A Dynamic Priority MAC Protocol for Time-Bounded Services in Wireless Networks

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Abstract. Wireless Local Area Networks have gained popularity at an unprecedented rate over the last few years. However, as the spectrum of applications they are called to support broadens, their inefficiency in meeting the diverse requirements of a wider range of applications becomes evident. Most existing access mechanisms cannot provide Quality-of-Service (QoS) assurances. Even those that are QoS aware can only provide relative service differentiation. In this work, we propose a dynamic priority medium access scheme to provide time-bounded services. By approximating an ideal Earliest Deadline First (EDF) scheduler, the proposed scheme can offer delay and delay jitter assurances while achieving high medium utilization. Analytical studies and simulation experiments document and confirm the positive characteristics of the proposed mechanism.

Keywords: EY-NPMA, medium access, wireless LANs, EDF, QoS

1. Introduction

Holding the promise of making ubiquitous mobile access to IP-based applications and services a reality, wireless networks have gained popularity at an unprecedented rate over the last few years. Concurrent with the expansion of wireless networks is a high demand for real-time applications with very stringent and diverse Quality-of-Service (QoS) requirements. Providing QoS requires the network to guarantee hard bounds on a set of measurable prespecified attributes, such as delay, bandwidth, probability of packet loss, and delay variance (jitter). However, the unstable nature of WLANS and their different characteristics compared to those of their wired counterparts, have a direct impact on their ability to guarantee bounds on these QoS metrics.

Soft guarantees can be provided instead, to increase the satisfaction level of users. Recent advances in encoding techniques allow real-time applications to adapt to network conditions and adjust their sending rate in the presence of time-varying channel capacities. Moreover, they

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allow a low ratio of packet loss without the Quality-of-Service perceived by the end user being affected. However, when delay bounds are concerned, average performance may be proven insufficient. Packets whose delay exceeds a given threshold will be dropped, resulting in wasteful consumption of the scarce wireless resources. Providing delay guarantees becomes even more important if wireless access is considered to be just another hop in the communication path. End-to-end delay guarantees can be provided only if delays are bounded at each node along the path. If a node fails to meet local delay requirements, the end-to-end delay experienced by a packet may exceed its delay budget, resulting in a waste of the resources assigned to it at each node along the path. It would be therefore, desirable to design a medium access scheme that can meet the delay requirements of delay-sensitive traffic.

When delay-sensitive traffic is to be supported by the network, the optimal choice is to use the Earliest Deadline First (EDF) service discipline [1]. The EDF scheduler is a dynamic priority scheduler where the priorities for each packet are assigned as it arrives. The priority of each packet is given by its arrival time plus the delay budget associated with the flow that the packet belongs to. The scheduler selects the packet with the smallest deadline for transmission on the link. The priority of the packet increases with the amount of time it spends in the system. It has been proven that for any packet arrival process where a deadline can be associated with each packet, the EDF policy is optimal in terms of minimizing the maximum difference between the deadline of a packet and the time it is actually transmitted on the link [2].

Using EDF to control channel access in a distributed wireless environment, comprises a number of challenges, since there is not a management entity that can obtain all the information (e.g. number of active sessions, link states, statuses of the session queues) needed to make a scheduling decision. Therefore, a station with a lower priority packet may not defer access. Implementing a dynamic priority scheme with multiple priority levels can ensure that the station with the highest priority packet will gain access to the common medium. However, the probability of correct scheduling will be less than one, since two or more packets with different deadlines may belong to the same priority class. The problem then is to design a medium access scheme that can approximate EDF to the largest extent possible while achieving high levels of efficiency.

EY-NPMA [16], the HIPERLAN MAC protocol, is a dynamic priority scheme, which provides hierarchical independence of performance by means of channel access priority. EY-NPMA shows very good characteristics regarding collision rates and also provides support for service differentiation, elements which make it a good choice for wireless networks. However, its ability to track an ideal EDF scheduler, and thus provide service differentiation degrades severely as traffic load increases and the number of contending nodes grows. This is mainly due to the fact that EY-NPMA supports only 5 priority levels.

Based on EY-NPMA, we propose a dynamic priority Medium Access Control protocol to support time-bounded services in wireless networks. We modify the channel access scheme of EY-NPMA to support a high number of priority levels. Analytical studies and simulation results show that our scheme can closely approximate an ideal EDF scheduler while achieving high medium utilization.

The rest of the paper is structured as follows. In section 2 we provide an overview of distributed QoS capable medium access algorithms. Section 3 reviews EY-NPMA, the MAC protocol for HIPERLAN. Section 4 describes the design of the proposed protocol and presents its theoretical analysis. Section 5 deals with the performance evaluation of the proposed scheme, while section 6 concludes the paper.

2. Related Work

In this section we review some of the existing approaches to provide service differentiation at the distributed wireless MAC layer. The common feature of these distributed medium access algorithms is their attempt to provide QoS support by applying the ideas behind scheduling algorithms proposed for wireline networks.

Following the paradigm of Weighted Fair Queueing (WFQ), [3][4] and [5] propose distributed algorithms for rate-based differentiation and throughput fairness. WFQ is an idealized fluid discipline with the desirable properties of fair resource sharing among flows and the provision of minimum rate guarantees. However, the tight coupling between rate and delay under WFQ renders it inappropriate for providing delay guarantees, especially in the case of low-rate traffic requiring low delay bounds. Indeed, none of the schemes proposed in the above papers addresses the problem of delay differentiation.

The objective of another class of QoS capable medium access protocols proposed in the literature is to provide service differentiation by allowing faster access to the channel to traffic classes with higher priority.

[6][10][11] propose modifications to the IEEE 802.11 Distributed Coordinated Function (DCF) [17] to incorporate differentiated service by supporting two or more priority levels. [6] proposes to modify the backoff scheme of DCF and set different values of CW_{min} and CW_{max} for different priority classes such that higher priority packets are more

likely to be transmitted first. In [11] priorities are introduced by having each priority class use a different exponential increase factor during the backoff stage. Since this mechanism cannot ensure that contending nodes will defer to other contending nodes with higher priority packets, the authors propose a second mechanism that uses different DIFS values for different priority classes. The DIFS of a priority class j is defined as the sum of DIFS and the maximum contention window of the higher priority class $j+1$. As each station waits for the entire DIFS duration before it starts to count down the backoff interval, this scheme provides nodes with higher priority packets absolute priority to channel access. In [10] the backoff scheme of the IEEE 802.11 is modified and different interframe space (IFS) intervals are used, to support multiple priority levels. Higher priority stations use a shorter IFS and smaller "Contention Windows"; however, it is not assured that higher priority stations will have shorter backoff time than lower priority ones.

In [8] the authors propose a MAC protocol that provides multiple priority levels and adopts the black-burst mechanism [9] to guarantee that higher-priority packets will be always transmitted earlier than lower-priority ones. Packets with the same priority are then transmitted in a round robin manner. The Busy Tone Priority Scheduling (BTPS) [7] protocol makes use of two busy tone signals to create two priority levels and adds an additional interframe space to the 802.11 DCF to ensure channel access of high priority packets.

All of the above schemes attempt to provide distributed service differentiation by assigning traffic to fixed priority classes. However, even if hierarchical independence of performance is achieved, ensuring channel access to high priority traffic, performance guarantees cannot be provided on a per-flow basis. It can only be assured that a higher priority class of traffic will receive better service than a lower one; thus, only relative service differentiation can be provided. Better service assurances can be offered if the priority level of packets contending for access to the wireless medium is updated in a dynamic manner. This allows packets with loose QoS requirements to obtain better service than they would in a static priority scheduler without sacrificing the tight QoS guarantees that may be provided to other flows.

In [15] a distributed dynamic priority scheme is proposed which piggybacks the priority index of a head-of-line packet onto existing handshake messages of the 802.11 DCF. Neighbors monitor these transmissions and keep a table of their times in order to assess the relative priority of their own head-of-line packet. A station defers from contention as long as a time on its table precedes the arrival time of its own head-of-line packet. It is shown that this scheme can achieve a closer approximation to an ideal deadline based schedule than IEEE

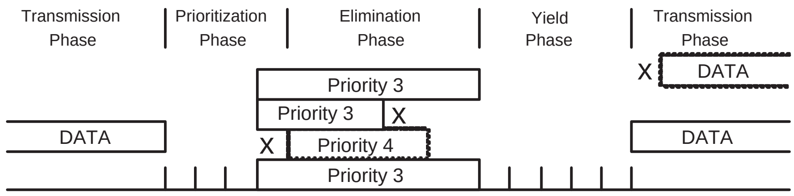

Figure 1. EY-NPMA's synchronized channel access cycle

802.11. EY-NPMA, the MAC protocol for the HIPERLAN, is another QoS aware medium access scheme that follows the dynamic priority approach for providing service differentiation.

3. EY-NPMA

EY-NPMA stands for Elimination-Yield Non-Pre-emptive Priority Multiple Access. Elimination-Yield describes the contention resolution scheme, while NPMA refers to the principle of the HIPERLAN medium access mechanism that provides hierarchical independence of performance by means of channel access priority.

The channel access priority of a packet is defined by two parameters: the user priority (low and high) and the residual lifetime. When a new packet arrives, its lifetime is set to a value that cannot exceed 500 ms. At the beginning of the next channel access cycle the residual lifetime of the packet is updated. Depending on its residual lifetime, the packet is assigned one of the five priorities from 0 to 4, with 0 being the highest priority. Packets that cannot be delivered within the allocated lifetime are discarded. User priority determines whether the channel access priority of a packet can be upgraded to the highest priority level.

According to the HIPERLAN MAC protocol, every node that has data to transmit senses the channel for a period of 1700 bits. If no transmission takes place, the channel is considered free and the node starts transmitting immediately. Otherwise, the node synchronizes itself at the end of the current transmission interval and contends for the channel at the next channel access cycle according to the EY-NPMA scheme.

The NPMA channel access cycle is non-pre-emptive, so that only data transmission attempts ready at the start of a channel access cycle may contend for channel access in that channel access cycle. The synchronized channel access cycle comprises three phases: the prioritization, contention and transmission phase.

During the prioritization phase, priority resolution is performed, ensuring that only those data transmission attempts with the highest channel access priority will survive this phase. Each node having data to transmit senses the channel for as many slots as the priority of the packet in its buffer. If the channel is sensed idle for the whole interval, the contending node asserts the channel access priority by transmitting immediately a channel access burst (priority assertion slot). Otherwise, the node stops its data transmission attempt in the current channel access cycle.

The prioritization phase is immediately followed by the contention phase, during which only the data transmission attempts that have survived the prioritization phase contend for the right of transmission. The contention phase consists of two-subphases: elimination phase and yield phase. The objective of the elimination scheme is to eliminate as many as possible, but not all, contending nodes from competing for the right of transmission. A contending node transmits a channel access burst, whose length in slots is random between 0 and a predefined maximum, according to a truncated geometric distribution and then listens to the channel. If the channel is sensed as idle the node proceeds to the yield phase; otherwise, the node is eliminated and withdraws from the right of transmission in the current channel access cycle.

The yield phase complements the elimination phase by further resolving contention between the contending nodes that survived from the elimination scheme. During the yield phase, the contending nodes sense the channel for a random number of slots, and if the channel is sensed idle, they immediately enter the transmission phase by transmitting the packet stored in their buffer. All other stations sense the beginning of the transmission and refrain from transmitting.

Each phase reduces the number of contending nodes, so that there is a high probability that at the start of the transmission phase, the transmitting node will be unique. Moreover, the contention resolution scheme ensures that each contending node has a statistically equal chance to gain the right of transmission. In Figure 1, an example of an EY-NPMA access cycle is presented. Solid line boxes represent actual transmissions, while dashed line boxes represent projected transmissions that did not take place because the station left the contention process. The X marks show when stations left the cycle.

The parameters in the HIPERLAN standard were chosen so as to achieve a collision rate of 3.5% that is independent of the number of simultaneous contending nodes, for a predefined maximum population of 256 simultaneous transmitting nodes. The maximum number of slots for which a station may burst during elimination (m_{es}) was set to 12, while the maximum number of slots that a station may backoff during the yield phase (m_y) was set to 9. Finally, the probability that defines the truncated geometric distribution used for deciding for how many slots a station should burst was set to 0.5. The working parameters of EY-NPMA may be expressed as a triplet of values $\{m_{es}, m_y, p_e\}$, which obviously the HIPERLAN standard defines as {12, 9, 0.5}.

A performance study of EY-NPMA can be found in [12] and [14], where extended analytical and simulation results are presented. Furthermore, it has been compared with DCF and EDCF in [18] and [13] respectively.

4. Proposed Protocol

Based on EY-NPMA, we propose a dynamic priority Medium Access Control protocol (DP-TB), to support time-bounded services in wireless networks. The proposed medium access scheme provides support to traffic with delay requirements by closely approximating an ideal EDF schedule. Providing delay assurances to time-constraint traffic is actually a scheduling porblem. The likelihood of meeting the deadline of a time-bounded packet is higher for EDF than for any other scheduling policy. By closely approximating an EDF scheduler, the proposed medium access protocol ensures that packets whose deadline is about to expire will not be preempted by packets that have enough delay budget (residual lifetime) to be transmitted in succeeding channel access cycles. Consequently, DP-TB minimizes the number of lost packets due to incorrect scheduling, achieving increased medium utilization.

4.1. DP-TB

The proposed scheme preserves all of the three phases of the synchronized access cycle of the EY-NPMA scheme; yet, it features a different structure for the prioritization phase. Instead of a maximum of 5 prioritization slots, we propose a scheme that uses at most M slots for the prioritization phase. The prioritization phase, in the proposed DP-TB scheme, is further sub-divided in m sub-phases, where sub-phase j consists at most of α_j slots, such that $\sum_{i=1}^{m} \alpha_i = M$. We do not fix M and m to constant values, but rather let them be parameters of the system. Depending on the choice of M and m there is a trade-off between the extent that the ideal EDF scheduler can be approximated to and the throughput that can be achieved.

EY-NPMA uses M prioritization slots to support M priority levels. By sub-dividing the prioritization phase in m sub-phases, DP-TB can provide a maximum of $Q = \prod_{i=1}^{m} \alpha_i$ priority levels, with 0 denoting the highest priority and $Q - 1$ the lowest one.

As it has been mentioned the lifetime of a packet that has just arrived, is set to a value that cannot exceed 500 ms. We divide the interval of 500 ms into Q time intervals, each of which has a duration of $t_p = 0.5/Q$ sec. Then the priority index q of a packet with residual lifetime RL can be computed as:

$$q = \{k : k * t_p \leq RL < (k+1) * t_p\} = \left\lfloor \frac{RL}{t_p} \right\rfloor \tag{1}$$

Given the priority index of a packet, the algorithm presented below can be used to determine for how many slots p_j a node should sense the channel in each sub-phase j in order to determine if it has the currently higher priority packet for transmission.

$for(i = 1; i < m; i++)$

$\{p_i = \left\lfloor \frac{q}{\prod_{j=i+1}^{m} \alpha_j} \right\rfloor$

$q = q - p_i \cdot \prod_{j=i+1}^{m} \alpha_j$

$\}$

$p_m = q$

As soon as the set of parameters $\{p_1, ..., p_m\}$ has been computed a packet can contend for channel access in the prioritization phase. The prioritization phase of DP-TB works as follows. At the beginning of the first sub-phase, a station that has a packet ready for transmission senses the channel for as many as p_1 slots. If the channel is idle for the whole sensing interval, the station transmits a priority assertion slot and proceeds to the second sub-phase. Otherwise, the station exits contention and will have another chance for accessing the channel at the next cycle. In the same manner, during the second sub-phase the station senses the channel for p_2 slots, and if the channel is sensed idle it transmits a priority assertion slot. The procedure is repeated until the last sub-phase, where the node transmits a priority assertion slot and then a burst of random length. The length of this burst is between 0 and a predefined maximum number of slots.

Let us illustrate how the prioritization phase works in DP-TB with an example. Suppose that we want to support 27 priority levels by using at most 9 slots. This leads us to divide the prioritization phase into 3 sub-phases, each consisting of at most 3 slots. Next, suppose that at the beginning of a channel access cycle the priority index of the highest priority packet is 11. The node having the highest priority packet computes the values of the $\{p_1, p_2, p_3\}$ parameters as $\{1, 0, 2\}$. During the first sub-phase the station senses the channel for 1 slot and since the channel is idle, it transmits a burst in the second slot and immediately enters the second sub-phase. Note that any other station with a packet, whose priority index is in the range 12-17, will also transmit a burst in the second slot of the first sub-phase. During the second sub-phase, the station with the highest priority index will sense the channel for as many as 0 slots, thus it will transmit a priority assertion slot in the first slot of the second sub-phase and it will proceed to the last sub-phase. During the last sub-phase, the station will sense the channel for the maximum number of slots, and since no transmission of a burst will have occurred, it will transmit a priority assertion slot and then a burst of random length to eliminate any other node that might have had a packet with the same priority index.

The contention phase in DP-TB works as in EY-NPMA. However, during yield, a station, instead of randomly choosing an interval to backoff, will compute the duration of the backoff interval as:

$$Backoff\_Interval = \left\lfloor \frac{RL - q * t_p}{t_p} * (m_y + 1) \right\rfloor \tag{2}$$

where m_y is the maximum number of slots that a station may backoff during the yield phase. This ensures that if there is a successful transmission, the station that transmits is the one with the lowest residual lifetime among those who survived the elimination phase.

4.2. Overhead Reduction

The medium access protocol proposed, allows us to define a large number of priority levels by using a relatively small number of prioritization slots. When the length of the data payload is large, the added overhead of the prioritization phase in DP-TB can be alleviated by the lower collision rates. Indeed, as the number of the provided priority levels increases, the probability that two or more packets belong to the same priority class decreases. Consequently, not only a closer approximation to the ideal schedule can be achieved but, moreover, the collision rate is drastically reduced, as most of the time, very few (if more than one) packets will proceed to the elimination phase.

However, the above assumption does not hold true for short payloads. In [12] the authors examine the relationship between the payload size and efficiency of the EY-NPMA scheme and show that the increased overhead has an adverse impact on the throughput of the protocol for short payloads. In such scenarios, the time needed to transmit a control slot is a significant fraction of the time needed for the transmission of the actual payload. By optimally choosing the working parameters of EY-NPMA, the authors achieve a significant improvement in the utilization of the channel, despite an increase in the collision rate.

This problem is expected to severe in the proposed scheme, since DP-TB introduces extra overhead in the prioritization phase. Even, if all packets are transmitted at priority 0, the total duration of the prioritization phase in each access cycle cannot be made shorter than m slots, which is $m-1$ slots more than the minimum number of slots used in the prioritization phase of EY-NPMA. Nevertheless, by taking advantage of the broadcast nature of the wireless medium and the collisions of the priority assertion slots during the prioritization phase we show that the total overhead can be reduced.

During the prioritization phase, two or more stations may transmit a priority assertion slot simultaneously. This is more likely to happen in the first sub-phases, since the high number of priority levels in DP-TB ensures that the probability of two or more packets having the same priority is very small. Suppose that there is a simultaneous transmission of priority asserion slots in the $j^{'}$th slot of the first sub-phase. Then, the priority index of the stations that transmitted the burst can be computed to be in the range $[q^{'}_{min,} q^{'}_{max}]$:

$$q^{'}_{min} = (j^{'} - 1) \cdot \prod_{i=2}^{m} \alpha_i$$

$$q^{'}_{max} = j^{'} \cdot \prod_{i=2}^{m} \alpha_i$$

Proceeding to the next sub-phase another simultaneous transmission of priority assertion slots may occur in the $j^{''}$th slot, allowing the range $[q^{''}_{min,} q^{''}_{max}]$ of the priority index to be calculated with higher precision:

$$q^{''}_{min} = (j^{''} - 1) \cdot \prod_{i=3}^{m} \alpha_i + q^{'}_{min}$$

$$q^{''}_{max} = j^{''} \cdot \prod_{i=3}^{m} \alpha_i + q^{'}_{min}$$

This range will become shorter as long as simultaneous transmissions of priority assertion slots take place in the subsequent sub-phases.

Next assume that, during the kth channel access cycle, at least one simultaneous transmission of priority assertion slots takes place in the prioritization phase. This means that there is at least one station i

with a packet, other than the one that will be transmitted (if no collision occurs), that will be eligible for transmission at the start of the $(k+1)$th channel access cycle and whose priority index is in the range $[q_{min}^{i,k}, q_{max}^{i,k}]$. At the beginning of the $(k+1)$th channel access cycle, the priority level of this packet will have increased and all stations can compute it to be in the range $[q_{min}^{i,k+1}, q_{max}^{i,k+1}]$. If $q_{min}^{i,k+1} \geq 0$, the residual lifetime of the packet will not have expired and the packet will surely contend for channel access. In this case, all stations compute the set of parameters $\{p_1^{i,k+1}, \ldots, p_m^{i,k+1}\}$ that correspond to $q_{max}^{i,k+1}$.

Suppose that $p_1^{i,k+1}$ is equal to 0 and that, during the kth access cycle, station j generated a packet that is eligible for transmission at the start of the $(k+1)$th cycle and whose priority index is $q^{j,k+1} \leq q_{max}^{i,k+1}$. Both stations will transmit a priority assertion slot in the first slot of the first sub-phase, since both of them compute the value of parameters $p_1^{i,k+1}$ and $p_1^{j,k+1}$ equal to 0. It is evident that, if all stations know that at least one station (station i) will transmit a priority assertion slot in the first slot of the first sub-phase, this sub-phase cannot help to resolve the priorities of contending packets since it will not cause lower priority packets to defer access. Thus, if $p_1^{i,k+1}$ is equal to 0, the first sub-phase can be omitted, reducing the overhead introduced by the prioritization phase by 1 slot. In the same manner, the second sub-phase can be omitted if $p_1^{i,k+1} = 0$ and $p_2^{i,k+1} = 0$, reducing the overhead by one more slot. A maximum of $m-1$ sub-phases can be omitted if $\{p_1^{i,k+1}, \ldots, p_{m-1}^{i,k+1}\} = 0$, reducing to the maximum degree the overhead introduced by the prioritization phase.

4.3. Theoretical Analysis

The theoretical analysis of DP-TB aims at developing a simple analytical model to calculate the average medium utilization and the probability of correct scheduling achieved by the proposed protocol. In [12], an analytival model is presented to compute the mean medium utilization of EY-NPMA as a function of the number of contending stations (N) and the triplet $\{m_{es}, m_{ys}, p_e\}$. However, it is assumed that all nodes contending for channel access belong to the same priority level. We extend this analysis to derive the average medium utilization and the probability of correct scheduling of DP-TB as a function of the contending population N, the triplet $\{m_{es}, m_{ys}, p_e\}$, the number of sub-phases of DP-TB (m) and the number of slots α_i allocated to each sub-phase i. The probability of correct scheduling is the probability that the transmitted packet in a given channel access cycle is the one with the smallest residual lifetime among all packets that contended for channel access in this access cycle. It should be noted that, the computation of the probability of correct scheduling takes into account all channel access cycles; both those with a successful transmission and those where a collision takes place. Consequently, when a collision occurs, it is assumed that the proposed scheme did not make the correct scheduling decision. Our analysis adopts the assumption made in [12] and [15] that each stations has always a packet to transmit and the assumption of [15] that the priority indices of stations are uniformly distributed in the range $[0, Q-1]$.

Since the priority indices of contending stations are uniformly distributed between 0 and $Q-1$, the probability that the priority level of a station is q is equal to:

$$P_P(q) = \frac{1}{Q} \tag{3}$$

The probability that the priority level of a station is q or lower can be derived from the previous equation:

$$P'_P(q) = \sum_{i=q}^{Q-1} P_P(i) = \frac{Q-q}{Q} \tag{4}$$

The probability that the priority level of the highest priority station(s) is q is equal to the probablity that the priority level of all stations is q or less and the priority index of at least one station is exactly q.

$$P_{PD}(q) = \begin{cases} P'_P(q)^N - P'_P(q+1)^N, & 0 \leq q < Q-1 \\ (\frac{1}{Q})^N, & q = Q-1 \end{cases} \tag{5}$$

Given the prioity index q of the highest priority station(s) we can calculate the duration $D(q)$ in slots of the prioritization phase:

$$D(q) = \{\sum_{i=1}^{m} p_i, \text{ such that } \sum_{i=1}^{m-1} [p_i \cdot \prod_{j=i+1}^{m} \alpha_i] + p_m = q\} \tag{6}$$

The average length in slots of the prioritization phase can then be easily derived:

$$\overline{L_P} = \sum_{q=0}^{Q-1} D(q) \cdot P_{PD}(q) \tag{7}$$

Equations (3) and (4) can be combined to derive the probability that n stations, which belong to the highest priority class q, survive the prioritization phase:

$$P_{nq\_P}(n,q) = \begin{cases} \binom{N}{n} P_P(q)^n P'_P(q+1)^{N-n}, & q < Q-1 \\ (\frac{1}{Q})^N, & q = Q-1, n = N \\ 0, & q = Q-1, n < N \end{cases} \tag{8}$$

Summing up $P_{nq\_P}(n,q)$ for all possible values of q, we can calculate the possibility of having n stations proceed to the elimination phase, regardless of their priority level.

$$P_{n\_P}(n) = \sum_{q=0}^{Q-1} P_{nq\_P}(n,q) \tag{9}$$

All stations that survived the prioritization phase, transmit a channel access burst, whose length in slots is random between 0 and a predefined maximum m_{es}, according to a truncated geometric distribution. The probability $P_E(k)$ that a station bursts for exactly k slots and the probability $P'_E(k)$ that a station bursts for k slots or less are given by the following equations:

$$P_E(k) = \begin{cases} p_e^k(1-p_e), & 0 \le k < m_{es} \\ p_e^{m_{es}}, & k = m_{es} \end{cases} \tag{10}$$

$$P'_E(k) = \sum_{i=0}^{k} P_E(i) = \begin{cases} 1-p_e^{k+1}, & 0 \le k < m_{es} \\ 1, & k = m_{es} \end{cases} \tag{11}$$

Given that N_E stations survive the prioritization phase, the probability that the elimination phase lasts k slots is equal to:

$$P_{ED}(k,N_E) = \begin{cases} (1-p_e)^{N_E}, & k = 0 \\ P'_E(k)^{N_E} - P'_E(k-1)^{N_E}, & 0 < k \le m_{es} \end{cases} \tag{12}$$

while its mean length in slots is equal to:

$$\overline{L_E} = \sum_{N_E=1}^{N} \Big[P_{n\_P}(N_E) \cdot \sum_{k=0}^{m_{es}} k \cdot P_{ED}(k,N_E) \Big] \tag{13}$$

If N_E stations enter the elimination phase, the probability that it lasts k slots and n stations survive elimination is given by the following relation:

$$P_{nkN_E\_E}(n,k,N_E) = \begin{cases} \binom{N_E}{n} P_E(k)^n P'_E(k-1)^{N_E-n}, & 0 < k \le m_{es} \\ (1-p_e)^{N_E}, & k = 0, n = N_E \\ 0, & k = 0, n < N_E \end{cases} \tag{14}$$

The probability that n stations survive the elimination phase, regardless of its length and the number of stations N_E surviving the prriroritization phase is:

$$P_{n\_E}(n) = \sum_{N_E=n}^{N} P_{n\_P}(N_E) \cdot \Big[\sum_{k=0}^{m_{es}} P_{nkN_E\_E}(n,k,N_E) \Big] \tag{15}$$

All stations that survived elimination back off for a random number of l slots with probability:

$$P_Y(l) = \frac{1}{m_{ys}+1} \tag{16}$$

where m_{ys} is the maximum number of slots that a station can back off. The probability that a station backs off for at least l slots is:

$$P'_Y(l) = \sum_{i=l}^{m_{ys}} P_Y(i) = \frac{m_{ys}-l+1}{m_{ys}+1} \tag{17}$$

If N_Y stations survive elimination, the probability $P_{YD}(l, N_Y)$ that the yield phase lasts l slots can be used to derive its average length $\overline{L_Y}$:

$$P_{YD}(l, N_Y) = \begin{cases} P'_Y(l)^{N_Y} - P'_Y(l+1)^{N_Y}, & 0 \le l < m_{ys} \\ (\frac{1}{m_{ys}+1})^{N_Y}, & l = m_{ys} \end{cases} \tag{18}$$

$$\overline{L_Y} = \sum_{N_Y=1}^{N} \Big[P_{n\_E}(N_Y) \cdot \sum_{l=0}^{m_{ys}} l \cdot P_{YD}(l, N_Y) \Big] \tag{19}$$

Given that N_Y stations enter the yield phase, the probability that n stations transmit a packet after sensing the channel for the minimum number l of slots is equal to:

$$P_{nlN_Y\_Y}(n, l, N_Y) = \begin{cases} \binom{N_Y}{n} P_Y(l)^n P'_Y(l+1)^{N_Y-n}, & 0 \le l < m_{ys} \\ (\frac{1}{m_{ys}+1})^{N_Y}, & l = m_{ys}, n = N_Y \\ 0, & l = m_{ys}, n < N_Y \end{cases} \tag{20}$$

Analogously to equation (15), the probability that n stations tarnsmit a packet, regardless of the length of the yield phase and the number of stations N_Y that survived the elimination phase, is:

$$P_{n\_Y}(n) = \sum_{N_Y=n}^{N} P_{n\_E}(N_Y) \cdot \Big[\sum_{l=0}^{m_{ys}} P_{nlN_Y\_Y}(n, l, N_Y) \Big] \tag{21}$$

Equations (7),(13) and(19) can be used to calulate the average length $\overline{L_{cycle}}$ of a channel access cycle of DP-TB. Table I provides an overview of the constants that represent the overhead of the protocol.

$$\overline{L_{cycle}} = i_{cs} + \overline{L_P} \cdot i_{PS} + m \cdot i_{PA} + \overline{L_E} \cdot i_{ES} + i_{ESV} + \\ + \overline{L_Y} \cdot i_{YS} + i_{SYN} + L_{pck} + i_{AK} + i_{ACK} \tag{22}$$

Combined with the probability $P_{n\_Y}(1)$ that no collision occurs, the previous equation can be used to derive the average medium utilization of DP-TB.

$$MediumUtilization = \frac{L_{pck}}{\overline{L_{cycle}}} \cdot P_{n\_Y}(1) \tag{23}$$

Table I. Operating parameter settings

Parameter	Value (bits)	Description
i_{CS}	256	channel synchronization interval
i_{PS}	168	size of prirorítization slots
i_{PA}	168	size of prirority assertion slots
i_{ES}	212	size of burst slots
i_{ESV}	256	elimination survival verification interval
i_{YS}	168	size of yield slots
i_{SYN}	450	synchronization bits
L_{pck}	max: 2383	packet length
i_{AK}	512	interval preceeding the transmission of an ACK
i_{ACK}	368	size of ACK

In order to calculate the probability of correct scheduling achieved by DP-TB, we must first find the probability that the station with the packet that has the smallest residual lifetime will survive the contention phase. It should be noted that the prioritization phase ensures that this station will always proceed to the elimination phase. For a given number of stations entering the elimination phase, N_E, the probability that the station with the smallest residual lifetime survives elimination is:

$$P_{SE}(N_E) = \begin{cases} 1, & N_E = 1 \\ \sum_{n=1}^{N_E} [\frac{n}{N_E} P_{nN_E\_E}(n, N_E)], & N_E > 1 \end{cases} \quad (24)$$

By summing up $P_{SE}(N_E)$ for all possible values of N_E, we can derive the probability that this station survives elimination regardless of the number of nodes entering contention.

$$P'_{SE} = \sum_{N_E=1}^{N} P_{n\_P}(N_E) \cdot P_{SE}(N_E) \quad (25)$$

The yield phase of DP-TB ensures that if the station with the smallest residual lifetime survives the elimination phase and no collison occurs, then the transmitted packet will be the one with the smallest residual lifetime. Thus, the probability of correct scheduling can be easily computed as:

$$P_{CorrectScheduling} = P'_{SE} \cdot P_{n\_Y}(1) \quad (26)$$

5. Protocol Evaluation

The experiments conducted in this work aim at evaluating the performance of the proposed medium access scheme, as well as comparing it to the base EY-NPMA protocol. The performance metrics of interest are average medium utilization and probability of correct scheduling. The ability of the proposed scheme to approximate an ideal EDF scheduler while preserving high medium utilization is evaluated. Its performance is compared to the base EY-NPMA. The working parameters of EY-NPMA are set both to the values defined in the HIPERLAN standard and to the optimum ones. In [12] an exhaustive search is conducted in the parameters space, to find the optimal triplet $\{m_{es}, m_y, p_e\}$ that maximizes the throughput of EY-NPMA for different packet sizes and station populations. We will refer to EY-NPMA as EY-NPMA $\{m_{es}, m_y, p_e\}$ when its working parameters are other than the ones specified in the standard.

5.1. Analytical Results

Through analytical results, we study the performance of DP-TB when designed to provide 3125 priority levels, by subdividing the prioritization phase in 5 sub-phases and allocating a maximum of 5 slots to each sub-phase, and when designed to support 625 priority levels, by subdividing the prioritization phase in 4 sub-phases and allocating a maximum of 5 slots to each sub-phase. The triplet $\{m_{es}, m_y, p_e\}$ was set to $\{2, 2, 0.3\}$ in each case. The optimum working parameters for EY-NPMA are $\{4, 9, 0.4\}$. The residual lifetimes of contending packets are assumed to be uniformly distributed in the interval [0, 500 ms]. Consequently, in the case of EY-NPMA, packets may belong to any of the five priority classes and not only to one priority class as assumed in previous studies. The channel capacity was set to 23.5 Mbps, while the values of the constants that add to the overhead of the two protocols can be found in Table I. The medium utilization achieved by each scheme and its ability to make the correct scheduling decision are examined for different network populations and packet lengths (2383 and 128 bytes). As it has been mentioned, for large packet sizes the throughput of each protocol is mainly affected by its collision rate, while for small packet lengths the dominant factor becomes the overhead.

In terms of medium utilization, DP-TB with 625 priority levels performs better than EY-NPMA when the size of packets is set to 2383 bytes. As illustrated in Figure 2, the medium utilization curves of both schemes exhibit a decreasing trend, which is owed to their increasing collision rate. The decrease is more rapid for EY-NPMA,

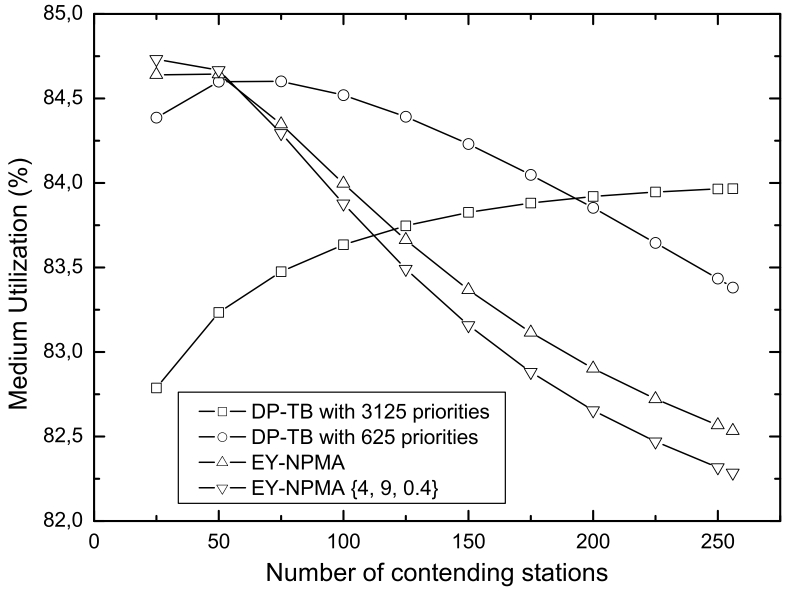

Figure 2. Medium utilization vs. number of contending stations for 2383 bytes packet size

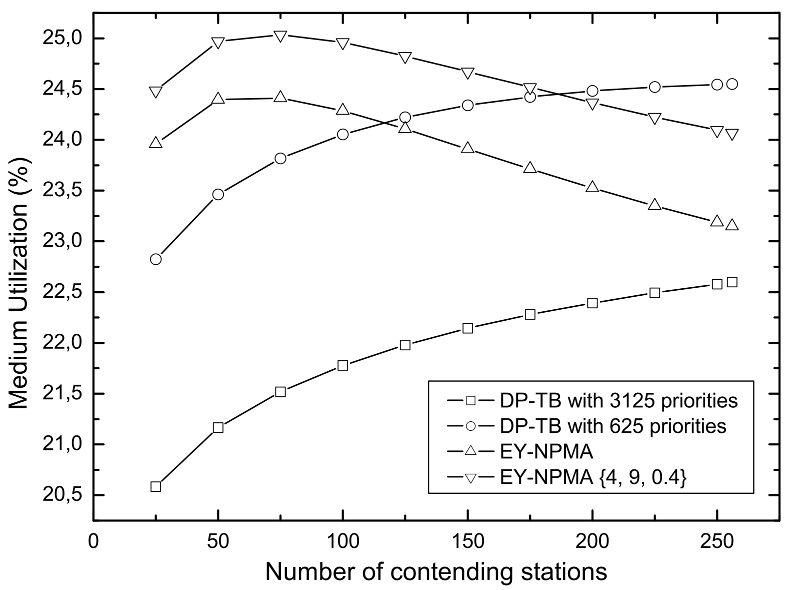

Figure 3. Medium utilization vs. number of contending stations for 128 bytes packet size

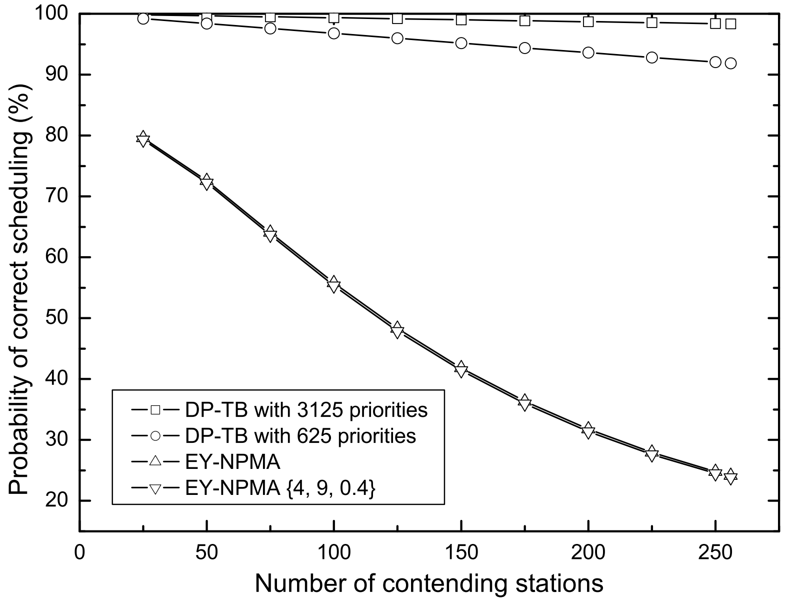

Figure 4. Probability of correct scheduling vs. number of contending stations

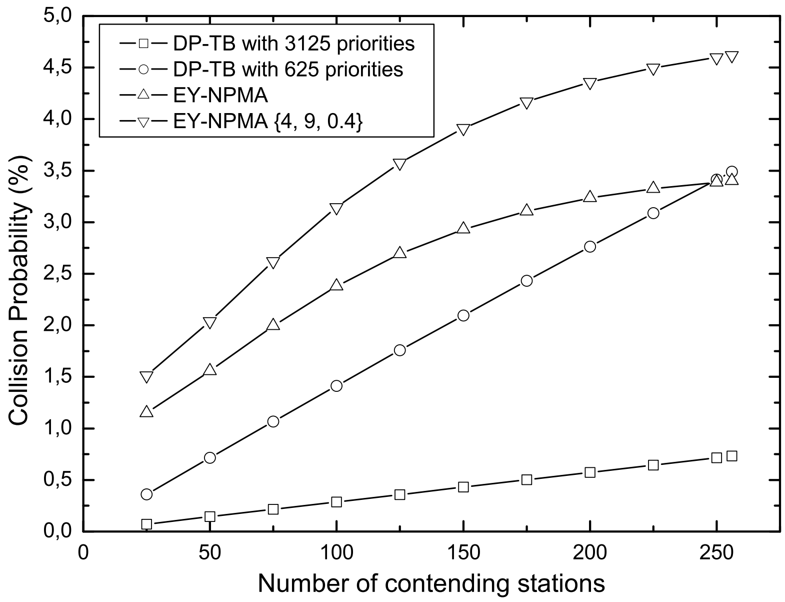

Figure 5. Collision probability vs. number of contending stations

since it exhibits a higher collision probability, as can be seen in Figure 5. Moreover, for large network populations, the overhead of EY-NPMA slightly increases, while the overhead of DP-TB has a decreasing trend regardless of how many priority levels it is designed to support. Consequently, for a large number of contending stations DP-TB benefits from both its lower overhead and lower collision probability compared to EY-NPMA. The increase in the overhead of EY-NPMA, when the number of contending stations is large, is accounted to the increase in the number of slots that are used during the elimination phase. DP-TB with 3125 priority levels, suffering from its large overhead, exhibits lower throughput than EY-NPMA when the number of contending stations is low to medium. However, when the number of contending nodes increases, its overhead is significantly reduced. For medium to large network populations, the reduction in the number of slots used during its prioritization phase combined with its low collision probability allows DP-TB with 3125 priority levels to achieve high efficiency. Moreover, it can be noticed that for large packet sizes the parameters of EY-NPMA are well chosen. EY-NPMA$\{4, 9, 0.4\}$ has slightly better performance than EY-NPMA only when the number of contending stations is small (less than 50).

In Figure 3 the mean medium utilization of each scheme for 128 bytes packet size is presented. For small network populations, EY-NPMA and EY-NPMA$\{4, 9, 0.4\}$ have the highest throughput, by taking advantage of their lower overhead compared to DP-TB. As it has been mentioned, when the packet size is small, the overhead is the dominant factor that affects the protocols' efficiency. It is the low overhead that allows EY-NPMA$\{4, 9, 0.4\}$ to retain its efficiency for medium network populations as well. However, when the number of contending stations is large, both EY-NPMA and EY-NPMA$\{4, 9, 0.4\}$ are outperformed by DP-TB with 625 priorities. In this case, DP-TB benefits from both its lower collision probability and its reduced overhead to achieve higher throughput. It should be mentioned that, for 256 contending stations, the overhead of DP-TB is lower than that of EY-NPMA$\{4, 9, 0.4\}$. This phenomenon is accounted to the fact that the overhead introduced by the prioritization phase of DP-TB decreases as the number of contending stations increases, while the number of slots used during contention remains quasi-constant. On the other hand, EY-NPMA uses more slots during elimination, when the number of contending nodes increases, and so its overhead is slightly increased. DP-TB with 3125 priority levels has the lowest throughput of all scemes. Despite the fact that the collision rate of this scheme is extremely low, its high overhead restrains it from achieveing high utilization.

The probability of correct scheduling is independent of the packet size. Figure 4 makes evident the efficiency of DP-TB in approximating an ideal EDF scheduler. Even when 256 nodes contend to gain channel access, the probability of correct scheduling of DP-TB with 625 priority levels is higher than 91%, while EY-NPMA and EY-NPMA$\{4, 9, 0.4\}$ fail to make the correct scheduling decision. As expected, DP-TB with 3125 priority levels exhibits the highest probability that the transmitted packets is the one with the lowest residual lifetime. The probability of correct scheduling of DP-TB with 3125 priority levels is higher than 98%, for any network population.

Analytical results show that DP-TB can closely approximate an ideal EDF scheduler, while achieving high medium utilization. Moreover, in practice, the throughput achieved by DP-TB is expected to be even better than that of EY-NPMA, since the assumptions made in the theoretical analysis of the proposed scheme differ from reality in two ways. First, the analytical model assumes that no packets are lost due to lifetime expiration. Consequently, the computation of the mean medium utilization of EY-NPMA and DP-TB did not account for discarded packets. However, in realistic scenarios, packets whose deadline expires will be lost, having an adverse impact on the medium utilization achieved by DP-TB and EY-NPMA. Their number is expected to be larger in the case of EY-NPMA. The inability of EY-NPMA to make the correct scheduling decision will result in an increased number of lost packets compared to DP-TB.

Second, the theoretical analysis of DP-TB assumes that the priority indices of contending stations are uniformly distributed in the range [0, Q-1], but does not take into account the fact that the priority level of competing packets is updated at the start of each access cycle. Consequently, when the number of contending stations is small, the probability that packets are transmitted at the highest priority level is low. Most of the time, the priority index of competing packets will be medium to low, requiring a high number of slots for priority resolution. For small network populations, the large overhead of the prioritization phase of DP-TB will restrain it from achieving high medium utilization. However, in realistic scenarios, where the priority of packets will be dynamically updated, the overhead introduced by the prioritization phase of DP-TB will depend on the offered load rather than on the number of contending stations. Under low traffic conditions, most of the packets will be transmitted at lower priority levels. Nevertheless, the large overhead required for priority resolution will not adversely affect the mean utilization achieved by DP-TB. For medium to high traffic load, packets will gain access to the common medium at the highest priority levels, reducing significantly the overhead introduced by the prioritization phase and allowing DP-TB to achieve high throughput. Moreover, the overhead reduction mechanism of DP-TB will decrease even further the overhead of the proposed scheme.

5.2. Simulation Experiments

5.2.1. *Simulation Environment*

The tool that was used for the simulation experiments was customly coded by the authors in C++. Regarding the physical channel, the capacity of the common medium was set to 23.5 Mbps and was considered to be ideal, that is the only reason behind erroneous reception was the simultaneous transmission of more than one stations (packet collision). Furthermore, all network stations were within one hop from each other, eliminating thus the appearance of hidden/exposed terminals.

Each station initiates a video stream with QoS requirements, which are expressed in terms of a maximum allowable delay. Video applications exhibit high variability in the frame sizes and bit rates, especially for low-quality encodings and, as they require stringent delay guarantees, they are expected to benefit significantly from a medium access scheme capable of providing time-bounded services. Moreover, encoded video traffic is expected to account for large portions of the traffic in future wireline and wireless networks. Upon its arrival, each packet is assigned a lifetime which is equal to the delay budget associated with the flow that it belongs to. The residual lifetime of a packet is then used to compute its priority level. Packets that cannot be delivered within the allocated lifetime are discarded.

To better approximate compressed video traffic, real frame sizes of H.263 encoded video were used. The video frame traces were from a sport event, namely the final match of the 1996 European football championship and can be found in [19] and [20]. The bit rate of the encoder output for this video sequence is 64 kb/s, its peak to mean bit rate ratio is equal to 6 and the peak to mean frame size is equal to 5.13. The maximum packet size was set to 2383 bytes, as defined in the HIPERLAN standard [16].

5.2.2. *Simulation Results*

Two sets of experiments were performed. Each station is assumed to initiate one video stream. The performance metrics were examined for different node populations (1-256 stations). In the first set of simulations, the delay requirements of video flows are looser as they are distributed over a wider range. Each newly generated flow has a delay budget, which is uniformly distributed in the interval [0.5 ms, 500 ms].

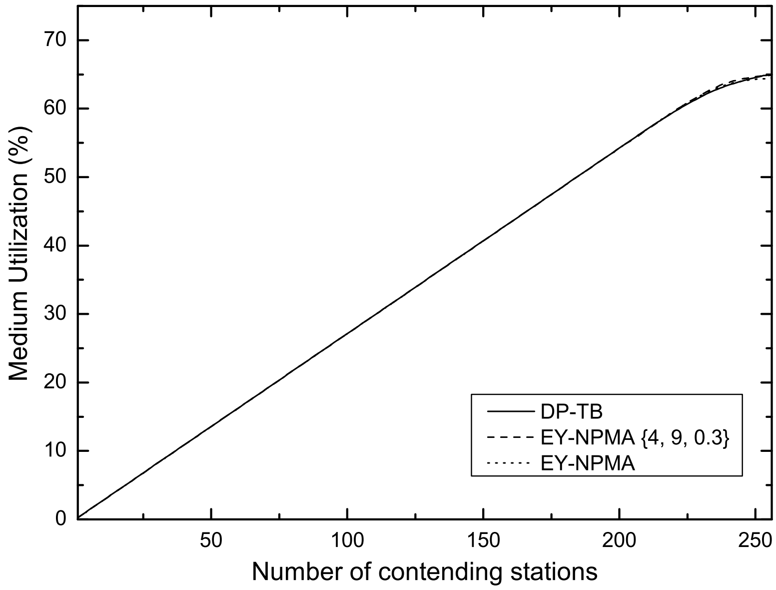

Figure 6. Scenario 1: Medium utilization vs. number of contending stations

Upon an arrival of a new packet, the residual lifetime assigned to it is equal to the delay requirement of the flow that it belongs to.

The optimum working parameters for EY-NPMA were found to be {4, 9, 0.3}, which are close to the values indicated by the theoretical analysis of EY-NPMA. DP-TB supports 3125 priority levels, by sub-dividing the prioritization phase in 5 sub-phases and allocating a maximum of 5 slots to each sub-phase. The triplet $\{m_{es}, m_y, p_e\}$ was set to $\{5, 3, 0.5\}$ for DP-TB.

In Figure 6 the mean medium utilization achieved by each scheme is presented. All of the three schemes have the same throughput under any traffic load. However, the mechanisms behind each scheme that allow them to achieve high efficiency differ, as they correspond to a different option in the tradeoff between the collision rate and the introduced overhead. While EY-NPMA{4, 9, 0.3} and EY-NPMA exhibit high collison rates, DP-TB does not suffer from any collisions when the number of contending nodes is 188 or less, as shown in Figure 8. The optimized version of EY-NPMA has the highest collision probability, as it uses a low number of slots during the contention phase and a lower probability that a station continues bursting during the elimination phase. Nevertheless, its reduced overhead allows it to achieve the same level of utilization with EY-NPMA. EY-NPMA makes use of more slots

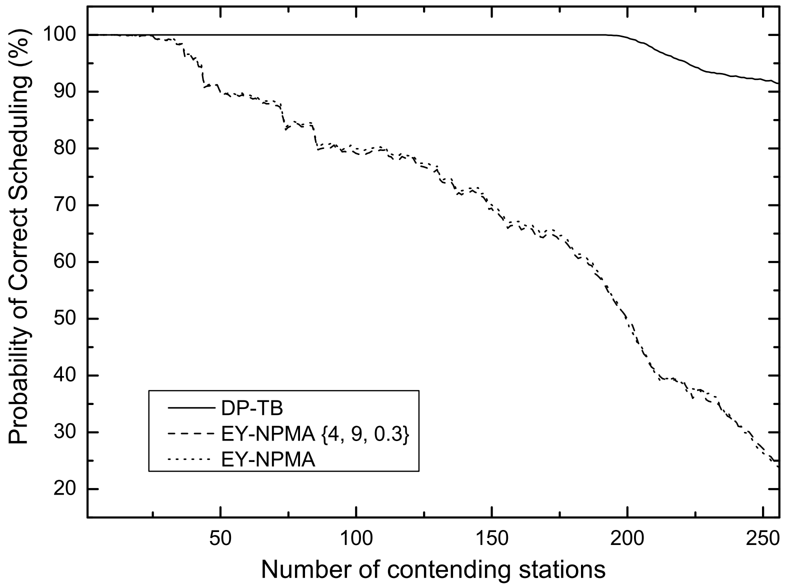

Figure 7. Scenario 1: Probability of correct scheduling vs. number of contending stations

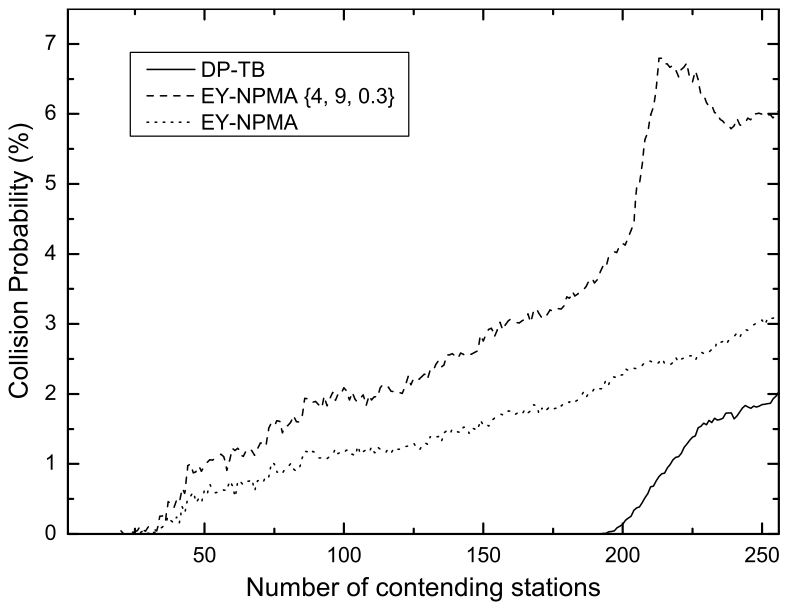

Figure 8. Scenario 1: Collision probability vs. number of contending stations

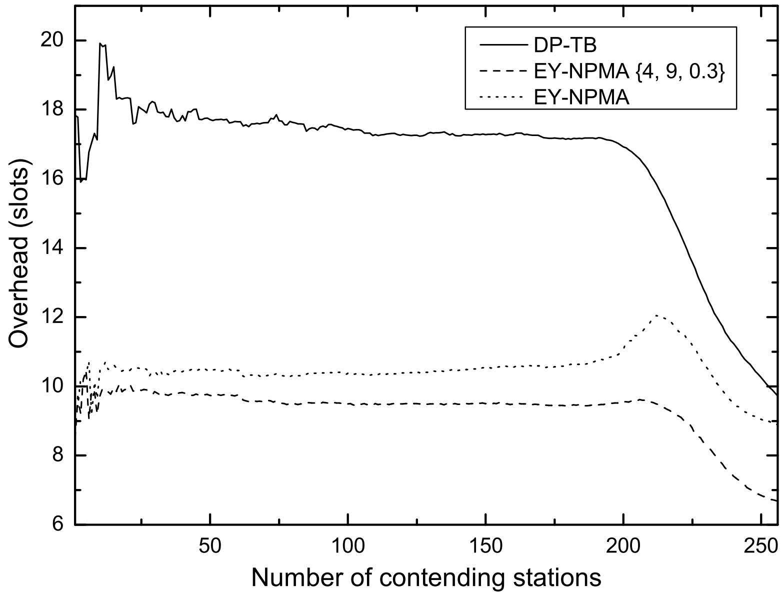

Figure 9. Scenario 1: Overhead vs. number of contending stations

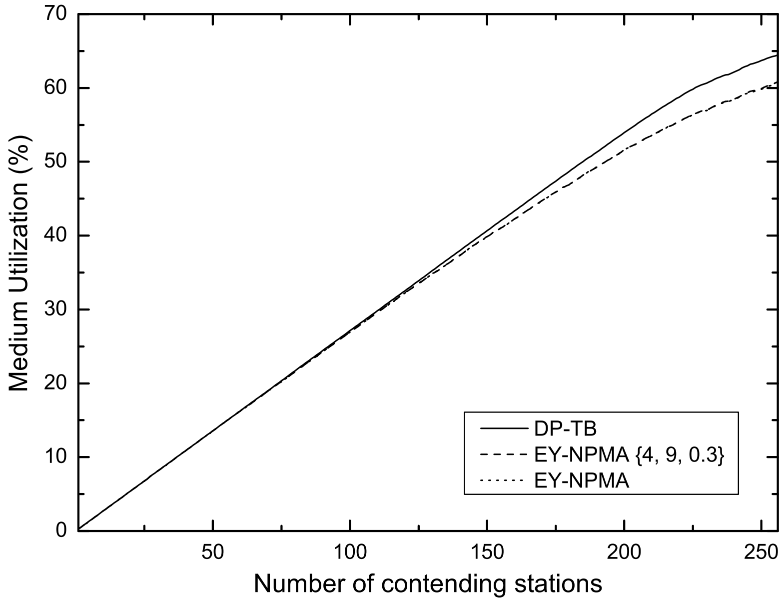

Figure 10. Scenario 2: Utilization vs. number of contending stations

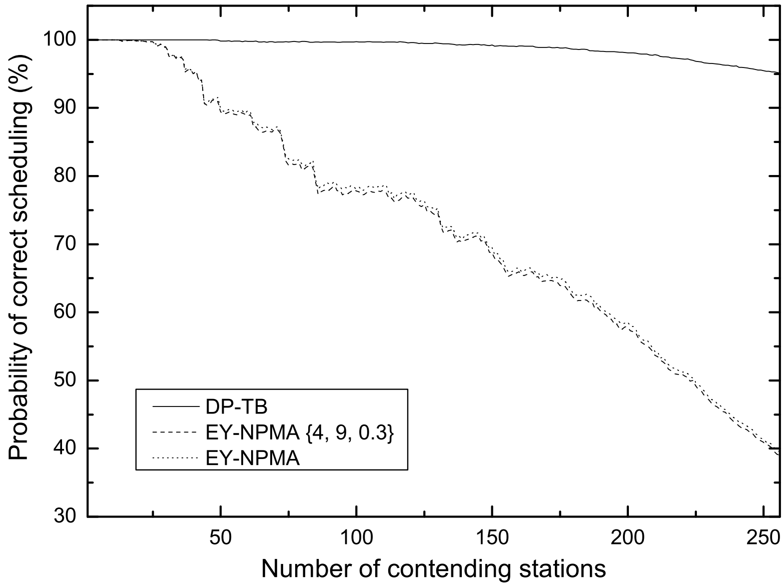

Figure 11. Scenario 2: Probability of correct scheduling vs. number of contending nodes

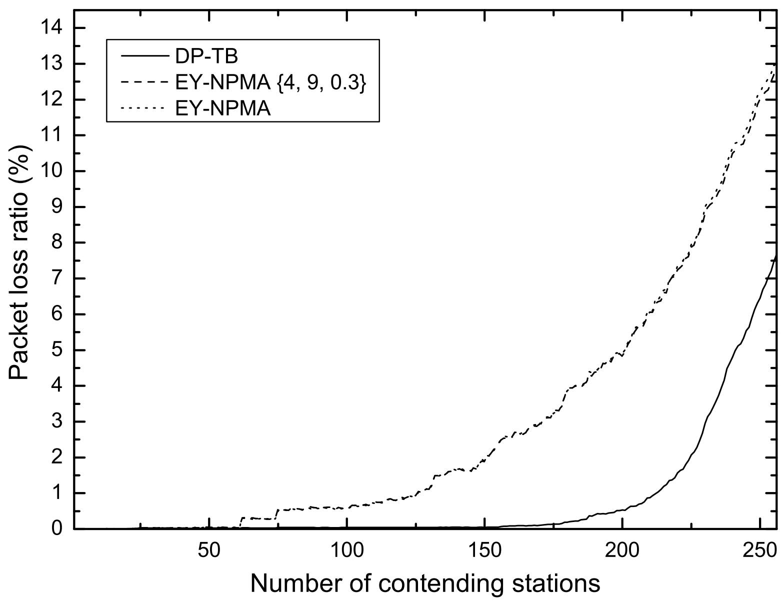

Figure 12. Scenario 2: Packet loss probability vs. number of contending stations

during contention, but the extra overhead is alleviated by its lower collision rate.

DP-TB exhibits much higher overhead. However, the introduced overhead is drastically reduced as traffic load increases. Under low traffic conditions, packets with long deadline are transmitted shortly after they are generated, at low priority levels, requring a high number of slots for priority resolution. As traffic load increases, packets are transmitted at higher priority levels, just before their lifetime expires, making use of a much smaller number of prirorization slots to resolve their prirorities. Moreover, the overhead reduction mechanism allows DP-TB to respond even faster to an increase in the offered load. As it is shown in Figure 9, for the maximum number of contending stations, the overhead of DP-TB approaches the overhead exhibited by EY-NPMA.

In terms of probability of correct scheduling, DP-TB outperforms EY-NPMA{4, 9, 0.3} and EY-NPMA for any number of contending stations. Figure 7 shows that, the proposed protocol makes the correct scheduling decision for any population of contending nodes in the range [1-146] and the probability of correct scheduling is higher than 91% even for the maximum number of contending stations. On the other hand, the probability of correct scheduling of EY-NPMA and its optimized version decreases as the number of contending nodes increases, and for 256 contending stations it is lower than 25%. It should be noted that, even though Optimized EY-NPMA exhibits higher collision rate, its ability to make the correct scheduling decision is not inferior to that of EY-NPMA.

In the second set of simulation experiments, the QoS requirements are more stringent, since the target delay of each contending station is uniformly distributed in the interval [0.5 ms, 10 ms]. Considering that wireless access is just another hop in a heterogeneous communication path that provides end-to-end delay guarantees, the delay budget of a flow at each node along the path will be small. The working parameters of each protocol were set to the values used in the first scenario.

As illustrated in Figure 10, DP-TB and EY-NPMA have the same throughput under low load conditions. However, as the number of contending stations increases the superiority of DP-TB becomes evident. The medium utilization achieved by DP-TB is higher than that of EY-NPMA. For the maximum number of contending stations, the throughput of DP-TB is 6.5% better, regardless of the values that the triplet $\{m_{es}, m_y, p_e\}$ of EY-NPMA is set to. The increased medium utilization of DP-TB is primarily owed to its ability to closely approximate an ideal EDF schedule.

As it has been mentioned, DP-TB approximates an ideal EDF scheduler by supporting a high number of priority levels. Although this is accomplished by introducing extra overhead, its low collision rate and its ability to make the correct scheduling decision have a positive impact on its efficiency. The probability of correct scheduling of DP-TB is higher than 95%, for any number of contending stations, while EY-NPMA struggles to make the correct scheduling decision, as shown in Figure 11. In this way, DP-TB ensures that packets with short deadline are transmitted first before packets with a longer deadline, minimizing the number of packets that are lost due to incorrect scheduling.

The packet loss ratio is a significant metric of the ability of each scheme to provide service assurances, since the QoS requirements of most applications are expressed in terms of both maximum allowable delay and packet loss. In Figure 12, the packet loss probability of each scheme is presented. Given that the mean packet loss ratio should not exceed a predefined threshold, we can define the maximum number of video sessions that could potentially be admitted by each protocol. DP-TB exhibits no packet loss when the number of contending stations is less than 23 and the probability that it loses packets remains close to 0 for as many as 150 stations. On the other hand, EY-NPMA suffers from its inability to make the correct scheduling decision. When the number of contending stations exceeds 13, EY-NPMA starts losing packets and the portion of lost packets increases significantly for medium and large contending populations. DP-TB can accept 69% more flows than EY-NPMA while ensuring that no packets are lost. This result is rather significant, since many time-bounded applications (telemetry, telnet, interactive games, transaction services) require that no packets are lost. On the other hand, video applications can tolerate a small amount of lost packets without the quality perceived by end users being affected. 3GPP defines that the performance of real-time video applications will not be harmed as long as their packet loss ratio remains below 1%, while video streaming applications can tolerate 2% of their packets being lost [21]. In the first case, DP-TB could admit 70% more sessions than EY-NPMA (213 to 125 admissible sessions), while in the second case the admissible region of DP-TB would be 49% better than that of EY-NPMA (224 to 150 admissible sessions). Moreover, it should be noted that the packet loss probability of DP-TB remains quasi-constant irrespective of the interval in which the stations' target delays are distributed, while EY-NPMA loses much more packets when the delay requirements of the competing flows are tight.

6. Conclusions

In this work, we have proposed and evaluated the performance of a distributed dynamic priority medium access scheme to support time-bounded services in wireless networks. The mechanisms behind the proposed protocol that allow it to achieve better performance rely on the approximation of an ideal EDF scheduler. By closely approximating an ideal EDF scheduler we are able to mimize the number of packets that are lost due to incorrect scheduling and eventually achieve high medium utilization. The proposed scheme makes the correct scheduling decision even under high traffic conditions. The good characteristics of the proposed scheme were confirmed via anlytical studies and simulation experiments, where significant gains in performance were witnessed.

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