Performance Evaluation of BATMAN Routing Protocol for VoIP services: a QoE perspective

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***Abstract*— MANETs are experiencing an unstoppable growth due to their decentralized topology and their ease and low-cost deployment. The dynamic nature of MANETs entails the use of appropriate routing protocols in order to obtain good performance in the services supported by the network; even more if these services present tough temporal requirements, such as multimedia or VoIP services. One routing protocol that has been devoted a notable research effort during the last years is the BATMAN protocol, which proposes an interesting paradigm avoiding the explicit interchange of routing information among nodes. In this paper, we focus on evaluating the performance of BATMAN supporting VoIP traffic on low power-consumption nodes, from a Quality of Experience (QoE) point of view. Specifically, we evaluate the impact on BATMAN performance of i) the PHY layer, by employing a fading characterization of the transmission channel, ii) the number and density of ad-hoc nodes, and iii) the nodes mobility. All the results obtained for BATMAN are compared with those attained by using the widely used OLSR routing protocol. From the results, we conclude that neither BATMAN nor OLSR in their respective current implementations are suitable enough for VoIP traffic support in MANETs composed by energy-saving nodes.**

***Index Terms*—MANET, VoIP, QoE, Fading, Green Networking**

I. Introduction

NOWADAYS Mobile Ad-hoc NETwork, also known as MANET, is one of the wireless network-access topologies receiving more attention by the research community. This type of networks offers a completely decentralized architecture, extremely attractive for mobility purposes, and very suitable under situations where it is not possible to deploy a centralized transmission system, such as in the event of disasters or the need of setting up temporary networks. In other words, MANETs can be deployed at any place in a very short time, providing access to information and services regardless of geographic position [1]–[3]. Thus, MANETs are considered as a future networking facility, which will allow replacing the expensive infrastructure [4]–[6]. Due to the dynamic nature of MANETs, they are able to form a self-reconfigurable network in which all their nodes collaborate in the routing tasks; consequently, nodes in the network can perform the roles of both hosts and routers. By using appropriate routing protocols, all these tasks are transparent to the final user, which facilitates the deployment of these systems.

On the other hand, there are no doubts about the current growth of multimedia services, which represents more than 50% of current Internet traffic [7]. For instance, the use of Voice over IP (VoIP) services has become a common practice among Internet users. The levels of quality reached, the low-cost calls, and the possibility of communication with anyone, no matter his/her location and access technology, are the VoIP most valued features by users. However, voice transmissions over wireless networks have some inherent challenges to beat. Focusing on VoIP transmissions over MANETs, the unique characteristics of the underlying peer-to-peer architecture, nodes motion, shared and varying wireless medium, as well as the limited resources, such as battery, memory, computation power, etc., pose a number of non-trivial challenges to provide a VoIP service with acceptable levels of quality in terms of both Quality of Service (QoS) and Quality of user Experience (QoE). Consequently, using efficient routing protocols is a must in order to satisfy high-quality performance on demanding traffic services, such as multimedia communications.

One routing protocol that has been devoted a notable research effort during the last years is the Better Approach To Mobile Ad-hoc Networking (BATMAN) protocol. BATMAN is an open-source proactive protocol designed to operate in multi-hop ad-hoc mesh networks. Currently, it is defined as an IETF's draft [8], and its main contribution is that nodes in the network do not try to determine the whole path to each destination; instead, BATMAN nodes only know the best next-hop to a given destination without routing-information exchange among nodes. With this feature, BATMAN aims to

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outperform other widely-used routing protocols such as OLSR (Optimized Link State Routing), AODV (Ad-hoc On-Demand Distance Vector Routing), or DSDV (Destination-Sequenced Distance Vector) [9], [10], by employing a simpler algorithm, which consumes less CPU resources, and, therefore, allowing battery saving. Green networking is an emerging trend, focused on the development of environmental-friendly architectures by reducing the power consumption of network devices, and it stands also as a key factor for the deployment of long lifetime wireless technologies such as MANETs and Wireless Sensor Networks (WSN).

Regarding quality issues, the design of multimedia services is progressively converging to user-centric approaches. For that reason, not only the QoS from a networking point of view is needed, but QoE should be also satisfied by assessing the level of quality that the customer actually perceives. The most extended methodology used to evaluate QoE is the absolute category rating (ACR) method, which outputs a Mean Opinion Score (MOS) that is a subjective rating of the service. However, using ACR is time-consuming, expensive, and does not permit continuous monitoring of networks. An alternative is the PESQ model defined in the ITU-T Rec.P.862. This double-ended model makes use of the clean original source as a reference, which is compared with the received signal, evaluating the distortions suffered by the voice stream. By means of this analysis, PESQ assesses the listening quality of a voice call and is used to predict customer's QoE, since its estimation is provided in a MOS scale.

In this paper, we focus on evaluating the performance of the BATMAN routing protocol supporting a multimedia service on low battery-consumption nodes. Specifically, we assess by simulation the MOS estimated by the PESQ model in a number of simultaneous VoIP transmissions with different MANET configurations employing low transmission power. First, we evaluate the effect of the physical layer (PHY) on BATMAN characterizing the wireless transmission channel by the Nakagami-m propagation model. Thereby, we analyze the effect of the medium hostility on the performance of a variable number of simultaneous VoIP calls accessing the system in terms of QoE (in a MOS scale) and QoS (delay, packet loss, etc.). Results obtained in fading scenarios are compared with those achieved under free space conditions. We also evaluate the effect of the number and density of ad hoc nodes (nodes per unit of area) on BATMAN performance for a VoIP service. Finally, we investigate the impact of moving nodes on the VoIP QoE, with the aim of analyzing how BATMAN reacts to topology changes and the influence of the "marginal mobility model" [11]. All the results obtained for BATMAN are compared with those attained by using OLSR [12], whose status is denoted as experimental rfc by the IETF; this protocol has showed superior performance than other pro-active routing protocols in VoIP scenarios in the work presented in [13].

The rest of the paper is organized as follows. Section II reviews the most relevant research work related to the performance evaluation of MANET routing protocols under VoIP traffic. Section III describes the operation of BATMAN and OLSR routing schemes. A description of the simulation environment employed in this work is included in Section IV. Section V shows the results achieved and discusses the response of the two different routing protocols BATMAN and OLSR in terms of the effect of (i) fading channels, (ii) number and density of nodes, and (iii) nodes mobility. The paper concludes summarizing the most important facts.

II. Related work

The performance of VoIP services over MANET scenarios has not been investigated with the same intensity as it occurs for infrastructure networks. Nevertheless, some works analyzing the suitability of ad-hoc environments to support VoIP communications can be found in the literature [4], [13]–[18], but few take into consideration the BATMAN protocol [19], [20].

Anand *et al.* analyzed in [13] the behavior of different codecs and WLAN schemes carrying VoIP traffic and drew a conclusion on the performance of the network, based on the criteria of different QoS parameters, namely, throughput, delay, and jitter. The suitability of different routing protocols for VoIP traffic was evaluated. Authors found OLSR protocol to reach the highest level of quality in terms of throughput and delay, compared to other protocols such as AODV, Dynamic Source Routing (DSR), and Geographic Routing Protocol (GRP).

Vanhatupa *et al.* presented in [4] a performance evaluation of MANETs supporting VoIP traffic. They investigated the effect of VoIP packet size and coding scheme on multi-hop WLANs. Authors obtained that the number of hops and the small packet-size together cause low throughput and long delays that are unacceptable for the VoIP application. However, authors employed static ad-hoc networks with pre-existing shortest path routes, so neither the effect of the routing protocol nor the nodes motion were taken into consideration.

In [14] the effect of the physical layer on VoIP traffic in ad-hoc environments was assessed via computer simulation. Nascimento *et al.* employed the E-Model to estimate the MOS on scenarios under different propagation models, namely, Free Space, two-ray ground, and shadowing. As shown by their results, authors found that the QoE is affected by the wireless-channel conditions, so that, the most the channel hostility, the higher degradation on the estimated QoE. Moreover, they demonstrated that OLSR is more sensitive to channel disturbances than other routing protocols, such as AODV.

Authors of [15] focused on the effect of coding scheme on the quality achieved in VoIP transmissions. Islam *et al.* found that for a small-scale scenario high data-rate codecs, such as G.711, get optimal performance; however, in a large scale scenario, low bit-rate codecs are best suited, because of their minimum bandwidth consumption.

Focusing on the performance evaluation of BATMAN, some works have evaluated it from different perspectives.

Kulla *et al.* [19] and Barolli *et al.* [20] deployed similar real test-beds to analyze the impact of the number of hops on BATMAN, supporting simulated multimedia traffic. In both works, authors deployed an IEEE 802.11b network formed by 5 nodes, obtaining quite satisfactory results for both, voice and video traffic, in terms of throughput, delay, and packet loss. However, these results should be carefully generalized given the limited size of the network and the use of just one multimedia flow from a transmitter to a receiver. As shown in [21], [22], the number of nodes is a key factor in MANET performance supporting multimedia traffic, as it determines the network load. Additionally, work in [19] ignored the impact of motion, nodes disconnections, and other sources of impairments affecting the routing protocol, and consequently the quality of the multimedia service using the network.

III. Routing protocols in MANETs

Due to the dynamic nature of MANET scenarios, efficient multi-hop routing protocols are needed. One of the most extended classifications to sort ad-hoc routing protocols is to differentiate them into proactive, reactive, or hybrid protocols.

Proactive protocols, also known as table-driven protocols, maintain the routing information even before it is needed, i.e., every node in the network keeps routing information to every other node. Therefore, proactive protocols are not suitable for large-scale networks, as each node needs to maintain node entries in their routing tables for every element in the network, and much control information is needed, which causes extra bandwidth consumption. On the other hand, the routing information is always up-to-date and the nodes are able to retransmit immediately an incoming packet to the destination next hop, hence reducing network delays which suppose an improving on time-sensitive services and applications. Examples of proactive protocols are BATMAN, OLSR, or DSDV protocols.

The reactive or on-demand routing protocols only calculate the route when it is required. In other words, there is no routing information maintained or even routing activity at the network nodes if there is no communication; if a node has to send a packet to other one, then the route is looked-up on-demand and the connection is established. That type of operation reduces the bandwidth consumption but increases the latency when a packet has to be retransmitted. AODV, DYnamic Manet On-demand routing (DYMO), or Temporally-Ordered Routing Algorithm (TORA) are examples of such reactive protocols.

Finally, hybrid protocols combine the advantages of proactive and reactive algorithms. The routing is initially established with some proactively prospected routes and then serves the demand from additionally activated nodes through reactive flooding. An example of this category is the Zone Routing Protocol (ZRP) [23].

Due to the tough requirements imposed by multimedia services, the routing-protocols efficiency is crucial in order to provide these services with high quality. In a MANET context, it is essential reacting to network changes, finding dynamically the best routes by introducing as less delay and packet loss to the VoIP stream as possible. Next, we present a brief description of the routing protocols under study: OLSR and BATMAN. The election of these algorithms is aimed at fairly comparing the performance of BATMAN, which is a promising proactive algorithm up to date, with the yield of one of the most extended proactive routing protocols: OLSR.

A. OLSR

This routing algorithm for MANETs is a well-known IETF's experimental-draft, based on the traditional concept of link-state routing algorithm. OLSR makes use of two different types of control packets, namely, HELLO and Topology Control (TC) packets. HELLO packets are employed by nodes to find out their neighboring nodes, so these packets are not retransmitted to the entire network. Once each node knows its "neighborhood", it starts sending TC packets including its neighbors and the state of the links established between them. This helps other nodes to build the network topology. The improvement introduced by OLSR is that the amount of control traffic, specifically TC packets, in the network is reduced by employing the Multi-Point Replaying (MPR) strategy. To do this, each node selects a set of its neighbors to retransmit its TC packets, including them in a field within the packet header; the remaining nodes can read these packets but are not allowed to retransmit them. With a proper strategy selecting the re-transmitter neighbors, all the destinations are reachable by all the nodes in the system without flooding the entire network. Additionally, TC packets include a sequence number in order to avoid infinite retransmissions due to undesirable loops.

The performance of OLSR working in different environments and supporting multimedia transmission has been analyzed in the extensive bibliography related to this protocol, e.g., [13], [14]. For VoIP services, it has obtained good results in terms of QoS in comparison with other routing algorithms [13], [24]. These results have led us to choose OLSR as the reference scheme to compare BATMAN with.

B. BATMAN

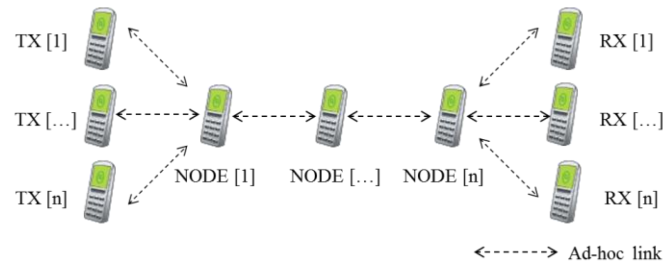
This proactive protocol is under development by the "Freifunk Community" [25]. The novelty of BATMAN resides in the decentralization of the knowledge about the routes; in other words, single nodes do not have routing tables for the entire network. Instead, each node determines one single-hop neighbor for each destination in the mesh, which can be utilized as the best gateway to communicate with the destination node. Thus, a very fast and efficient routing scheme is developed, creating a network of collective intelligence, and allowing low CPU and consequently less battery consumption for each node [26]. The protocol operation is as follows. On a regular basis every node broadcasts an OriGinator Message (OGM), thereby informing its link-local neighbors about its existence. Link-local neighbors which are receiving the OGM messages are relaying them by rebroadcasting, according to the specific BATMAN forwarding rules. The BATMAN mesh network is therefore flooded with OGM messages until every node has received each of them at least once, or until they got lost due to packet loss occurred in the communication links, or until their TTL value has expired. The number of OGM messages received from a given node via each link-local neighbor is used to estimate the quality of a route. In order to be able to find the best route to a particular end node, BATMAN counts the OGM messages received from each node in the network and logs which link-local neighbor relayed the message. Using this information BATMAN maintains a table with the best link-local route towards every other node in the network. By using a sequence number, included in each OGM, BATMAN can distinguish between new OGM packets and their duplicates, ensuring that every OGM gets only counted once. Notice that OGMs should not be taken actually as routing-information interchange packets, as they only act as a “hello packet”, not containing any information about routing tables, link states, etc.

This protocol has attracted great attention by the research community; consequently, a considerable number of works can be found evaluating its routing efficiency in different scenarios. For example, Kulla *et al.* have intensively studied its performance in different environments and under several node-motion conditions [19], [27]–[29]. The security in BATMAN has also been investigated and improved by several authors [30], [31]. However, to the authors’ knowledge, the BATMAN protocol has been barely addressed in terms of QoS/QoE support of multimedia and VoIP communications, and even less regarding low energy-consumption by the nodes. These services have some stringent requirements, such as delay-sensitive constrains, which make them quite complex traffic to manage; therefore, it is necessary to evaluate the capability of the MANET routing protocols in general, and the BATMAN protocol in particular, to support these time-critical communications.

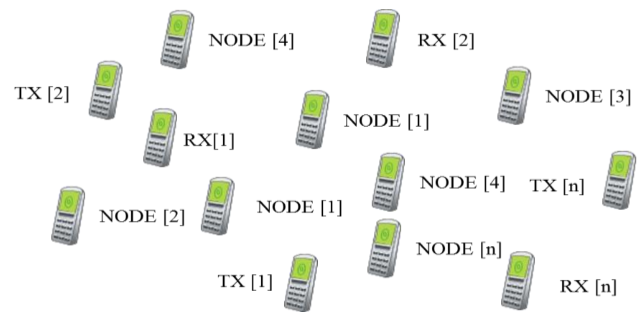
IV. Simulation environment

The environment selected for the simulation study was Omnet++ v4.2.2, with the Inet framework in its version 2.1 [32]. This framework provides several network devices as well as the implementation of multiple communication protocols.

The simulated scenario is an IEEE 802.11g wireless network at 54 Mbps in ad-hoc mode. Channel access is performed according to the Distributed Coordination Function (DCF) scheme. We use two ad-hoc network topologies: (i) a static chain of nodes with a variable number of hops between VoIP transmitters (TX) and VoIP receivers (RX) as shown in Fig. 1.a, and (ii) a mesh topology illustrated in Fig. 1.b, for two different node densities and three mobility configurations, which are static, partial, and full dynamic movement. In both topologies, (i) and (ii), we consider a different number of simultaneous VoIP calls in the system. 10 simulation instances with different seeds have been run for every evaluated scenario. Hence, in order to produce our results, we take the average value for every measured parameter, avoiding non-representative singularities. We have also calculated the variance and confidence intervals for every measurement, although they have not been included in our results due to



(a) Ad-hoc chain



(b) Ad-hoc mesh

Fig. 1. Simulation scenarios. TX[n] are the transmitters; RX[n] are the receivers; NODE[n] are the intermediate nodes.

their low significant values. The distance between nodes in the chain topology is 25 m; thus, each node is only capable to communicate with its direct neighbors and no shortcuts can be employed when calculating the route between TXs and RXs.

As we are obtaining our results from simulated scenarios, it is important modeling the transmission channel as realistic as possible. Some works [33] posed some concerns about the results on evaluations made on simulation platforms instead of real experiments because of the simplicity of some wireless channel models. For that reason, we introduce the effect of the fading channels on the wireless transmission medium. The impact of fading channels is assessed by comparing the results obtained under free space conditions with those attained in Nakagami-m scenarios. This characterization for the PHY layer has been widely employed in the related literature [34], [35] and its accuracy is guaranteed. In order to introduce a moderate level of fading in the transmission channel, we shape the Nakagami-m model with an *m* value of 5. Regarding nodes movement, it imitates the motion of a pedestrian; each node initiates each simulation at a random position and begins its motion toward a random direction following a linear trajectory with a speed characterized by a Gaussian distribution with a mean value of 1.34 m/s and a standard deviation of 0.26 m/s [36].

We are interested in evaluating the performance of low battery consumption devices. The two main energy-consuming processes in a regular ad-hoc node are routing algorithm and packets transmission/reception. As BATMAN allows low CPU load due to its simpler path-finding algorithm, we set the wireless card transmission power to the lowest standard value for different-manufacturer wireless cards, such as the Cisco Aironet Series, i.e., 1 mW. We set the wireless cards sensitivity to -72 dBm, with a carrier frequency given by the 802.11g standard, i.e., 2.4 GHz, and a SNIR (Signal to Interference and Noise Ratio) threshold of 4 dB. From these values and characterizing the PHY layer with the Free Space model, the resulting transmission distance is 40 m, therefore consistent with the topologies presented in this study.

As part of the Inet framework, we make use of the VoIP traffic generator, which generates a stream of VoIP packets from an arbitrary sound file using different audio codecs. In our simulations, we employ the ITU-T standard codec G.711 A-law (64 Kbps). To assess the quality of the VoIP transmissions, we use the PESQ implementation included in the ITU-T Rec. P.862, which has been embedded in the simulation platform. We assume a VoIP header, i.e., RTP, of 12 bytes and a packet time-length of 20 ms. The starting time for each VoIP call is chosen randomly according to a Poisson distribution in a time range of (0, 10 s), after the convergence time for each routing protocol. The audio sources last 30 s and the MAC queue size for each node is 50 frames. The remaining 802.11g parameters are set as Table I indicates.

V. Results

In this section, we show the simulation results obtained to study the VoIP system behavior for the different network configurations and channel conditions presented above. We will focus on evaluating how different factors, namely, (i) the physical layer in terms of fading, (ii) the number of nodes and the node density, and (iii) the nodes motion influence on the performance of BATMAN, and consequently, on the QoE of the VoIP calls. To this end, we evaluate the MOS, delay, and packet loss rate for each call and compare these results with those obtained for OLSR.

In order to set each individual call as valid, from a QoS/QoE perspective, several metrics are usually used in the bibliography, e.g., MOS value, one-way delay, or packet loss probability. Following the guidelines of the ITU-T Rec. G.114 and G.1010, we define a call as valid if the final MOS value attained for this call is over 3.1. This metric allows joining the effect of all the different impairments suffered by the VoIP stream in one single parameter. As discussed above, the MOS estimation has been calculated using the PESQ model.

As a first step, and in order to evaluate the performance of BATMAN under regular network nodes power-consumption conditions, we simulated the described scenarios for a transmission power of 100 mW. We obtained no significant differences in the performance of both protocols, obtaining for the chain scenario the MOS values shown in Fig. 2. In turn, for the mesh topology, in both scenarios, with mobile and static nodes, we attained the maximum value of MOS, regardless the routing protocol employed, the fading conditions and size of the simulated scenario, the number and speed of the nodes in the network, or the number of simultaneous VoIP calls. This behavior is explained by the fact that in the simulated scenarios (50 m x 50 m and 125 m x 125 m), all the area is covered by the nodes coverage range, and no node-isolation occurs, so the VoIP communications flow perfectly.

As we are interested in evaluating the performance of BATMAN in networks composed by low energy-consumption nodes, we finally set the transmission power to 1 mW. This configuration provokes the appearance of multi-hop paths, and makes nodes to follow the “marginal mobility model” [11], in which several nodes could be located at the edge of the network coverage area. Thus, during its movement, a mobile node exits and enters the network coverage area at different periods of time, which causes the temporal disconnection from the network and the consequent drop in the MOS of the calls.

A. Fading

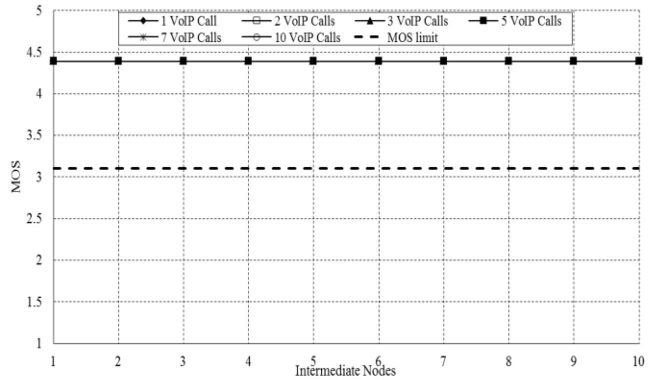
Fig. 3 illustrates a comparison between the average MOS achieved for different number of simultaneous VoIP calls under the effect of the physical layer. In this case, we have used the ad-hoc chain topology shown in Fig. 1.a. The aim of analyzing this topology is to study the number of simultaneous calls that a single node can support and to evaluate the significance of the number of hops in the performance of the VoIP service.

The effect of fading channels on the VoIP traffic using OLSR is shown in Fig. 3.a and 3.b. Observe the severe drop in the MOS attained in Nakagami-m scenarios (Fig. 3.b) compared with the MOS values obtained in free space environments (Fig. 3.a): just one call is accepted with one hop between TX and RX, (the rest of the MOS values are under 3.1). These results agree with those obtained by Nascimento *et al.* [14] and Singh [37]. In both cases, by employing different propagation models, authors found the same OLSR poor performance in hostile scenarios.

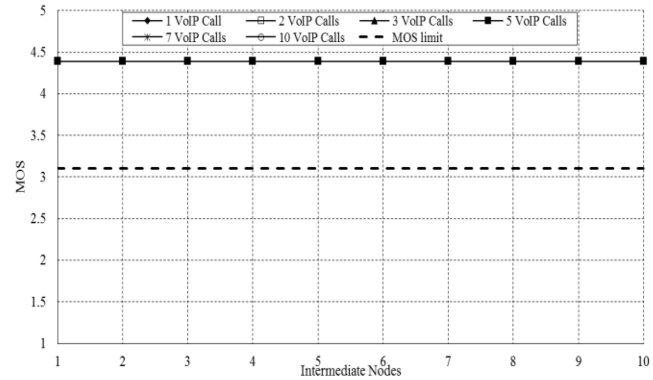
In comparison, the MOS fall in fading scenarios is less pronounced using BATMAN (please compare Fig. 3.b and Fig. 3.d). BATMAN accepts up to 3 calls with 3 hops between VoIP TXs and RXs. Moreover, 1 and 2 simultaneous calls are established with good levels of MOS when up to 10 and up to 5 nodes separate TXs and RXs, respectively.

TABLE I
802.11g AND ROUTING PROTOCOLS PARAMETERS

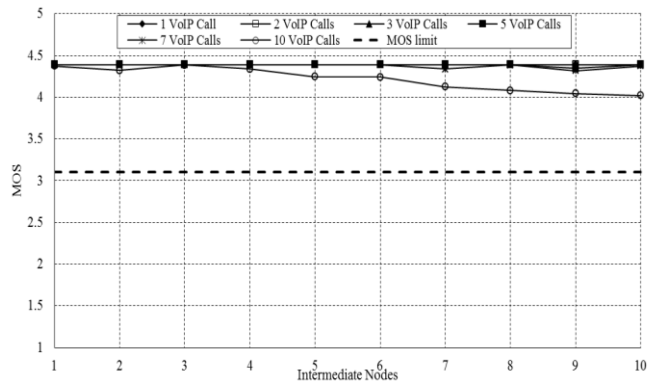
Parameters	Bytes	Time
SIFS, DIFS, SLOT (μs)	-	{10, 28, 9}
CW_{MIN} (slots)	-	31
PLCP preamble (μs)	-	4
{PLCP, MAC, SNAP} headers (μs)	-, 28, 8	{16, 4.15, 1.18}
IP + UDP + RTP headers (μs)	40	5.92
Voice (G.711, 20 ms) (μs)	160	23.70
ACK (μs)	14	2.07
BATMAN OGM interval (s)		1
BATMAN purge timeout (s)		200
OLSR {HELLO, TC, MID} intervals (s)		{2, 5, 5}
OLSR {Neighbor, Topology} hold times (s)		{6, 15}



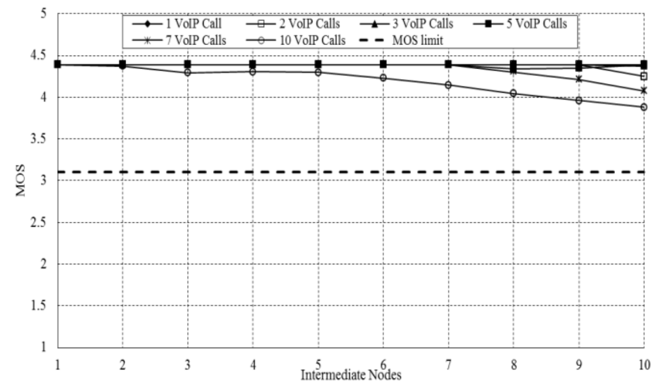
(a) OLSR. Free Space



(b) OLSR. Nakagami-m

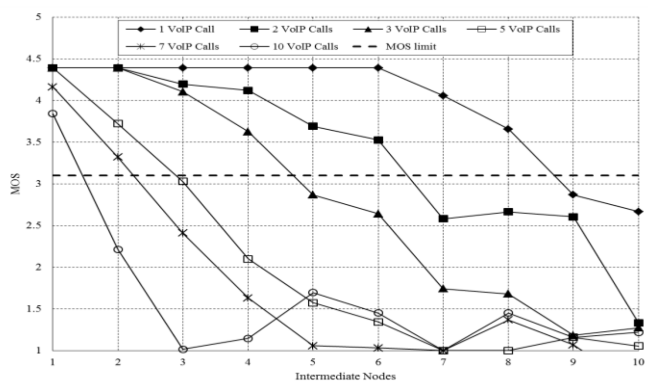


(c) BATMAN. Free Space

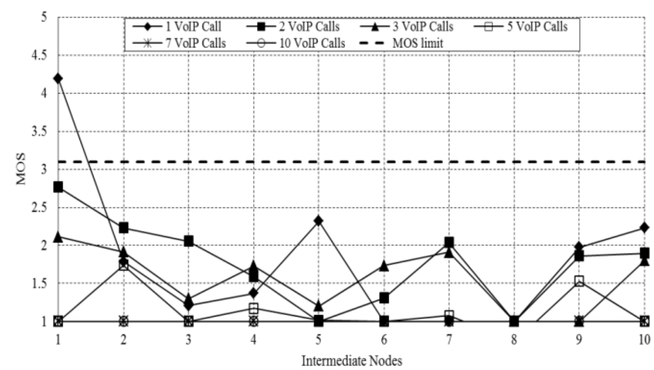


(d) BATMAN. Nakagami-m

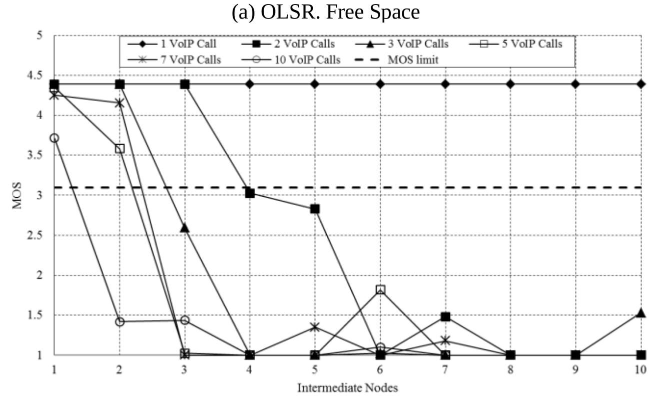
Fig. 2. MOS attained for a variable number of VoIP calls and hops between transmitters and receivers with a transmission power of 100 mW. Results for OLSR and BATMAN with Free Space and Nakagami-m propagation models.



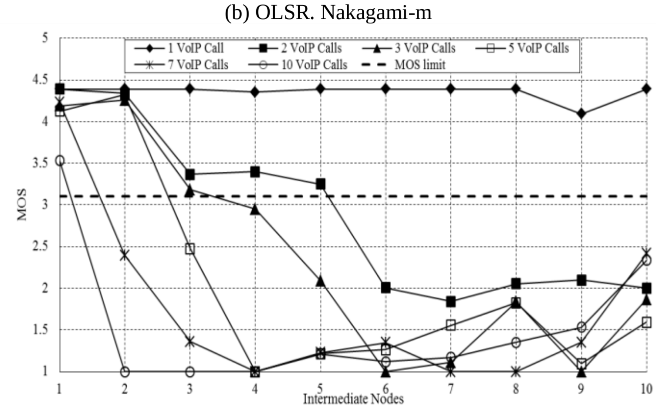
(a) OLSR. Free Space



(b) OLSR. Nakagami-m



(c) BATMAN. Free Space



(d) BATMAN. Nakagami-m

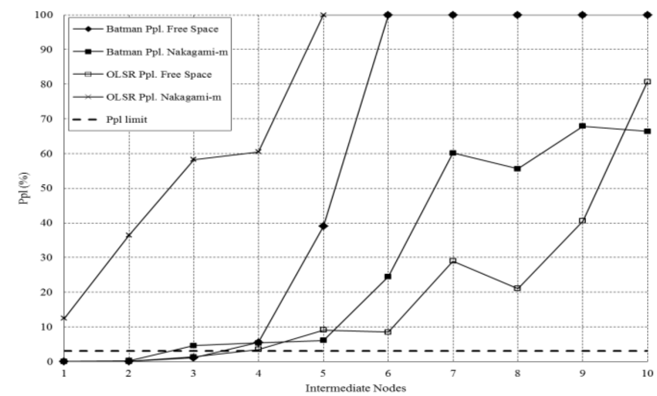
Fig. 3. MOS attained for a variable number of VoIP calls and hops between transmitters and receivers with a transmission power of 1 mW. Results for OLSR and BATMAN with Free Space and Nakagami-m propagation models.

We ascribe the dramatic degradation in the OLSR network performance to the size of its control messages. OLSR makes use of larger packets than BATMAN, so their transmission is more prone to the effect of fading [38], causing an increase in the control packets loss rate, which encumbers the right establishment of the OLSR routes. Hence, the VoIP communications are interrupted or directly cannot be established. In the light of these results, we can conclude that BATMAN seems to be more robust than OLSR under adverse channel conditions. This is further confirmed from a QoS point of view in Fig. 4, which depicts the evolution of the Probability of Packet Loss (Ppl) and the delay attained in the VoIP streams for a scenario with two simultaneous calls. Notice the vast rise of packet loss (Fig. 4.a) and delay (Fig. 4.b) in fading scenarios managed by OLSR in comparison with those accomplished under free space conditions, which explains the deep drop on the MOS showed in Fig. 2.b Also we can observe in Fig.4 how BATMAN shows its strength to the impact of fading channels, obtaining a more controlled Ppl and delay in Nakagami-m scenarios than OLSR.

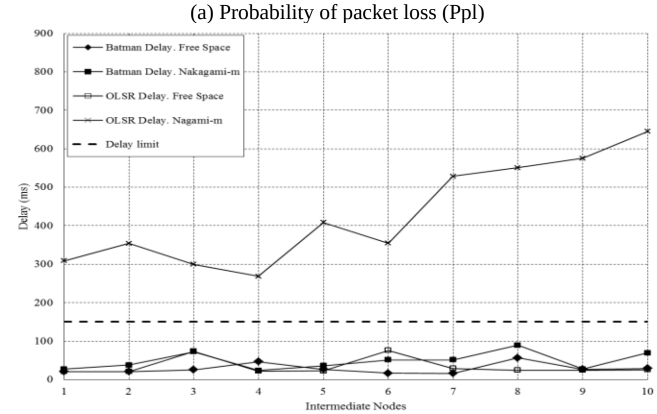
On the contrary, OLSR over performs BATMAN in the free space scenarios (see Fig. 3.a and 3.c). Using OLSR, the system accepts up to 2 simultaneous calls in a 6 hops connection and 3 simultaneous calls are supported in transmissions up to 4 hops. However, only one VoIP call is accepted as valid with BATMAN when there are more than 3 hops between TX and RX. Similarly, the system just allows up to 2 simultaneous VoIP calls when the distance between VoIP nodes is 3 hops. Observing Fig. 3.c, Fig. 3.d and Fig. 4, it is clear that BATMAN behaves better in a scenario with fading than in free space. This decline in BATMAN performance in terms of MOS at free space scenarios, as well as in the system capacity in terms of valid number of VoIP calls, is due to the excess of Originator Messages (OGM) generated by the BATMAN algorithm in free-space, since under these conditions very low packet losses occur. Fig. 5 shows a comparison of the MOS obtained for the VoIP calls using the default time interval between OGMs (1 s) and that achieved by increasing the OGMs interval up to 2 s in scenarios characterized by the Free Space model. Observe that setting an interval of 2 s, both the number of VoIP calls accepted by the system and the number of hops allowed with a MOS over the limit established increase. We obtain that up to 3 calls are accepted as valid with 4 intermediate nodes, achieving also greater MOS values for these accepted calls. That is, the default time interval between OGMs (1 s) produces an increase in both, the transmission-channel occupation and the nodes buffers, with the corresponding growth in packet losses. This behavior is also shown in Fig. 6 that describes the evolution of the Ppl in a scenario with two VoIP calls (two TX and two RX) and different time intervals between OGMs. Observe the big difference in the Ppl obtained for the different scenarios. As discussed above, using an OGM interval of 1 s, the surplus of OGM messages in the network collapses both the wireless transmission channel and the nodes buffers, increasing the number of VoIP packets dropped. As stated in BATMAN IETF's draft [8], and confirmed by Murray *et al.* [39], BATMAN was not designed to operate on stable and reliable media, so its performance depends on packet loss. This is because of the mentioned broadcasting of OGMs by the nodes, which without packet loss, leads to the network saturation. As the free space environment does not introduce many packet losses, the OGMs harm the VoIP traffic, resulting in a reduction of the system capacity and VoIP quality. On the other hand, the lack of control messages happened in scenarios with longer OGM intervals, such as 5 s, produces a decrease in the network performance, revealed as an important increase of Ppl in the VoIP stream. We attribute this behavior to the speed of convergence of the routing algorithm, which turns very slow for a low number of OGM messages received. It is clear that, for this scenario, an OGM interval of 2 s provides the lowest Ppl on the VoIP flows. Therefore, we can conclude that it is necessary tuning the OGM interval, adapting it to the current network characteristics and considering the trade-off between the number of OGM packets in the network and the lack of enough information in the nodes to establish the routes.

B. *Number and density of nodes*

Focusing on the effect of the number of nodes composing the network on the QoE performance, we have carried out a set of simulations configuring the topology as a mesh network and locating the nodes at fixed random positions. Two different square areas of 50 m x 50 m and 125 m x 125 m



(a) Probability of packet loss (Ppl)



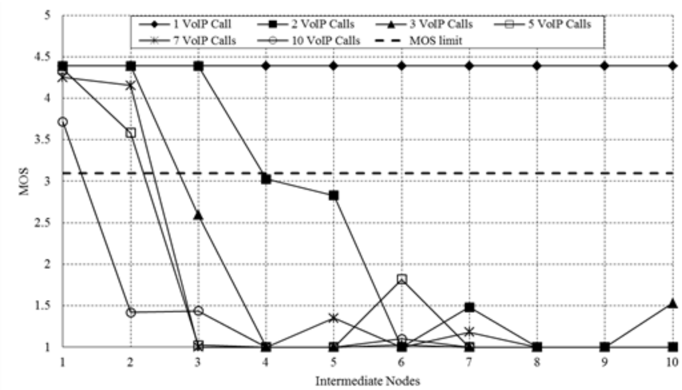
(b) Delay

Fig. 4. Ppl (a) and delay (b) suffered by the VoIP streams in chain scenario with two simultaneous calls and variable number of hops between transmitters and receivers, using BATMAN and OLSR.

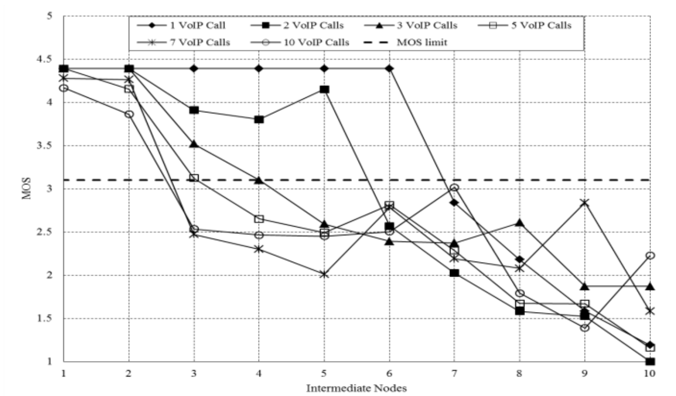
are used. In addition, we also consider two different numbers of nodes, namely, 25 and 50 nodes.

Fig. 7 shows the evolution of the average MOS in the 50 m x 50 m scenario for two different densities of nodes, two different propagation models, and the two routing protocols under study. Using BATMAN, it is noticeable an important drop on the quality for the 50-node topology. Observe that, regardless the number of simultaneous VoIP calls in the system, the configuration with fewer nodes always achieves better results. In addition, we always obtain better results using OLSR than using BATMAN in topologies with a larger number of nodes; even in fading environments, which have a deep impact on the performance of OLSR as discussed above.

On the other hand, in the 25-node scenario, BATMAN reaches a slightly lower level of quality than OLSR in free space situations (Fig. 7.a), and obtains significantly better results in fading scenarios (Fig. 7.b). Fig. 8 represents the average MOS attained with BATMAN for several system loads and different-sized Free Space scenarios with a variable number of nodes composing the network. Observe that, as



(a) Interval among OGMs: 1 s



(b) Interval among OGMs: 2 s

Fig. 5. MOS obtained for a variable number of VoIP calls and hops between transmitters and receivers using BATMAN with different time intervals between OGMs with Free Space propagation model.

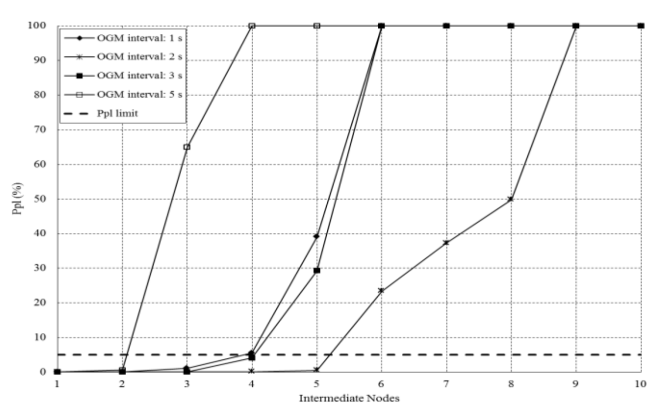
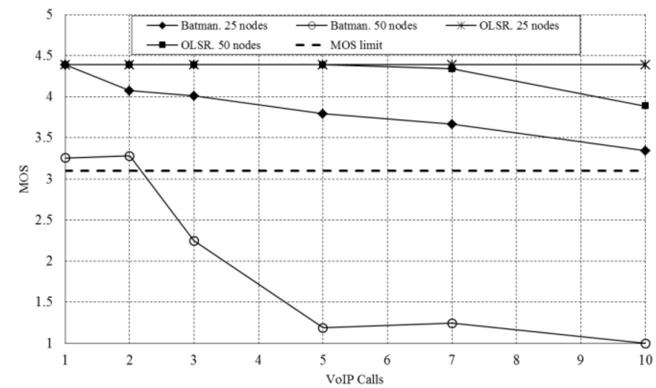
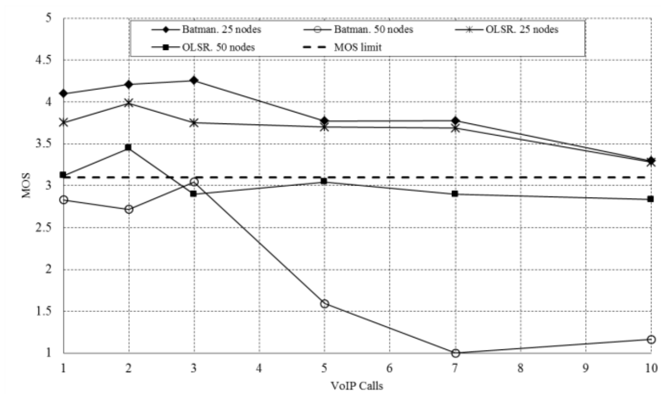


Fig. 6. Probability of VoIP packet loss in a Free Space chain-network scenario, employing 2 different BATMAN OGMs time intervals.



(a) Free Space



(b) Nakagami-m

Fig. 7. MOS evolution for different node population in the 50 m x 50 m scenario in Free Space and Nakagami-m environments.

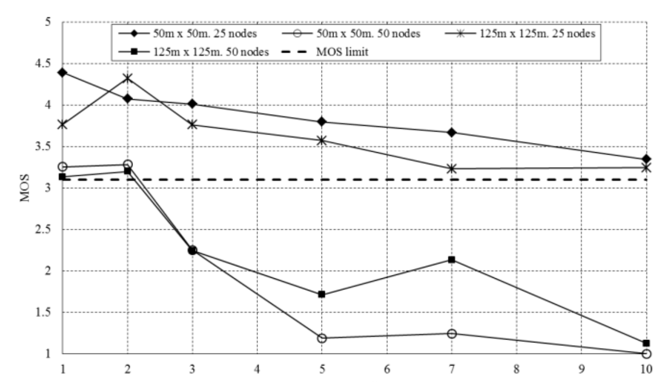
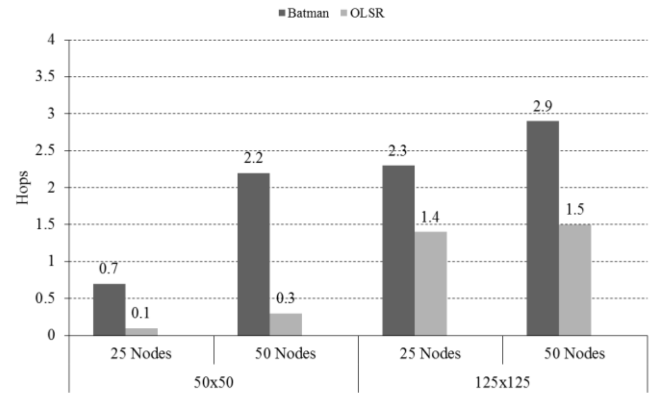


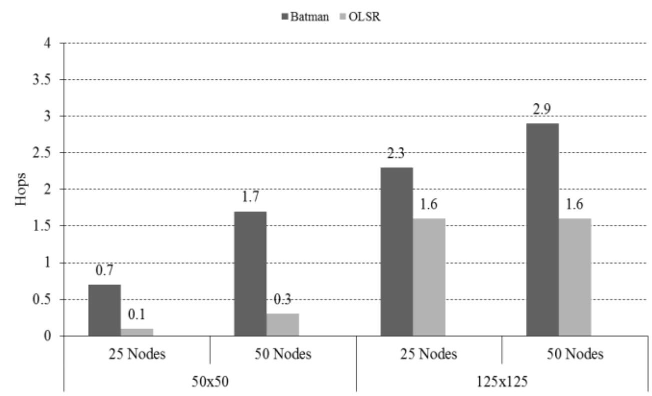
Fig.8. Comparison between the MOS reached using BATMAN in different-sized Free Space scenarios.

mentioned above, the MOS reached in topologies with 25 nodes is greater than that obtained when the network consists of 50 nodes, regardless the size of the scenario. In the 25-node topologies, 10 simultaneous VoIP calls are supported by the network, with MOS levels around 3.3. On the other hand, in more crowded scenarios, just 2 calls are supported by the network satisfying the minimum established level of MOS. Furthermore, focusing on the network composed by 25 nodes, there is a little decrease in the estimated MOS for the largest scenario (125 m x 125 m) comparing with the one obtained in the (50 m x 50 m) case. This fact could be explained because of the BATMAN path-finding algorithm. Fig. 9 shows a comparison between the average number of hops in the path between the VoIP transmitters and the VoIP receivers in a static mesh network with random node positions. There is a notable difference between the number of hops in the routes calculated by BATMAN and those computed by OLSR, particularly under high density conditions, e.g., in 50 m x 50 m scenarios. The routes obtained by OLSR are always shorter than those established by BATMAN. Additionally, we found in the simulations conducted for the chain scenario (Fig. 1.a) that, even with this simple configuration, the number of hops calculated by OLSR is lower than that computed by BATMAN. Particularly, OLSR always obtains the best possible result, i.e., the number of hops between TXs and RXs was exactly equal to the number of intermediate nodes in the chain network. However, if we use BATMAN and there are several VoIP TXs in the system, some of them use each other as an intermediate node; thus, the established route has one or more extra hops, i.e., the number of intermediate nodes in the chain topology does not match the number of hops in the path. In conclusion, BATMAN algorithm seems to be less accurate than OLSRs when calculating the shortest route to the destination, hence the delay and the Ppl increase with the consequent impact on the estimated MOS. As an example, Fig. 10 depicts a significant high delay in scenarios with 50 nodes using BATMAN. These results are for the 125 m x 125 m scenario and the Free Space propagation model. Whereas BATMAN shows delays up to 1050 ms, observe that in the other cases (OLSR with 25 or 50 nodes and BATMAN with 25 nodes), the delay ranges between 20 ms and 110 ms, therefore below the ITU-T established delay limit of 150 ms for VoIP valid calls.

Similarly to the chain scenario, we have also investigated the effect of the OGM interval on the performance of BATMAN affecting the VoIP MOS. Fig. 11 represents a comparison among the MOS reached by setting different OGM intervals in a 50 m x 50 m Free Space scenario with 50 nodes. It is clear that using an interval of 5 s, the MOS attained in every simulated scenario is greater than those obtained employing the rest of intervals. The poorest performance in terms of MOS is achieved when the OGM interval takes the default value of 1 s. According to these results, BATMAN shows again the need of tuning the OGM interval depending on the network size and nodes density, in order to avoid the network collapse due to the great amount of control packets.



(a) Free Space



(b) Nakagami-m

Fig. 9. Average number of hops between VoIP TXs and RXs in Free Space and Nakagami-m environments.

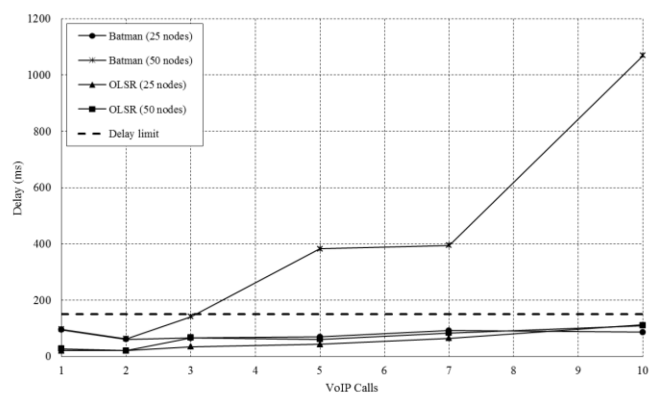


Fig. 10. Comparison between the measured delay using BATMAN and OLSR for different number of VoIP calls and node densities in the 125 m x 125 m scenario using the Free Space propagation model.

C. *Nodes mobility*

We have also studied the effect of the nodes mobility on the VoIP QoE. Setting the mesh network topology to 25 or 50 nodes, we have simulated three different movement patterns for the nodes: (i) all the nodes maintain their initial random position (static case, only for comparison purposes), (ii) only the VoIP TXs move (partial dynamic), and (iii) all the nodes in the network move (full dynamic) as follows. The simulated movement imitates the motion of a pedestrian handling a mobile handset device, i.e., a linear trajectory with a speed characterized by a Gaussian distribution with a mean value of 1.34 m/s and standard deviation of 0.26 m/s.

Fig. 12 shows a comparison between the three motion patterns under study in the 50 m x 50 m and 125 m x 125 m scenarios, for the Free Space model, and with 25 nodes. Observe that for the smaller surface scenario (Fig. 12.a), node motion has a slight impact on the quality of the calls. Both BATMAN and OLSR attain the maximum MOS for the static configuration. In full-motion (dynamic) scenario, a little decrease in the MOS is observed for OLSR, but always reaching MOS values over the established minimum threshold of 3.1. However, the VoIP MOS employing BATMAN suffers a noticeable drop under the full-motion condition. In the larger scenario (Fig. 12.b), the drop in the MOS due to full-motion is even higher, being perceptible no matter the employed routing algorithm. Comparatively, BATMAN seems to be slightly more affected than OLSR by the nodes motion; observe that the MOS level for a BATMAN-managed full-motion scenario is always under the MOS estimation of the rest of the simulated conditions. The difference in the results obtained for the two scenarios (50 m x 50 m and 125 m x 125 m) can be explained as follows. In the 50 m x 50 m scenario, the nodes motion does not affect the quality of the transmission since all the area is perfectly covered and there are no isolated nodes. However, in the 125 m x 125 m scenario and depending on the trajectory taken by each node, some TXs or RXs are temporarily isolated from the rest of the network due to the short coverage range provided by the low transmission power employed; for that reason a decreasing in the MOS level of the VoIP calls is attained.

In order to clarify these outcomes from a QoS perspective, Fig. 13 shows the Ppl suffered by the VoIP streams in the 125 m x 125 m full-motion scenario. Notice the great amount of packet losses in a 50-node Free Space scenario managed by BATMAN (Fig. 13.a). This particular scenario exhibits the main flaws of BATMAN analyzed previously. First, it illustrates the network congestion due to the OGMs-flooding, affecting especially to low loss environments as those exemplified by the Free Space model. Second, it presents the scalability problems showed by BATMAN for networks consisting of a high number of nodes, in addition to the performance degradation obtained in scenarios with mobility.In scenarios with low number of nodes, 25, BATMAN obtains a noticeable performance improvement. However, in this scenario with low loss, OLSR still shows a better response and the Ppl suffered by the VoIP streams is clearly lower than that attained employing BATMAN. This situation turns in high-loss scenarios (see Fig. 13.b). Now, the low performance of OLSR in fading environments is manifested, and the Ppl rises notably for both densities of nodes. On the other hand, BATMAN shows its robustness to fading scenarios, achieving good level of Ppl for the 25 nodes scenario, but maintains its scalability issues in the network composed by 50 nodes with full motion.

As in previous sections, and in order to evaluate the impact of the BATMAN OGM interval on mobility scenarios, we have also conducted a set of simulations in a 125 m x 125 m Free Space scenario, studying the performance of a network composed by 25 nodes. This is the same configuration used to obtain the discussed mobility results by employing the OGM by default interval (Fig. 12.b and Fig. 13.a). Thus, Fig. 14 depicts the MOS accomplished for a variable number of simultaneous calls in the network and different time interval between OGMs. Observe that we achieve quite similar results, no matter the OGM interval employed. Just one call is

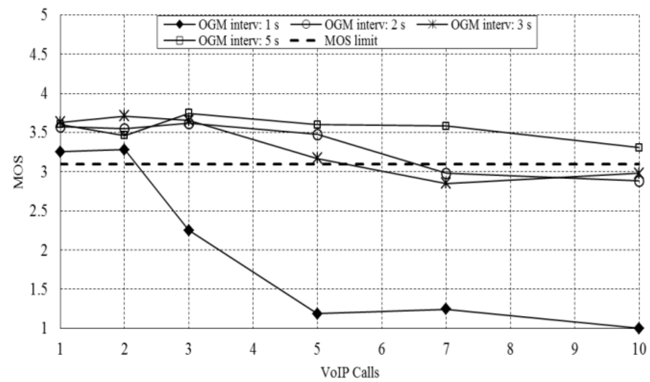
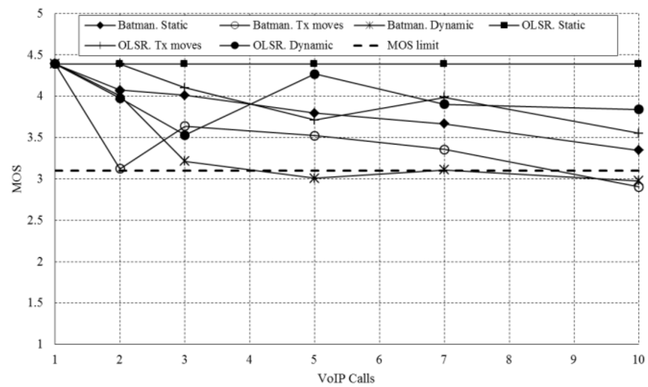
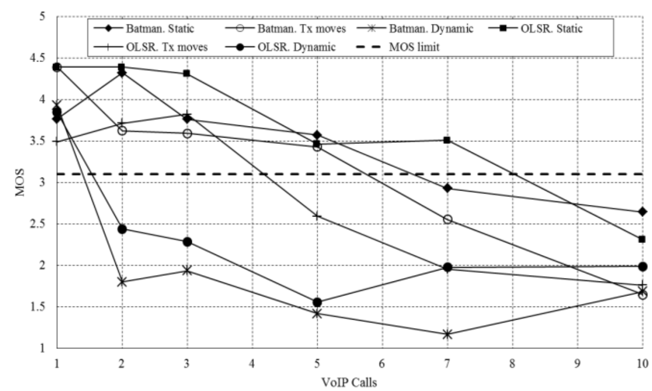


Fig. 11. MOS evolution for different OGM intervals and variable number of simultaneous VoIP calls in a 50 m x 50 m Free Space scenario with 50 static nodes.

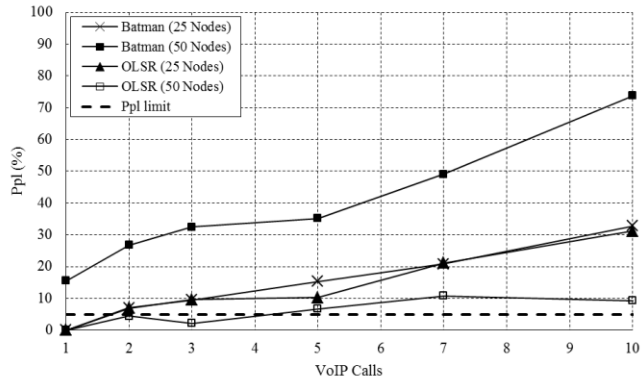


(a) 50 m x 50 m

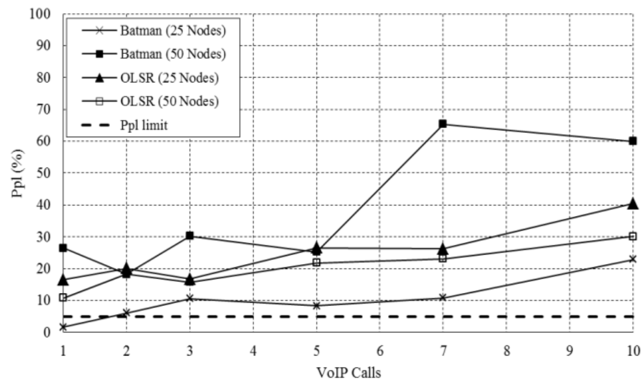


(b) 125 m x 125 m

Fig. 12. Comparison between the obtained MOS for different movement scenarios with 25 nodes and using the Free Space propagation model.



(a) Free Space



(b) Nakagami-m

Fig. 13. Ppl suffered by the VoIP streams in 125 m x 125 m full-motion scenario using BATMAN and OLSR for different number of VoIP calls using the Free Space (a) and Nakagami-m (b) propagation models.

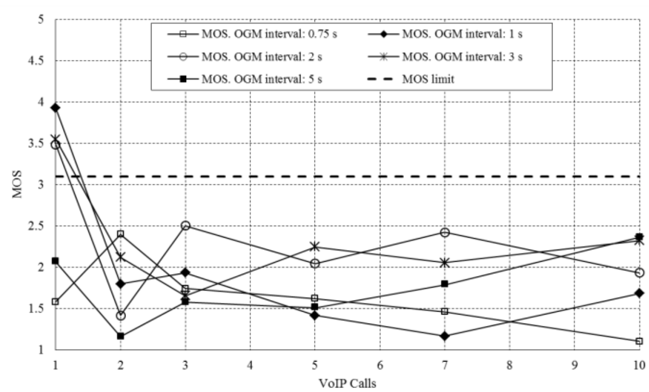


Fig. 14. MOS evolution for different OGM intervals and a variable number of simultaneous VoIP calls in a 125 m x 125 m Free Space scenario with 25 dynamic nodes.

accepted when using an interval of 1, 2, or 3 s, meanwhile, no calls are accepted as valid when tuning the interval to 0.75 or 5 s. In this scenario, the low quality of the calls is not caused by an excess of OGMs in the network, since the density of nodes is quite low. As discussed above, we attribute the VoIP quality drop to the greater size of the scenario in comparison with the nodes coverage range, which provokes the temporary isolation of TXs or RXs during the communication. As explained in [11], currently in-developing-techniques as “waiting for destination” or “follow the destination”, not implemented yet in the current versions of the routing protocols under study, are needed to overcome this transient connectivity problems and no actions can be taken to improve the MOS of the VoIP calls when the nodes follow “the marginal mobility model” under the management of BATMAN or OLSR.

VI. Conclusion

We evaluated the pros and cons of the novel ad-hoc routing protocol BATMAN to manage a MANET composed by low energy-consumption nodes, supporting VoIP traffic. Simulations focused on the widespread wireless IEEE 802.11g networks, evaluating the system performance from a QoE perception. In order to compare the results obtained by using BATMAN, we also evaluated the performance of the well-known routing protocol OLSR, which is an IETF’s experimental-draft. First, we analyzed the effect of the physical layer on the performance of the routing protocols. BATMAN obtained better results than OLSR in scenarios under fading conditions characterized by the Nakagami-m propagation model, which is a hostile medium with fading channels. This behavior is related to the bigger size of OLSR control packets in comparison with BATMAN shorter control packets, which make them more exposed to the impairments introduced by the channel. On the other hand, OLSR over performed BATMAN in free space environments. We noticed some problems regarding the BATMAN OGMs interval; using the default value of 1 s, the OGM messages saturated the network, so the system capacity and VoIP MOS dropped dramatically in Free Space scenarios, since they present a lower packet loss rate. We showed that the system performance can be improved by increasing the OGM interval, e.g., up to 2 s. Afterward we studied the impact of the number of nodes and nodes density on BATMAN performance. We detected some scalability issues in this routing algorithm operating in mesh networks having a medium/high number of nodes. We attribute such behavior to the BATMAN path-finding algorithm, which always obtained longer routes than those calculated by OLSR. We also found a possible solution to these issues, by tuning properly the OGM interval. Finally, we evaluated also the effect of nodes motion on the estimated MOS of the VoIP calls. We showed that, whereas its effect is hardly noticeable in small-sized networks, a MOS drop appeared when the nodes were spread on greater areas, especially for BATMAN. From our study, we conclude that neither BATMAN nor OLSR in their respective current implementations are suitable enough to manage MANETs formed by low energy-consumption nodes, focused on VoIP traffic support. Joining BATMAN robustness to adverse channel conditions with OLSR better scalability to large and highly crowded networks could be a future step towards a more appropriate routing protocol for MANETs giving support to demanding multimedia services. As future work, we consider to carry out additional tests, employing real measurements in order to validate the results obtained in this work. Additionally, we consider that the use of cross-layer techniques with the aim of improving the QoE performance of VoIP on wireless scenarios could be a trend to follow because, as demonstrated in this paper, a proper action in the correct OSI layer depending on the environment under study and the impairments affecting the transmission, could suppose a significant improvement in the QoE of the multimedia communication.

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