On the interaction between IEEE 802.11e and routing protocols in Mobile Ad-hoc Networks *

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Abstract

The upcoming IEEE 802.11e standard was developed to offer QoS capabilities to WLAN, offering significative improvements to multimedia traffic. MANETs will also benefit from this new technology since the most widely deployed and used wireless interfaces are IEEE 802.11 based. In this paper we expose results relative to 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, offering a holistic view of the phenomena.

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, 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 ISM 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 them 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. 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. In fact, IEEE 802.11e documentation also indicates that this is the correct procedure, as exposed in section 2.

Routing protocols typically belong to two main families: proactive routing protocols and reactive routing protocols. Example of proactive routing protocols are OLSR [3] and TBRPF [4]. These routing protocols rely on "Hello" messages to continuously maintain the topology of the MANET, and so the time to detect broken links is typically long [5]. Therefore, assigning higher priority to the control packets of these protocols shall not have very noticeable effects in terms of traffic performance. On the other hand, routing protocols such as AODV [6] and DSR [7] discover routes on demand and typically rely on link-level information to detect broken links. Therefore, the latter should improve their responsiveness considerably when combined

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with IEEE 802.11e, especially when the network is very congested.

In [8] Mangold et al. 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 contrast of the performance achieved with the *HCF controlled channel access* (HCCA) and the *enhanced distributed channel access* (EDCA). Papers evaluating the performance of IEEE 802.11e in MANET environments, though, are scarce.

Relatively to the interactions between different stack elements in MANET, in [9] authors suggest how the performance of the AODV routing protocol can be enhanced through feedback between the MAC layer and the ARP module. Barret et al. [10, 11] study the interaction between Network Protocols, Topology and Traffic, as well as the interaction between the routing protocol and the MAC layer in MANETs using statistical techniques. Roy et al. [12] use specialized MAC and routing protocols to exploit the advantages of directional antennas.

Our approach in this paper is to assess the improvements that the IEEE 802.11e technology offers to multi-hop wireless networks. Specifically, we focus on the improvements on TCP and UDP traffic derived from increased responsiveness of the routing mechanisms.

Concerning the structure of this paper, in the next section we refer to some related works. In section 2 we offer an overview of the IEEE 802.11e technology, along with a strategy to map user QoS requirements to the IEEE 802.11e framework. A performance analysis in terms of TCP and UDP traffic using both AODV and DSR routing protocols is made in section 3, along with comments on the phenomena experienced by the different routing mechanisms. Finally, in section 4 we present the conclusions to this work.

2. 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 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 contention-free period (CFP) since it no longer depends on it to provide QoS guarantees.

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 (according to IEEE 802.1D)

With IEEE 802.11e, the *point coordinator* is replaced by a *hybrid coordinator* (HC) which also resides in an AP. A Basic Service Set (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 802.11e stations implementing EDCA. For more information on HCs, the HCF and the HCCA refer to [2].

Concerning 802.11e enabled stations forming an ad-hoc network, these must implement the EDCA. The 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 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-

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

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.

2.1. Mapping QoS requirements to IEEE 802.11e parameters

QoS parameters are typically set at the application level depending on the requirements of a particular application. The Internet Protocol (IP) supports traffic differentiation mechanisms in the sense that it allows tagging the packets according to QoS requirements, so that successive network elements can treat them adequately. This is achieved using the 8 bits of the "Type of service" field in an IPv4 datagram header or the "Traffic class" field in an IPv6 datagram header. In this work our proposal consists of using the 3 TOS bits, part of both "Type of service" (IPv4) or "Traffic class" (IPv6) fields, to indicate the desired user priority. These shall then be mapped to IEEE 802.11e ACs according to table 1.

The IEEE 802.11e draft [2] states that stations that depend on IEEE 802.11e for communication are able to offer to packets differentiated treatment by negotiating them with the IEEE 802.11e MAC Service Access Point. The IEEE 802.11e MAC Service Access Point (MAC_SAP) allows to negotiate QoS specifications in two ways: either directly by setting a traffic category (TC), or indirectly by making a traffic specification (TSPEC) instead. It is the value of the user priority (UP) parameter which indicates to the MAC_SAP the desired choice using values in the range 0 through 15. Priority parameter values 0 through 7 are interpreted as actual user priority values according to table 1, and so outgoing MSDUs are therefore marked according to the correspondent access category. Priority parameter values 8 through 15 specify traffic stream identifiers (TSIDs), and allow selecting a TSPEC instead.

The value of the chosen user priority is mapped to packets transmitted by setting the QoS Control field, part of the IEEE 802.11e MAC header, accordingly. The QoS Control field is a 16-bit field that identifies the traffic category or traffic stream (TS) to which the frame belongs and various other QoS-related information about the frame that varies for the particular sender and by frame type and subtype. In particular, it is the TID field (part of the QoS Control field) the one that identifies the TC or TS of traffic for which a TXOP is being requested. The most significant bit of the TID, when set to 0, indicates that the request is for data associated with prioritized QoS and, when set to 1, indicates that the request is for data associated with parameterized QoS. The remaining bits define the UP value or the TSID accordingly.

When receiving a packet, the IEEE 802.11e MAC analyzes the QoS Control field and also offers a differentiated treatment to packets with different QoS requirements when passing them to upper stack layers.

3. Performance improvements offered by IEEE 802.11e

In the previous section we explained how a system can and should be configured in order to assign different priority to packets. In our evaluation we modify the IP header of routing packets to tag them as Network Control packets, which are assigned the maximum access category (AC_VO) by the IEEE 802.11e MAC.

In our experiments we assess the performance improvements achieved by the prioritization of routing packets on TCP and UDP traffic. As referred before, 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 and DSR, and so our experiment will focus on both of them.

To conduct our experiments we used the ns-2 simulator [13] with the IEEE 802.11e extentions by Wietholter and Hoene [14]. 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 radio model of the simulator 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

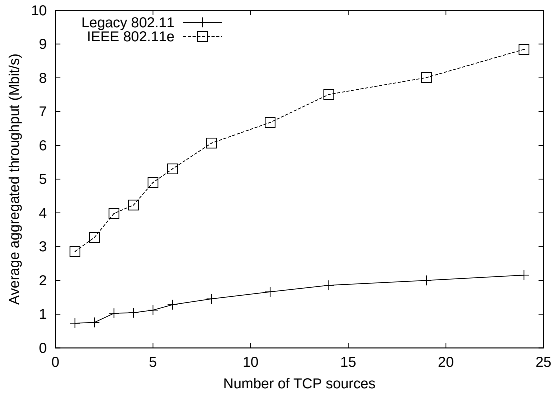
Table 3. ns-2 PHY settings for IEEE 802.11a/g

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

For our experiments we used a rectangular scenario sized 1900x400 meters, where the average number of hops from source to destination is four. 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 mobility setup chosen aims at generating scenarios where the effectiveness of the routing protocol has noticeable effects on the performance experienced by traffic. Our measurements were made over a period of 300 seconds on five distinct scenarios, and all results presented are an average of those obtained on the different scenarios. We set an initialization period of 100 seconds where UDP traffic is sent at a very slow rate to allow routing protocols to converge. The purpose is to make measurements in an environment where routes are already stable, so that fair comparisons between traffic measurements can be made.

Relatively to the sources of traffic, TCP traffic sources are bandwidth greedy continuously. We simulate this behavior 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 experience a different treatment and so all improvements will only depend on the increased responsiveness of the routing mechanism itself.



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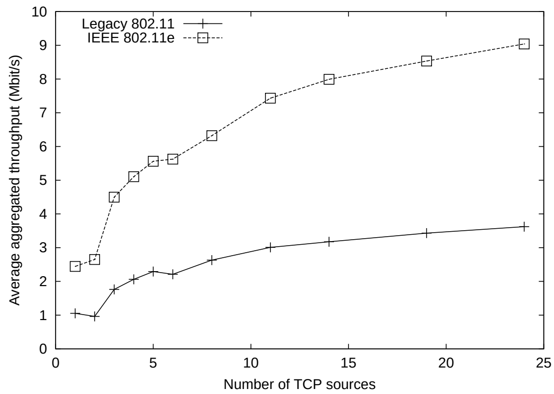

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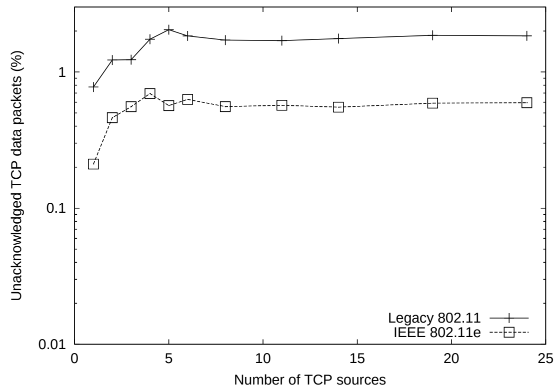
Figure 1. TCP throughput performance using a) AODV and b) DSR for different MAC solutions

3.1. Improvements on TCP traffic

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

In figure 1 we show the TCP throughput performance results. When using the AODV routing protocol 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 [15, 16] 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 2) 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



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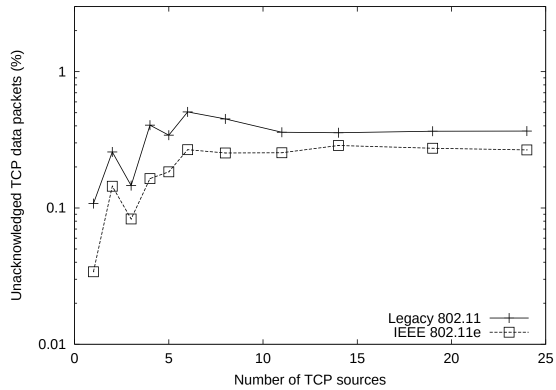

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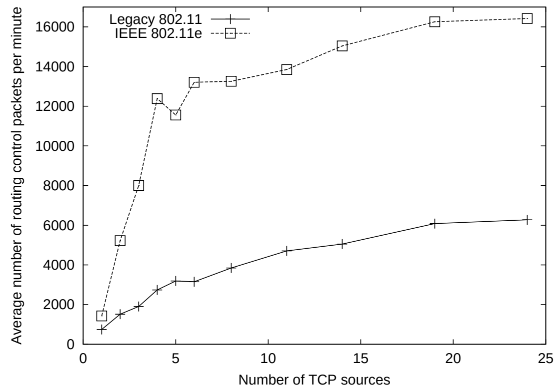
Figure 2. TCP data packets lost using a) AODV and b) DSR for different MAC solutions



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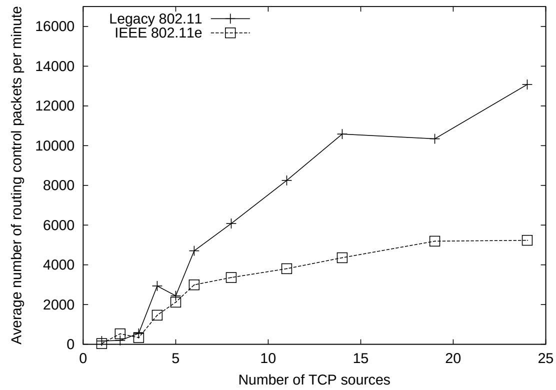

b)

Figure 3. Number of routing control packets using a) AODV and b) DSR for different MAC solutions

on the direct path, or to the loss of TCP ACK packets on the inverse path.

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 1. 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. This fact is also put in evidence by observing the results shown in figure 3 relative to the routing overhead.

Figure 3 shows that the number of routing control packets transmitted with AODV increases when using IEEE 802.11e. So, IEEE 802.11e has the effect of increasing the robustness of the AODV routing mechanism by making routing related communication more reliable (fewer routing packets dropped). When using the DSR routing protocol the results are the opposite of those found for AODV. Here giving routing packets more priority when accessing the medium makes routing related communication between stations much faster. The effect this produces is that fewer timeouts are triggered, and therefore fewer routing control packets are generated.

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 data and ACK packets.

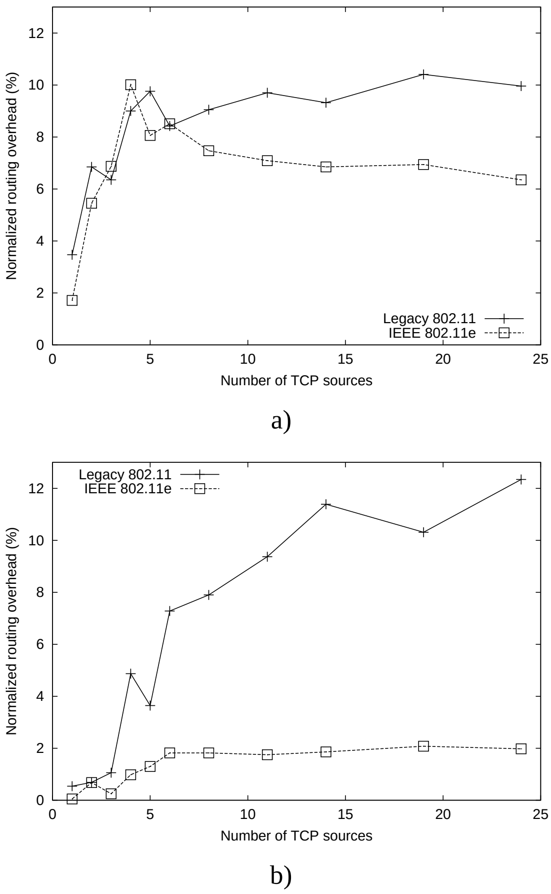

Figure 4. Normalized routing overhead using a) AODV and b) DSR for different MAC solutions

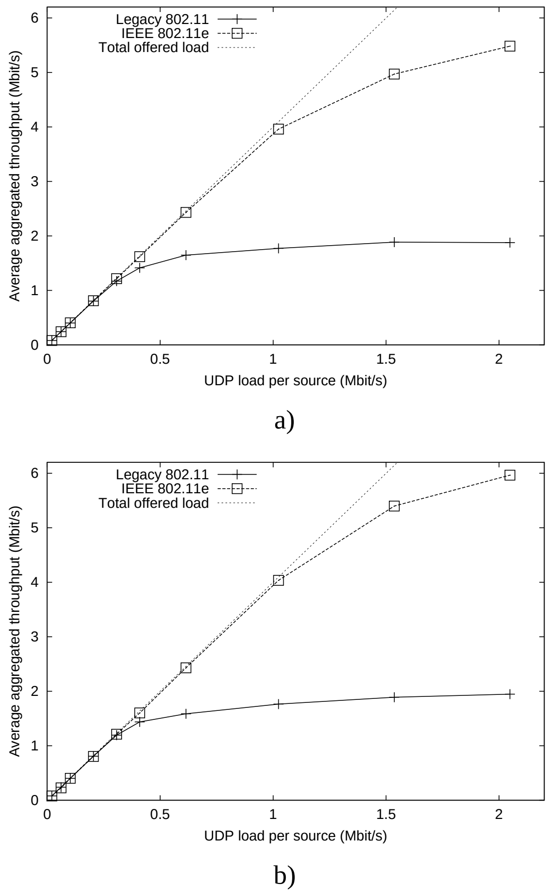

Figure 5. UDP throughput using a) AODV and b) DSR for different MAC solutions

The results relative to AODV, see figure 4, 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.

3.2. 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 5.

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 figure 6 we show the variation in routing overhead using the two different MACs.

As the traffic load increases routing protocols need to increase their responsiveness, which means more control packets. If we look at the results for AODV with legacy IEEE 802.11 we find that after a certain point the number of control packets in the network is kept at constant levels, and so it is no longer able to increase its responsiveness. When IEEE 802.11e is used the number of control packets increases steadily, “on demand” as necessary. With

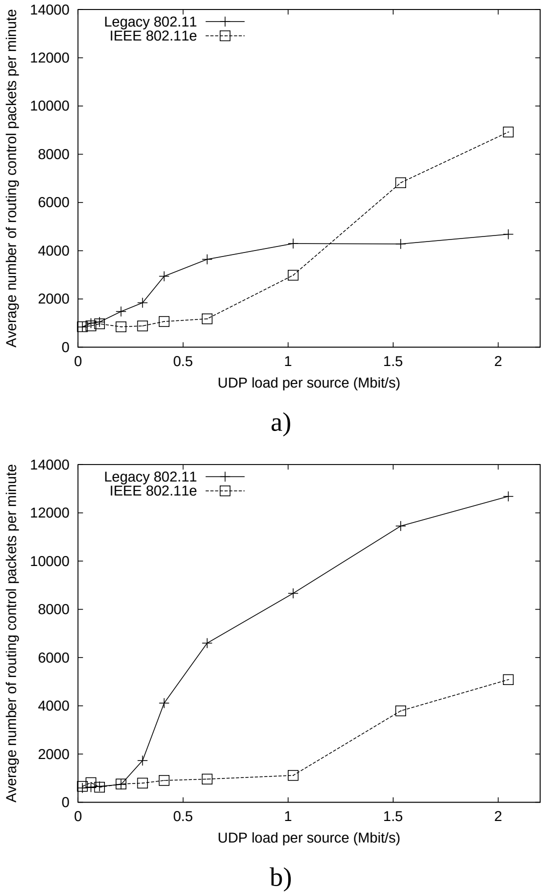

Figure 6. Number of routing control packets using a) AODV and b) DSR for different MAC solutions

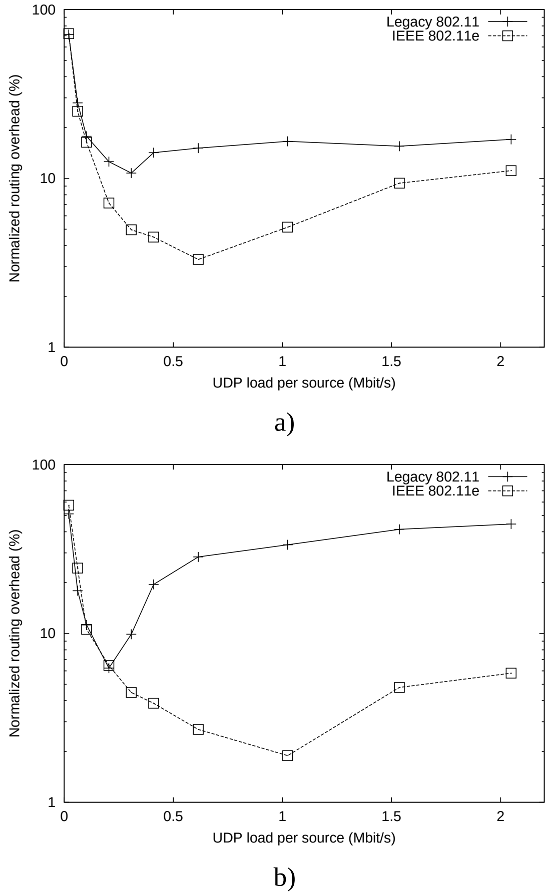

Figure 7. Normalized routing overhead using a) AODV and b) DSR for different MAC solutions

DSR the phenomena experienced is different because, as exposed in the previous section, IEEE 802.11e makes routing related communication between stations much faster, which provokes fewer timeouts to be triggered. Also notice that routing packets are always put at the front of the interface queues, independently of using legacy IEEE 802.11 or IEEE 802.11e. This means that routing packets normally will not be lost due to queue overflows, but only due to channel noise or collisions. Since a significative share of DSR's packets are unicasted (and so acknowledged), they will typically not be lost when flowing through the MANET, though experiencing different degrees of delay. This explains why in figure 6 DSR's control packets depending on legacy IEEE 802.11 increase steadily.

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 legacy IEEE 802.11 achieves very high values, clearly indicating that congestion is leading the routing protocol mechanism to perform poorly (see figure 7).

4. Conclusions

In this paper we offered an insight into the interaction of routing protocols and the MAC implementations of IEEE 802.11 and IEEE 802.11e. Our study focused on the performance improvements in terms of TCP and UDP traffic in a typical MANET environment when uniquely routing packets are assigned to the highest priority access category under IEEE 802.11e. We detail the difference in behavior of two reactive routing protocols - AODV and DSR - relating the traffic throughput and routing overhead results to their internal mechanisms.

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.

Overall, we consider that upgrading the MAC layer of MANET stations to IEEE 802.11e is very important not also for multimedia traffic support, but also to improve the efficency of the routing mechanism used, especially if it is a reactive one.

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