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Two Alternative Schemes to EY-NPMA for Medium Access in High Bitrate Wireless LANs

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Abstract. The growing penetration of WLANs in the market, as well as the wider spectrum of applications that these kinds of networks are called to support, demands the introduction of new methods for efficient medium access. Today, the two dominating paradigms in medium access control are those of dynamic assignment and contention based ones. EY-NPMA is a contention based scheme that exhibits very low collision rates, while being quality of service aware. In this paper, we propose a solution to the highly criticised drawback of the EY-NPMA protocol – the increased overhead. Towards this end, we propose and evaluate the performance of two medium access schemes that are based on EY-NPMA and compare them to the base protocol. The theoretical analysis of the proposed schemes shows that they make better utilization of the common medium. It also allows us to determine the optimal working parameters for each one. Furthermore, extended simulation trials validate these results and confirm the good characteristics of the proposed protocols.

Keywords: EY-NPMA, medium access, wireless LANs.

1. Introduction

Wireless LANs provide an efficient and inexpensive way for the creation of networks that do not constrain the users' mobility. Spontaneous, hassle free communication has become possible through ad hoc networks, while infrastructure based wireless LANs have permitted true flexibility and freedom without demanding installation of new cables or retrofitting. Furthermore, advanced physical layer techniques have allowed wireless LANs to support bitrates that until recently were attainable only in their wired counterparts. The growing penetration of WLANs in the market, as well as the wider spectrum of applications that these kinds of networks are called to support, demands the introduction of new methods for efficient medium access, since it is the MAC which defines how efficiently the available raw bandwidth is used.

A medium access scheme must possess a number of characteristics in order to be an efficient one. It must ensure that the common medium is fairly shared between the stations that comprise the network, provide explicit quality of service (QoS) guarantees for different classes of traffic and finally maximize the medium utilization by minimizing the wasted capacity that is caused by packet collisions and/or overhead. Furthermore, all of the above should be implemented in a design that is both robust and simple. In the field of wireless LANs, there are two dominating families of protocols for medium access. The first one includes those that are based on the paradigm of dynamic assignment, while the other includes the protocols that are based on contention. A more thorough survey on medium access schemes for wireless LANs is provided in [7].

Medium access schemes following the dynamic assignment approach gain access to the common medium either via an arbitrator (e.g. a terminal that polls each station in a round-robin fashion) or through a well-defined process that ensures that only one terminal at a time has permission to gain access to the channel (e.g. reservation or token passing schemes). With dynamic assignment schemes there is usually a need for a management entity, undertaking the role of polling, creating tokens when they get lost and validating reservations. In infrastructure based wireless LANs, the access point (AP) is the obvious candidate for such a role, but in ad hoc networks a station is dynamically chosen to become channel coordinator, usually through clustering techniques. The election of an ordinary station to take up the role of coordinator, however, poses important issues regarding fairness in terms of energy consumption: to fulfill its duties as a coordinator, a station spends valuable resources (battery charge) without actually transmitting or receiving data.

The performance of dynamic assignment protocols scales very well as the traffic load increases, while the deterministic access to the channel inherently provides quality of service support. On the other hand, the fact that each station must explicitly acquire access permission (i.e. get polled or capture the token), introduces a latency that is mostly notable in cases of light traffic, while traffic load asymmetries tend to deteriorate the performance of these protocols. Also, the hidden terminal problem [16] proves to be more difficult to alleviate in dynamic assignment protocols, rather than in contention based ones. Protocols that follow the dynamic assignment paradigm are PRMA (Packet Reservation Multiple Access) [6], the medium access layers of the HIPERLAN/2 [5] and Bluetooth [14] standard, as well as the PCF (Point Coordination Function) access mode of the IEEE 802.11 standard [8].

Contention based medium access schemes represent a paradigm that has been traditionally connected with Local Area Networks (mostly because of the widespread deployment of IEEE 802.3 – Ethernet). According to protocols belonging to this family, packet transmissions take place in a completely stochastic way, with minimal or totally absent coordination between the stations participating in the network. Consequently, there exists a probability that multiple transmissions take place simultaneously, resulting in erroneous reception. To reduce such occurences, the concept of carrier sensing is widely employed, since it prevents network stations from transmitting, when they sense that a transmission is already in progress. For technical reasons, the variant of carrier sensing that uses collision detection (CSMA/CD) cannot be applied in wireless networks, so the technique of collision avoidance (CSMA/CA) is used instead. Also, a handshake before the actual data transmission can reduce the impact of collisions, as initially proposed by Karn in [10]. According to this scheme, packet collisions are restricted only between small Request-To-Send, Clear-To-Send packets (RTS/CTS), while the actual data packets are transmitted collision-free. Furthermore, this handshake between transmitter and receiver effectively mitigates the hidden terminal problem.

Contention based medium access schemes are particularly well fit for bursty traffic (which is the case for most data communications), but generally they are not well suited for providing quality of service guarantees for different traffic classes. Furthermore, their stochastic nature has an adverse impact on delay sensitive data. Regarding throughput, as a rule contention based protocols perform best under light to medium traffic loads, since the rate of collisions increases sharply as the traffic load exceeds a threshold. However, in the last few years, the importance of service differentiation has triggered intense research activity on embedding quality of service (QoS) capabilities in contention based medium access schemes. Protocols that are QoS aware include Blackburst proposed by Sobrinho and Krishnakumar in [15], DFS (Distributed Fair Scheduling) [17], the under standardization by the 802.11e task group medium access protocol EDCF (Enhanced Distributed Coordination Function) [2], as well as the EY-NPMA protocol of the HIPERLAN [4] standard. On the other hand, the protocol that is dominating in the market today, DCF (Distributed Coordination Fuction) of the original IEEE 802.11 [8] standard for wireless LANs, is insensitive to different traffic classes. In response to that, there have been many attempts to infuse QoS capabilities in 802.11 based networks [11, 13].

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. In this paper, we propose a solution to the most criticised drawback of the EY-NPMA protocol – the increased overhead. Towards this end, we propose and evaluate the performance of two medium access schemes that are based on EY-NPMA and compare them to the base protocol.

The rest of the paper is structured as follows. In Section 2 we present the mechanism of the base EY-NPMA scheme and also provide a theoretical analysis of its performance. Section 3 contains the description of the proposed schemes and their theoretical analysis. In Section 4, we compare the performance of the three presented schemes, based on the results of the previous sections, as well as extended simulation trials of the proposed protocols. Finally, Section 5 concludes the paper.

2. EY-NPMA

2.1. Protocol Description

EY-NPMA stands for Elimination-Yield Non-pre-emptive Priority Multiple Access. It is a protocol for medium access control that has been one of the basic building blocks of the HIPERLAN standard. EY-NPMA provides good support for different classes of traffic reqarding quality of service and demonstrates very low collision rates. Its performance has been studied in [1], while it has been compared to IEEE's 802.11 DCF mode for medium access in [18]. According to the HIPERLAN standard, each station may attempt to access the channel when a condition out of a group of three is met. These three conditions are: channel free condition, synchronized channel condition and hidden elimination condition. In this section, we will describe in detail only the synchronized channel access cycle, since this is where EY-NPMA is employed.

The synchronized channel condition occurs when the channel is idle in the channel synchronization interval, which starts immediately after the end of the previous access cycle. The synchronised channel access cycle consists of four distinct phases: Prioritization, Elimination, Yield and Data Transmission. During prioritization, EY-NPMA recognizes five distinct priorities from 0 to 4, with 0 being the highest priority. The cycle begins with each station having data to transmit sensing the channel for as many slots as the priority of the packet in its buffer. All stations that successfully sense the channel as idle for the whole interval proceed to the next phase – elimination. Those that do not, exit the contention process and wait for the next synchronized channel condition to make another attempt. During the elimination phase, each station transmits an energy burst of random length. These bursts ensure that only the stations having the highest priority data at a time proceed to the elimination phase and also provide a mechanism for reducing the number of contending stations. The length of the energy burst is a multiple of slots up to a predefined maximum. As soon as a station finishes bursting, it immediately senses the channel. If the channel is sensed as idle, the station proceeds to the next phase; otherwise, it leaves the cycle. During the yield phase, the stations that survived

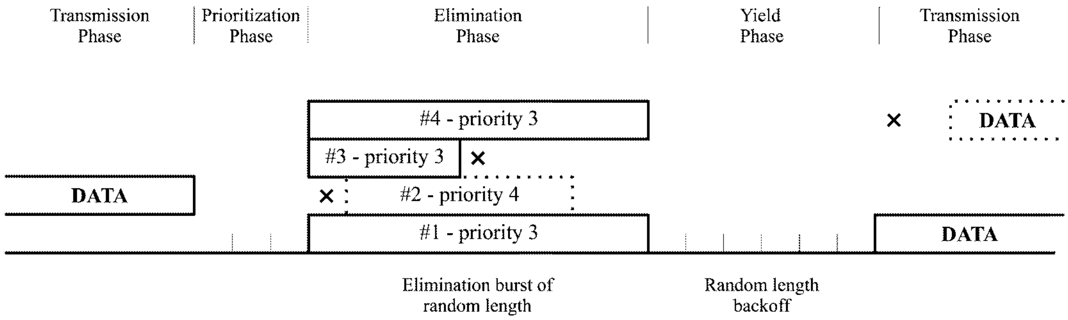

Figure 1. EY-NPMA's synchronized channel access cycle.

the two previous ones, back off for a random number of slots. The station that backs off for the shortest interval eventually accesses the channel for data transmission. All other stations sense the beginning of the transmission and refrain from transmitting. Each phase reduces the number of stations that remain into the contention process, so that (hopefully) the station that will commence transmitting data in a given time will be unique. In Figure 1, we present a typical synchronized channel access cycle. 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 and why a station left the cycle.

Through this four-phases cycle, EY-NPMA manages to provide a low and quasi-constant rate of collisions, independent of the number of contending stations, up to a predefined maximum. The parameters chosen in the HIPERLAN standard (i.e. maximum number of slots for bursting and backing off, probability for bursting for one more slot) aimed at a target collision rate of 3.5% for a population of 256 simultaneously contending stations, a figure that guaranteed that for most real-life situations communications would practically be collisions-free. However, this important merit of EY-NPMA turns out to also be its most severe disadvantage. In order to achieve such a low rate of collisions, a large number of slots is allocated to the elimination and yield phase and thus are being experienced as overhead. As advances in the physical layer lead to higher bitrates, this effect becomes even more intense. Typical values for the duration of each slot are around 10 μs, a value which at high bitrates becomes a significant fraction of the time needed to transmit the actual data payload. Because of the wireless environment, but also for technical reasons, there is a lower limit to the slot duration. Turnaround times, propagation delay and delay spread demand that the slot duration for both elimination and yielding exceeds a certain threshold, while especially for bursting, rise and fall times of each burst place this threshold even higher.

2.2. Theoretical Analysis

The theoretical analysis of the EY-NPMA scheme which follows below provides a closed analytical form for the calculation of the mean medium utilization achieved by the protocol. Our analysis aims at finding the average medium utilization as a function of the contending population (N), the maximum number of slots allowed for bursting (m_{es}), the probability that a station continues bursting for one more slot (p_e) and the maximum number of slots allowed for backing off (m_{ys}). In all occurances later on, these parameters will be written in a triplet as (m_{es}, m_{ys}, p_e), defining an instance of EY-NPMA in a unique way.

To determine for how many slots to burst, each station picks up a random integer which follows a truncated geometric distribution. The probability that a station bursts for k slots is given by the following relation:

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

From Equation (1) we can easily calculate the probability that an individual burst lasts k or less slots:

$$P'_E(k) = \sum_{i=0}^{k} P_E(i) = \begin{cases} 1 - p_e^{k+1}, & \text{if } 0 \le k < m_{es} \\ 1, & \text{if } k = m_{es} \end{cases} . \tag{2}$$

The probability that the elimination phase lasts k slots is equal to the probability that all stations burst for a maximum of k slots and at least one station bursts for exactly k slots. That is, all stations should not burst for fewer than k slots. For $k = 0$, all stations must simply not burst at all, an event that happens with probability $(1 - p_e)^N$.

$$P_{ED}(k) = \begin{cases} (1-p_e)^N, & \text{if } k = 0 \\ P'_E(k)^N - P'_E(k-1)^N, & \text{if } 0 < k \le m_{es} \end{cases} . \tag{3}$$

With the help of Equation (3), the average duration in slots of the elimination phase can be calculated:

$$\overline{elimDur} = \sum_{i=1}^{m_{es}} i \cdot P_{ED}(i). \tag{4}$$

Using Equations (1) and (2), we can derive the probability that the elimination phase lasts k slots and n stations have k-slot bursts (i.e. n stations survive elimination). It should be noted here that in the case of an elimination phase of 0 slots, all N stations are not bursting and hence survive this phase.

$$P_{nk\_E}(n,k) = \begin{cases} \binom{N}{n} P_E(k)^n P'_E(k-1)^{N-n}, & \text{if } 0 < k \le m_{es} \\ (1-p_e)^N, & \text{if } n = N, k = 0 \\ 0, & \text{if } n < N, k = 0 \end{cases} . \tag{5}$$

Summing up $P_{nk\_E}(n,k)$ for all possible values of k (i.e., $[0, m_{es}]$), we can calculate the possibility of having n stations survive the elimination phase, regardless of its length.

$$P_{n\_E}(n) = \sum_{k=0}^{m_{es}} P_{nk\_E}(n,k). \tag{6}$$

Regarding the yield phase, let m_{ys} be the maximum number of slots that a station can back off. All stations that survive the elimination phase pick up a number of slots between $[0, m_{ys}]$ to back off according to a uniform distribution. Consequently, the probability that a station backs off for k slots is equal to:

$$P_Y(k) = \frac{1}{m_{ys}+1}. \tag{7}$$

The probability that a station backs off for at least k slots can be easily derived from the previous equation:

$$P'_Y(k) = \sum_{i=k}^{m_{ys}} P_Y(i) = \frac{m_{ys} + 1 - k}{m_{ys} + 1}. \quad (8)$$

Analogously to Equation (3), if N_Y stations enter the yield phase, the probability that it lasts k slots is equal to:

$$P_{YD}(k, N_Y) = \begin{cases} P'_Y(k)^{N_Y} - P'_Y(k+1)^{N_Y}, & \text{if } 0 \leq k < m_{ys} \\ (\frac{1}{m_{ys}+1})^{N_Y}, & \text{if } k = m_{ys} \end{cases} . \quad (9)$$

Using Equation (9), we can find the average duration in slots of the yield phase when N_Y stations back off.

$$\overline{yieldDur}(N_Y) = \sum_{i=1}^{m_{ys}} i \cdot P_{YD}(i, N_Y) . \quad (10)$$

From Equation (6), we know the probability that n stations survive the elimination phase and consequently enter the yield phase. Using this information, we can calculate the overall average duration in slots of the yield phase.

$$\overline{yieldDur} = \sum_{i=0}^{N} P_{n\_E}(i) \cdot \overline{yieldDur}(i) . \quad (11)$$

If N_Y stations survive the elimination phase and hence enter the yield phase, the probability that n stations are the first that end their backoff period at the k-th slot is:

$$P_{nk\_Y}(n, k, N_Y) = \begin{cases} \binom{N_Y}{n} P_Y(k)^n P'_Y(k+1)^{N_Y - n}, & \text{if } k < m_{ys} \\ (\frac{1}{m_{ys}+1})^{N_Y}, & \text{if } k = m_{ys}, n = N_Y \\ 0, & \text{if } k = m_{ys}, n < N_Y \end{cases} . \quad (12)$$

For a given number of stations entering the yield phase, N_Y, the probability that there is no collision is equal to the probability that only one station ends first its backoff period.

$$P_{NC}(N_Y) = \sum_{i=0}^{m_{ys}} P_{nk\_Y}(1, i, N_Y). \quad (13)$$

The overall mean probability that there is no collision can be calculated by summing Equation (13) for all possible values of N_Y, each one weighted by the probability that N_Y stations survive the elimination phase:

$$\overline{P}_{NC} = \sum_{i=0}^{N} P_{n\_E}(i) \cdot P_{NC}(i). \quad (14)$$

At this point, we have figured out all the characteristics of an EY-NPMA cycle. In order to calculate the average medium utilization, we must first find the average duration of a cycle. Let T_e be the duration of a priotitization/elimination slot, while T_y is the duration of a yielding slot.

pri is the priority level of the contending stations, T_{pck} the time needed for the transmission of a packet and T_{other} the time that is accounted in a cycle for everything else, such as transmission of an ACK packet, sensing and guard times etc. The average duration of a cycle is equal to:

$$T_{cycle} = (pri + \overline{elimDur}) \cdot T_e + \overline{yieldDur} \cdot T_y + T_{pck} + T_{other}\,. \tag{15}$$

The mean medium utilization can be calculated now by combining Equation (14) and (15):

$$mu = \frac{\overline{P}_{NC} \cdot T_{pck}}{T_{cycle}}\,. \tag{16}$$

3. Proposed Protocols

3.1. EY-NPMA/TP

3.1.1. *Protocol Description*

The EY-NPMA/TP (TP stands for Twin Priorities) scheme for medium access control features a different structure for the prioritization phase and a mechanism for dynamically promoting the priority for packets that have survived the elimination process, but did not survive the yield phase. Instead of 5 priority classes, we propose a scheme with 4 priorities. The three lower ones consist of two subclasses, namely a low and a high. The structure of the prioritization slots for the two schemes is depicted in Figure 2. A data packet of priority x that is placed in the transmission buffer of the MAC controller by an upper layer is automatically labeled as being x-low priority. Let x-low be the highest priority when a channel access condition occurs and a number of N stations enter the contention process with all N stations commencing bursting at the same slot. At the end of the elimination phase, a fraction of the initial population, N_s, will have survived elimination and will choose a random number of slots to backoff. At this point all N_s stations switch their packets priorities from x-low to x-high. At the next channel access cycle, through the prioritization phase only the N_s stations will enter the elimination phase, in contrast to the at least $N - 1$ stations that would enter contention according to the base EY-NPMA scheme. Access cycles at x-low priority will be postponed, until there are no more x-high packets, which will happen at the end of at least N_s cycles. When there are no more packets of x-high priority, an access cycle of x-low will follow, and the whole process will be repeated.

Since at x-high priority level there are much fewer contending stations, a reasonable rate of collisions can be achieved with fewer slots dedicated to elimination and yielding, than in the case of x-low priority. Hence, by demanding that all x-high cycles employ fewer slots for the two contention resolution phases, we are led to better medium utilization figures, since for the same data payload the access cycles become shorter. The cost of this modification is the reduction of the traffic classes by one and the addition of two extra slots for the prioritization phase. Consequently, when a big population of stations wants to send data in the same base priority class x, according to the base EY-NPMA scheme in each access cycle this big population will contend for channel access. On the contrary, with EY-NPMA/TP, the whole population contends for one cycle, while for a number of subsequent cycles only a subset of these stations will participate in the contention process. Furthermore, the protocol's behaviour to the base priority classes does not change by this modification. That is a priority 3 packet will always be of lower priority than a priority 2 packet, no matter what subclass – low or high – the packets happen to be.

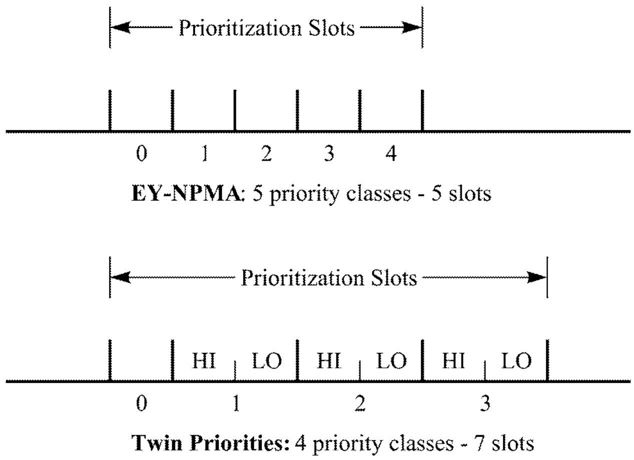

Figure 2. Structure of the prioritization phase for EY-NPMA and EY-NPMA/TP.

3.1.2. *Theoretical Analysis*

Concerning the theoretical analysis of the TP variant of EY-NPMA, we regard as a single hyper-cycle the first cycle at x-low, plus all subsequent cycles at x-high. To calculate the average medium utilization of this scheme, we need to measure two values: the average duration of a hyper-cycle and the average number of packets that are succesfully transmitted in a hyper-cycle. Since all stations that survive elimination in a x-low cycle are automatically upgraded to x-high and the hyper-cycle lasts until all packets at x-high are successfully transmitted, the average number of packets that are delivered in a hyper-cycle is equal to the average number of stations that survive elimination at x-low priority. Consequently, the average number of packets succesfully delivered in a hyper-cycle (N_{pck}) is:

$$N_{pck} = \sum_{i=0}^{N} i \cdot P_{n\_E}(i). \tag{17}$$

The mean duration of a hyper-cycle is expressed as the weighted sum of the hyper-cycle duration with variable number of stations surviving the initial x-low cycle.

$$\begin{aligned} T'_{cycle} \;=\; & \sum_{i=0}^{N} P_{n\_E}(i)(T_{cycle}|_{N_Y=i} + P_{NC}(i) \cdot T_{high}(i-1) \;+ \\ & + (1 - P_{NC}(i)) \cdot T_{high}(i)), \end{aligned} \tag{18}$$

where $T_{cycle}|_i$ is the average cycle duration at x-low, under the restriction that i stations survive the elimination phase, and $T_{high}(i)$ the mean total duration of the subsequent cycles in x-high with i stations upgrading their priority. If there is no collision in the x-low cycle, then $i - 1$ stations enter the x-high cycles. Otherwise, all i stations enter the high priority cycles. Since a packet is succesfully delivered according to a Bernoulli trial, the average time needed to succesfully deliver a data packet is equal to the average cycle duration divided by the probability that there are no collisions.

$$T_{high}(n) = \sum_{i=1}^{n} \frac{N_e \cdot T_e + N_y \cdot T_y + T_{pck} + T_{other}}{\overline{P}_{NC}|_{N=i}}. \tag{19}$$

N_e is the mean number of slots used in a cycle for prioritization/elimination, while N_y is the mean number of slots used in a cycle for yielding, which are equal to

$$N_e = pri + \overline{elimDur}|_{N=i} - 1 \quad (20)$$

$$N_y = \overline{yieldDur}|_{N=i} \,. \quad (21)$$

In the above equations, both average durations of the elimination and yield phase, as well as the probability that there is no collision are calculated for i stations entering the cycle. Combining Equations (17), (18) and (19), we can calculate the mean medium utilization of this scheme

$$mu = \frac{T_{pck} \cdot N_{pck}}{T'_{cycle}} \,. \quad (22)$$

3.2. EY-NPMA/ZP

3.2.1. *Protocol Description*

EY-NPMA/ZP (ZP stands for Zeroed Priority) is based on the assumption that the highest priority, namely priority 0, is unpopulated and reserved mainly for signalling and network management purposes. If actual data transmissions are being done at 0 priority, we expect them to be much fewer, than the transmissions at all other lower priorities. The main idea behind this variant of EY-NPMA is to allow a small subset of stations to avoid the heavy contention at their normal priority classes and make a few attempts at the highest poossible priority (i.e. 0), without however placing an excessive load at the highest priority class and consequently increasing contention at sessions that were originally placed in it. Let N stations having data packets of the same priority for transmission enter the elimination phase. According to this scheme for medium access, all the stations that survive from being eliminated, upgrade their packets' priorities to 0. A station will fall back to its original priority when one of the two following conditions is met:

1. A station succesfully transmits a packet, or
2. A total number of N_0 cycles are made in zero priority.

The benefit of this temporary priority upgrade is two-fold. First, a smaller population contends for channel access, a fact which results in less overhead (fewer slots are used in the elimination phase) and also smaller probability of collisions. Second, there are no slots wasted for prioritization and consequently overhead is reduced even more, while the utilization of the medium is increased. However, by the above it is evident that when a group of stations upgrade their priorities, they cannot be preempted, since they are temporarily using the highest possible priority. This means that packets of original 0 priority will meet some extra competition, while packets of orginally higher priority but lower than 0 will be prohibited from attempting to access the channel. Regarding the balance of the different priorities, we notice that there is an upper bound on the time that these extra stations will contend in 0 priority and is equal to N_0 multiplied by the maximum duration of a cycle. By choosing a relatively small value for N_0, we can be certain that inter-priorities interference will be minimal. Second, in order to upgrade its priority, a station must first survive elimination in a cycle of low priority. This means that, among the whole network population, at that time this station will have the highest priority packet for transmission. Consequently, the packets that will be temporarily locked out from accessing the cycle are those that will be generated during the short period that some stations are upgraded to 0 priority.

Disrupting the balance of the priorities by temporarily upgrading stations of lower priority has a positive side-effect; it introduces a small amount of fairness in the medium access control protocol. Since low priority traffic gets some extra cycles for packet transmissions, the mean delay and throughput of it is increased. However, at the end starvation cannot be avoided, since low priority stations will not even get a chance at accessing the channel at their priority, when the aggregate traffic of higher priorities is equal or exceeds the available capacity.

EY-NPMA/ZP, like EY-NPMA/TP, enhances the performance of the base scheme by adding memory to the access model. In the case of the memoryless EY-NPMA, the outcome of previous access cycles has absolutely no effect on future cycles. On the other hand, according to the two proposed variants of EY-NPMA, previous access cycles have a significant impact on how and which nodes will enter the contention process in future cycles. A similar method has been adopted in [9] by Janczak and Wozniak, who propose a EY-NPMA variant which also adds memory to the base access scheme. In their work, each node chooses a number of slots for bursting not only according to a truncated geometric distribution, but also by taking into account the overall bursting length of the previous access cycle. According to this scheme, performance is enhanced by reducing the average length of the elimination phase, while leaving the collisions probability low.

3.2.2. *Theoretical Analysis*

With this variant of the EY-NPMA scheme for medium access, all stations surviving elimination at any priority level, upgrade their priority to 0 for a maximum of N_0 cycles. In order to calculate the medium utilization of this scheme, we regard as a hyper-cycle the low priority cycle plus all the subsequent cycles in 0 priority. As was the case with the EY-NPMA/TP scheme, the mean medium utilization is expressed as the ratio of the time allocated to succesfull data transmissions in a hyper-cycle divided by the length of a hyper-cycle. The number of packets succesfully delivered in a hyper-cycle is equal to:

$$N'_{pck} = \sum_{i=1}^{N_0+1} \sum_{j=i}^{N} i \cdot P_{n\_E}(j)(P_{NC}(j) \cdot P_T(i-1, j-1, N_0) + (1 - P_{NC}(j)) \cdot (P_T(i, j, N_0)). \tag{23}$$

In Equation (22), we calculate the probability that during the hyper-cycle, i packets are succesfully delivered when j stations survive the elimination phase. $P_T(i, j, n)$ represents the probability that i packets get succesfully delivered in n zero-priority slots, when j stations upgrade their priority to 0. For the calculation of P_T, as well as the calculation of T_{zero} later on, we assume that only the stations that just upgraded their priorities will contend for channel access in priority 0. P_T is defined recursively and is presented below:

$$P_T(i, j, n) = \begin{cases} 0, & \text{if } i > j \text{ or } i > n \\ 1, & \text{if } i = 1, j = 1 \\ (1 - \overline{P}_{NC}|_{N=i})^n, & \text{if } j = 0 \\ \overline{P}_{NC}|_{N=i} \cdot P_T(i-1, j-1, n-1) + & \\ (1 - \overline{P}_{NC}|_{N=i}) \cdot P_T(i, j, n-1) & \text{otherwise} \end{cases} \tag{24}$$

It should be stressed in this point that for the above equation the probability that there is no collision is calculated for i contending stations. In order to find the average duration of a hyper-cycle, we sum the hyper-cycle durations for i stations surviving elimination at the initial, low priority cycle.

$$\begin{aligned} T''_{cycle} \;=\; & \sum_{i=0}^{N} P_{n\_E}(i)(T_{cycle}|_i + P_{NC}(i) \cdot T_{zero}(i-1, N_0) \;+ \\ & + (1 - P_{NC}(i)) \cdot T_{zero}(i, N_0)) \,. \end{aligned} \quad (25)$$

The $T_{zero}(i, n)$ function represents the time needed for n cycles in 0 priority, when i stations upgrade their priorities to 0. As was the case for P_T, this function is also defined recursively.

$$T_{zero}(i, n) = \begin{cases} 0, & \text{if } i = 0 \text{ or } j = 0 \\ T_{cycle}|_{N=i} + \overline{P}_{NC}|_{N=i} \cdot T_{zero}(i-1, n-1) + & \\ (1 - \overline{P}_{NC}|_{N=i}) \cdot T_{zero}(i, n-1) & \text{otherwise} \end{cases} \quad (26)$$

In the equation above, the cycle duration as well as the probability of no collision are calculated with i stations entering contention and priority level equal to zero. Combining the above equations, we can finally express the mean medium utilization of the proposed scheme:

$$mu = \frac{N'_{pck} \cdot T_{pck}}{T''_{cycle}} \,. \quad (27)$$

3.3. Compatibility Issues

The two proposed variants of EY-NPMA alter the access mechanism by dynamically promoting the priorities of data streams and also – in the case of EY-NPMA/TP – by changing the mapping of different priorities during prioritization. Consequently, it is essential that we examine mixed population scenarios, that is networks consisting of nodes employing EY-NPMA and nodes employing one of the two proposed variants.

Coexistence between EY-NPMA and EY-NPMA/TP is problematic, but not impossible; even though transmissions will take place without problem, since the access cycle retains the same architecture, nodes which employ the base scheme will be favoured compared to those employing the TP variant. For packets of the same priority, EY-NPMA/TP nodes listen to twice the number of slots compared to those using EY-NPMA. Consequently, EY-NPMA nodes will be more aggressive during the prioritization phase, prohibiting thus EY-NPMA/TP nodes to gain access. For example, an EY-NPMA/TP node with a data packet of priority 2 will initially content for access with EY-NPMA nodes having data packets of priority 4 and if it succeeds to get a priority promotion, it will enter the access cycle with competition from EY-NPMA nodes having data packets of priority 3. Based on the above, it is evident that the co-existence between base and variant protocols guarantees a total disruption of the priorities balance.

On the other hand, EY-NPMA/ZP is better suited for such coexistence scenarios. Unlike EY-NPMA/TP, with this variant the mapping of the different priority classes on the prioritization phase remains the same and consequently EY-NPMA/ZP nodes will content for channel access with their EY-NPMA peers having data packets of the same priority. However, under this scenario EY-NPMA/ZP nodes will be favoured and receive more opportunities to gain channel access. With the ZP scheme, nodes may temporarily upgrade their priority to 0, prohibiting other nodes with lower priorities, even though originally higher, to gain access to the channel. As we recall from the previous subsection, however, EY-NPMA/ZP nodes will get their priorities upgraded only if at that time they have the highest priority packets, while they will remain upgraded for a small number of access cycles.

4. Performance Evaluation

In this section, we evaluate the performance of the EY-NPMA protocol, as well as the two proposed variants based on it. The main metric used for comparing the performance of the protocols throughout this section is the mean medium utilization; we compare the three protocols in how efficiently they use the available raw bandwidth. For the first round of comparisons, we employed the analytical results that were calculated in Sections 2 and 3. Subsequently, we conducted a set of simulation trials testing each protocol in multi-priority traffic. Besides the mean medium utilization, for this scenario the three protocols were compared in terms of mean packet delay, which is defined as the interval between a packet reaching the head of the corresponding priority queue and its successful transmission.

4.1. Analytical Results

Initially, we measured the performance of the three medium access control schemes based on the analytical forms that were calculated in the previous sections. Even though all three protocols are based on the same mechanism, the optimal set of parameters is not the same for the three protocols. Having this in mind, we made an exhaustive search in the parameters space, in order to find the optimal triplet (m_{es}, m_{ys}, p_e) for different packet sizes, station populations and priorities. The channel capacity was assumed to be equal to 20 Mbps, while the duration of a slot was set to 10.6 μs for prioritization/elimination slots (212 bit periods) and 8.4 μs for yielding slots (168 bit periods). Also, specifically for the EY-NPMA/ZP protocol, the N_0 parameter was set to 4. The metric that we wanted to maximize is the average medium utilization. The results of this search are summarised in Tables 1–3, where we provide the maximum medium utilization figure, together with the triplet(s) that correspond to this performance. Also, in each case we provide in italics the average probability that there is no collision in a cycle. In the case of the EY-NPMA/TP and EY-NPMA/ZP schemes, we allowed the protocols to employ different parameters in the upgraded cycles than in the cycles of low priority and hence provide two triplets in every instance of the optimization problem, one for the low priority cycles and one for the higher ones. In all three protocols examined, the average medium utilization depends on two figures: the probability of no collision and the number of slots used in the first three phases of the access cycle (prioritization, elimination, yield). Examining the tables, we can see that these two quantities are not valued equally for all packet sizes. In the one extreme, for small packets speedy delivery is valued more than having fewer collisions. That's why in this case fewer slots are allowed for bursting and backing off, even though this results in a higher probability of collisions. On the other hand, the opposite happens in the case of bigger packets. More slots are used, in order to achieve lower collision rates, even though the average cycle becomes longer.

In terms of medium utilization the EY-NPMA/ZP scheme achieves the highest performance in all configurations (packet size, network population, priority level). The highest difference between the ZP variant and the base EY-NPMA scheme is observed when the network serves small packets of low priority, where EY-NPMA/ZP increases the medium utilization by 30%. This result is very positive for interactive data communications, consisting

Table 1. Best medium utilization figures and the correspondent parameters for the base EY-NPMA protocol.

# Nodes	Packet size							
	125		**250**		**500**		**1000**	
Priority 1								
25	**0.301** (2, 6, 0.2)	*0.857*	**0.447** (2, 8, 0.2)	*0.886*	**0.596** (3, 9, 0.2)	*0.908*	**0.725** (4, 9, 0.3)	*0.934*
50	**0.29** (3, 6, 0.2)	*0.869*	**0.436** (3, 7, 0.2)	*0.883*	**0.586** (3, 9, 0.2)	*0.905*	**0.717** (4, 9, 0.3)	*0.933*
100	**0.284** (3, 6, 0.2)	*0.865*	**0.428** (3, 7, 0.2)	*0.88*	**0.58** (4, 9, 0.2)	*0.91*	**0.71** (4, 9, 0.2)	*0.924*
Priority 2								
25	**0.28** (2, 7, 0.2)	*0.873*	**0.425** (2, 8, 0.2)	*0.886*	**0.576** (3, 9, 0.2)	*0.908*	**0.710** (4, 9, 0.3)	*0.934*
50	**0.271** (3, 6, 0.2)	*0.869*	**0.414** (3, 7, 0.2)	*0.883*	**0.566** (3, 9, 0.2)	*0.905*	**0.703** (5, 9, 0.3)	*0.935*
100	**0.265** (3, 6, 0.2)	*0.865*	**0.407** (3, 8, 0.2)	*0.892*	**0.561** (4, 9, 0.2)	*0.92*	**0.696** (4, 12, 0.2)	*0.929*
Priority 3								
25	**0.262** (2, 7, 0.2)	*0.873*	**0.404** (2, 8, 0.2)	*0.886*	**0.558** (3, 9, 0.2)	*0.908*	**0.696** (4, 9, 0.3)	*0.934*
50	**0.254** (3, 6, 0.2)	*0.869*	**0.394** (3, 7, 0.2)	*0.883*	**0.548** (3, 9, 0.2)	*0.905*	**0.689** (4, 10, 0.3)	*0.938*
100	**0.249** (3, 7, 0.2)	*0.88*	**0.389** (3, 8, 0.2)	*0.892*	**0.543** (4, 9, 0.2)	*0.91*	**0.683** (4, 12, 0.2)	*0.929*

of small requests and replies, input of user data etc. Generally, as was expected, EY-NPMA/ZP benefits mostly small packets since it aims at reducing the number of slots experienced as overhead. The impact of the number of the overhead slots is more intense, when the duration of a slot is comparable to the size of the actual data packet. Of course, in case of larger packets there is an increase in medium utilization too, but this increase is not as impressive as in the case of smaller packets. Low priority packets are also benefitted more than high priority packets, since the EY-NPMA/ZP scheme completely eliminates the overhead in form of prioritization slots when stations upgrade their priority. Consequently, the decrease in the number of overhead slots is bigger, when the network serves traffic of lower priority.

Table 2. Best medium utilization figures and the correspondent parametres for the EY-NPMA/TP scheme.

# Nodes	Packet size							
	125		**250**		**500**		**1000**	
Priority 1								
25	**0.327**		**0.479**		**0.629**		**0.751**	
	(2, 11, 0.4)	*0.879*	(2, 13, 0.4)	*0.9*	(2, 15, 0.4)	*0.925*	(2, 15, 0.3)	*0.945*
	(2, 3, 0.3)		(2, 4, 0.3)		(2, 5, 0.4)		(2, 6, 0.4)	
50	**0.327**		**0.479**		**0.627**		**0.748**	
	(2, 13, 0.3)	*0.876*	(2, 15, 0.3)	*0.898*	(2, 15, 0.3)	*0.919*	(3, 15, 0.4)	*0.942*
	(2, 3, 0.3)		(2, 4, 0.3)		(2, 5, 0.4)		(3, 5, 0.5)	
100	**0.326**		**0.477**		**0.626**		**0.747**	
	(2, 11, 0.2)	*0.874*	(2, 13, 0.2)	*0.896*	(2, 15, 0.2)	*0.912*	(3, 15, 0.3)	*0.944*
	(2, 3, 0.3)		(2, 4, 0.3)		(2, 5, 0.3)		(3, 5, 0.5)	
Priority 2								
25	**0.283**		**0.431**		**0.587**		**0.721**	
	(2, 12, 0.4)	*0.898*	(2, 14, 0.4)	*0.914*	(2, 15, 0.4)	*0.925*	(2, 15, 0.3)	*0.945*
	(2, 4, 0.3)		(2, 4, 0.4)		(2, 5, 0.4)		(2, 6, 0.4)	
50	**0.283**		**0.43**		**0.585**		**0.718**	
	(2, 14, 0.3)	*0.896*	(2, 15, 0.3)	*0.898*	(2, 15, 0.3)	*0.919*	(3, 15, 0.4)	*0.942*
	(2, 4, 0.3)		(2, 4, 0.3)		(2, 5, 0.4)		(3, 5, 0.5)	
100	**0.282**		**0.429**		**0.583**		**0.717**	
	(2, 12, 0.2)	*0.894*	(2, 14, 0.2)	*0.898*	(2, 15, 0.2)	*0.92*	(3, 15, 0.3)	*0.944*
	(2, 4, 0.3)		(2, 4, 0.3)		(2, 6, 0.3)		(3, 5, 0.5)	
Priority 3								
25	**0.25**		**0.392**		**0.55**		**0.693**	
	(2, 13, 0.4)	*0.9*	(2, 13, 0.4)	*0.915*	(2, 15, 0.4)	*0.925*	(2, 15, 0.3)	*0.945*
	(2, 4, 0.3)		(2, 4, 0.4)		(2, 5, 0.4)		(2, 6, 0.4)	
50	**0.249**		**0.391**		**0.548**		**0.69**	
	(2, 15, 0.3)	*0.898*	(2, 15, 0.3)	*0.909*	(2, 15, 0.3)	*0.919*	(3, 15, 0.4)	*0.942*
	(2, 4, 0.3)		(2, 4, 0.4)		(2, 5, 0.4)		(3, 5, 0.5)	
100	**0.249**		**0.39**		**0.547**		**0.689**	
	(2, 13, 0.2)	*0.896*	(2, 15, 0.2)	*0.912*	(2, 15, 0.2)	*0.92*	(3, 15, 0.3)	*0.944*
	(2, 4, 0.3)		(2, 5, 0.3)		(2, 6, 0.3)		(3, 5, 0.5)	

Table 3. Best medium utilization figures and the correspondent parametres for the EY-NPMA/ZP scheme.

# Nodes	Packet size							
	125		**250**		**500**		**1000**	
Priority 1								
25	**0.348**		**0.5**		**0.648**		**0.766**	
	(2, 11, 0.4)	*0.908*		*0.925*		*0.966*		*0.975*
	(2, 3, 0.3)		(2, 4, 0.3)		(3, 4, 0.4)		(2, 4, 0.3)	
50	**0.346**		**0.498**		**0.643**		**0.76**	
	(2, 12, 0.3)	*0.909*	(2, 15, 0.3)	*0.914*	(2, 15, 0.3)	*0.939*	(3, 15, 0.4)	*0.969*
	(2, 4, 0.3)		(2, 4, 0.3)		(3, 5, 0.4)		(4, 5, 0.5)	
100	**0.346**		**0.498**		**0.644**		**0.76**	
	(2, 11, 0.2)	*0.903*	(2, 13, 0.2)	*0.921*	(2, 15, 0.2)	*0.939*	(3, 15, 0.3)	*0.973*
	(2, 3, 0.3)		(2, 4, 0.3)		(3, 4, 0.4)		(4, 5, 0.5)	
Priority 2								
25	**0.341**		**0.493**		**0.64**		**0.76**	
	(2, 11, 0.4)	*0.908*	(2, 13, 0.4)	*0.925*	(2, 15, 0.4)	*0.942*	(2, 15, 0.4)	*0.975*
	(2, 3, 0.3)		(2, 4, 0.3)		(3, 4, 0.4)		(4, 4, 0.5)	
50	**0.339**		**0.491**		**0.637**		**0.755**	
	(2, 12, 0.3)	*0.909*	(2, 15, 0.3)	*0.914*	(2, 15, 0.3)	*0.938*	(3, 15, 0.4)	*0.969*
	(2, 4, 0.3)		(2, 4, 0.3)		(3, 5, 0.4)		(4, 5, 0.5)	
100	**0.399**		**0.491**		**0.638**		**0.755**	
	(2, 11, 0.2)	*0.903*	(2, 13, 0.2)	*0.921*	(2, 15, 0.2)	*0.946*	(2, 15, 0.2)	*0.954*
	(2, 3, 0.3)		(2, 4, 0.3)		(3, 5, 0.4)		(4, 5, 0.5)	
Priority 3								
25	**0.344**		**0.486**		**0.634**		**0.754**	
	(2, 11, 0.4)	*0.908*	(2, 13, 0.4)	*0.925*	(2, 15, 0.4)	*0.942*	(2, 15, 0.3)	*0.975*
	(2, 3, 0.3)		(2, 4, 0.3)		(3, 4, 0.4)		(4, 4, 0.5)	
50	**0.332**		**0.484**		**0.631**		**0.751**	
	(2, 12, 0.3)	*0.909*	(2, 15, 0.3)	*0.914*	(2, 15, 0.3)	*0.938*	(3, 15, 0.4)	*0.969*
	(2, 4, 0.3)		(2, 4, 0.3)		(3, 5, 0.4)		(4, 5, 0.5)	
100	**0.332**		**0.483**		**0.631**		**0.751**	
	(2, 11, 0.2)	*0.903*	(2, 13, 0.2)	*0.921*	(2, 15, 0.2)	*0.946*	(2, 15, 0.2)	*0.954*
	(2, 3, 0.3)		(2, 4, 0.3)		(3, 5, 0.4)		(4, 5, 0.5)	

The EY-NPMA/TP scheme also overperforms EY-NPMA in most cases, but in contrast to EY-NPMA/ZP, the difference between the two schemes decreases as traffic of lower priority is served. Eventually, in the case of priority 3 traffic, for small populations EY-NPMA/TP performs worse than the base EY-NPMA scheme. This phenomenon is accounted to the usage of two slots for each priority class during the prioritization phase. Because of this, with priority 3 traffic each station senses for 6 slots before bursting, rather than 3 which is the case for the base EY-NPMA protocol. These 3 extra prioritization slots are translated to a waste of bandwidth and the gain from the fewer contending stations during the x-high cycles is not enough to cover this loss. The same effect makes the introduction of more priority levels inefficient, this being the main reason behind the 4 priority classes for EY-NPMA/TP. Another important characteristic of this scheme is that compared to the other two protocols, its performance decreases more slowly as the network population increases. From the figures of Table 2, we come to the conclusion that this scheme scales very well to more densely populated networks.

For the next set of experiments, we picked up a parameter set from those presented in Tables 1–3 and examined the behaviour of each protocol for different network populations. Valuing lower collision rates more than shorter access cycles, we chose the optimal triplet(s) that were observed in the case of 1000 bytes packets. Regarding network population and priority we chose the worst case, namely 100 simultaneously contending stations and priority 3. The results of these experiments are shown in Figure 3. Regarding EY-NPMA, it can be seen that for all packet sizes, the medium utilization curves show a moderately decreasing trend. This decrease is primarily owed to the fact that on average the elimination phase becomes longer as more stations enter contention, and not that much to an increase in collisions probability. The decline decelerates as the network population increases, a characteristic that is attributed to the fact that during the elimination phase each station determines for how long to burst according to a geometric distribution. Consequently, the number of stations entering the yield phase remains quasi-constant as the network becomes more populated. The curves that correspond to different priorities exhibit exactly the same behaviour and their difference is equal to the cost imbued by their difference in slots during the prioritization phase.

In the case of the EY-NPMA/TP scheme, we observe that initially the medium utilization decreases as the network becomes more populated, but later the same curves follow an increasing trend. When few stations contend for channel access, the number of stations that survive elimination is small. Consequently, the ratio of x-high to x-low cycles is very low. Furthermore, for small numbers of contending stations, the most impotant feature of the EY-NPMA/TP scheme – introducing access cycles of fewer contending stations – remains underutilized, since competition is nevertheless low. As the network becomes more populated, however, there are more cycles at x-high and the number of slots being experienced as overhead becomes smaller, resulting in the observed increase in performance. Compared to the base EY-NPMA scheme, we observe that for most cases EY-NPMA/TP initially performs worse, but as the network population increases the performance of the protocol becomes better than that of EY-NPMA. As was also hinted by the results of Tables 1 and 2, for lower priorities the crossing point between the two curves is observed at larger network populations.

The EY-NPMA/ZP scheme clearly outperforms both other protocols in all packet size scenarios. The initial fall is accounted to the increasing duration of the elimination phase, while the subsequent increase in performance is owed to the growing number of stations temporarily upgrading their priority to 0. As was aforementioned, the most benefitted priorities by this scheme are the low ones. It can be seen on Figure 3 that even for relatively small network population, priority 3 of this scheme outperforms in terms of medium utilization

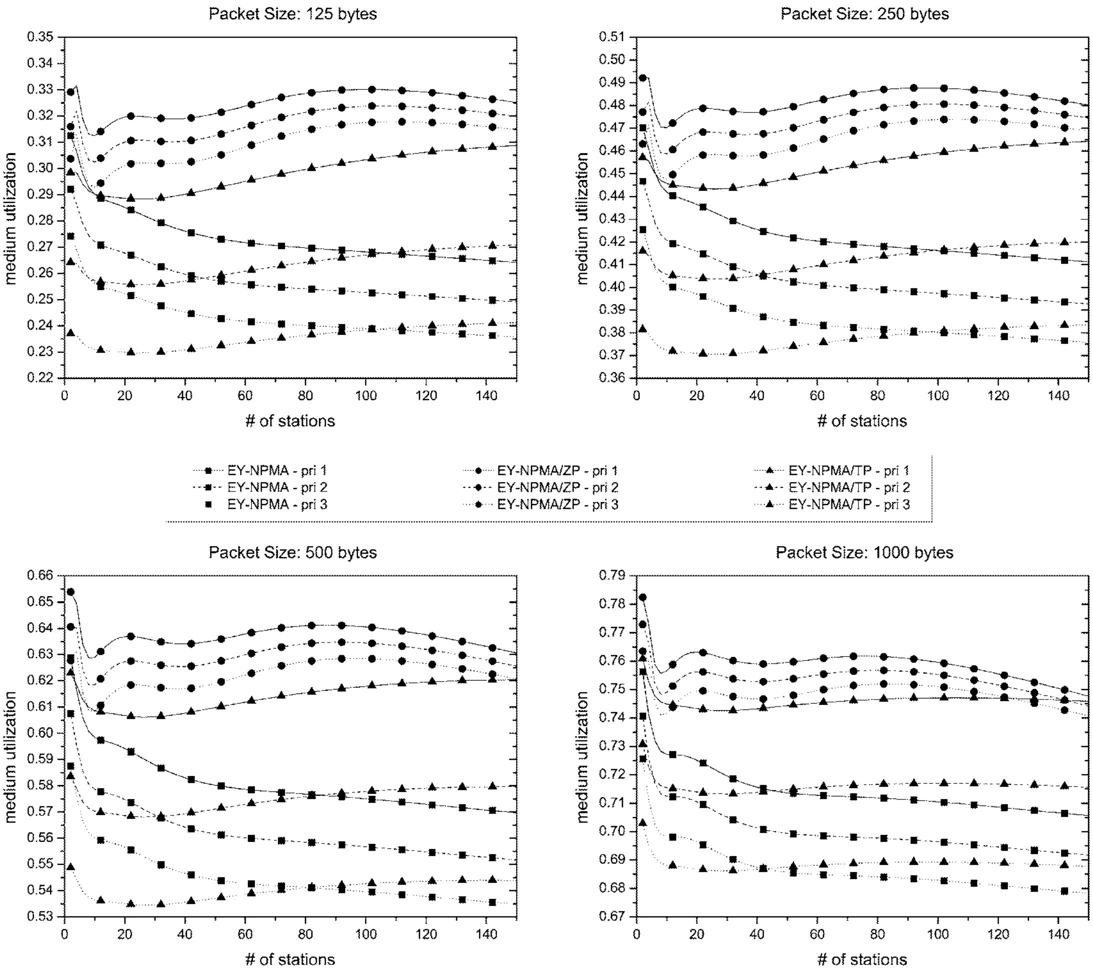

Figure 3. Medium utilization vs number of contending stations for different packet sizes.

both other protocols even when serving loads of higher priority. Also, we observe that the difference between the curves of subsequent priorities is compressed, a feature that allows the introduction of more priority classes and better service differentiation.

4.2. Simulation Results

For the next set of experiments, we measured the performance of a network simultaneously serving high and low priority traffic. For the needs of these experiments, the simulation runs were conducted using a custom simulation tool that was developed in C++ by the authors. In our simulations, we chose not to employ the NRL (Normalised Residual Lifetime) scheme which dynamically upgrades the packets' priorities. Our decision is based on two facts. The first one is that the NRL scheme is defined in the HIPERLAN standard, but resides in a higher layer of network stack, thus not being a part of the core EY-NPMA protocol. Second, NRL is not the only available scheme for the migration of packets to different priorities, with alternatives that could be used in place of it.

The measured quantities were average medium utilization and mean packet delay. The metric of average medium utilization has been already defined above, while the metric of mean packet delay expresses the time needed between a data packet reaching the head of the corresponding priority queue and positive acknowledgement of its reception. In this scenario, we examine the behaviour of a network of 80 stations, under a variable offered load. The network population is divided into two groups, each consisting of 40 stations: a group generating high priority data packets (priority 1), and another group generating low priority data packets (priority 2). For both priority classes, the packet size is equal to 500 bytes. High priority packets are born at constant intervals, while low priority packets are born according to a poisson process, with the packet generation rate being equal for all streams. Furthermore, on each station is attached a source that generates signaling traffic. Each one of these sources generates 160 bytes long packets each second. As was the case with the theoretical results, the channel capacity was set to 20 Mbps and the slot duration was set to 10.6 μs and 8.4 μs for prioritization/elimination and yielding respectively. The parameters that were initially used for each protocol were taken from Tables 1–3 for the scenario that optimized a network of 50 stations.

Our initial simulation runs showed very good performance for the two proposed protocols when the network operated beyond its saturation point – when there is heavy competition between the stations for channel access – but under light load, performance was not as good. This behaviour was expected, since both protocols were optimized for heavy loads. In order to achieve good performance under a wider range of traffic loads, we conducted another search for optimized parameters for the three examined protocols, maximizing this time the sum of medium utilization for light (2 contending stations) and heavy load (40 contending stations). In all cases, changes were experienced in the number of slots allocated for yielding. Specifically, for the base EY-NPMA scheme the number of yielding slots changed from 9 to 8. In the case of EY-NPMA/TP, the number of yielding slots at low cycles changed from 15 to 8, while in the case EY-NPMA/ZP, at low cycles 9 slots were allocated for yielding, instead of 15. We notice, that more drastic changes were observed for the two proposed schemes, compared to the base EY-NPMA scheme. The reason behind this observation is that under high loads, the protocols' performance depends mostly on the parameters of the high priority cycles.

The simulation results for the data streams are presented in Figures 4 and 5 and rovide a confirmation of the analytical results provided in previous subsections. In Figure 4 the mean medium utilization and the average packet delay for high priority traffic is presented. Regarding medium utilization initially all protocols show the same behaviour. However, when the network becomes saturated and there is heavy contention, the best performance is due to EY-NPMA/ZP, being followed by EY-NPMA/TP. Medium utilization is increased by 9% and 5% respectively, compared to the base EY-NPMA scheme. In terms of mean packet delay, in the lightly loaded region, the base EY-NPMA scheme and EY-NPMA/TP show almost indentical performance. On the other hand, the EY-NPMA/ZP scheme shows a much different behaviour. When the aggregate offered load passes 12 Mbps, the curve that corresponds to EY-NPMA/ZP increases and settles near 1 *ms*. Beyond 12 Mbps, the offered load is more than what the network may serve. Consequently, low priority traffic gets fewer access cycles and contention gradually becomes heavier in that class. Since low priority stations get upgraded to 0 priority with increasing frequency, high priority traffic experiences increased delay. Finally, as the network reaches its saturation point, EY-NPMA is the first protocol to abruptly experience long mean packet delays, being followed by EY-NPMA/TP and EY-NPMA/ZP.

In Figure 5, the same metrics are presented for low priority traffic. Regarding medium utilization, as low priority traffic is gradually phased out, the EY-NPMA/ZP scheme exhibits the best performance, a result of the upgraded priority and the extra cycles that are given

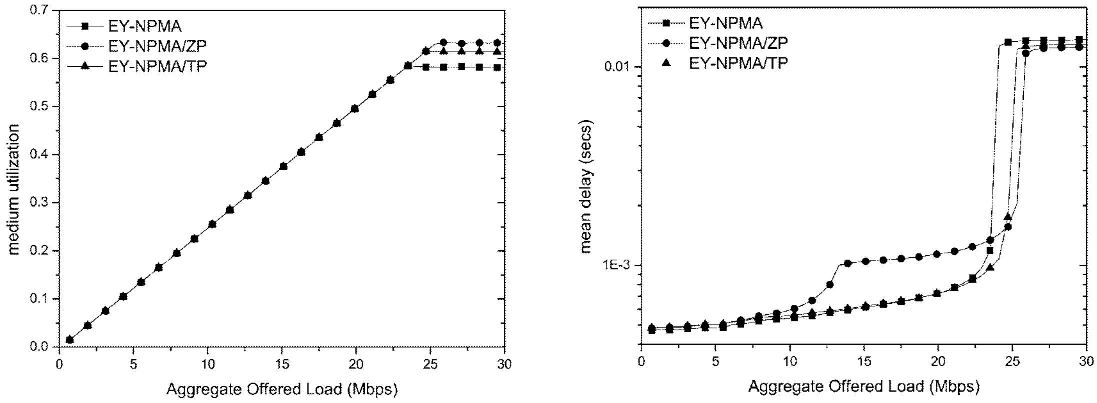

Figure 4. Simulation results for the high priority traffic.

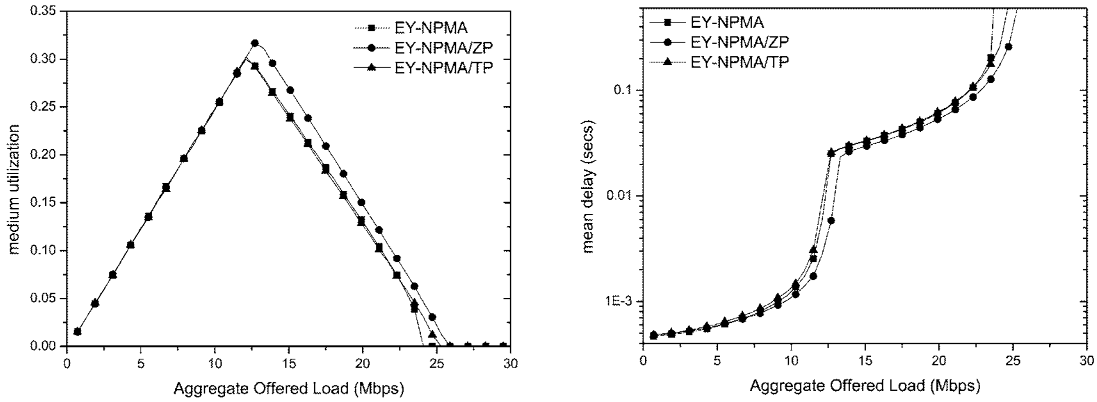

Figure 5. Simulation results for the low priority traffic.

to the low traffic class. In all protocols, however, low priority traffic is ultimately led to starvation. As low priority is gradually phased out, EY-NPMA/ZP achieves better throughput for these streams, which is higher by 0.5 Mbps, compared to the other two protocols which exhibit similar performance. The base EY-NPMA scheme is the first whose low priority traffic reaches zero, followed be EY-NPMA/TP, while the last one is EY-NPMA/ZP. In terms of mean packet delay, EY-NPMA/ZP again shows the best performance, while the two other protocols exhibited almost identical behaviour. For all traffic values, the mean packet delay of the EY-NPMA/ZP scheme was lower than the other protocols, counterweighting the increased mean packet delay that was observed for the same protocol in the case of the high priority traffic.

In Table 4, we present the impact each of the three examined protocols has on signaling traffic. Specifically, this table contains the mean packet delay experienced by signaling (priority 0) packets. Generally, all three protocols show very good performance, demonstrating mean packet delays that are well below 1 *ms* for all offered loads. However, each one of the three examined protocols exhibits different characteristics. Under light loads, EY-NPMA shows the best performance, being followed by EY-NPMA/TP. In the case of high loads, on the other hand, EY-NPMA/TP outperforms EY-NPMA, while with EY-NPMA/ZP mean packet delay is twice that compared to the other two protocols. As mentioned in the respective subsection, this behaviour on part of EY-NPMA/ZP was expected, since priority 0 traffic meets

Table 4. Mean delay figures for signaling traffic.

Aggregate load (Mbps)	Mean delay of priority 0 traffic		
	EY-NPMA	EY-NPMA/ZP	EY-NPMA/TP
5	337 μs	356 μs	352 μs
10	323 μs	362 μs	329 μs
15	299 μs	498 μs	304 μs
20	303 μs	462 μs	305 μs
25	301 μs	463 μs	299 μs
30	304 μs	604 μs	298 μs

extra competition, especially when the level of contention in lower priorities is high. As it can be seen from this table, however, the extra delay introduced in this case is not unacceptable.

5. Conclusions

In this paper we presented and evaluated the performance of EY-NPMA, as well as two variants based on it, both from an analytical point of view and simulation results. The theoretical analysis aided us in determining the maximum performance that these protocols may achieve and also provided us with the parameters that lead to such performance. The conclusions of this study were very positive regarding the performance of the two proposed medium acces control schemes. The two proposed protocols were found to lead to shorter access cycles, without increasing the collisions probability, while simultaneously demonstrating excellent scalability to dense, populated networks. The simulations results further documented the good characteristics of the two schemes. However, through this study an important shortcoming of the whole protocol family became evident; none of the protocols examined possessed self-configuring capabilities. The triplet that defined each protocol's behaviour was fixed, regardless of the offered load or the degree of contention. In our line of work, our next priority is to embed a mechanism in EY-NPMA based protocols, that allows them to choose the optimal triplet for different network configurations.

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