a short time interval. Consequently, considering fast mobile MCs, the controlled strategy dynamically adapts the event-based strategy to a periodic-based strategy.

To further reduce the signaling overhead, MLSD adopts an *incremental strategy* for disseminating link state information. In such a strategy, instead of propagating the whole set of link state information, MLSD propagates only updates related to modifications detected in the state of wireless links among MRs and MCs. Thus, it reduces the size of the signaling messages and consequently the signaling overhead.

Unlike other link-state routing protocols, which do not bother with reliability, MLSD adopts a *reliable strategy* for disseminating link state updates as another mechanism for reducing signaling overhead. In such a strategy, MLSD adapts the classical flooding process as a mean to implement an implicit scheme known as *positive acknowledgement with retransmission*, which guarantees reliability of flooded

 ISBN: 978-1-61208-318-6

signaling messages, ensuring consistent and synchronized topological databases without the need of repeatedly propagate the same link state information, as implemented by other link-state routing protocols.

In complement, the proposed protocol adopts a compact format for messages, grouping link state information whenever possible and eliminating outdated link state information. By acting together, all of such strategies have the potential of reducing the signaling overhead.

The MLSD protocol has been designed taking into account IWMNs architectural features. In summary, MLSD assumes that IWMNs meet the following requirements: *(i)* the set of stationary MRs provides a multi-hop wireless backbone that completely covers the interested area; *(ii)* the set of MRs are power enabled devices directly connected to an unlimited power supply; *(iii)* MCs can move or stay stationary within the wireless backbone area; and *(iv)* wireless links are bidirectional. In this initial version of the proposed protocol, each MR and MC has only one wireless network interface card.

In the following, the main concepts, strategies, and features of the MLSD protocol are presented and discussed. Initially, an overview of the proposed protocol and its operation are described. Then, the message and data structures adopted by MSLD are introduced, depicting how the protocol propagates and stores topological information. Thereafter, the strategies for disseminating link state information are detailed, describing their control mechanisms. Note that, due to space limitation, several details have to be omitted, but can be found in [15].

A. Fundamentals

The MLSD protocol implements the topology layer of the IWMRA architecture. It is responsible for disseminating link state information throughout the wireless backbone using topology update messages, which are emitted whenever occurs an event related to establishment and disconnection of wireless links among MRs and MCs. Such events are triggered by the neighborhood layer of the IWMRA architecture, which is implemented by another protocol called *Scalable Neighborhood Discovery Protocol* (SNDP) [16]. As examples of events, it can be cited a given MR adding or removing a given MC as a neighbor.

In MLSD, only MRs can source, process and broadcast topology update messages, called *Link State Updates* (LSUs). Thus, MCs cannot source, process or broadcast LSUs. MLSD manages the emission of LSUs for reducing the signaling overhead, making possible to provide better scalability by allowing a large collection of MCs in the wireless network. Besides, the proposed protocol eliminates outdated link state information, avoiding inconsistences in the topological database, which must be identical in all MRs, allowing each one to construct a complete and consistent picture of the wireless network topology.

The main MLSD contribution is the generation of messages using a reliable, incremental and event-based strategy for disseminating link state information. The consistence of the topology databases are ensured by two cooperating processes: *(i)* a reliable, incremental flooding process for disseminating link state updates, and *(ii)* a synchronization process for synchronizing topological databases in all MRs.

In order to reduce the total number of LSUs, MLSD controls the emission of messages aggregating several events in a single LSU message. In addition, it controls the time interval between consecutive LSUs by managing and delaying the dissemination of events related to fast mobile MCs. In complement, by adopting a compact format for representing link state operations, it also reduces the signaling overhead transported in LSUs.

B. Message Structure

Each *Link State Update* (LSU) is a packet employed by MLSD for disseminating link state updates in the wireless backbone. As illustrated in Fig. 1, each LSU can carry one or several announcements related to events that occur in the network topology. In MSLD, such announcements are called *Link State Advertisements* (LSAs). In turn, each LSA can carry one or several *Link State Operations* (LSOs) that occur in a given MR, represented by the establishment or disconnection of wireless links with other MRs or MCs.

When generated, an LSU message is directly encapsulated in a frame of the data link or *Media Access Control* (MAC) layer and then transmitted in broadcast. All MRs that receive an LSU must evaluate each encapsulated LSA, and then decide whether or not to process or forward (or both) each encapsulated LSO.

In complement, each LSO can require an additional processing taking into account the type of neighboring node (MR or MC) involved in the respective link state update. On the one hand, if the involved node is a MC, such a processing is always the simple addition or removal of the wireless link in the topological database. On the other hand, if the involved node is another MR, such a processing can also initiate a synchronization process for synchronizing topological databases or a garbage collection process for removing all unreachable nodes from the topological database.

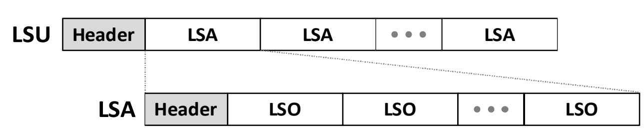

Figure 1. Message structure.

C. Send Buffer

The send buffer is an internal data structure adopted by all MRs for storing LSOs and their related information. Considering a given MR, all LSOs present in its send buffer can have the following origin: *(i)* auto-generated by the own MR, considering link state updates with its neighboring nodes; and *(ii)* received in LSUs generated or forwarded by other neighboring MRs. Note that, all LSOs in the send buffer must be disseminated in broadcast for all MRs in the wireless backbone. Therefore, LSOs in the send buffer constitute the base for creating LSAs and then LSUs, which are flooded in the wireless backbone.

Each LSO in the send buffer is classified as: *(i)* a new operation that still needs to be forwarded to all neighboring MRs; or *(ii)* an already-transmitted operation that needs to be confirmed by or retransmitted to neighboring MRs. Besides, MLSD also keeps timers that indicate when the LSO must be transmitted for the first time or retransmitted, if at all need.

The retransmission of a given LSO is required whenever the delivery control mechanism detects that one or several neighboring MRs did not acknowledge the receipt of the previous transmission of the LSO. Such a delivery control mechanism is implemented by defining a list of forwarders associated with each LSO in the send buffer. The list of forwarders represents all neighboring MRs that still need to receive and forward the respective LSO.

D. *Topological Database*

The topological database represents a map of the wireless network topology. It is important to emphasize that the topological database is employed by the routing layer of the IWMRA architecture for proactively calculating all routes between each pair of nodes. In a given MR, its topological database stores link state information, which are directly auto-generated by the neighborhood layer of the own MR or received in LSUs propagated by other neighboring MRs.

It is important to note that link state information in the topological database does not expire ever. Such information can only be included or removed through LSOs propagated by the MLSD protocol. The topological database must be identical, consistent and synchronized in all MRs that compose the wireless backbone. Thus, all MRs know the state of the wireless links defined among all MRs and MCs in the wireless network.

MLSD also adopts a versioning scheme for LSOs. In such a scheme, each LSO generated by a given MR has a unique sequence number, which is managed and assigned by the initial source MR. Upon receiving a given LSO, the receiving MR substitutes the old version of the LSO in its topological database with the new one.

E. *Link-State Propagation*

As already indicated, the MLSD protocol keeps consistent topological databases exploring two independent but cooperating processes: *(i)* a reliable, incremental flooding process for disseminating link state updates, and *(ii)* a synchronization process for synchronizing topological databases in all MRs.

The dissemination of link state updates integrated in the MLSD protocol adopts the well-known concept of flooding. The flooding process is performed via LSUs, which contain incremental updates of the network topology in encapsulated LSAs, which in turn encapsulate LSOs. Such LSOs, when processed by a given MR, are forwarded to its neighboring MRs, until reaching hop-by-hop all MRs in the wireless backbone.

In order to perform the reliable delivery, the flooding process implements an implicit scheme known as positive acknowledgement with retransmission. Besides, when processing LSU messages, it determines the type of action to be taken for each encapsulated LSO, which can be to forward, acknowledge, retransmit or simply ignore the LSO. Thus, the flooding process allows disseminating link state updates throughout the wireless backbone and, together with the versioning scheme, also ensures that old versions of LSOs, identified by their sequence numbers, do not affect the consistence of the topological databases. In complement, MLSD manages the time interval between retransmissions, avoiding the excess of messages triggered by topological events in the wireless network.

Taking into account the implicit, positive acknowledgement with retransmission scheme, a given *MR-X* that propagates an LSU detects the effective reception of each encapsulated LSO by all neighboring MRs, indicated as the list of forwarders for each LSO in the send buffer, when they forward the same LSOs in their own LSUs. Since all LSUs are transmitted in broadcast, *MR-X* also receives the LSUs from its neighbors, and so, such LSUs can serve as delivery acknowledgements from the forwarders to *MR-X*.

If a given forwarding *MR-F* does not transmit a given LSO within a specified time interval, *MR-X* retransmits the LSO again, until detecting that *MR-F* has forwarded it. Upon detecting that all forwarders have received the LSO, internally, *MR-X* declares the successful forwarding of the LSO, removing it from the send buffer.

Fig. 2 illustrates the implicit, positive acknowledgement scheme. In Fig. 2a, *MR-A* sends an LSU that contains an LSO to its unique forwarder *MR-B*, indicating the establishment of a wireless link between *MR-A* and *MC-X*. In turn, *MR-B* forwards the LSO in another LSU, indicating *MR-C* as a forwarder (Fig. 2b). In this case, note that, the LSU from *MR-B* is received by both *MR-A* and *MR-C*. On the one hand, *MR-A* interprets the LSU from *MR-B* as an acknowledgement. On the other hand, since *MR-C* has been indicated as forwarder by *MR-B*, it must forward the LSO. Though, *MR-C* does not have neighbors to forward the message. Even thus, *MR-C* transmits the LSO with no forwarders, allowing *MR-B* to acknowledge that *MR-C* has successfully received the LSO (Fig. 2c).

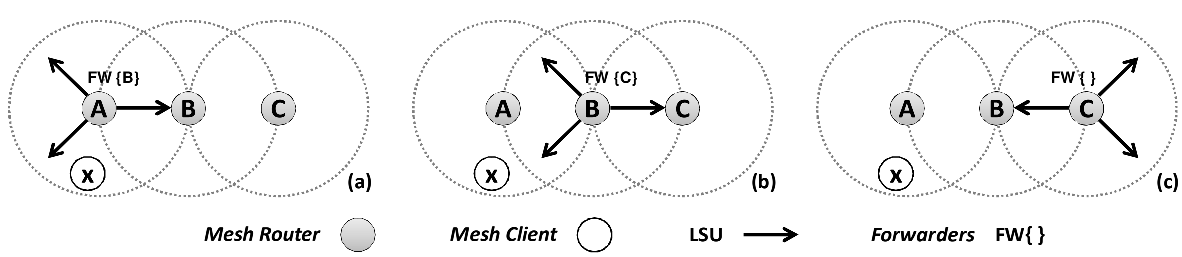

Figure 2. Implicit, positive acknowledgement mechanism.

It is important to stress that no extra message needs to be sent since the acknowledgement is implicit. Thus, when LSOs are successfully received and forwarded, each MR needs transmit each LSO only one time. Such a strategy is different from the flooding process employed by the OLSR protocol, in which topology control messages are also transmitted only one time by each node, however, since OLSR does not provide any guarantee of delivery, messages have to be periodically retransmitted.

In order to avoid collisions between neighboring MRs that forward link state updates in the flooding process, and so retransmissions of LSUs, MLSD adopts a *time-slot based strategy*. In such a strategy, time slots are time intervals in which MRs are allowed to transmit LSUs. Considering a given transmitted LSU, all forwarding MRs configure their time slots according to the position of each MR in the list of forwarders indicated in the LSU. Thus, each LSU indicates the specific and distinct time slot for each forwarding MR.

Note that the MAC layer of IEEE 802.11 wireless networks adopts the *Distributed Coordination Function* (DCF) with a contention window for dealing with collisions. However, in MLSD, upon receiving an LSU, all forwarding MRs would try at the same time to forward the encapsulated LSOs, and so, as widely known, DCF can lead to collisions in situations in which many nodes attempt to communicate at the same time. Thus, in a more efficient way, the time-slot mechanism distributes in different time slots the instant at which each forwarding MR tries to transmit.

In a given MR, upon receiving an LSU, the forwarding of the encapsulated LSOs is delayed by taking into account the time slot allocated to the forwarding MR in the LSU. As mentioned, the time slots are calculated using the position of the MR in the list of forwarders indicated in the LSU. Thus, the first MR in the list forwards in the first slot, the second MR in the second slot, and so on. Note that the time-slot mechanism acts together with the 802.11 DCF, but now, forwarding MRs do not try at the same time to send LSOs, avoiding collisions that could not be avoided by DCF only.

F. Synchronizing Topological Databases

Whenever an MR is initialized in the wireless backbone, it needs to create a topological database, which ought to have all link state information already stored in other MRs. Consequently, once a given MR detects as neighbor another MR, they must perform the synchronization of their topological databases.

Such a synchronization process is initiated by the MR that firstly detects the establishment of the wireless link with another neighboring MR. In the initial phase, the detecting MR assemblies all LSOs based on its topological database, and then inserts them in the send buffer, indicating as forwarder the recently discovered neighboring MR. The assembly of LSOs is possible because the topological database stores the original sequence number of each stored link state information.

LSOs associated with the synchronization process only have operations for adding wireless links between MRs and MCs, since no information is stored in the topological database about already disconnected wireless links.

In the synchronization process, the dissemination of LSOs follows the same procedures and rules adopted in the flooding process. It is important to emphasize that, upon receiving LSOs, the forwarding MR evaluates each one and decides what to do according to the implicit, positive acknowledgement with retransmission scheme. For instance, the forwarding MR can decide to retransmit as an acknowledgement. However, in case of partitioned backbone, it has to forward to other neighboring MRs.

Fig. 3 depicts the synchronization process. When *MR-B* detects the wireless link with *MR-A*, it inserts in its send buffer all LSOs related to link state information stored in its topological database, indicating *MR-A* as a forwarder. Then, *MR-B* sends one or more LSUs encapsulating such LSOs (Fig. 3a). Thus, upon receiving LSUs, *MR-A* confirms *MR-B* as neighbor, if at all needed. Then, *MR-A* inserts in its send buffer LSOs related to link state information stored in its own topological database and also LSOs received from *MR-B* that need to be acknowledged. Thereafter, *MR-A* sends one or more LSUs encapsulating such LSOs (Fig. 3b). After receiving LSUs, *MR-B* declares as successful the transmission of its LSOs to *MR-A*, and besides, it sends acknowledgements for all LSOs received from *MR-A* (Fig. 4c). In conclusion, *MR-A* declares as successful the transmission of its LSOs to *MR-B*.

IV. PERFORMANCE EVALUATION

The signaling overhead generated by topology discovery protocols has a strong impact on the performance of the routing protocols [17]. Thus, in order to evince the MLSD performance gains, a simulation-based performance evaluation has been conducted using the NS-2 simulator [18], contrasting MLSD and the OLSR topology discovery process. Note that other protocols for IWMNs, including RA-OLSR [12], HWMP [12] and WPR [13], also adopt topology discovery processes similar to OLSR. Thus, it makes sense to contrast MLSD against the OLSR topology discovery process, which is the basis for all other ones.

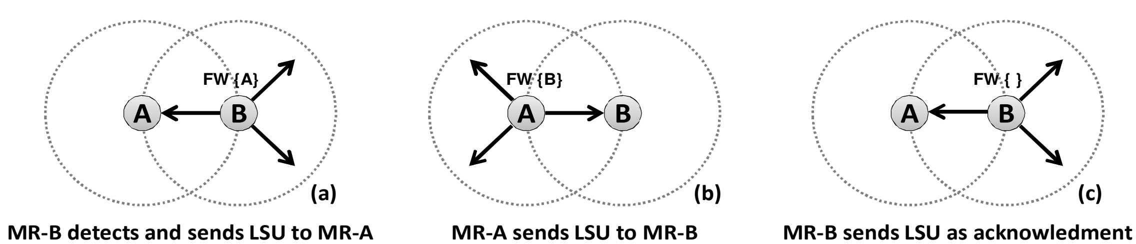

Figure 3. Synchronizing topological databases.

The efficiency of MLSD has been evaluated in several simulated scenarios, varying the number and the speed of devices. As a way to show the general MLSD behavior, this paper presents the performance gains in scenarios defined by a grid of 10x10 stationary MRs, in which up to 100 mobile MCs adopt an average speed of 10 m/s, varying uniformly between 0 and 20 m/s. For each scenario, average values of the signaling overhead are calculated based on several simulation experiments, considering a relative estimation error of 5% and a confidence interval of 95%. Each experiment has a simulation time of 3.000 seconds, from which the first 160 seconds are discarded as an initial transient. Interested readers can find in [15] a detailed description of simulation settings, scenarios and outcomes.

In the context of IWMNs, as illustrated in Fig. 4, simulation results make clear that MLSD is a better option than the OLSR topology discovery process in terms of signaling overhead in bytes. In Fig. 4, it is possible to note that OLSR suffers more influence from the increase in the quantity of mobile MCs in the wireless network. The poor behavior of the OLSR protocol is mainly influenced by its periodic-based strategy, adopted by MRs and also MCs for disseminating link state information through their MPRs. In contrast, the excellent MLSD behavior is a direct consequence of the combination of its controlled, event-based strategy, in which only MRs disseminate LSUs in the event that occur modifications in the network topology.

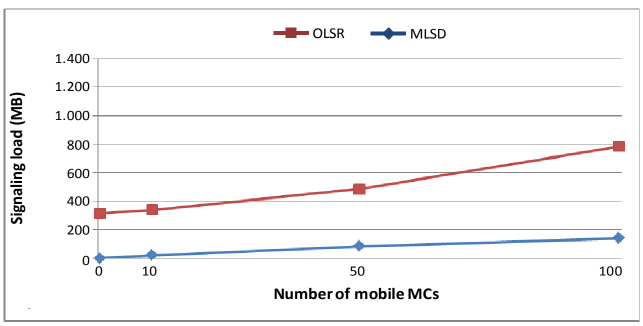

Figure 4. Signaling overhead

In Fig. 4, considering 0, 10 and 50 MCs, the event-based strategy makes possible MLSD to have a significant smaller signaling overhead, but that grows in a comparable way with OLSR. But, from 50 to 100 MCs, the controlled strategy begins to act in MLSD when the frequency of link state updates increases as a whole, and consequently the signaling overhead for MLSD has a growth smaller than OLSR.

V. CONCLUSION

This paper has proposed MLSD, a network topology discovery protocol based on the link-state approach and specifically designed for IWMNs. Regarding the signaling overhead, MLSD has an excellent behavior in typical IWMNs, becoming much more scalable than the OLSR topology discovery process. Thus, it is possible to guess that MLSD has the potential to become a better choice than the IEEE 802.11s proposal for mesh networks, in which RA-OLSR adopts the OLSR topology discovery process.

Despite the interesting outcomes in terms of signaling overhead, as a future work, it is still needed to evaluate MLSD in relation to other performance metrics. For instance, it is under laboratory work the evaluation of the convergence time for the topological database, which can reveal the time interval required for synchronizing link-sate information in all nodes. In pilot investigations, considering the reliable strategy adopted by MLSD for disseminating link-state updates, it is expected to confirm that MLSD also has a behavior better than OLSR in terms of convergence time. Also, as known, OLSR has problems with topological database convergence, which do not occur in MLSD.

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 ISBN: 978-1-61208-318-6