ns-2 vs. OPNET: a comparative study of the IEEE 802.11e technology on MANET environments

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ABSTRACT

In this work we present the results of a comparative study between two well-known network simulators: ns-2 and OPNET Modeler. In particular, we focus on a performance evaluation of the IEEE 802.11e technology on Mobile Ad-hoc Networks (MANETs) in both stationary and mobile scenarios. The paper describes the tested scenarios in detail, and discusses simulation results obtained with OPNET Modeler, comparing them with those obtained with ns-2. The performance of IEEE 802.11e in the presence of legacy IEEE 802.11 stations is also analyzed. Due to the significant differences between both simulators, we enumerate those changes required so as to make results obtained via both simulators comparable. The results that have been reached support the conclusion that the behavior of both simulators is quite similar in general.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication

General Terms

Algorithms, Measurement, Performance

Keywords

MANET, 802.11e, Network simulators, performance comparative

1. INTRODUCTION

A Mobile Ad-hoc Network (MANET) is composed by a group of stations that communicate wirelessly with each other to form a network without the need for any infrastructure or centralized control. Two of the most important factors that characterize MANETs are the routing protocol and the wireless technology employed by the stations within the network. When referring to wireless technology we mean the combination of the physical (PHY) and Medium Access Control (MAC) layers of the protocol stack.

The IEEE 802.11 standard [1] was created to provide wireless local area networks (WLANs) to different environments, such as public access networks, enterprise networks, or home networks. It operates in free bands such as the industrial, scientific and medical (ISM) band at 2.4 GHz or in the unlicensed 5 GHz band. The IEEE 802.11e [2] task group has finished some extensions to the IEEE 802.11 standard to provide Quality of Service (QoS) at the MAC level. The availability of a wireless technology that offers QoS support is one of the most important requirements to deploy a QoS framework in MANET environments. By enabling traffic differentiation at the MAC level it is possible to design a strategy, built on top of the IEEE 802.11e technology, that can successfully support traffic with QoS constraints. Examples of QoS traffic include VoIP, videoconference, and that generated by any other real-time application.

Supporting real-time video and voice traffic in MANETs is an upcoming need that results from the fusion of two technological areas that have been receiving much interest in the past few years. On the one hand, the proliferation of devices with embedded audio/video capturing and processing capabilities has made audiovisual communications the new human communication paradigm. On the other hand, recent improvements in network technologies aim at supporting mobile wireless communications through self-configuring and fully flexible networks. Therefore, one of the greatest technological challenges to be met, according to the current state-of-the-art, is providing real-time peer-to-peer videoconference systems in MANETs. To achieve this goal QoS support stands as an essential condition.

Most published research works about MANETs use simulation tools [11], but the reliability of such simulation studies has been questioned [7, 17, 3]. Because of this, some comparative studies have been conducted in order to validate the obtained results [12, 8]. This paper presents a comparative analysis of two well-known network simulators, ns-2 v2.26 [15] and OPNET Modeler v14.0 [16]. We focus on the accuracy in simulating IEEE 802.11e technology in MANET environments. For IEEE 802.11e evaluation in ns-2 we relied on the extensions from [20], while for OPNET we relied on the IEEE 802.11e model that is built-in. Results obtained with the ns-2 simulator have already been published in [5]. The motivation of this paper is to repeat all the experiments under the same conditions using OPNET, in order to validate the accuracy of both simulators for some particular MANET scenarios. Similarly to that previous paper, all

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Table 1: UP-to-AC mappings

User Priority	Access Category	Designation
1	AC_BK	Background
2	AC_BK	Background
0	AC_BE	Best Effort
3	AC_BE	Best Effort
4	AC_VI	Video
5	AC_VI	Video
6	AC_VO	Voice
7	AC_VO	Voice

Table 2: Default EDCA parameter values

AC	$\mathrm{CW}_{min..max}$	AIFSN	TXOP limit
AC_BK	15..1023	7	0 ms
AC_BE	15..1023	3	0 ms
AC_VI	7..15	2	3.008 ms
AC_VO	3..7	2	1.504 ms

nodes in all scenarios of this paper run the IEEE 802.11 [1] or 802.11e [2] in the ad-hoc mode, that is, without infrastructure, and all the mobile experiments are conducted using the Ad-hoc On-demand Distance Vector (AODV) [13] routing protocol. Since important divergences at different levels have been found between both simulators, several changes are necessary when replicating ns-2 experiments in the OPNET models, as explained later.

The remainder of the paper is organized as follows. Annex E of the IEEE 802.11 standard is briefly presented in Section 2, including an introduction to EDCA, the distributed medium access mechanism proposed in IEEE 802.11e to offer traffic differentiation in infrastructure-less wireless networks. Section 3 describes the methodology employed in conducting the different experiments, along with the divergences detected in the comparison process. The static and mobile scenarios used are described in Sections 4 and 5, respectively, followed by the discussion of the obtained results. Section 6 describes a similar experiment to that of the mobile scenario, now comparing results of both simulators in the presence of legacy 802.11 nodes. Finally, conclusions are drawn in Section 7, along with references to future work.

2. AN OVERVIEW OF IEEE 802.11E

The IEEE 802.11e is an improvement to the original IEEE 802.11 standard in order to support QoS at the MAC level. To achieve this, packets received from upper levels are handled in a different manner depending on their QoS requirements, meaning that IEEE 802.11e supports service differentiation. Similarly, the MAC layer also offers a differentiated treatment to packets with different QoS requirements when passing them to upper stack layers.

This new standard introduces the Hybrid Coordination Function (HCF), which defines two new medium access mechanisms to replace the legacy Point Coordination Function (PCF) and Distributed Coordination Function (DCF). These are the HCF Controlled Channel Access (HCCA) and the Enhanced Distributed Channel Access (EDCA). Concerning IEEE 802.11e enabled stations forming an ad-hoc network, these must implement the EDCA. As in this paper we focus on ad-hoc networks, we are only interested in 802.11e stations implementing EDCA.

At the Application layer, packets are assigned a priority value ranging from 0 (the lowest) to 7 (the highest), referred as User Priority (UP). Depending on this UP, when a packet arrives at the MAC layer it is classified into one of the four Access Categories (AC); the mapping between the different UPs and these four ACs is illustrated in Table 1.

Contrarily to the legacy IEEE 802.11 stations (nQSTA), where all MAC Service Data Units (MSDU) have the same priority and are assigned to a single backoff entity, IEEE 802.11e stations (QSTA) have four backoff entities (one for each AC) so that packets are sorted according to their priority. Each backoff entity has an independent packet queue assigned to it, as well as a different parameter set for medium access. Table 2 presents the default MAC parameter values for the different ACs (referred as EDCA parameters) for an IEEE 802.11a/g radio. For IEEE 802.11 legacy stations this parameter set was fixed, and so the Contention Window limits (CW_{min} and CW_{max}) where set to 15 and 1023, respectively (for IEEE 802.11g); also, the time interval between frames - interframe space (IFS) - was set to a constant value: DCF Inter-Frame Spacing (DIFS). IEEE 802.11e introduces a new feature referred to as transmission opportunity (TXOP). A TXOP is defined by a start time and a duration; during this time interval a station can deliver multiple MAC Protocol Data Units (MPDU) consecutively without contention with other stations. This mechanism, also known as Contention-Free Bursting (CFB), increases global throughput through a higher channel occupation. From Table 2 we can notice that smaller values for the CW_{min}, CW_{max}, and Arbitration Inter-Frame Space Number (AIFSN) parameters are associated in a higher priority when accessing the channel; relative to the TXOP limit, higher values result in larger shares of capacity and, therefore, higher priority. With IEEE 802.11e, as the values of EDCA parameters depend on the AC itself, they are referred to as CW_{min}[AC], CW_{max}[AC], AIFSN[AC] and TXOP limit[AC].

3. METHODOLOGY

In order to make a rigorous comparative study, the same scenarios have been tested in both ns-2 and OPNET Modeler simulators, with special attention to the characteristics of OPNET's models and the simulation parameters used. Since several differences have been identified between both simulators, modifications have been carried out, which can be classified into five categories.

Default values of simulation parameters. Most of the simulation parameters match in both simulators, because they are related to the IEEE 802.11 standard [1] (e.g., the default EDCA parameter values). However, the default value for other parameters like the transmission range or the wireless buffer size are different, which could affect the results significantly. The former is quite different in both simulators; for a data rate of 54 Mbit/s, the default transmission range in ns-2 is 250m, which is significantly lower than that in OPNET (371m). Concerning buffer size, the default size is of 50 packets (204800 bits for a packet size of 512 bytes) in ns-2, whereas the default value in OPNET is 256000 bits. To make meaningful comparisons using OPNET, those parameters were set to the default values of ns-2, that is, the values used in [5].

Routing priority. The routing traffic of the AODV protocol was set to a higher priority (AC_VO) according to the recommendations in annex E of the IEEE 802.11 standard

[1]. Besides being the recommended procedure, it will also improve the overall network performance (see [6] for details).

Virtual collisions. In the experiments using ns-2 in [5], each source QSTA supports up to four different AC flows. Unexpectedly, when doing the same with OPNET, the results obtained showed high variability, and the ranking of ACs in terms of throughput seemed to be random in most cases. This was due to a failure in accurately implementing internal collisions between the four backoff entities at the MAC layer. To deal with this problem, instead of setting each source QSTA to generate traffic in all four ACs, as with ns-2, each node in a group of four source QSTAs was set to generate traffic in only one distinct AC. In this case, to reach the desired network load, the traffic generated is four times the original data rate in each of them. However, virtual collisions can still occur, since routing traffic is always generated for the Voice AC (AC_VO), as explained above, and intermediate nodes retransmit all flows received.

Metric definitions. A critical difference detected between both simulators is the meaning of some important metrics, namely, *load* and *throughput.* In ns-2, these parameters are calculated from the Application point of view. In other words, offered *load* is evaluated by adding up data sent by the application layer on the source node, and *throughput* is measured by adding up data received by the application layer on the destination node. On the other hand, OPNET considers network *throughput* and *load* at MAC level, which has two direct consequences. Firstly, overhead from network protocol, MAC frame headers, and MAC control packets is included. Secondly, both statistics are evaluated considering all nodes within the network, not only sources or destinations. When any node retransmits a packet, the total load is also incremented, even if that node is an intermediate node. Similarly, when each intermediate node receives a packet, the corresponding aggregate throughput is incremented. This severely affects the comparability of the final results, changing the relative ranking among those statistics per AC. To solve this problem, we defined new statistics evaluated as end-to-end, that is, at Application level, as similar to ns-2 as possible.

Coexistence of QoS-enabled and legacy nodes. Another significant difference has been found when legacy 802.11 (nQSTA) and 802.11e (QSTA) nodes coexist in a same scenario. In the original IEEE 802.11 standard [1] there is no support for service differentiation, that is, a nQSTA just support one traffic category. Despite of this, with ns-2, an intermediate nQSTA is *transparent* in the sense that when a packet is received from a QSTA, although the QoS information of the incoming packet (the Type-of-Service or ToS) is not processed, it is preserved when the packet is forwarded to the next hop, which could be QSTA or not. On the other hand, with OPNET this information is lost since an intermediate nQSTA automatically sets the ToS field of the IP packet header (which includes the UP subfield) to zero before retransmission. This causes all packets crossing that node to arrive at destination with UP set to zero, mapping it to the Best effort AC (AC_BE), as we can see in Table 1. Evidently, this has a great impact on the results in terms of throughput per AC.

Hence, it was necessary to make the above described modifications to match as closely as possible ns-2's behavior in order to make a direct comparison with the results presented in [5]. The modified models were debugged and validated using several test-bench scenarios prior to running all simulation sequences. The implemented scenarios can be divided into two types: static and mobile scenarios. In the first case - static scenarios - we initially vary the traffic load, and we then vary the average hop count between source and destination; a third experiment was conducted in order to examine the stability of higher priority ACs when the data rate of lower priority ACs varies. Section 4 describes such scenarios and discusses in detail the results. For mobile scenarios, two sets of experiments were performed: first varying the number of sources, and, secondly, varying the percentage of legacy 802.11 nodes; the results are presented in Sections 5 and 6, respectively.

Table 3: Simulation parameters

Parameter	Static scenario	Mobile scenario
Size	1900m x 400m	
Commun. range	250m	
Data rate	54 Mbit/s	
Nodes		
+ Nb. of nodes	[8..15]	50
+ Placement	See Fig. 1	Random
+ Legacy nodes	0 %	[0..100] %
Traffic		
+ Load per AC	[Variable]	0.2 Mbit/s
+ Nb. of sources	4	[4..48]
Mobility	No	[No,Yes]
+ model	-	RWM
+ speed	-	5 m/s
+ pause time	-	0 s

RWM = random waypoint model

Table 3 shows the more important simulation parameters. In all cases, the offered traffic is generated at a constant bit rate (CBR) using fixed size UDP packets (512 bytes) for all four ACs. Statistics are collected just after a transient established period (60s) to drive the network to a steady state, discarding the initial values to mitigate the initial transient problem [14, 18].

The results involve the following metrics:

- *Throughput*: the amount of data traffic successfully delivered to a final destination node for a certain data flow.
- *Latency* or *end-to-end delay*: the average amount of time measured from the instant a data packet is originated until the packet is successfully delivered to the final destination.
- *Average number of hops*: number of router nodes in the end-to-end path (source not included).
- *Routing overhead*: total number of routing packets or bytes generated by the routing protocol.
- *Bandwidth share per AC*: percentage of the total throughput obtained by a certain AC.

Results from OPNET include error bars in the graphs representing the 90% confidence interval of the average, whereas the graphs from ns-2 do not show error bars because they are not visible, even with a 99% confidence interval. This discrepancy could be due to several limitations found in the OPNET's built in Random Number Generator (RNG) [4] or weaknesses of the ns-2 RNG [9].

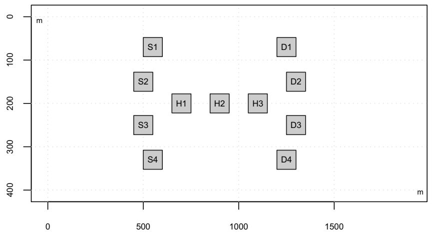


Figure 1: Static scenario

4. STATIC SCENARIO

4.1 Description

The static scenario consists of several fixed nodes, placed as shown in Figure 1. It consists of four source/destination pairs (S_i,D_i), for i=1..4, whereas the remaining nodes (H_i) are intermediate routers. All nodes transmit with an identical data rate (54 Mbit/s) and transmission range (250m).

In this scenario, three cases are considered. The first one, with an average number of hops of four, increases the offered traffic from 20.5 Kbit/s to 2.048 Mbit/s per AC per source. In the second case the total offered traffic per AC is set to 12 Mbit/s (3 Mbit/s per source), varying the average number of hops from 1 to 8. Additionally, in the third case, the AC_VO and AC_VI traffic were fixed at a data rate of 0.5 Mbit/s and 1.0 Mbit/s, respectively, while varying the low priority ACs traffic from 20.5 Kbit/s to 4.096 Mbit/s.

4.2 Results

This section presents the results collected during the simulation of the scenario described above using the OPNET Modeler simulator, comparing them with those from ns-2 [5]. Each simulation lasts 360s, and we average the results of 10 runs (different seeds).

When varying the offered traffic, analysis of the throughput per AC results shows a similar trend, though different absolute values for both simulators, as depicted in Figures 2(a) and 2(b). When increasing network load the throughput per AC stabilizes, and the relative ranking among all ACs matches with the priorities assigned to each traffic flow. As desired, activating the CFB in both simulators clearly favors the Video AC throughput (see Table 2). Contrarily to ns-2, best-effort and background traffics keep a minimal throughput as the load increases; with ns-2, both suffered starvation for an offered load above 4 Mbit/s per AC. On the other hand, in order to compare the total aggregated throughput achieved (for all ACs and all sources) in both simulators, the Achieved Throughput Ratio (ATR) is defined as: $ATR = Throughput/Load$, and the results are shown in Figure 2(c). As can be seen, the total bandwidth used with OPNET is always significantly lower than that for ns-2 at a same load, independently of the CFB being used or not, although this difference decreases as the network load increases. Thus, the wireless channel with OPNET shows a lower utilization than with ns-2.

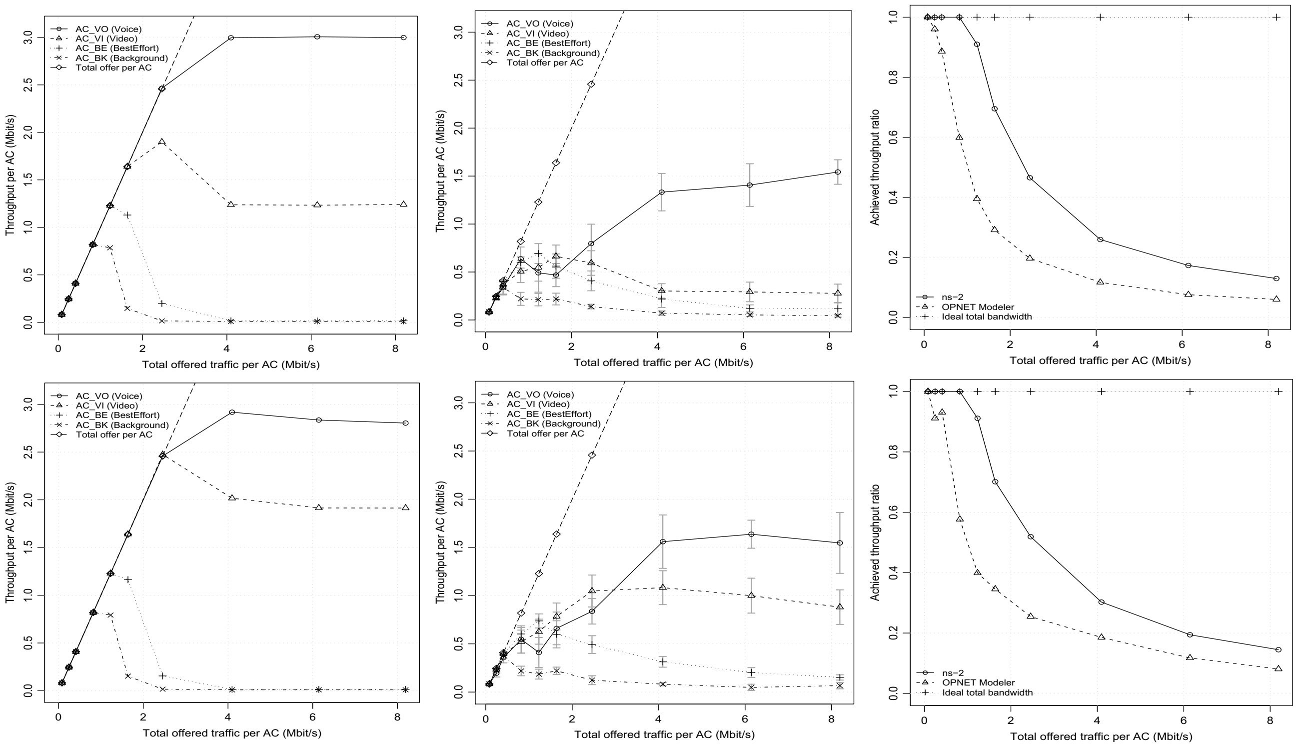
Figures 3(a) and 3(b) show the results in terms of end-to-end delay. Similarly, low priority ACs experience higher delays with both simulators. However, the absolute delays values with ns-2 are higher for all ACs compared to OPNET, especially when the load is high. Figure 3(c) shows the control overhead that is obtained with OPNET at different network loads. As can be seen, this overhead does not depend much on the offered traffic, since the number of control packets in maintained constant as the traffic increases.

In a second experiment we vary the average hop count between source and destination nodes, and the offered traffic per AC is set to a fixed value (3 Mbit/s per source). In terms of total aggregated throughput (Figure 4(c)), as with the previous experiment, the achieved throughput ratio with OPNET is always less than that of ns-2, although both simulators show a similar loss trend. As we can see in Figures 4(a) and 4(b), throughput decreases quickly for all ACs as the average number of hops increases, although relative rankings are maintained according to their priority. This throughput degradation is due to the additional delay that each intermediate node introduces, including the queuing, processing, transmission, and propagation delays. Additionally, the topology and the high load in the network cause a high contention situation, and many collisions on the wireless medium occur. With the AODV routing protocol, link failures are detected by means of sending periodic *hello* messages to the neighboring nodes, which may collide. In this case, the next hop is not guaranteed to be reachable and a link break occurs. Then Route Error packets (RERR) are sent by all nodes in the network toward the end nodes (i.e., source and destination). As illustrated in Figure 5(c), the number of RERR control packets is directly proportional to the path length.

On the other hand, a clear loss of effectiveness of the differentiation mechanism is also observed with OPNET as the number of hops increases, because the throughput achieved for all four ACs tends to converge, whereas results with ns-2 show that this mechanism is independent of the average number of hops. Again, activating the CFB mechanism clearly has a favorable impact on the Video AC, similarly to ns-2, at the expense of Voice AC data. The channel utilization is improved but, as we increase the number of hops, the influence of the CFB mechanism is lowered in both simulators from the point of view of the total aggregated throughput (see Figure 4).

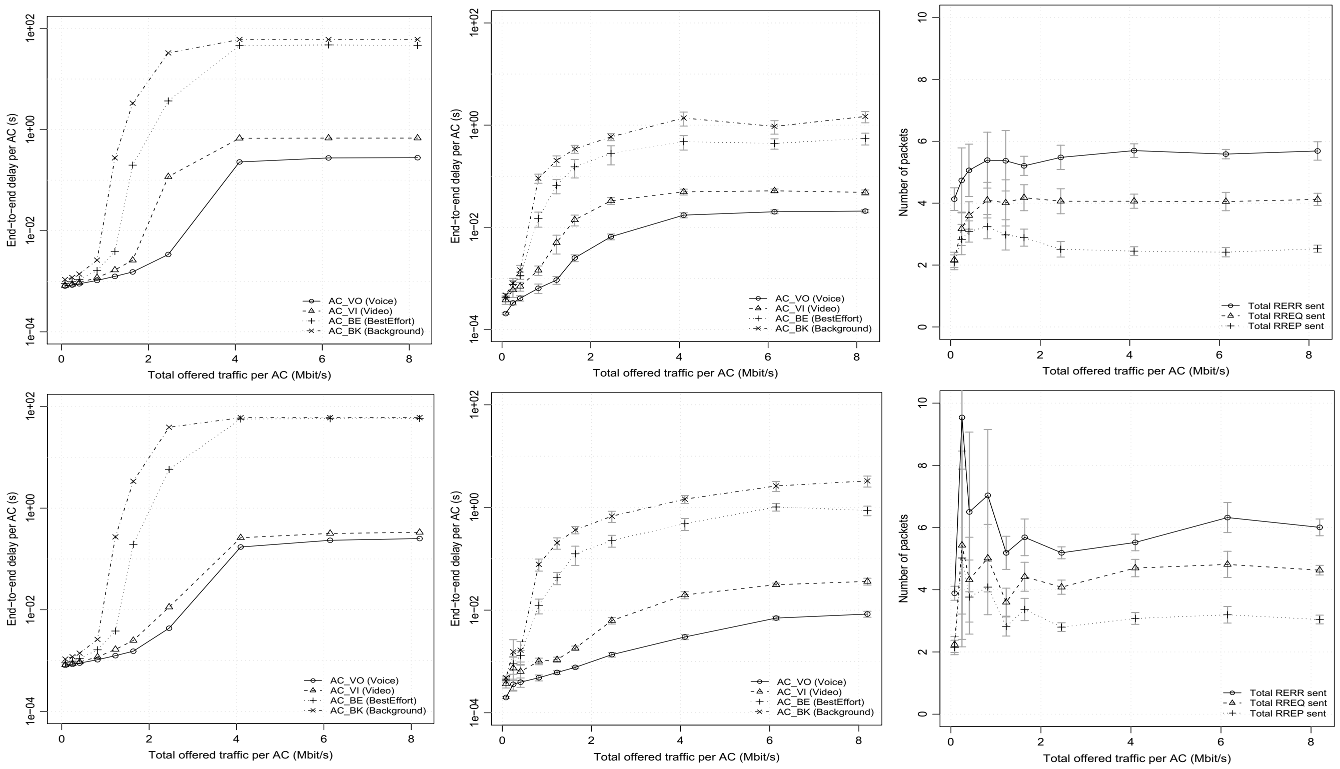
The results in terms of bandwidth share are shown in Figure 5. With ns-2 the results show that all four ACs maintain a nearly steady share of the available bandwidth as we increase the number of hops, whether the CFB mechanism is turned on or off, and the low priority traffic (AC_BE and AC_BK) increases a little but is always maintained low. Contrarily, in the case of OPNET, this traffic increases considerably, and a fair bandwidth share between all ACs is achieved, corroborating that the differentiation mechanism loses some of its effectiveness.

Finally, in the last experiment, we examine the stability of AC_VO and AC_VI traffics when varying the data rate of the lower priority ACs. As expected, both simulators show that Voice and Video traffic maintain stable in terms of throughput, although they are slightly affected with OPNET (see Figure 6). However, the total aggregated throughput achieved with OPNET is up to 50% (for 1.5 Mbit/s) lower than that of ns-2 due to low priority traffic does not increases as much as expected. This occurs because low priority packets are discarded due to overflow of higher layer data buffer at the intermediate nodes. Similarly to ns-2, activating the CFB mechanism has no impact on the results, and variations suffered in terms of end-to-end delay are quite similar.



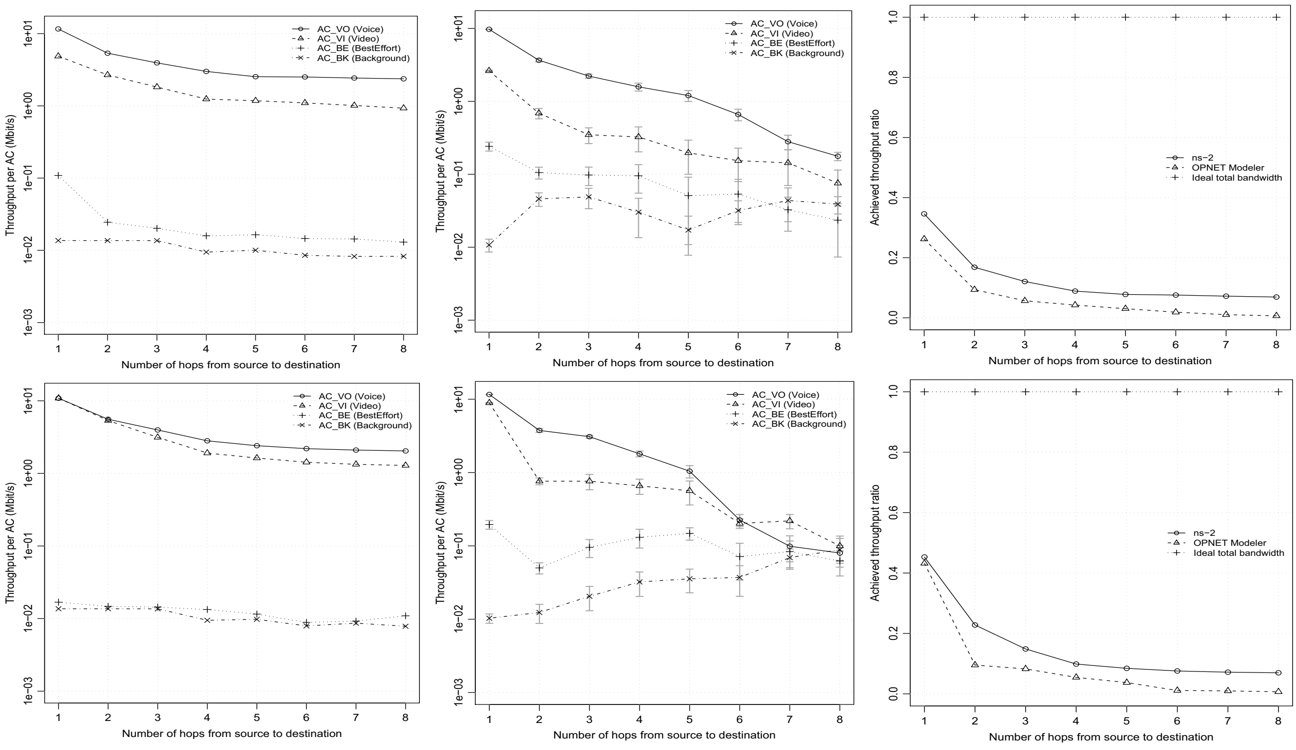
(a) ns-2 (b) OPNET Modeler (c) ns-2 vs. OPNET

Figure 2: Throughput achieved with no CFB (top) and CFB activated (bottom)



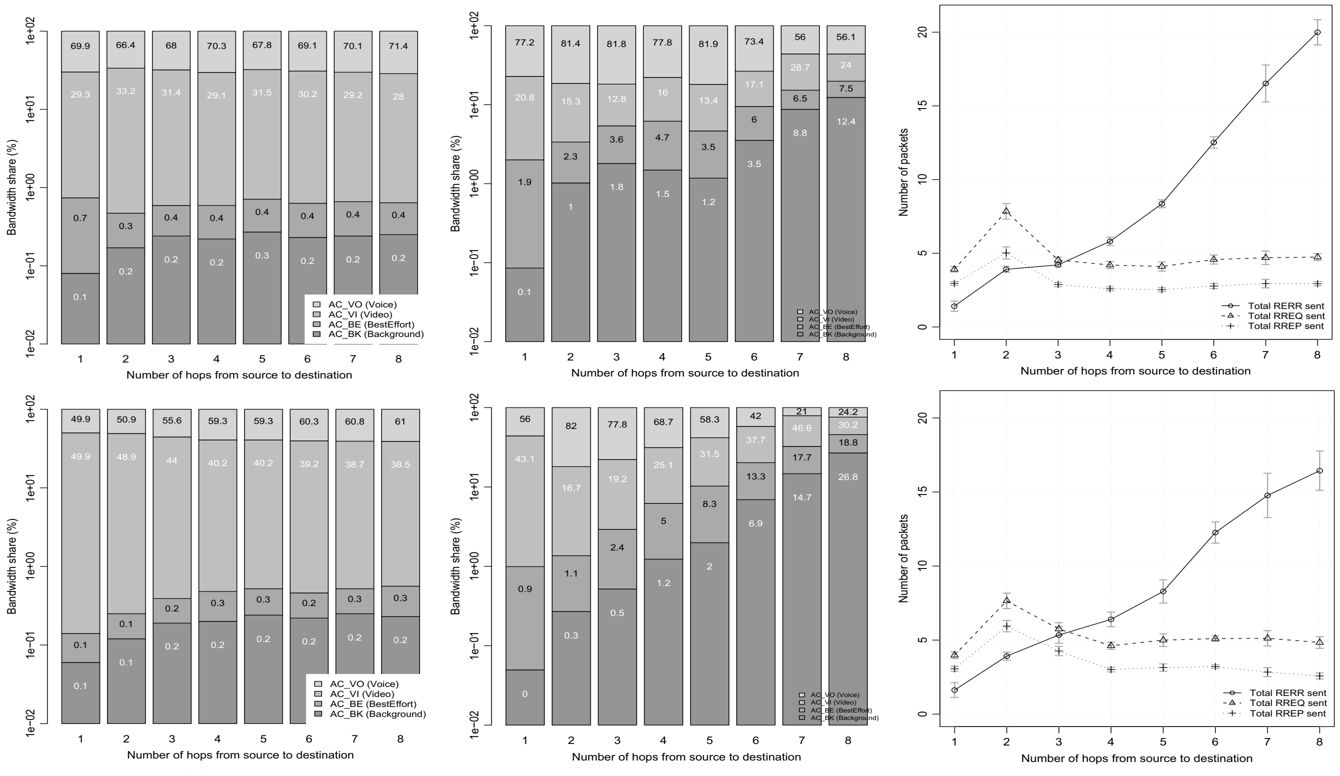
(a) ns-2 (b) OPNET Modeler (c) AODV traffic (OPNET)

Figure 3: End-to-end delay achieved and OPNET's control traffic with no CFB (top) and CFB activated (bottom)



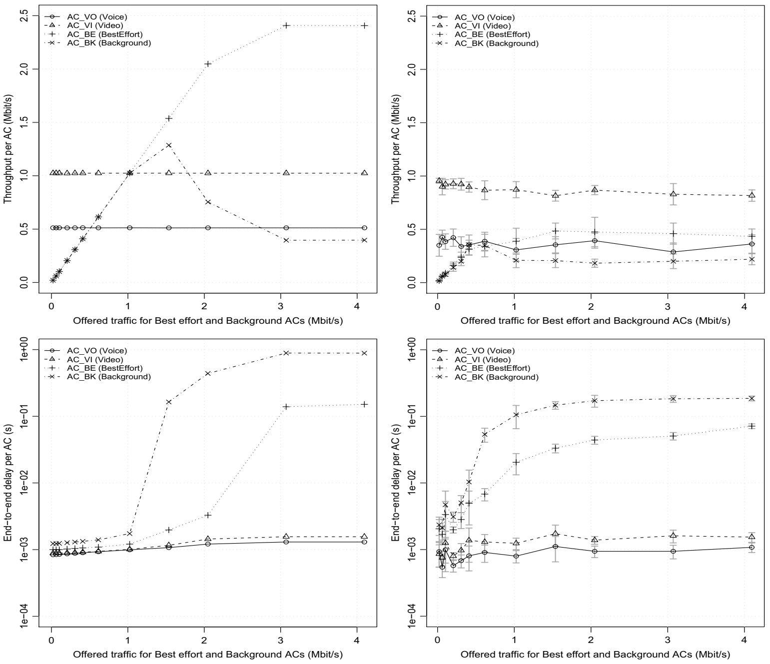
(a) ns-2 (b) OPNET Modeler (c) ns-2 vs. OPNET

Figure 4: Throughput achieved with no CFB (top) and CFB activated (bottom)



(a) ns-2 (b) OPNET Modeler (c) AODV traffic (OPNET)

Figure 5: Bandwidth share and OPNET's control traffic for varying number of hops with no CFB (top) and CFB activated (bottom)



(a) ns-2 (b) OPNET Modeler

Figure 6: Throughput variation (top) and end-to-end delay variation (bottom) with different degrees of Best effort and Background traffic

5. MOBILE SCENARIO

5.1 Description

In this section, a suite of ten randomly generated scenarios is considered, each composed of 50 mobile nodes randomly placed on a rectangular scenario sized 1900m x 400m. The initial location of the nodes and the different trajectories followed by them have a great impact on the results. Although the placement of nodes could have been randomly determined by the simulator, an external program was implemented for this purpose. This program generates a set of scenarios (initializing the random series with different seeds) and selects those with lower degree of network partitioning, not only at the initial state but also at any time. Once the suite of scenarios was generated, the model was first simulated as static, that is, without mobility, and then, with a predefined trajectory assigned to each node within the working area using the random waypoint model (RWM) [10, 14]; this model is commonly used for mobility in MANETs, as stated in [21]. In both cases, the CFB functionality was disabled, and the generated traffic was CBR/UDP with a bit rate of 0.2 Mbit/s (50 packets/s) per AC. The number of communicating pairs is variable, ranging from 4 to 48.

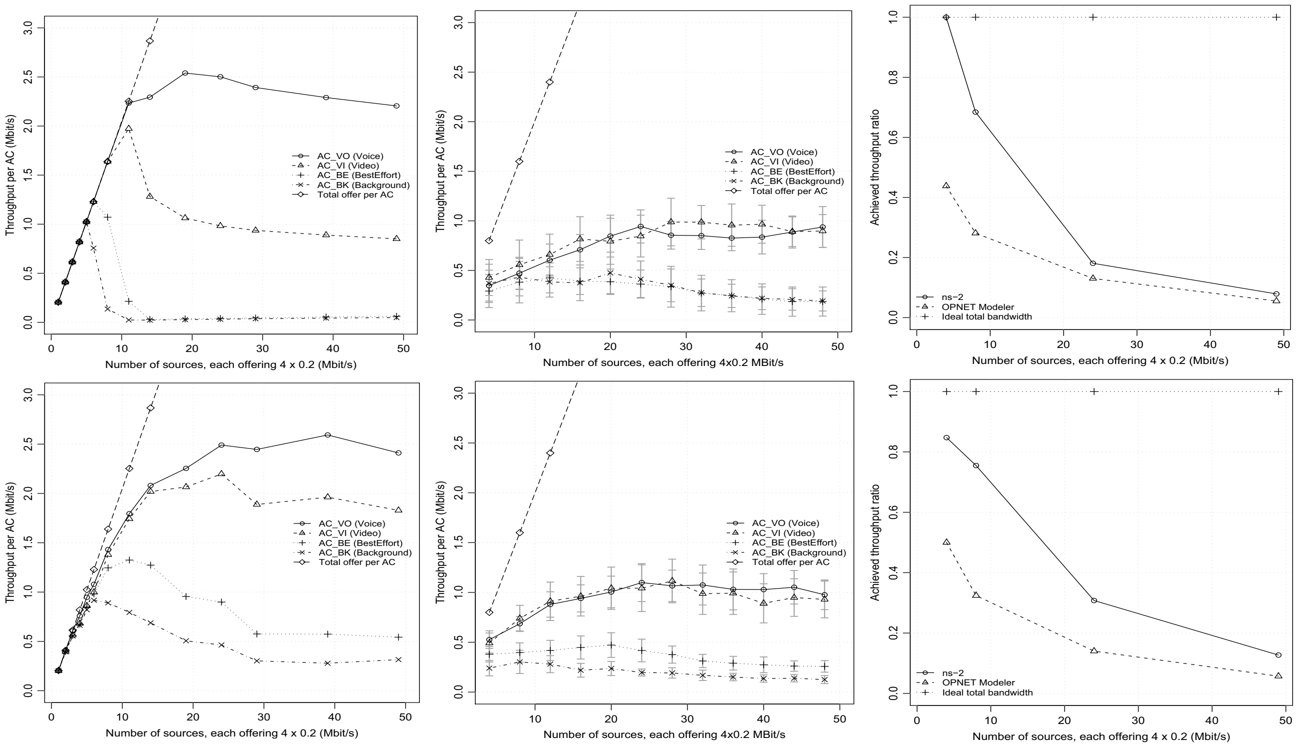
The purpose of this experiment is to evaluate the impact of node mobility on the different metrics, and all results are presented in the following section.

5.2 Results

Concerning the results of the mobile scenarios, all the statistics are measured over the 10 randomly generated scenarios for each number of sources. As for results presented in previous sections, the total aggregate throughput is always lower than that in ns-2 for any number of sources, both with the static and the mobile scenarios, as can be seen in Figure 7(c).

When the nodes have no mobility (static scenario), the throughput achieved for all four ACs with ns-2 is equal to the network load (ideal total bandwidth) while the network is not saturated (see Figure 7). On the other hand, values obtained with OPNET are very low compared to that of ns-2. Similarly to the previous section, low priority traffic achieves more bandwidth in OPNET compared to ns-2.

For the mobile scenario, the results obtained with ns-2 show that the throughput achieved is higher for all 4 ACs than when they are static, for any number of sources. Also, saturation limits are reached for a higher number of sources. As stated in [5], this is a direct consequence of the fact that there is a greater number of path variability in the mobile scenario. Although the results obtained with OPNET in terms of throughput are not as clear as with ns-2, the previous conclusion is corroborated by the higher number of RREP control packets sent compared with RREQ. This is because of multiple routes is received in response to a single RREQ. Figure 8(c) shows the control overhead with different number of source nodes with OPNET. As expected, when the number of source nodes increases, control overhead increases accordingly. Control overhead obtained in the static scenario is lower compared to the mobile scenario. Moreover, the mobile scenario presents a lower average number of hops than in the static one, indicating that sorter routing paths from the sources to destinations are found. As shown in Figure 8, the greater the number of sources the greater is the end-to-end delay experienced with both simulators. However, the rate of growth with OPNET is constant and progressive, whereas with ns-2 delay converges rapidly, leveling out at a stable value for all ACs.

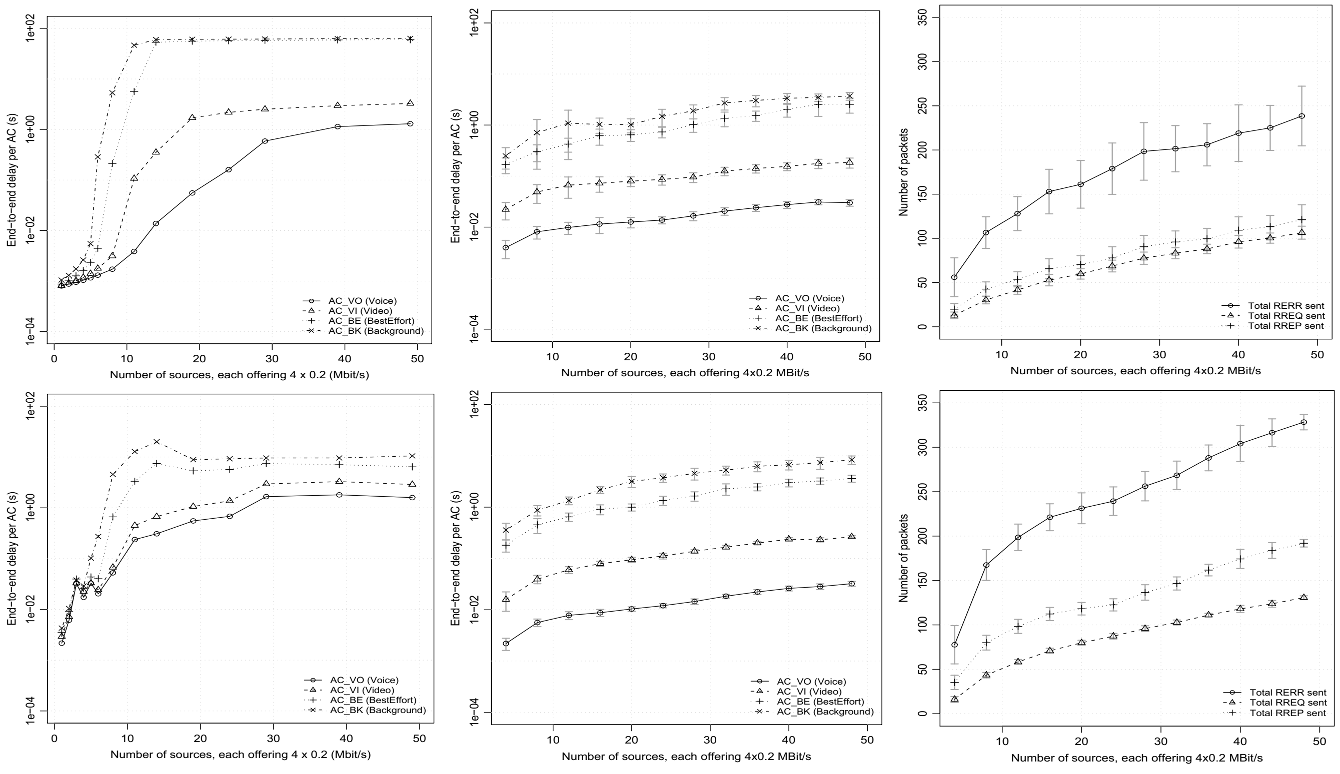


(a) ns-2

(b) OPNET Modeler

(c) ns-2 vs. OPNET

Figure 7: Throughput achieved in the static scenario (top) and mobile scenario (bottom)

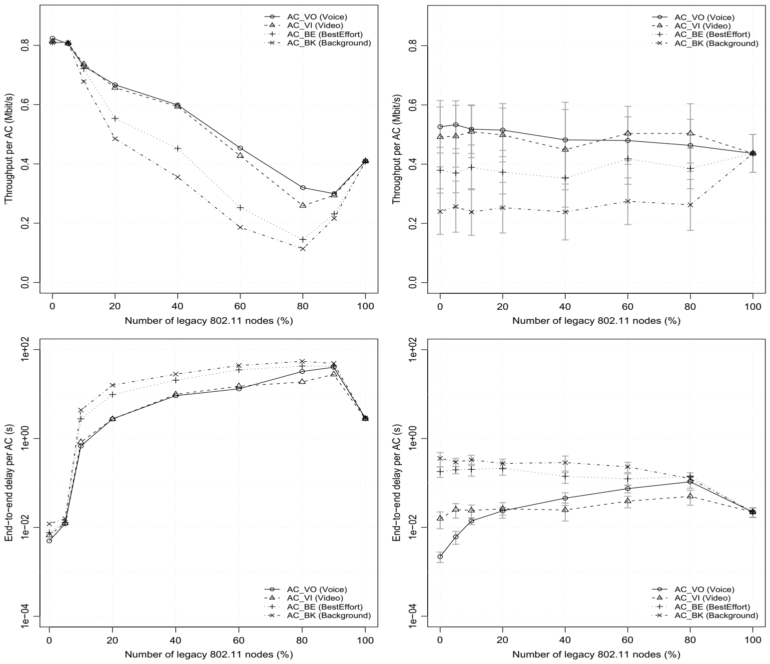


(a) ns-2

(b) OPNET Modeler

(c) AODV traffic (OPNET)

Figure 8: End-to-end delay achieved and OPNET's control traffic for the static scenario (top) and mobile scenario (bottom)



(a) ns-2 (b) OPNET Modeler

Figure 9: Throughput (top) and end-to-end delay (bottom) for different shares of legacy IEEE 802.11 stations

6. HETEROGENEOUS SCENARIO

6.1 Description

This analysis is similar to the one made in the previous section, except that the number of sources is set to a fixed value (4) and that legacy 802.11 stations (nQSTA) and 802.11e stations (QSTA) coexist, that is, some nodes do not support QoS. The same suite of ten scenarios was used, varying the percentage of legacy stations from 0% (case of the previous section) to 100% (case when all network nodes are nQSTA). Legacy 802.11 nodes were randomly chosen, with the restriction that only QSTAs could be traffic sources or destinations. The main goal is to analyze the decay in QoS support in presence of nQSTAs.

6.2 Results

In this section, the performance behavior of both simulators in the heterogeneous scenario are discussed. Only the particular case of the mobile scenario is shown. Unexpectedly, the results obtained with the first OPNET simulations showed an anomalous behaviour. As referred in Section 3, throughput achieved was severely influenced by the percentage of legacy nodes. The greater the number of nQSTA, the greater the values achieved by AC_BE, that is, the lowest traffic priority grew significantly whereas the rest of ACs drop, reaching zero when all network nodes were legacy 802.11. This problem was addressed as explained before, although results are still different (see Figure 9). Again, the scenarios chosen have a great influence because, for example, some of the source or destination nodes could become unreachable by other nodes due to a network partition, which is an important characteristic of MANETs in presence of mobility. From the large confidence intervals shown in the plot for OPNET, it can be deduced that, in addition to the initial location of the nodes and the trajectories followed by them, the choice of source, destination and nQSTAs nodes has a great impact on the results too. Contrarily to ns-2, throughput achieved by all ACs with OPNET is independent of the proportion of legacy stations. However, similarly to ns-2, results converge when all the nodes are nQSTAs, since there is no support for QoS and the differentiation mechanism has no effect, validating at least the results obtained in such case.

In terms of end-to-end delay, Figure 9 shows much lower values with OPNET than with ns-2, indicating that the network load is lower in the case of OPNET.

7. CONCLUSION

In this paper, a comparative study between two common network simulation tools, namely, ns-2 and OPNET Modeler, has been carried out, involving several static and mobile MANETs scenarios using IEEE 802.11g/e. Some important differences between the two simulators have been reported, and the corresponding modifications to deal with each of them are presented. After describing the scenarios, the obtained results using OPNET are shown, comparing them with the previously published results using ns-2.

Results showed that the referred modifications are necessary in order to address such critical differences and to obtain comparable results. The conclusions based on the simulation results for the different MANET scenarios are that the trend of all the metrics in both simulators were rather consistent, although in certain experiments absolute values are quite different.

From the results obtained we can conclude that more comparisons between network simulators in general, and between ns-2 and OPNET Modeler in particular, could be done. Specifically, we will carry out more experiments comparing both simulators under different topology parameters, signal propagation models, complex traffic patterns, or the behavior of different routing protocols, like DSR, OLSR, etc.

Finally, it will be interesting to develop a topology generator tool that is able to build scenarios for MANETs, enabling the user to set the initial position of the nodes and to define trajectories, both manually and randomly, and then could be able to export the topology to several network simulators (including ns-2 and OPNET Modeler). Alternatively, building another tool that allows to import the scenarios created for ns-2 to OPNET would also be useful. With either of such tools, the comparison would be more exact. On the other hand, the use of other tools like CostGlue [19] could simplify the comparison process of the simulation results.

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9. REFERENCES

[1] IEEE Standards for Information Technology – ANSI/IEEE Std 802.11 – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. online, 1999.

[2] IEEE Standards for Information Technology – IEEE Std 802.11e – Draft Supplement to Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Medium Access Control (MAC) Quality of Service Enhancements. online, 2005.

[3] Andel, T., and Yasinsac, A. On the credibility of manet simulations. *Computer 39*, 7 (July 2006), 48–54.

[4] Becker, M., Weerawardane, T. L., Li, X., and Görg, C. Extending OPNET Modeler with external pseudo random number generators and statistical evaluation by the limited relative error algorithm. In *Proceedings of Recent Advances in Modeling and Simulation Tools for Communication Networks and Services* (2007), N. Ince and A. Bragg, Eds., Springer, pp. 241–255.

[5] Calafate, C. T., Manzoni, P., and Malumbres, M. P. Assessing the effectiveness of IEEE 802.11e in multi-hop mobile network environments. In *Proceedings of the 12th IEEE Annual Int. Symp. on Modeling, Analysis, and Simulation of Computer and Telecommunications Systems (MASCOTS)* (Oct. 2004), pp. 205–212.

[6] Calafate, C. T., Manzoni, P., and Malumbres, M. P. On the interaction between IEEE 802.11e and routing protocols in mobile ad-hoc networks. In *13th Euromicro Conf. on Parallel, Distributed and Network-Based Processing (PDP)* (Feb. 2005), pp. 110–117.

[7] Cavin, D., Sasson, Y., and Schiper, A. On the accuracy of MANET simulators. In *2nd ACM int. workshop on Principles of Mobile Computing (POMC)* (2002), pp. 38–43.

[8] Flores Lucio, G., Paredes-Farrera, M., Jammeh, E., Fleury, M., and J Reed, M. Opnet modeler and ns-2 - comparing the accuracy of network simulators for packet-level analysis using a network testbed. *WSEAS Transactions on Computers 2*, 3 (July 2003), 700–707.

[9] Hechenleitner, B., and Entacher, K. On shortcomings of the ns-2 random number generator. In *Communication Networks and Distributed Systems Modeling and Simulation Conference (CNDS 2002)* (2002).

[10] Johnson, D. B., and Maltz, D. A. Dynamic source routing in ad hoc wireless networks. In *Mobile Computing*, Imielinski and Korth, Eds., vol. 353. Kluwer Academic Publishers, 1996.

[11] Kurkowski, S., Camp, T., and Colagrosso, M. Manet simulation studies: the incredibles. *SIGMOBILE Mob. Comput. Commun. Rev. 9*, 4 (2005), 50–61.

[12] Malowidzki, M. Network simulators: A developer's perspective. In *Int. Symp. on Performance Evaluation of Computer and Telecommunication Systems (SPECTS)* (2004).

[13] MANET Working Group. Ad hoc On-demand Distance Vector (AODV) routing, July 2003. Request For Comments 3561.

[14] Navidi, W., Camp, T., and Bauer, N. Improving the accuracy of random waypoint simulations through steady-state initialization. In *15th Int. Conf. on Modeling and Simulation (MS)* (2004).

[15] The Network Simulator – ns-2. `http://www.isi.edu/nsnam/ns/`.

[16] Opnet Technologies Inc. OPNET Modeler. `http://www.opnet.com/`.

[17] Pawlikowski, K., Jeong, H. D. J., and Lee, J. S. R. On credibility of simulation studies of telecommunication networks. *IEEE Communications Magazine 40*, 1 (2002), 132–139.

[18] Perrone, L. F., Yuan, Y., and Nicol, D. M. Modeling and simulation best practices for wireless ad hoc networks. In *Proceedings of the 35th Winter Simulation Conference (WSC)* (2003), pp. 685–693.

[19] Savić, D., Pustišek, M., and Potortì, F. A tool for packaging and exchanging simulation results. In *Valuetools'06: Proceedings of the 1st Int. Conf. on Performance evaluation methodologies and tools* (New York, NY, USA, 2006), ACM Press, p. 60.

[20] Wiethoelter, S., and Hoene, C. Design and verification of an IEEE 802.11e EDCF simulation model in ns-2.26. Tech. Rep. TKN-03-019, Telecommunication Networks Group, Technische Universität Berlin, Nov. 2003.

[21] Yoon, J., Liu, M., and Noble, B. Random waypoint considered harmful. In *IEEE INFOCOM Conference* (2003).