Achieving enhanced performance in MANETs using IEEE 802.11e

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Resumen— **IEEE 802.11e is an upcoming standard that aims at offering QoS support to WLANs. In this work we analyze the performance of the IEEE 802.11e proposal on ad-hoc networks (multi-hop) in terms of throughput and end-to-end delay. Our results include a measure of the effectiveness of this new technology in static and a fully dynamic networks with a variable number of source stations. We also analyze the interaction of reactive routing protocols for MANETs and the IEEE 802.11e technology. We find that very substantial improvements in terms of throughput and normalized routing overhead are achieved due to increased routing responsiveness. We also detail the relation between the behavior experienced in each case and the internal mechanisms of the routing protocol being used.**

Palabras clave— **IEEE 802.11e, MANETs, performance, routing, QoS**

I. INTRODUCTION

Mobile Ad-hoc Networks, also known as MANETs, are packet radio networks composed by independent and heterogeneous stations which cooperate in routing and packet forwarding tasks, achieving this way a dynamic multi-hop network. The interest in this kind of networks has been growing in the last few years, since they have proved to be an adequate solution for military and disaster relief scenarios, home environments, etc. They are also being used for other useful purposes, such as extending the coverage of networks mainly to provide Internet access to the members of large disperse communities (e.g. university campus, rural areas, etc.).

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, home networks, etc. It operates in free bands such as the industrial, scientific and medical (ISM) band at 2.4 GHz or the unlicensed 5 GHz band. The IEEE 802.11b version operates in the 2.4 GHz band and offers data rates up to 11 Mbit/s. IEEE 802.11a and IEEE 802.11g offer data rates up to 54 Mbit/s, but while IEEE 802.11a operates in the 5 GHz band, IEEE 802.11g operates in the 2.4 GHz band (the same as IEEE 802.11b). These different technologies offered by IEEE 802.11, as well as their good performance and error robustness, have made this standard the technology of choice for WLANs and MANETs.

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Recently there has been an increasing interest in supporting QoS in MANETs. The proliferation of devices with multimedia and wireless networking capabilities pave the way towards ubiquitous audiovisual communication among peers. To meet this need, the IEEE 802.11e [2] working group is enhancing the IEEE 802.11 standard to provide QoS at the MAC level.

The main purpose of IEEE 802.11e is to give multimedia streams higher priority when accessing the medium, decreasing end-to-end delay and allocating more bandwidth to such traffic if necessary. However, routing protocols can also benefit from the differentiation mechanism of IEEE 802.11e if routing packets are assigned a higher priority than the remaining traffic.

Previous works such as [3] mainly focus on the analysis of IEEE 802.11e in environments where stations communicate with an *access point* (Infrastructure mode in IEEE 802.11). However, MANET environments (*ad-hoc* mode) differ from these in the sense that no *access point* is available and that packets may have to be forwarded by several stations before reaching the final destination. In MANET environments we also have to take into account other problems such as mobility and terminal disconnection.

In this paper we assess the effectiveness of the current IEEE 802.11e technology in multi-hop wireless networks, evidencing the performance and drawbacks of this new technology. We show that, in terms of traffic differentiation capabilities, it maintains its effectiveness in mobile multi-hop environments. Relatively to routing protocols, we show that IEEE 802.11e allows increasing their responsiveness dramatically, resulting in improved performance for TCP/UDP traffic.

Concerning the structure of this paper, in the next section we introduce IEEE 802.11e. In section III we evaluate the effectiveness of IEEE 802.11e in MANETs in terms of traffic differentiation. In section IV we present the enhancements achieved with IEEE 802.11e in terms of the responsiveness of routing protocols. Finally, in section V we present conclusions to this work, as well as future work.

II. IEEE 802.11E: MAC ENHANCEMENTS FOR QUALITY OF SERVICE

The IEEE 802.11e working group is extending the IEEE 802.11 MAC in order to provide QoS support. This new standard introduces the *hybrid coordination function* (HCF) which defines two new medium access mechanisms to replace legacy PCF

and DCF. These are the *HCF controlled channel access* (HCCA) and the *enhanced distributed channel access* (EDCA).

With the HCF there may still exist a contention period and a contention-free period in a superframe, but now the HCCA is used in both periods, while the EDCA is used only during the CP. This new characteristic of HCF obviates the need for a CFP since it no longer depends on it to provide QoS guarantees.

With IEEE 802.11e, the *point coordinator* is replaced by a *hybrid coordinator* (HC) which also resides in an AP. A BSS including a HC is referred to as a QBSS. In this paper we focus on ad-hoc networks and, therefore, we are only interested in IEEE 802.11e stations implementing EDCA. For more information on HCs, the HCF and the HCCA refer to [2].

Concerning IEEE 802.11e enabled stations forming an ad-hoc network, these must implement the EDCA. The IEEE 802.11e QoS support is achieved through the introduction of different *access categories* (ACs), and their associated backoff entities.

In table I we can see the mapping between different user priorities and the different access categories available in IEEE 802.11e stations.

TABLA I

User Priority to IEEE 802.11e Access Category Mapping (according to IEEE 802.1D)

User Priority	Designation	Access Category
1	BK (Background)	AC_BK
2	BK (Background)	AC_BK
0	BE (Best-effort)	AC_BE
3	EE (Video/Excellent-effort)	AC_BE
4	CL (Video/Controlled Load)	AC_VI
5	VI (Video)	AC_VI
6	VO (Voice)	AC_VO
7	NC (Network Control)	AC_VO

Contrarily to the legacy IEEE 802.11 stations, where all MSDUs have the same priority and are assigned to a single backoff entity, IEEE 802.11e stations 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. In IEEE 802.11 legacy stations this parameter set was fixed, and so the inter-frame space was set to DIFS and the CWmin and CWmax where set to 15 and 1023 respectively (for IEEE 802.11a). With IEEE 802.11e the inter-frame space is arbitrary and depends on the access category itself (AIFS[AC]). We also have AC-dependent minimum and maximum values of the contention window (CWmin[AC] and CWmax[AC]). Also, IEEE 802.11e introduces an important 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 MPDUs consecutively

without contention with other stations. This mechanism, also known as *contention-free bursting* (CFB), increases global throughput through a higher channel occupation. An EDCA-TXOP (in contrast to an HCCA-TXOP) is limited by the value of TXOPLimit, which is a parameter defined for the entire QBSS and that also depends on the AC (TXOPLimit[AC]).

Table II presents the default MAC parameter values for the different ACs [2]. Notice that smaller values for the AIFSN, CWmin and CWmax parameters result in a higher priority when accessing the channel; relative to the TXOPLimit, higher values result in larger shares of capacity and, therefore, higher priority.

TABLA II

IEEE 802.11e MAC parameter values for a IEEE 802.11a/g radio

Access category	AIFSN	CWmin	CWmax	TXOPLimit (ms)
AC_BK	7	15	1023	0
AC_BE	3	15	1023	0
AC_VI	2	7	15	3.008
AC_VO	2	3	7	1.504

The relation between AIFS[AC] and AIFSN[AC], is the following:

$AIFS[AC] = SIFS + AIFSN[AC] \times aSlotTime$, $AIFSN[AC] \geq 2$, where *SIFS* is the shortest interframe space possible and *aSlotTime* is the duration of a slot. AIFSN[AC] should never be less than 2 in order not to interfere with AP operation.

III. IEEE 802.11e evaluation in MANETs

In order to assess the performance and effectiveness of IEEE 802.11e in multi-hop environments we perform several simulation tests focusing on throughput and end-to-end delay values for different degrees of network saturation and different number of competing sources.

We created both a static reference scenario and a mobile reference scenario. The static reference scenario, shown in figure 1, is a controlled environment used in order to make strict performance measurements. Therefore, all changes in static scenario situations will always be made relative to this reference scenario.
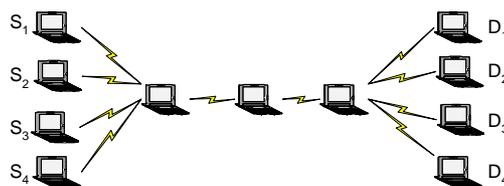

Fig. 1. Static multi-hop scenario

As shown in figure 1, we have four source/destination pairs (S_i, D_i) which are 4 hops away from each other (3 intermediate nodes).

All traffic sources are set to generate the same data rate in all four ACs, and the traffic type chosen is constant bit-rate UDP sources with packet size fixed at 512 bytes.

Relatively to the mobile reference scenario, it represents a typical mobile MANET environment. It consists of a rectangular scenario sized 1900x400 meters, where the average number of hops from source to destination is four, the same that in the static reference scenario presented above. The number of stations participating in the MANET is 50, and all of them are moving at a constant speed of 5 m/s according to the random waypoint mobility model. The routing protocol used is AODV, and routing traffic is assigned the highest priority (AC_VO).

To conduct our experiments we used the ns-2 simulator [4] with the IEEE 802.11e extentions from Wietholter and Hoene [5]. Our setup of the simulator's radio model is valid for both IEEE 802.11a and IEEE 802.11g since the simulator does not differentiate between both. Concerning the IEEE 802.11e MAC, it was configured according to the values presented previously in table II with CFB turned off.

All values presented are average values, and simulation times are of 300 seconds in each scenario.

A. Determining the saturation limits

Using the static reference scenario, we start our analysis by observing the behavior in terms of throughput and end-to-end delay when applying different traffic generation rates to the sources. Remember that the same packet generation rate is used for all ACs and for all stations acting as traffic sources.
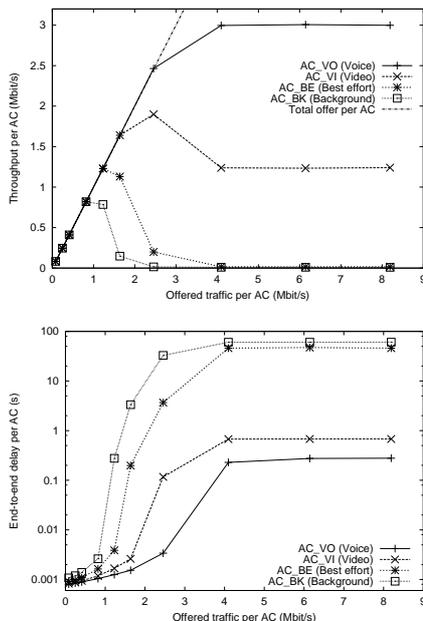
Fig. 2. Throughput (top) and end-to-end delay (bottom) results for the static scenario

Figure 2 shows the results achieved in terms of throughput. We can clearly observe that traffic with a higher priority access category is it able to sustain its throughput for higher values of offered traffic than

traffic of the access category immediately below. We also observe that the throughput per AC under saturation reaches a steady state value that depends on the probabilistic prioritization mechanism proposed by the IEEE 802.11e technology.

In terms of end-to-end delay, figure 2 shows that the IEEE 802.11e technology is quite effective in providing traffic differentiation. When offered traffic is low we see that low priority access categories also achieve low end-to-end delay values. This shows that IEEE 802.11e is able to assign available bandwidth to lower priority ACs in an efficient manner. We also observe that under strong saturation (more than 4 Mbit/s per AC) best-effort and background traffic suffer from starvation, which can be verified analyzing both throughput and end-to-end delay graphs.

B. Impact of mobility on QoS performance

In this section we evaluate the performance of IEEE 802.11e in both static and mobile environments. The number of traffic sources is variable and each traffic source generates 0.2 Mbit/s (50 packets per second) per AC.
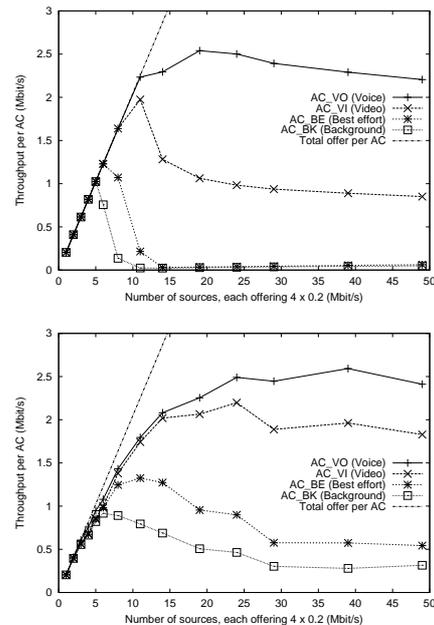
Fig. 3. Throughput achieved in the static scenario (top) and mobile scenario (bottom)

Figure 3 shows the throughput behavior in both static and mobile scenarios. The results for the static scenario show that throughput values follow the offered traffic closely before saturation. After saturation is reached, the throughput increase rate is no longer maintained, and it starts dropping after a certain point due to the contention mechanism of IEEE 802.11.

Relative to the scenario with mobility, we observe that throughput values no longer follow the offered traffic so strictly, though the points of saturation for the different ACs are reached for a higher number of source stations. This is due to the higher degree of path diversity achieved in the mobile scenario. So, while in the static scenario the maximum aggregated
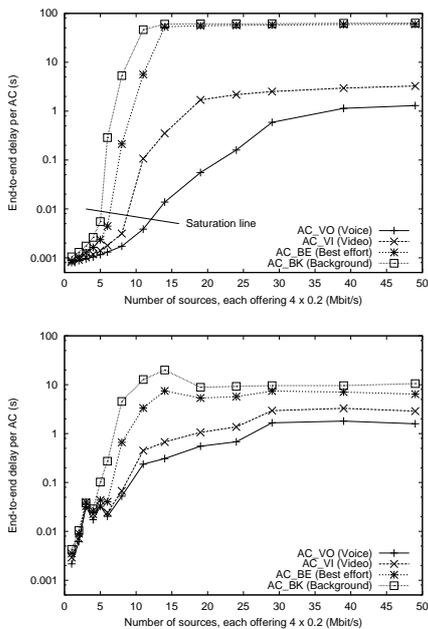
Fig. 4. End-to-end delay achieved in the static scenario (top)
and mobile scenario (bottom)

throughput is of 4,1 Mbit/s (6 sources), in the mo-
bile scenario this value is increased to 6 Mbit/s (14
sources).

Concerning the end-to-end delay, the results
shown in figure 4 relative to the static scenario are
quite representative in the sense that they allow ob-
serving two rates of growth: the one before satura-
tion (below the line shown) and the one when satu-
ration starts to cause queue drops (above the line).
We also see that Best effort and Background ACs
almost can not transmit data with 8 or more traffic
sources.

In the mobile scenario we observe that the mini-
mum end-to-end delay values are higher compared to
the static scenario. Moreover, the interval between
the various ACs is not very high when there are only
a few sources of traffic. This is due to mobility it-
self, which causes the routing protocol to react to
route changes by buffering traffic in their respective
queues. Similarly to what was found for throughput,
now the end-to-end delay values do not reach satu-
ration limits so quickly due to the expected traffic
dispersion effect in MANETs. In terms of traffic dif-
ferentiation, we observe that in both scenarios the
prioritization mechanism of IEEE 802.11e effectively
offers better QoS to higher priority traffic, and so we
consider that the effectiveness of this mechanism in
multi-hop environments is preserved.

IV. ROUTING ENHANCEMENTS WITH IEEE 802.11E

In this section our purpose is to assess the im-
provements offered by IEEE 802.11e to best effort
traffic when routing packets are assigned the maxi-
mum access category (AC_VO) in the IEEE 802.11e
framework.

In our experiments we assess the performance im-
provements achieved on both TCP and UDP traf-

fic. These improvements are more relevant when
the routing protocol used is reactive and relies on
the link-layer feedback for the detection of broken
links. Currently, the only reactive routing protocols
for MANETs that follow the standardization process
in the IETF are AODV [6] and DSR [7], and so our
experiment will focus on both of them.

Simulations are set up similarly to the mobile sce-
nario described in the previous section. Relatively to
the sources of traffic, TCP traffic sources are band-
width greedy continuously. We simulate this behav-
ior through an FTP file transfer that lasts the entire
period under analysis. TCP traffic tests are made
with different numbers of TCP connections. When
simulating UDP traffic, we fix the number of sources
at four and we vary the data generation rate. The
purpose is to saturate the network gradually.

In all experiments we compare the performance
when using only legacy IEEE 802.11 MAC or only
the new IEEE 802.11e MAC. For the comparison to
be fair, both TCP and UDP traffic is assigned to
the best-effort access category (AC_BE) under IEEE
802.11e. This way, only routing packets will experi-
ence a different treatment and so all improvements
will only depend on the increased responsiveness of
the routing mechanism itself.

A. Improvements on TCP traffic

In this section we analyze the improvements ob-
tained on TCP data transfers when using legacy
IEEE 802.11 or IEEE 802.11e MAC implementa-
tions. All experiments are conducted with both DSR
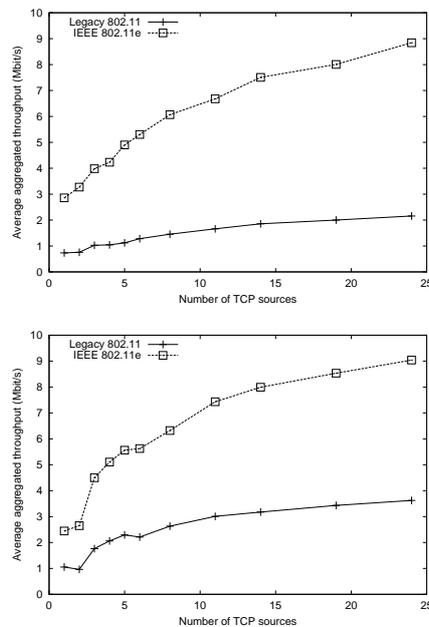and AODV routing protocols.

Fig. 5. TCP throughput performance using AODV (top) and
DSR (bottom) for different MAC solutions

In figure 5 we show the TCP throughput perfor-
mance results. When using the AODV routing proto-
col we encounter the most significant improvements.
In fact, TCP throughput increases by around 300%

for all points. When using DSR the increment is also significant, being close to 150% for all points. In [8], [9] authors show that TCP suffers from poor performance in mobile networks because it is not able to differentiate between congestion related packet losses and mobility related ones, treating all losses as congestion. To obtain an insight into the packet loss phenomena, we evaluate (see figure 6) the number of unacknowledged TCP data packets using both MAC technologies. Lack of acknowledgments can be due both to the loss of TCP data packets on the direct path, or to the loss of TCP ACK packets on the inverse path.
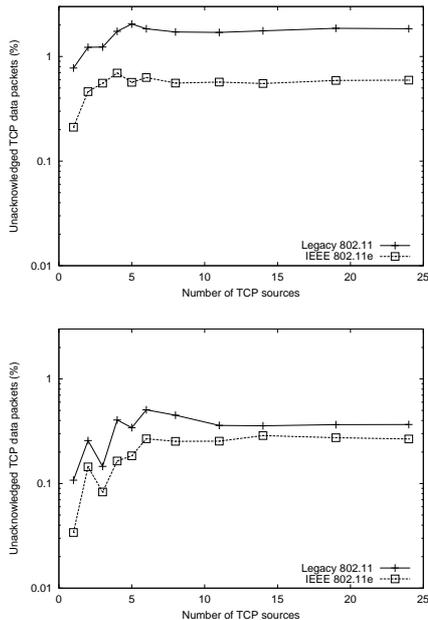

Fig. 6. Unacknowledged TCP data packets lost using AODV (top) and DSR (bottom)

The results show that there is a significative difference in the percentage of unacknowledged TCP data packets, especially when using the AODV routing protocol. In fact, when using AODV and the legacy 802.11 MAC, we find that there are up to 3 times more unacknowledged packets than with 802.11e. When using DSR the difference between both MAC technologies is lower, which is in concordance with the throughput results of figure 5. This difference is due mainly to a better performance of DSR when relying on legacy IEEE 802.11 for data transmission. DSR differs from AODV in its intensive use of caching and snooping of routes from packets in transit. Also, with DSR, a significative share of routing packets are unicasted due to gratuitous route replies and route replies from cache, contrarily to AODV which relies much more on broadcasting. Since broadcast packets are not acknowledged under IEEE 802.11, congested scenarios will provoke more losses of such packets due to collisions.

The goodness of routing protocols is usually evaluated in terms of normalized routing overhead, which is defined as routing packets required per data packet arriving to the destination. In our case the data packets arriving to the destination are both TCP
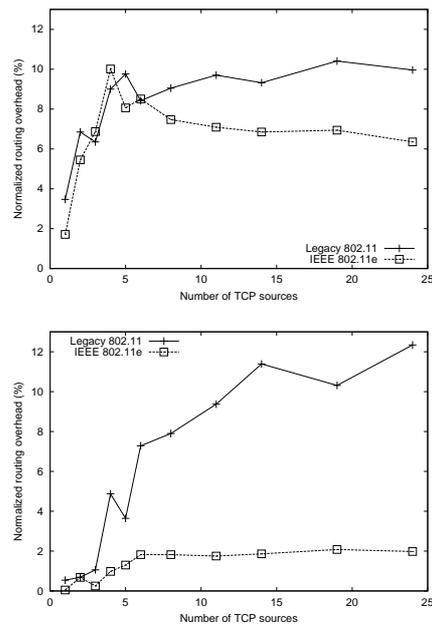

Fig. 7. Normalized routing overhead using AODV (top) and DSR (bottom)

data and ACK packets.

The results relative to AODV, see figure 7, show that, in general, the increase in throughput compensates the increase in routing overhead. In fact, with more than 5 stations, results using IEEE 802.11e are significatively better. When using DSR this difference is even more noticeable, and the normalized routing overhead can be decreased by up to 6 times when IEEE 802.11e is used.

B. Improvements on UDP traffic

In this section we analyze the improvements obtained with different UDP traffic loads. The purpose is to observe routing misbehavior as the congestion in the network increases. We start by analyzing the improvements in terms of throughput with increasing source load. Results are shown in figure 8.

We can see that, again, when using IEEE 802.11e the overall throughput increases, though all UDP traffic is assigned to the best effort access category (AC_BE). We find that for a source load up to 0.25 Mbit/s the difference in terms of throughput between using IEEE 802.11e or not usually does not exceed 1%. For higher source load the difference becomes quite noticeable. When using UDP traffic there is no loss-dependent behavior as with TCP traffic, and so the difference in terms of throughput can be directly related to the degree of responsiveness of routing mechanisms. In this situation we found that the differences between both routing protocols are not very relevant, though DSR always performs slightly better.

In terms of normalized routing overhead we find, as we did in the previous section, that using IEEE 802.11e results in improved performance. It is particularly relevant to notice the difference encountered with DSR as the source load achieves high values. In such cases the normalized routing overhead using
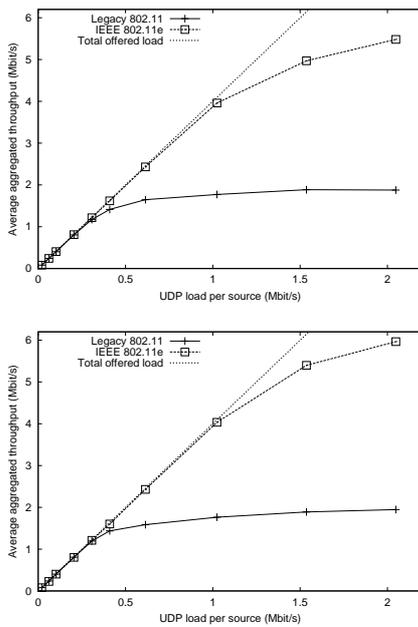
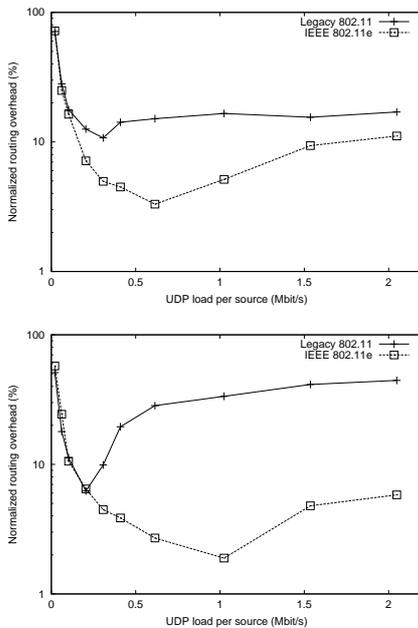Fig. 8. UDP throughput using AODV (top) and DSR (bottom)

Fig. 9. Normalized routing overhead using AODV (top) and DSR (bottom)

legacy IEEE 802.11 achieves very high values, clearly indicating that congestion is leading the routing protocol mechanism to perform poorly (see figure 9).

V. CONCLUSIONS AND FUTURE WORK

In this paper we have evaluated how effective the upcoming IEEE 802.11e technology is in multi-hop environments. We analyzed the performance achieved in a static scenario varying the levels of traffic. We then made a comparative evaluation of the static scenario configuration with five distinct mobile scenarios for a variable number of traffic source stations. Results show that in a mobile MANET the capacity is increased due to the spreading of traffic throughout the test area, though throughput values

are always lower than the offered ones due to mobility related losses.

We also assessed the improvements to best effort traffic achieved by giving routing packets high priority on media access. Results show that when routing packets benefit from the prioritization mechanism of IEEE 802.11e the performance is improved drastically. We find that this improvement is due to an increase in the responsiveness of the different routing protocols. In terms of TCP throughput we achieve an increase of up to 150% with DSR and up to 300% with AODV. Maximum UDP throughput is also increased substantially, up to 200% for both routing protocols. Relatively to normalized routing overhead, which is our reference metric to measure the performance of the routing protocols, we find that IEEE 802.11e allows achieving better results. The difference becomes more noticeable as we increase the level of saturation in the network, since saturation causes the routing protocol's mechanisms to malfunction.

As future work we intend to measure the improvements on multimedia traffic introduced by the IEEE 802.11e technology.

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