Assessing the effectiveness of IEEE 802.11e in multi-hop mobile network environments [*]

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Abstract

The IEEE 802.11e technology is receiving much interest due to the promising enhancements it will offer to wireless local area networks in terms of QoS support. Until now, research has focused on single hop, access point based environments, which are the most common. In this work we review the enhancements proposed in the last IEEE 802.11e draft (version 8.0). We analyze the performance of the IEEE 802.11e protocol on ad-hoc networks (multi-hop) in terms of throughput and end-to-end delay. We also measure the effectiveness for static and fully dynamic networks with a variable number of source stations. Eventually, we analyze the performance of IEEE 802.11e when legacy IEEE 802.11 stations (no IEEE 802.11e support) are present in the network. Simulation results show that IEEE 802.11e does not lose effectiveness in multi-hop mobile environments, though the existence of legacy stations in the MANET provokes a severe performance drop.

1. 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, forming 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.

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. MAC level QoS is fundamental in wireless networks to achieve traffic differentiation in terms of both throughput and delay.

In works such as [3, 4] the IEEE 802.11e technology has been thoroughly analyzed according to the current draft states.

In [5] the authors make an analysis of IEEE 802.11e in single and overlapping *access point* environments. The focus is on the effectiveness and limitations of IEEE 802.11e in such environments, also presenting a performance comparison of EDCA and HCCA, new media access technologies part of the IEEE 802.11e framework.

The previous works make an analysis of IEEE 802.11e in environments where stations communicate with an *access point* (Infrastructure BSS in IEEE 802.11). However, MANET environments 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

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[*] This work was supported by the *Ministerio de Ciencia y Tecnologia* under grant TIC/2003/00339, and the *Junta de Comunidades de Castilla La-Mancha* under grant PBC/03/001.

into account other problems such as mobility and terminal disconnection. Several alternatives to IEEE 802.11 have been proposed for multi-hop environments, such as those exposed in [6, 7]. In [6] authors analyze the trade-offs between time synchronization and performance in MANETs, proposing the MACA/PR protocol as a solution to offer MAC level QoS. In [7] the authors propose the PBC access mechanism, which is a prioritized binary countdown scheme. It is presented as an effective MAC protocol that supports service differentiation and collision control in mobile ad hoc networks.

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 use a static scenario to obtain performance results with a high level of accuracy, and we also analyze the behavior in a typical MANET environment while varying the number of sources. We also study the impact of mixing IEEE 802.11e compliant and non-compliant stations in the MANET in terms of QoS degradation.

Concerning the structure of this paper, in the next section we introduce the IEEE 802.11 technology, as well as the enhancements proposed in the current IEEE 802.11e draft [2]. Afterwards we present the simulation framework and the evaluation results, and finally we present conclusions to this work, as well as future work.

2. IEEE 802.11

The IEEE 802.11 standard is a technology whose purpose is to provide wireless access to local area networks (WLANs). Stations using this technology access the wireless medium using either the Point Coordination Function (PCF) or the Distributed Coordination Function (DCF).

The Point Coordination Function is a centralized access mode optionally used in a Basic Service Set (BSS) when a point coordinator (PC) is available. The PC is typically an *access point* (AP), and so the stations are said to operate in infrastructure mode. When relying on the PCF, contention-free periods (CFP) and contention periods (CP) alternate over time. The regular generation of beacons allows stations to associate and synchronize with the PC. Typically a CFP is started after a beacon management frame, followed by a CP; together they form a superframe. During the CFP there is no contention, and so stations are simply polled by the PC. The CF-End control frame is transmitted by the PC to indicate the end of the CF period, and the beginning of the CP. During the CP stations access the medium using the DCF.

The Distributed Coordination Function (DCF) uses a listen-before-talk scheme named *carrier sense multiple access* (CSMA) with *collision avoidance* (CA). It is used by stations in a BSS during the CP and also by stations in an IBSS operating in ad-hoc mode. The CSMA technology distributes the medium access task among all stations, making every station responsible for assuring the delivery of *MAC service data units* (MSDUs) and reacting to collisions. The collision avoidance scheme is used to reduce the probability of collisions between different stations. To achieve this it applies a backoff procedure before initiating a transmission if the medium was not found to be previously idle. Stations select a random number of slots to wait before transmission in the interval between 0 and the current *contention window* (CW) value. The value for CW is set initially to the minimum value for the radio technology being used (CWmin), being increased when consecutive collisions occur up to a maximum value (CWmax).

The CSMA/CA mechanism shows good adaptation to different numbers of transmitting stations, and probabilistically shares the channel equally among them. However, it offers no mechanisms to perform traffic differentiation, making it very difficult to offer QoS support. The IEEE 802.11e working group was created to focus on this issue, and a new international standard shall be available soon.

2.1. IEEE 802.11e: MAC enhancements for QoS

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

Contrarily to the legacy IEEE 802.11 stations, where all MSDUs have the same priority and are assigned to a sin-

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

Table 1. User Priority to IEEE 802.11e Access Category Mapping

gle 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 2 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.

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 inter-frame 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.

3. IEEE 802.11e evaluation in MANETs

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

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

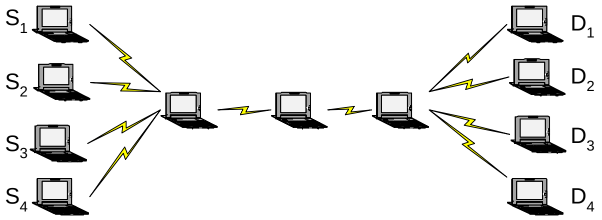

Figure 1. Static multi-hop scenario

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. Sources are unsynchronized by applying a random jitter to packet generation. This technique aims at avoiding the worst case scenario achieved when all traffic sources are synchronized.

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 as 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 rout-

Access category	AIFSN	CW$_{min}$	CW$_{max}$	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

Table 2. IEEE 802.11e MAC parameter values for a IEEE 802.11a/g radio

ing protocol used is AODV [8], and routing traffic is assigned the highest priority (AC_VO).

To conduct our experiments we used the ns-2 [9] discrete event simulator with the IEEE 802.11e extensions from [10]. We set up the IEEE 802.11 radio according to the parameters exposed in table 3. These values are valid for both IEEE 802.11a and IEEE 802.11g since the simulator's radio model does not differentiate between them.

Parameter	Value
SlotTime	9 μs
CCATime	3 μs
RxTxTurnaroundTime	2 μs
SIFSTime	16 μs
PreambleLength	96 bits $\cong$16 μs
PLCPHeaderLength	40 bits
PLCPDataRate	6 Mbit/s
DataRate	54 Mbit/s

Table 3. ns-2 PHY settings for IEEE 802.11a/g

Concerning the IEEE 802.11e MAC, it was configured according to the values presented previously in table 2.

The simulation results show a 99% confidence interval in all depicted points, though most are not visible (less than 1%). Concerning the results of the mobility scenarios, all points depicted are an average of 5 distinct MANET scenarios. Simulation times are of 300 seconds per scenario.

3.1. 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 for the sources. Remember that the same packet generation rate is used for all ACs and for all stations acting as traffic sources.

Figure 2 shows the achieved results in terms of throughput with and without the *contention-free bursting* (CFB) mechanism. We can clearly observe that activating this mechanism has a clear impact on throughput. This is especially relevant for the AC_VI (Video) access category, whose saturation point is much higher. We also find that the cost of this improvement in terms of Voice traffic is not high, being it mainly to impute to a better utilization of the wireless channel capacity thanks to the large TXOPLimit assigned to both AC_VO and AC_VI.

In terms of end-to-end delay, figure 3 shows that the probabilistic prioritization mechanism proposed by the IEEE 802.11e technology is quite effective in providing traffic differentiation. When offered traffic is low we see that low priority ACs also achieve low end-to-end delay values. This shows that IEEE 802.11e is able to assign available bandwidth to them 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, both from the throughput and the end-to-end delay values.

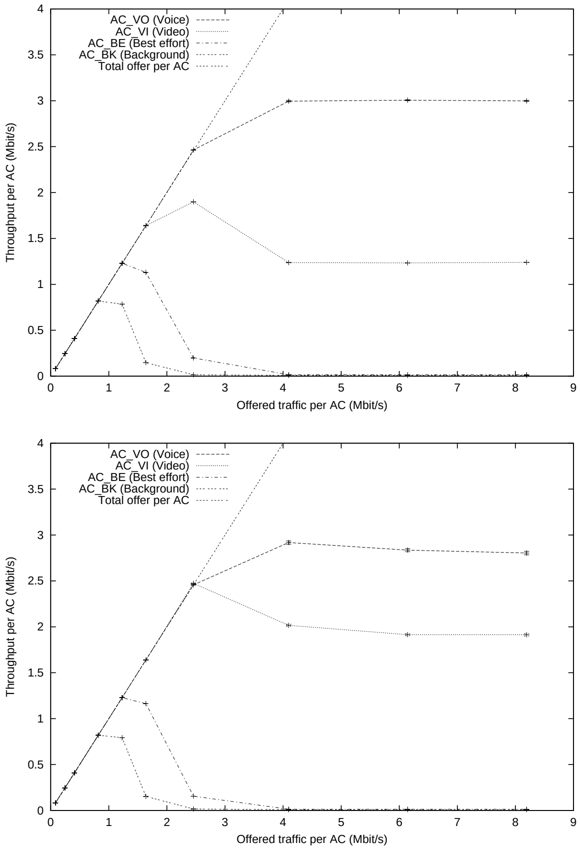

Figure 2. Throughput achieved with no CFB (top) and CFB activated (bottom)

Observing the decay in terms of throughput as the number of hops is increased, we wanted to assess if the share of bandwidth assigned to each AC in a single hop situation remains the same as the number of hops increases. If traffic with lower priority obtains significatively higher bandwidth shares while increasing the number of hops, we could conclude that the effectiveness of IEEE 802.11e is reduced. In this experiment we vary the number of hops from source to destination by varying the number of intermediate nodes. The total offered traffic per AC is set to 12 Mbit/s (3 Mbit/s per source), so that we operate under network saturation even when sources and destinations are one hop away.

In figure 4 we present the saturation throughput when varying the number of hops with and without the CFB mechanism. As expected, the throughput for all traffic categories decreases as the number of hops increases. In terms of total aggregate throughput, we observe that it drops from

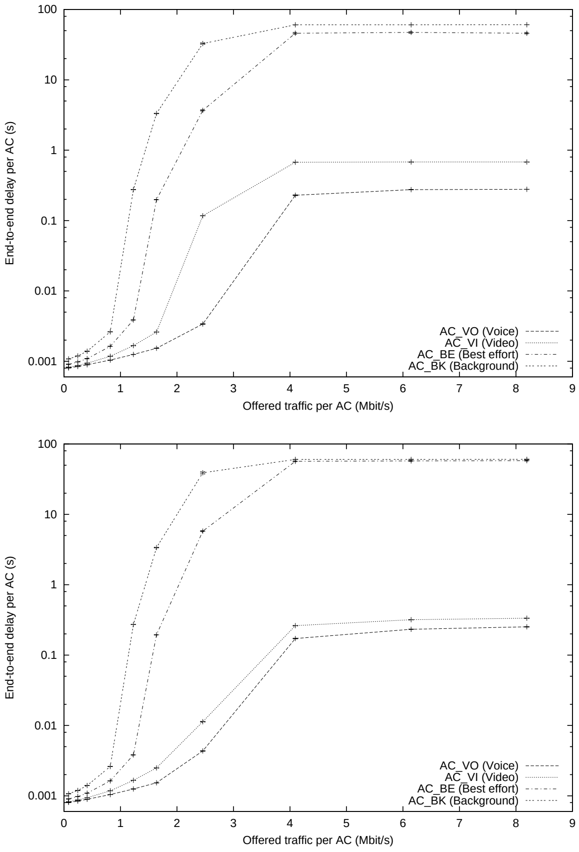

Figure 3. End-to-end delay achieved with no CFB (top) and CFB activated (bottom)

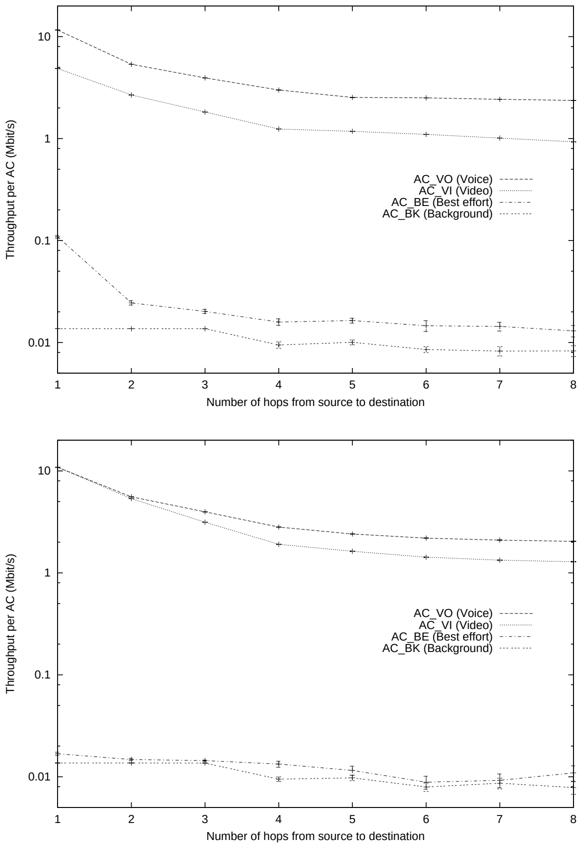

Figure 4. Throughput achieved with no CFB (top) and with CFB activated (bottom)

16,60 Mbit/s (1 hop) to 3,32 Mbit/s (8 hops) with no CFB, and from 21,74 Mbit/s to 3,34 Mbit/s with CFB. This result shows that, with increasing number of hops, the use of the CFB mechanism no longer results in improved channel utilization, though it still has influence on the channel shares obtained by each AC.

In terms of bandwidth share, figure 5 shows the allocation of bandwidth to the different ACs with and without CFB. We observe that both Voice (AC_VO) and Video (AC_VI) traffic maintain a steady share of the available bandwidth when CFB is off, as desired. When the CFB mechanism is activated, we observe that the Voice traffic share increases as the Video traffic share decreases. This variation, up to ten percent for eight hops, is due to the loss of effectiveness of the CFB mechanism when increasing the number of hops, as referred before.

The Best effort (AC_BE) traffic share slightly decreases with no CFB and increases with CFB. Background (AC_BK) traffic increases its share as the number of hops increases in both cases, though it is always maintained low.

Finally, we examine the stability of Voice and Video traffic when only Best effort and Background traffics vary. Simulation traffic is setup so that source S_1 transmits only Voice traffic at a rate of 0.5 Mbit/s, and source S_2 transmits only Video traffic at a rate of 1 Mbit/s. Sources S_3 and S_4 transmit variable rates of Best effort and Background traffic respectively. Using this setup we find no difference between using the CFB mechanism or not. This is because both voice and video traffic are generated at a constant bit-rate, and the data generation rate is not enough for the queue to hold several packets at any given time.

Figure 6 shows the results obtained with this new configuration. In terms of throughput we observe that neither the Video traffic nor the Voice traffic are affected by increasing Best effort and Background traffic. When the channel saturates Best effort traffic obtains a bandwidth share about six times greater than Background traffic. In terms of end-to-end delay we find that Voice traffic suffers from variations in its delay up to 55%, while Video traffic's delay can variate by up to 77%.

Overall, results show that the prioritization mechanism of IEEE 802.11e retains most of its effectiveness independently of the number of hops traversed by the traffic or the

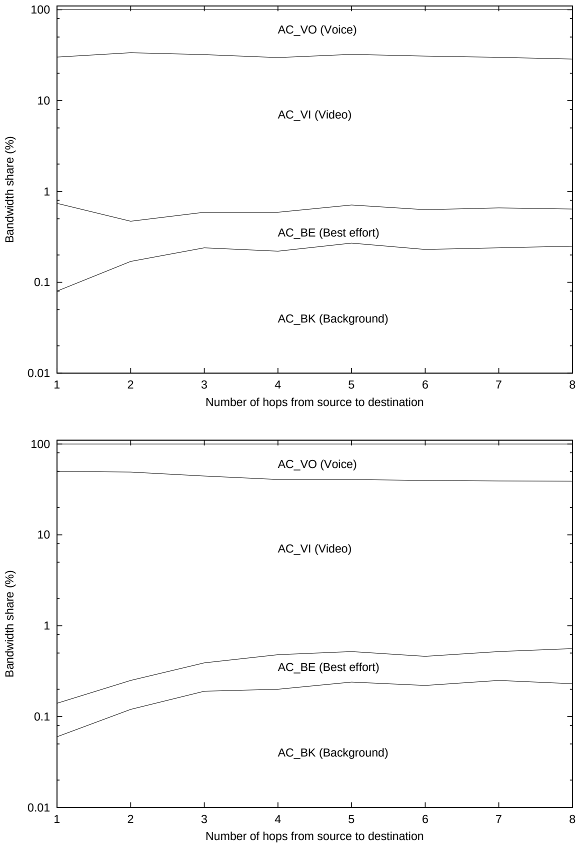

Figure 5. Bandwidth share for varying number of hops with no CFB (top) and CFB activated (bottom)

load of Best Effort and Background traffic. As with legacy IEEE 802.11 networks, though, the impact of the number of hops on available bandwidth is considerable.

3.2. 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. The CFB mechanism is turned off.

Figure 7 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 due to the contention mechanism of IEEE 802.11.

Relatively 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. While in the static scenario the maximum aggregated throughput is 4,1 Mbit/s (6 sources), in the mobile scenario this value increases to 6 Mbit/s (14 sources).

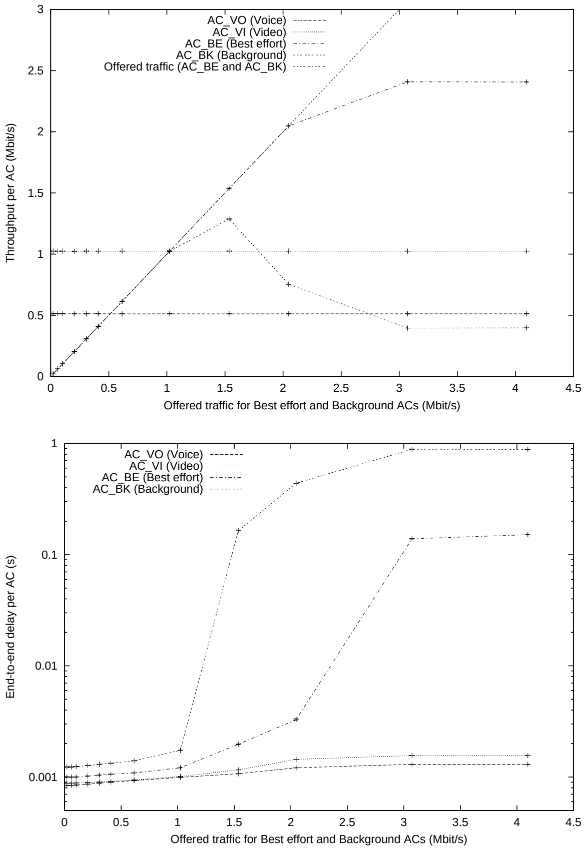

Figure 6. Throughput variation (top) and end-to-end delay variation (bottom) with different degrees of Best effort and Background traffic

Figure 8 shows the end-to-end delay results relative to the static scenario. These allow observing two rates of growth: the one before saturation (below the line shown) and the one when saturation 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 minimum end-to-end delay values are higher compared to the static scenario. Moreover, the difference between the various ACs is not very high when there are only a few sources of traffic. This is due to mobility itself, 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 saturation limits so quickly due to the traffic dispersion effect typical of MANETs. In terms of traffic differentiation, we ob-

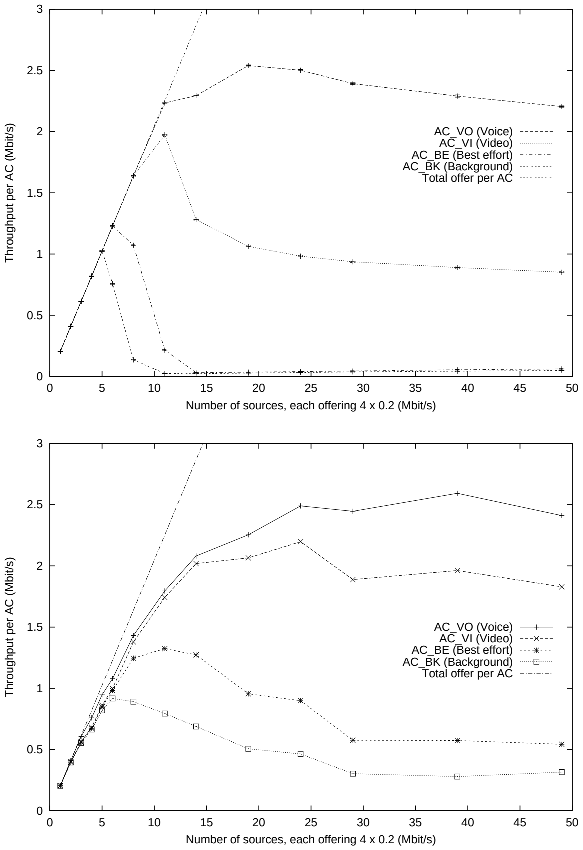

Figure 7. Throughput achieved in the static scenario (top) and mobile scenario (bottom)

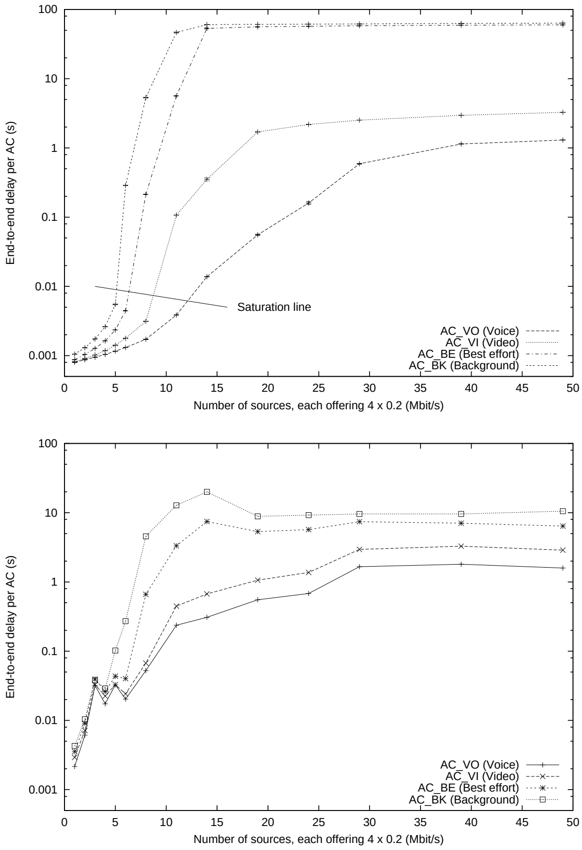

Figure 8. End-to-end delay for the static scenario (top) and mobile scenario (bottom)

serve 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.

3.3. Impact of legacy stations on the MANET

Due to the ad-hoc nature of MANETs, there is little or no control on the characteristics of terminals that compose it. Therefore, it should not be assumed that all terminals are equipped with the same technology (in our case, IEEE 802.11e). In this section we will evaluate the impact on a mobile MANET of different proportions between legacy IEEE 802.11 and IEEE 802.11e enabled stations. Relatively to the traffic setup, the number of source stations is four, each configured as in the previous section. Again, the CFB mechanism is turned off.

Figure 9 presents the results achieved in terms of throughput and end-to-end delay. We can observe that with only a 10% of legacy IEEE 802.11 nodes the performance drop is already severe, especially in terms of end-to-end delay which suffers from an increase of two orders of magnitude. We also observe that when the MANET is composed off a majority of legacy IEEE 802.11 nodes the performance increases. This can be explained by the impact that a few IEEE 802.11e enabled stations have on legacy ones in terms of channel monopolizing.

The worst performance case is observed when the legacy stations are in a proportion of 4 to 1 (80%) with respect to IEEE 802.11e enabled stations. Notice that when all stations are legacy IEEE 802.11 there is no sort of differentiation among classes as expected, validating the obtained results.

4. Conclusions and future work

In this paper we 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, along with the effect of different number of hops on the theoretical throughput limits. We showed that bandwidth share among different traffic categories depends on the number of hops traversed, and that the *contention-free bursting* mechanism loses some of

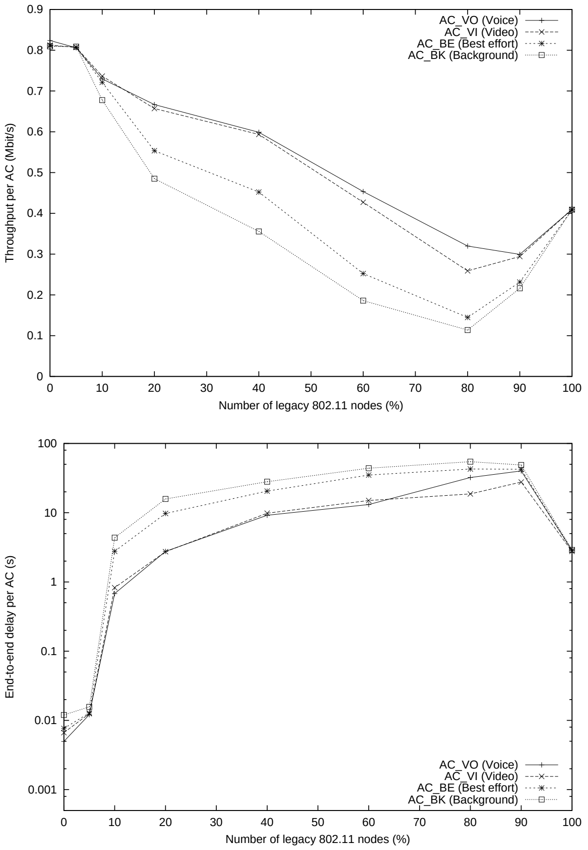

Figure 9. Throughput (top) and end-to-end delay (bottom) for different shares of legacy IEEE 802.11 stations

its effectiveness as the number of hops increases. We also showed that with IEEE 802.11e high priority traffic (Voice and Video) is able to maintain a steady throughput independently of the lower priority traffic load (Best effort and Background), and that in terms of end-to-end delay the impact is kept within acceptable bounds.

Our analysis also included a comparative evaluation of the static scenario configuration with five distinct mobile scenarios for a variable number of traffic source stations. Results showed 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. Overall, we found that the upcoming IEEE 802.11e technology maintains most of its effectiveness in both static and mobile multi-hop scenarios.

We concluded our work by studying the impact of having different shares of legacy IEEE 802.11 stations in a typical mobile MANET. Results showed that performance drops severely with just one legacy station every ten stations, which justifies a layer-2 aware routing agent in order to avoid forwarding traffic through legacy IEEE 802.11 stations for real-time applications.

As future work we intend to analyze the performance improvements in terms of routing effectiveness introduced by the IEEE 802.11e technology by allowing routing messages to benefit from higher priority when accessing the media, and we will measure the improvements on multimedia traffic.

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