Performance Enhancement of EY-NPMA through Variable Yield

Gerasimos Dimitriadis, Orestis Tsigkas, and Fotini-Niovi Pavlidou

***Abstract*— Previous studies have shown that significant gains can be achieved, when the parameters of the EY-NPMA protocol are updated on the fly. When EY-NPMA adapts dynamically to the offered load, improved figures both in throughput and access delay are observed. The estimation of the number of contending nodes, which is necessary for the calculation of the optimal parameters of EY-NPMA, also provides room for further enhancement of the protocol through the linking of the backoff distribution of the yield phase with the outcome of the elimination phase. In this work, a mechanism that implements this concept is proposed, with the analytical model and the simulation results documenting its positive characteristics.**

***Index Terms*– EY-NPMA, Wireless LANs, Medium Access.**

I. INTRODUCTION

Wireless Local Area Networks (WLANs) have known an impressive increase in popularity during the past decade. Unhindered mobility and hassle-free installation are the main attractive features of this networking solution, characteristics that have allowed WLANs to occupy a substantial share in the market. Furthermore, the major drawback of this family of networks, namely reduced speed, is gradually being alleviated, since the recent advances in the physical layer are raising the available bitrate figures and bringing WLANs on par with their wired counterparts. Indeed, the 2 Mbps of the original 802.11 [14] standard from IEEE have quickly evolved to the 54 Mbps employed by 802.11a [15], 802.11g [16] and HIPERLAN/2 [10], while even higher speeds are expected in the near future.

Even though the physical layer defines the raw speed of a wireless LAN, the performance of the service that is provided to the end user depends heavily on the characteristics of the MAC sublayer, since it is the medium access mechanism that arbitrates the sharing of the common medium between different users. Therefore, in parallel with the efforts in the physical layer, intense research activity is currently ongoing in the field of medium access, aiming towards maximizing the efficiency of the bandwidth sharing process. Depending on the mechanism that defines how network nodes gain access to the common resources, medium access protocols may be classified into two families. In contention based protocols, transmission attempts take place according to a stochastic procedure, with no or little coordination between the participants. Well known protocols that belong to this family are Distributed Coordination Function (DCF) and Enhanced Distributed Coordination Function (EDCF) of 802.11 and 802.11e [3] respectively, as well as EY-NPMA of HIPERLAN [11]. On the other hand, in protocols belonging to the dynamic assignment family, transmissions are managed either by a centralised entity or a common procedure that defines the sequence with which network nodes transmit. Consequently, techniques such as polling and token circulation, as well as all protocols based on such techniques belong to this family. The Point Coordination Function (PCF) of 802.11, the medium access mechanisms of Bluetooth [4] and HIPERLAN/2 are some of the established medium access protocols belonging to the dynamic assignment family.

In this paper, a contention based medium access protocol is proposed, analysed and evaluated. Specifically, a modification to the EY-NPMA protocol of the HIPERLAN standard is proposed, which aims at improving the medium utilization without adding to the complexity of the access mechanism. The innovation of the proposed mechanism lies in the coupling of the two contention resolution phases of EY-NPMA. In the standardized version of EY-NPMA, the elimination and the yield phase are independent from each other, while in the proposed one the characteristics of the distribution employed during the yield phase vary according to the outcome of the elimination phase. This modification is evaluated using an analytical model and compared with the corresponding results from EY-NPMA. Furthermore, simulation results further document the positive characteristics of the proposed scheme. The rest of the paper is structured as follows. In Section II, the mechanism of EY-NPMA is quickly outlined, together with some performance enhancing modifications that exist in the bibliography. Special attention is paid to Adaptive EY-NPMA [7], since it forms the basis on top of which the proposed protocol is built. In Section III, Adaptive EY-NPMA with Variable Yield is presented and analysed. In the next Section, some performance measures are drawn from the analytical model, as well as some simulation results are presented. Finally, Section V concludes this paper.

II. BACKGROUND WORK

A. EY-NPMA

EY-NPMA stands for Elimination Yield Non-Preemptive Medium Access and is one of the major building blocks of the HIPERLAN standard for Wireless LANs. EY-NPMA is a medium access protocol belonging to the contention based family and depends on multiple stages for contention resolution, achieving this way remarkable performance regarding collision rates. Furthermore, EY-NPMA possesses a number of powerful characteristics such as low collision rates, even for a very large number of contending stations, and QoS support for heterogeneous traffic. EY-NPMA supports service differentiation via hierarchically independent priorities (i.e. packets of low priority cannot be served when packets of higher priority are pending for access) and supports five priority classes; 4 is the lowest priority, while 0 is the highest. According to EY-NPMA, network time is divided into access cycles, each one consisting of four distinct phases — prioritization, elimination, yield and data transmission. In order to reach the data transmission phase and hence get access to the common

---

Manuscript received August 9, 2006; revised May 15, 2007.

This work was supported by the Hellenic State Scholarships Foundation (I.K.Y.) and by the Greek General Secretariat of Research Technology (GSRT) within the framework of the project 'Irakleitos'. The authors are with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Greece. (E-mails: {gedimitr, torestis, niovi}@auth.gr).

medium, a network station must survive all three previous phases.

All stations that have data to transmit enter the access cycle, with each one of the first three phases reducing the number of active stations within the cycle. The design goal of the cycle architecture is to reduce the number of active stations to that extent, so that the station that reaches the fourth and final phase — data transmission — is unique. The first phase is responsible for keeping into the cycle the stations with the highest priority packets at the time. By listening to the common medium for as many slots as the priority level, hierarchical independence between priorities is accomplished. The stations that perceive the channel as idle for the whole listening interval transmit an energy burst for one slot, essentially signaling stations of lower priority to leave the access cycle. Those that do survive proceed to the next phase, elimination.

During this phase, all stations transmit energy bursts of random length. At the beginning of this phase, each station picks a random number of slots to burst, which follows a truncated geometric distribution. This distribution is defined by two parameters and namely the maximum number of slots allowed for bursting (m_{es}) and the probability of bursting for one more slot (p_e). As soon as a station stops bursting, it immediately checks the common medium. If the medium is sensed as idle, the checking station had the longest burst and – possibly among others – proceeds to the next phase of the access cycle. On the other hand, if the common medium was sensed as busy, the checking station obviously did not transmit the longest energy burst and thus is forced to leave the cycle.

The yield phase is the equivalent of a normal backoff phase. During yield, all stations that survived elimination monitor the common medium for a random number of slots. If the channel is sensed as idle for the whole interval, the corresponding station proceeds to the next phase and commences transmitting its data packet. If the medium is sensed as busy, the corresponding station leaves the access cycle in order to avoid packet collisions. Each station picks up a random number of slots to back off according to a uniform distribution. This distribution can be defined by a single parameter, the maximum number of slots allowed for backing off (m_y).

From the above paragraphs, it becomes evident that the actual contention resolution takes place during the elimination and yield phases. The elimination is responsible for normalizing the number of stations that are led to the yield phase; the characteristics of the truncated geometric distribution employed during elimination guarantee that the number of stations that survive this phase is quasi-constant, regardless of how many stations did enter elimination. Of course, such a characteristic is necessary, because the distribution that determines the number of slots that each station backs off during yield is fixed.

The four phase architecture employed by EY-NPMA leads to very good results regarding collision rates, as well as good scalability to larger network populations. EY-NPMA is compared to other access protocols in [20], [2], [13], while its performance is evaluated in [1], [12], [21], [6], [18], [5] [17]. One of the most criticised drawbacks of this scheme is the increased overhead. The elaborate synchronized access cycle is prone towards spending a significant amount of the available network time at the first three phases, reducing this way the capacity of the system to transfer actual data packets. One of the solutions employed towards reducing the number of slots spent during the first three phases is the addition of memory to the protocol. According to the standardized version of EY-NPMA, each synchronized access cycle is completely independent from the subsequent ones. Consequently, all the interim results of the access cycle are lost and the contention resolution process starts from scratch. On the other hand, by adding memory to the system the characteristics of a given synchronized access cycle (e.g. elimination phase length) may alter the behavior of the contending stations during subsequent cycles. This approach is taken in [19] and [8], showing that the addition of memory to EY-NPMA may lead to substantial gains. A different approach is taken in the case of Adaptive EY-NPMA, which is described in the following subsection.

B. Adaptive EY-NPMA

Adaptive EY-NPMA [7] aims at improving the attained medium utilization, but employs a different mechanism to achieve this goal. According to the Adaptive EY-NPMA protocol, the stations comprising the network population are capable of dynamically reconfiguring the working parameters of the medium access protocol, in order to adapt to the offered traffic.

As was shown in the previous subsection, each instance of the EY-NPMA protocol may be fully described by the three parameters m_{es}, m_y and p_e. These parameters completely define the two distributions employed during the phases involved in contention resolution, namely elimination and yield. According to the analytical model developed in [1] and [8], the optimal working parameters depend on two characteristics of the offered load: number of contending stations and payload size. Adaptive EY-NPMA aims at allowing the network population to operate under the optimal parameters of EY-NPMA at any given time, by estimating the level of contention and the payload size. Using these two estimations, the optimal working parameters are calculated subsequently via an analytical model.

Out of the two estimates that are needed as input for the analytical model, the average payload size is easier to obtain. By monitoring many access cycles, samples of the data transmission length can be obtained, which in turn make it trivial to find the average payload size. On the other hand, the number of contending stations is more difficult to estimate, since there is no direct information on this measure within the access cycle. However, it can easily be proven that the length of the elimination phase is strongly correlated to the level of contention. By taking samples of the elimination phase length of many subsequent cycles and feeding this data to a maximum likelihood estimator, it is possible to approximate satisfactorily the number of stations entering the synchronized access cycle.

The first step towards deducing the number of contending nodes is the construction of a vector that records the frequency with which the different elimination phase lengths occur. Specifically, the station(s) that undertake this task create and preserve a vector L, which consists of $m_{es}+1$ elements $L(j)$, where j represents the length of the elimination phase in slots, thus $j \in [0, m_{es}]$. The maximum number of slots allowed for bursting is m_{es}, while m_y defines the maximum number of slots allowed for backing off during yielding and p_e the probability with which a station may burst for one more slot.

Initially, the elements of the vectors L are set to 0. The contents of the $L(j)$ cell are increased by one for each occurance of an elimination phase of j slots. By monitoring many subsequent access cycles, these vectors will soon mirror the frequency with which the various elimination phase lengths occur. By comparing these values with those calculated using an analytical model, an estimation of the number of contending nodes may be deduced. According to the analytical model, the length of the elimination phase depends on the following three values: number of contending nodes (N), maximum number of slots allowed for bursting (m_{es}) and the probability defining the truncated geometric distribution (p_e).

With the number of contending stations and average payload size available, the optimal working parameters are calculated using the analytical model of EY-NPMA. The triplet (m_{es}, m_y, p_e) is subsequently diffused to the whole network population, essentially reconfiguring their medium access controllers. The above described scheme is presented in detail in [7], where it is also shown that significant gains may be achieved when the network population dynamically adapts to the offered load.

III. VARIABLE YIELD FOR ADAPTIVE EY-NPMA

A. Description

Adaptive EY-NPMA with Variable Yield is a medium access protocol that builds upon the Adaptive EY-NPMA scheme which has been described in the previous section. The addition of the Variable Yield mechanism aims at further improving the already good medium utilization characteristics of Adaptive EY-NPMA. As was shown in the previous section, Adaptive EY-NPMA does not alter the structure of the synchronized access cycle. The mechanisms dictating the behavior at each phase remain the same with those of the standardized version of EY-NPMA. In the case of Adaptive EY-NPMA, the improvement in medium utilization is caused by adapting the working parameters (m_{es}, m_y, p_e) to the offered load.

Adaptive EY-NPMA with Variable Yield allows the network population to reconfigure the working parameters of the medium access scheme, but also introduces a modification to the core EY-NPMA mechanism. Adaptive EY-NPMA with Variable Yield is based on the fact that the length of the elimination phase is strongly correlated to the number of nodes both entering as well as surviving elimination. The former characteristic is employed by the adaptive EY-NPMA protocol in order to estimate the number of simultaneously contending nodes, and thus calculate the optimal working parameters. On the other hand, the latter property is not used in either base or adaptive EY-NPMA. If the number of nodes entering elimination is already estimated — something which is already achieved in adaptive EY-NPMA — then the length of the elimination phase can further be used to provide an indication of the number of nodes surviving elimination and thus, entering the yield phase. Under the same traffic conditions, different elimination phase lengths are coupled with different average numbers of nodes entering yield. This way the range of the uniform distribution for backoff can be optimized on a per elimination length basis, improving the protocol's performance.

In Fig. 1, the distribution of the number of nodes entering yield for different elimination phase lengths is provided, using the analytical model of EY-NPMA provided in [8]. For this example, a network consisting of 50 nodes is analysed, where the maximum number of slots allowed for bursting (m_{es}) is equal to 4, while the probability of bursting of one more slot (p_e) is set to 0.3. These values were produced after an optimization run where 1000 bytes long packets were offered in priority 1. For this scenario the optimal value of m_y was found equal to 9. In this figure the x axis depicts the number of nodes surviving elimination, while in the y axis there is the probability of such an event. In this figure we have omitted the distribution for the case of a zero length elimination phase, since this scenario is trivial; in the unlikely event that no nodes burst, automatically all nodes survive the elimination stage.

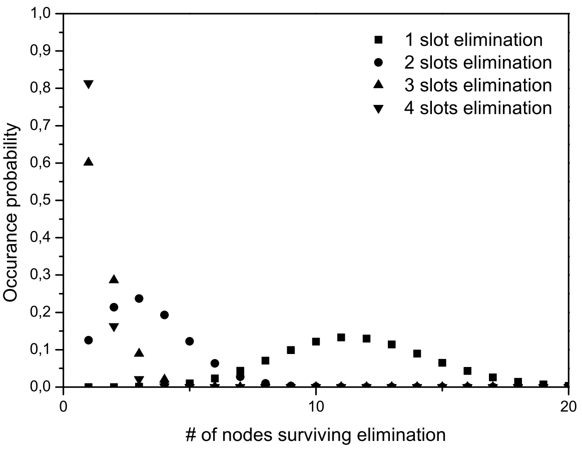


Fig. 1. Distribution of elimination survivors per elimination phase length.

TABLE I

PROBABILITY OF DIFFERENT ELIMINATION LENGTHS

Elimination Length	Occurrence Probability
0	∼ 0%
1	0.9%
2	24.6%
3	41.1%
4	33.4%

In table I, the probabilities with which the different elimination lengths occur are presented. From this table, it can be seen that in the majority of the cases the elimination phase lasts 2, 3 or 4 slots. On the other hand, a 1-slot elimination has a very slight probability of occurring, while a 0-slot elimination is almost impossible. Combining these results with those of Fig. 1, we can see that even though the elimination lengths of 2, 3 and 4 slots have comparable occurrence probabilities, the distributions of the surviving nodes have distinct differences. In the case of a 2 slot elimination, the occurrence probability is non-trivial up to 7 nodes, while for 3 and 4 slot eliminations, this is observed for 4 and 3 nodes respectively. In the unlikely event of a single slot elimination phase, the occurrence probabilities are non-trivial up to 19 nodes, with the peak being observed for 11 nodes.

According to the already established medium access schemes based on EY-NPMA, there exists a global maximum number of slots allowed for backing off during the yield phase. By observing the characteristics of the truncated geometric distribution, an example of which has been presented in Fig. 1, we can safely say that this global maximum m_y cannot possibly be the optimal choice for all outcomes of the elimination phase, since different elimination phase lengths lead to different distributions of the surviving nodes. Of course, in the base scheme, it would be impossible to differentiate m_y according to the elimination length, since the number of nodes entering the access cycle is not known. In this case the elimination stage serves to reduce and most importantly normalize the number of survivors entering the yield phase. On the other hand, in the adaptive version the combined knowledge of number of nodes entering the cycle and elimination phase length can be used to pick a value for m_y that maximizes the performance of the protocol.

Consequently, if the value of m_y depends on the outcome of the elimination phase, an instance of the protocol can no longer be described by the triplet (m_{es}, m_y, p_e). Rather, the scalar m_y must be replaced by a vector with $m_{es} + 1$ elements, symbolised as M_y. In order to enable variable yield in adaptive EY-NPMA, only minor modifications are needed. Specifically, instead of finding a global value of m_y that optimizes the overall performance, the optimization procedure picks the value of $M_y(i)$ that maximizes the performance in case of i-slot elimination phases, independently of the values that have been chosen for other elimination lengths. In all other accounts, the operation of the protocol is identical to that of adaptive EY-NPMA. After the optimal parameter set has been calculated, it is diffused to the network, with all participants reconfiguring themselves.

B. Analytical Model

In this subsection the analytical model of the proposed medium access scheme is presented. Moreover, the analytical model of adaptive EY-NPMA and the desing of the *maximum-likelihood estimator* are reviewed. The analytical model presented aims at providing a closed analytical form of the attainable medium utilization, given the number of stations entering the access cycle in the same priority (N) and the duration of a packet transmission (T_{pck}). The medium utilization is defined as the fraction of network time spent on successful data transmissions. It is a convenient metric, because it combines the effect of both overhead and packet collisions in a single result.

According to [8], 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 eq. (1) we can easily calculate the probability that an individual burst lasts k or less slots:

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

Finally, the probability that the elimination phase lasts exactly k slots may be calculated as:

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

Having this information at hand, an estimator for adaptive EY-NPMA is designed in [7] that take as input the vector L and provides at its output the estimation of the number of contending nodes N. The decision making criterion is to minimize the probability of error in mapping each given observation vector L into a decision. Consequently, the optimum decision rule states that:

$$P(n \text{ contending nodes}|L) \text{is maximum for } n = N \tag{4}$$

where P(n contending nodes$|L$) is the probability of having n simultaneously contending nodes, provided that we observed the vector L. The decision rule is shown that can be expressed as:

$$P(L|n \text{ contending nodes}) \text{is maximum for } n = N \tag{5}$$

Essentially, eq. (5) describes a *maximum-likelihood rule* and the estimator that employs it is referred to as a *maximum-likelihood estimator*. According to this rule, the estimator calculates P($L|n$ contending nodes) for all possible numbers of contending nodes and decides in favor of the maximum. To calculate these probabilities, however, it is necessary that we define the distribution that the vector L follows. L follows a multinomial distribution and the probability of having a specific instance of this vector is equal to:

$$P(L|n \text{ contending nodes}) = \frac{N_s!}{L(0)!\cdots L(m_{es})!} p_0^{L(0)} \cdots p_{m_{es}}^{L(m_{es})} \tag{6}$$

where p_k is the probability of having a k slots long elimination phase, when there are n simultaneously contending nodes. So:

$$p_k = P_{ED}(k)|_{N=n} \tag{7}$$

With the availability of the estimation of simultaneously contending nodes N, as well as the average packet length, it is easy to calculate the optimal working parameters of EY-NPMA. In order to calculate the optimal working parameters, the analytical model described in [8], which calculates the triplet that leads to the best throughput, is extended, so that it takes into account the dependence of the number of slots used during the yield phase on the length of the elimination phase.

Using eq. (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.

$$P_{nk\_E}(n,k) = \begin{cases} \binom{N}{n} P_E(k)^n P'_E(k-1)^{N-n}, & \text{if } 0 < k \le m_{es} \\ (1-p_e)^N, & \text{if } n = N, k = 0 \\ 0, & \text{if } n < N, k = 0 \end{cases} \tag{8}$$

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.

$$P_{n\_E}(n) = \sum_{k=0}^{m_{es}} P_{nk\_E}(n,k) \tag{9}$$

Consider that after an elimination phase that lasted l slots, N_Y stations out of N proceed to the next phase — yield. The probability that a station backs off for k slots is equal to:

$$P_Y(k,l) = \frac{1}{M_y(l)+1} \tag{10}$$

The probability that a station backs off for at least k slots, provided that an l-slot elimination took place is equal to:

$$P'_Y(k,l) = \sum_{i=k}^{M_y(l)} P_Y(i,l) = \frac{M_y(l)+1-k}{M_y(l)+1} \tag{11}$$

Consequently, the probability that the yield phase lasts k slots, provided that an l-slot elimination took place is equal to:

$$P_{YD}(k,l,N_Y) = \begin{cases} P'_Y(k,l)^{N_Y} - P'_Y(k+1,l)^{N_Y}, & \text{if } 0 \le k < M_y(l) \\ (\frac{1}{M_y(l)+1})^{N_Y}, & \text{if } k = M_y(l) \end{cases} \tag{12}$$

Using the above equation the average duration of the yield phase can be calculated, provided that the elimination phase lasted l slots and N_Y stations survived towards the yield phase.

$$\overline{S}_Y(l,N_Y) = \sum_{i=1}^{M_y(l)} i \cdot P_{YD}(i,l,N_Y) \tag{13}$$

The above equation can be used to find the overall (that is, regardless of the elimination phase length) yield phase length. In the following equation $P_{nk\_E}(i,l)$ represents the possibility of having i stations survive an l-slot elimination.

$$\overline{S}_Y = \sum_{i=1}^{N} \sum_{l=0}^{m_{es}} P_{nk\_E}(i,l) \cdot \overline{S}_Y(l,i) \tag{14}$$

If N_Y stations survive an l-slot elimination phase, the probability that n stations are the first to finish their backoff intervals at the k-th slot is equal to:

$$P_{nk\_Y}(n,k,l,N_Y) = \begin{cases} \binom{N_Y}{n} P_Y(k,l)^n P'_Y(k+1,l)^{N_Y-n}, & k < M_y(l) \\ (\frac{1}{M_y(l)+1})^{N_Y}, & k = M_y(l), n = N_Y \\ 0, & k = M_y(l), n < N_Y \end{cases} \tag{15}$$

Based on the above, the probability that there is no collision when N_Y stations enter yield after an l-slot elimination phase is equal to:

$$P_{NC}(l,N_Y) = \sum_{i=0}^{M_y(l)} P_{nk\_Y}(1,i,l,N_Y) \tag{16}$$

The overall probability of not having a collision can be obtained by summing the above equation for all l and N_Y, weighted with the probability of having such an elimination phase.

$$\overline{P}_{NC} = \sum_{i=1}^{N} \sum_{l=0}^{m_{es}} P_{nk\_E}(i,l) \cdot P_{NC}(l,i) \tag{17}$$

Now, all the characteristics of the access cycle are fully defined. Consequently, the achieved medium utilization may be calculated:

$$mu = \frac{\overline{P}_{NC} \cdot T_{pck}}{T_{cycle}} \tag{18}$$

In the above equation, T_{cycle} equals to the average duration of the synchronized access cycle.

C. Design Issues

The calculation of the optimal triplet employing this model is computationally intensive; thus it is highly impractical or even infeasible to have a mobile, battery powered device to execute this optimization process, which in order to have a beneficial effect must be repeated frequently. In order to avoid this resource consuming process, we propose the usage of precomputed EY-NPMA parameters for various instances of this optimization problem. According to this scheme, instead of calculating the optimal triplet from scratch, it is much more economical in terms of computational and power resources to find one of the precomputed scenarios that is most similar to the offered load sampled and then use the corresponding triplet. This way, the derivation of the EY-NPMA parameters becomes as easy as searching in a look up table, at the cost of a certaing degree of suboptimality. However, by precomputing a sufficient large number of offered load scenarios, the introduced error may be kept to a minimum, being overshadowed in fact by the error introduced while estimating the number of simultaneously contending nodes and the average payload size.

TABLE II
ANALYTICAL RESULTS FOR EY-NPMA

		Packet Size		
		250 bytes	**500 bytes**	**1000 bytes**
# of stations	**5**	2 5 0.35 ***0.476***	3 6 0.4 ***0.624***	3 7 0.45 ***0.748***
	10	2 6 0.25 ***0.462***	3 7 0.3 ***0.611***	4 8 0.35 ***0.738***
	20	2 7 0.2 ***0.452***	2 9 0.2 ***0.6***	4 9 0.3 ***0.727***

From the above, it becomes evident that the mechanism proposed may be employed in both distributed and centralized ways. However, while it is possible to allow each station in the network to find the optimal EY-NPMA parameters for itself, a number of issues associated with this approach dictate otherwise. First of all, a completely distributed approach demands that all nodes constantly monitor the common medium, an undertaking which is costly in resources, as for example computational power and battery energy. Also, for the estimation of the number of contending nodes, the mechanism presented assumes that all stations employ the same working parameters at all times. Consequently, in a distributed scenario all stations must have synchronised clocks and switch parameters at the same instant. Further, if each network node executes the above outlined process periodically based on the locally stored samples, there is a significant probability that diverse results are computed. Since, networks nodes are randomly added, switched on and off, it is high probable that the calculation of the optimal EY-NPMA parameters is executed with each node having slightly different data. This diversity may lead to groups of stations in the same wireless LAN operating under different parameters. Since the method for finding the optimal working parameters assumes that all network nodes employ the same set of parameters, this error will not only propagate, but grow. On the other hand, the centralized approach negates all the objections provided above. If the estimation of the optimal working parameters is a task allocated to one and only node of the wireless LAN, it is possible to choose for this role the access point to the wired network, which is free of energy concerns. If an access point is not available, high end devices may undertake this role, each for small amounts of time, so that this role does not become too taxing for a single network station and thus, unfair. Furthermore, if one node estimates the optimal working parameters and subsequently diffuses them to the network, there is no possibility that a loss of

TABLE III
ANALYTICAL RESULTS FOR EY-NPMA WITH VARIABLE YIELD.

		Packet Size		
		250 bytes	**500 bytes**	**1000 bytes**
# of stations	**5**	3 [19, 3, 0, 0] 0.15 ***0.503***	3 [24, 5, 1, 0] 0.2 ***0.649***	4 [29, 7, 3, 1, 0] 0.25 ***0.768***
	10	3 [29, 4, 0, 0] 0.1 ***0.496***	3 [29, 5, 1, 0] 0.1 ***0.638***	4 [29, 13, 4, 2, 1] 0.15 ***0.754***
	20	3 [29, 7, 1, 0] 0.1 ***0.474***	4 [29, 15, 4, 1, 0] 0.2 ***0.623***	5 [29, 23, 7, 3, 1, 0] 0.15 ***0.747***

synchronisation occurs. If a fraction of the network nodes miss the update message transmitted by the node that calculates the optimal parameters, this error will be short lived, since at the next update transmission, all network nodes will become synchronised again. Regarding the bandwidth requirements for the diffusion of the new parameters, the communications cost is negligible, since the contents of the broadcasted updates consist of a few numbers.

IV. PERFORMANCE EVALUATION

In this section, the impact of variable yield is evaluated. The comparison between EY-NPMA and EY-NPMA with Variable Yield is based on the corresponding analytical models, as well as on event-driven stochastic simulation runs that were conducted using a custom tool programmed by the authors in C++. In both cases, the channel rate is assumed to be 20 Mbps, while all stations are assumed to be entering the synchronized access cycle in priority 1. The slot lengths employed during elimination and yield are equal to those defined in the HIPERLAN standard. In the first set of experiments, each one of the protocols is optimized for a number of scenarios using the analytical models, with the achieved medium utilization and the optimal working parameters being recorded. In the second set of experiments the operation of a network is simulated. In the cases of adaptive EY-NPMA and adaptive EY-NPMA with variable yield, this means that the level of contention is estimated by monitoring subsequent cycles and is not known a priori, as is the case with the first set of experiments.

A. Analytical results

The results of this comparison are summarized in tables II and III, for EY-NPMA and EY-NPMA with Variable Yield respectively. Each cell in these tables corresponds to a specific level of contention-payload size combination. In the left hand of the cell the optimal working parameters for each protocol are presented, while in the right hand with bold italics the achieved medium utilization is recorded. The working parameters are written in the form (m_{es}, m_y, p_e) for EY-NPMA and (m_{es}, M_y, p_e) for EY-NPMA with Variable Yield. From a quick glance it is evident that the modifications introduced by Variable Yield have a positive effect on the data transferring capacity of the system. The same collisions probabilities may be achieved, without however spending as many slots during elimination and yield as with the standardized EY-NPMA protocol.

From table II, it can be seen that the optimal maximum slots allowed for backing off during yield are heavily dependent on the elimination phase length. As longer elimination phases are examined, the stations entering yield are fewer and thus the vector $M_y(l)$ shows a declining trend as l increases. This way the distribution used during yield adapts to the expected number of stations entering it, in contrast to EY-NPMA, where a good all-around distribution is employed. It should be noted here that because the optimization runs were conducted using numerical methods, an absolute maximum for the $M_y(l)$ was chosen. This value was set to 29 and this is the reason why $M_y(0)$ is equal to 29 in many of the examined instances.

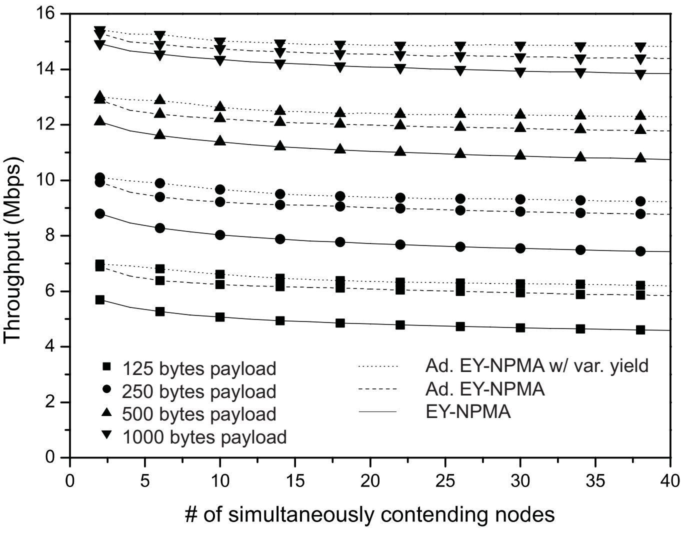


Fig. 2. Medium utilization versus number of contending nodes.

B. Simulation results

The simulation results are presented in Fig. 2 and 3. In Fig. 2 the attained throughput for different payload sizes and numbers of simultaneously contending nodes is depicted, while in Fig. 3 the mean access delay for the same scenarios are provided.

In this set of experiments EY-NPMA, Adaptive EY-NPMA and Adaptive EY-NPMA with Variable Yield are compared via simulation runs. In the case of the standardised version of EY-NPMA, it is assumed that all network stations operate using the set of parameters presented in the HIPERLAN standard, namely $(12, 9, 0.5)$. In the other two cases, the network stations reconfigure themselves according to the offered load and thus the operating parameters are not known a priori, but are chosen on the fly. The comparison of the three examined protocols in terms of throughput, confirms the initial hypothesis that differentiation of the backoff distribution per elimination phase length does lead to better usage of the available raw bandwidth. As can be seen from Fig. 2, adaptive EY-NPMA with variable yield achieves the best performance, being followed by adaptive EY-NPMA, while the base EY-NPMA scheme was the worst performer in the examined scenarios. More important, this classification holds true for all combinations of payload lengths and network populations that were examined. In absolute terms, the proposed protocol improved throughput, compared to adaptive EY-NPMA, by a margin that ranges between 0.4 and 0.6 Mbps, a difference that even though not impressive is substantial. In relative terms, this improvement ranges between 6% for the shortest packets, to almost 3% for the longest ones.

Regarding mean access delay, Fig. 3 shows that the variable yield mechanism has a beneficial effect, reducing the time that is needed for a packet to get transmitted. For all scenarios

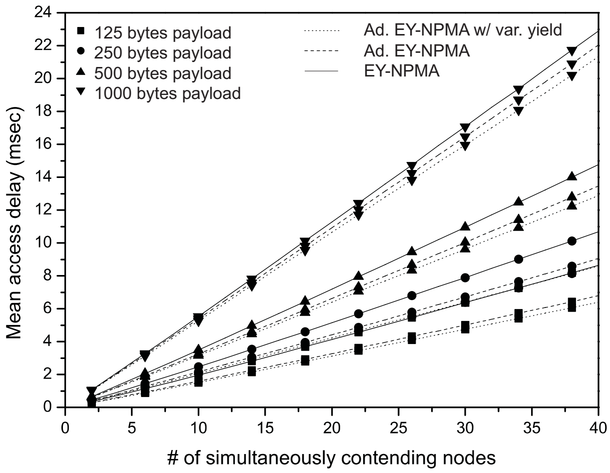


Fig. 3. Mean access delay versus number of contending nodes.

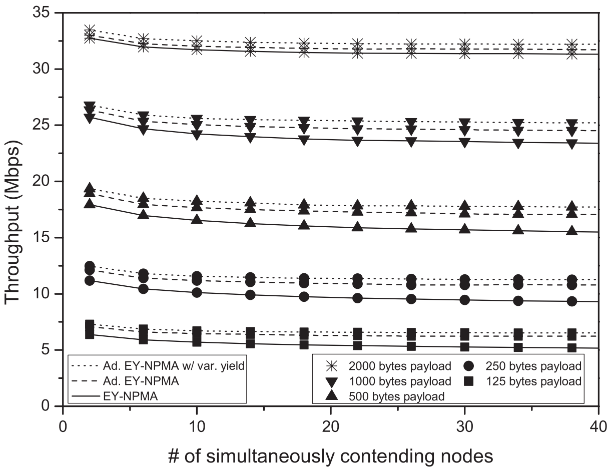


Fig. 4. Medium utilization versus number of contending nodes - Channel rate 47 Mbps.

examined, the adaptive EY-NPMA protocol with variable yield demonstrated the lowest access delay figures, with the base EY-NPMA showing the worst ones. Furthermore, the delay figures of the variable yield mechanism with 250 bytes long packets are the same with the delay figures of the base scheme when serving packets of the half size.

Based on the presented figures, it becomes evident that the optimal operating point of EY-NPMA, as well as of most distributed medium access schemes, depends on two characteristics of the offered load; number of simultaneously contending nodes and payload size. By continuously monitoring the offered load and periodically reconfiguring itself based on these measurements, adaptive EY-NPMA with variable yield achieves gains in terms of both throughput and access delay. The increased throughput of the proposed protocol is ascribed to its ability to balance two different qualities that are both desirable - low collision rates and short access cycles. Arbitrarily low collision rates may be achieved at the cost of long access cycles and vice versa. By intuition, one could justify longer access cycles in the case of large data payloads, since packet collisions are particlUarly destructive as the payload size increases. On the other hand, the opposite holds true in the case of short payloads. In such scenarios, the time needed for a slot during prioritization, elimination or yielding is a significant fraction of the time needed for the transmission of the actual payload. Consequently, it is inefficient to guarantee low collision rates, when most of the available capacity is expended as overhead. By introducing a controlled degree of collisions, the average cycle of adaptive EY-NPMA with variable yield becomes shorter and the medium utilization increases.

However, as advances in the physical layer lead to higher bitrates, the optimal operating point of adaptive EY-NPMA with variable yield will depend on the channel rate as well. This is due to the fact that 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.

Fig. 4 and 5 present the attained throughput for different payload sizes and numbers of simultaneously contending nodes, when the channel rate is set to 47 Mbps and 94 Mbps respectively. As in the case of 20 Mbps channel rate, adaptive EY-NPMA with variable yield achieves the best performance, being followed by adaptive EY-NPMA and the base EY-NPMA scheme. It should be stressed that, as the available raw bandwidth increases, the proposed scheme exhibits better performance for both long and short packet lengths. Its increased performance for both scenarios is accounted to the fact that, adaptive EY-NPMA with variable yield provides the best balance between the overhead and the collision rate among the three medium access schemes. For high bitrates, the time needed for a slot transmission is a significant fraction of the time needed for the transmission of the actual payload; therefore the low collision rate of EY-NPMA and adaptive EY-NPMA comes at the expense of their increased overhead and, consequently, their reduced efficiency.

For channel rate 47 Mbps and for long packet lengths, the proposed protocol improved throughput by 0.7 and 2 Mbps compared to adaptive EY-NPMA and EY-NPMA respectively. For short packet lengths, the proposed scheme outperformed adaptive EY-NPMA by 0.5 Mbps and EY-NPMA by 1.6 Mbps. In the case of 94 Mbps channel rate and long packet legths, the proposed protcol achieves 1.3 Mbps higher throughput than adaptive EY-NPMA and 4 Mbps higher throughput than the base scheme, while for short packet lengths the throughput of adaptive EY-NPMA with variable yield is 0.6 Mbps higher than that of adaptive EY-NPMA and 2.5 Mbps higher than the throughput of the base EY-NPMA scheme.

V. CONCLUSIONS

In this paper, a modification of the recently proposed Adaptive EY-NPMA was proposed, described and evaluated. By employing the strong correlation that exists between the length of the elimination phase and the number of nodes entering yield, substantial improvements of the protocol performance could be drawn. To achieve this, the characteristics of the uniform distribution used during backoff were not constant, but varied according to the outcome of the elimination phase.

REFERENCES

[1] G. Anastasi, L. Lenzini, and E. Mingozzi, “HIPERLAN/1 MAC protocol: Stability and performance analysis”, *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 9, September 2000, pp. 1787–1798.

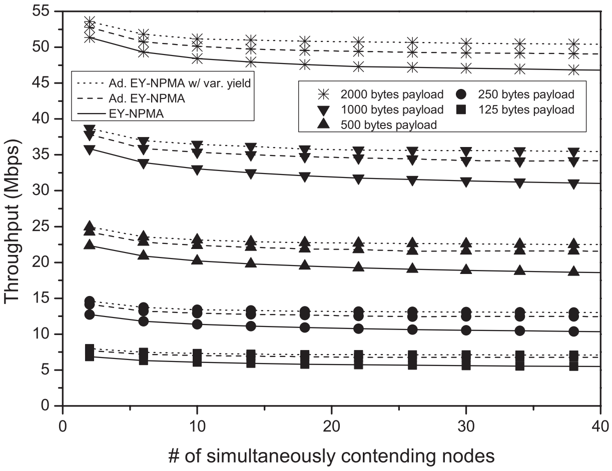


Fig. 5. Medium utilization versus number of contending nodes - Channel rate 94 Mbps.

[2] C. Apostolas, R. Tafazolli, and B.G. Evans, "Comparison between elimination yield non pre-emptive priority multiple access (EY-NPMA) and dynamic TDMA (D-TDMA)", in *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '96)*, Taipei, Taiwan, October 1996.

[3] M. Benveniste, G. Chesson, M. Hoeben, A. Singla, H. Teunissen, and M. Wentink, "EDCF Proposed Draft Text. IEEE Working Document 802.11-01/131r1", March 2001.

[4] Bluetooth SIG, "Specification of the Bluetooth System - Core v1.0b", 1999.

[5] S. Chevrel, A.H. Aghvami, H. Lach, and L. Taylor, "Analysis and optimisation of the HIPERLAN Channel Access Contention Scheme", *International Journal of Wireless Personal Communications*, vol. 4, no. 1, January 1997, pp. 27–39.

[6] C. Coutras and P.-J. Wan, "Evaluating performance of the HIPERLAN CAC layer protocol for asynchronous traffic", in *Proc. Conference on Local Computer Networks (LCN '99)*, Lowell, USA, 1999.

[7] G. Dimitriadis and F.-N. Pavlidou, "Adaptive EY-NPMA: A Medium Access Protocol for Wireless LANs", *Journal of Communication Networks*, vol. 6, no. 4, December 2004, pp. 307–316.

[8] G. Dimitriadis and F.-N. Pavlidou, "Two Alternative Schemes to EY-NPMA for Medium Access in High Bitrate Wireless LANs", *International Journal of Wireless Personal Communications*, vol. 28, no 2, January 2004, pp. 121–142.

[9] G. Dimitriadis and F.-N. Pavlidou, "Variable Yield for Adaptive EY-NPMA", in *Proc. WOCN 2005*, Dubai, United Arab Emirates, March 2005.

[10] ETSI, "DTS BRAN-0020004-1 v0.m: Broadband Radio Access Networks (BRAN): HIgh PErformance Radio Local Area Network (HIPERLAN) Type II: Data Link Control (DLC) Layer: Part 1: Basic Transport Functions", 1999.

[11] ETSI, "EN 300 652 v1.2.1: Broadband Radio Access Networks (BRAN): HIgh PErformance Radio Local Area Network (HIPERLAN) Type I: Functional Specification", 1998.

[12] K. Fu, Y.J. Guo, and S.K. Barton, "Performance of the EY-NPMA Protocol", *International Journal of Wireless Personal Communications*, vol. 4, no. 1, January 1997, pp. 41–50.

[13] Z. Hadzi-Velkov and B. Spasenovski, "Performance comparison of IEEE 802.11 and ETSI HIPERLAN type 1 under influence of burst noise channel", in *Proc. Wireless Communications and Networking Conference (WCNC 2000)*, Chicago, USA, September 2000.

[14] IEEE, "802.11: Wireless LAN Medium Access Control (MAC) and Physical Layer Specification", 1997.

[15] IEEE, "802.11a: Wireless LAN Medium Access Control (MAC) and Physical Layer Specifications, High-speed Physical Layer in the 5 GHz Band", 1999.

[16] IEEE, "802.11g: Further Higher Data Rate Extension in the 2.4 GHz Band", 2004.

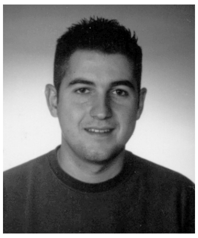
[17] P. Jacquet, P. Minet, P. Muhlethaler, and N. Rivierre, "Data Transfer in HIPERLAN", *International Journal of Wireless Personal Communications*, vol. 4, no. 1, 1997, pp. 65–80.

[18] P. Jacquet, P. Minet, P. Muhlethaler, and N. Rivierre, "Priority and Collision Detection with Active Signaling The Channel Access Mechanism of HIPERLAN", *International Journal of Wireless Personal Communications*, vol. 4, no. 1, 1997, pp. 11-25.

[19] T. Janczak and J. Wozniak, "Modified EY-NPMA Channel Access Scheme", *IEE Electronics Letters*, vol. 37, no. 10, May 2001, pp. 655-656.

[20] J. Weinmiller, M. Schlager, A. Festag, and A. Wolisz, "Performance Study of Access Control in Wireless LANs - IEEE 802.11 DFWMAC and ETSI RES 10 HIPERLAN", *ACM/BALTZER Mobile Networks and Applications*, vol. 2, no. 1, 1997, pp. 55–67.

[21] I. Vukovic, "HIPERLAN type I: performance analysis of the channel access control protocol", in *Proc. IEEE Vehicular Technology Conference (VTC '98)*, Ottawa, Canada, May 1998.



Gerasimos Dimitriadis received his Diploma in electrical and computer engineering from the Aristotle University of Thessaloniki, Greece in 2001. He is currently working towards his Ph.D. degree in the same department. His research interests include medium access, as well as routing in multihop wireless networks.

Orestis Tsigkas received his Diploma in electrical and computer engineering from the Aristotle University of Thessaloniki, Greece in 2002. He is currently working towards his Ph.D. degree in the same department. His research interests include medium access, as well as quality-of-service provisioning.

Fotini-Niovi Pavlidou received the Ph.D. degree in electrical engineering from the Aristotle University of Thessaloniki, Greece, in 1988 and the Diploma in mechanical-electrical engineering in 1979 from the same institution. She is currently a Professor at the Department of Electrical and Computer Engineering at the Aristotle University engaged in teaching for the under- and post-graduate program in the areas of mobile communications and telecommunications networks. Her research interests are in the field of mobile and personal communications, satellite communications, multiple access systems, routing and traffic flow in networks and QoS studies for multimedia applications over the Internet. She is being involved with many national and international projects in these areas (Tempus, COST, Telematics,IST) and she has been chairing the European COST262 Action on Spread Spectrum Systems and Techniques forWired andWireless Communications. She has served as member of the TPC in many IEEE/IEE conferences and she has organized/chaired some conferences like, the IST Mobile Summit 2002, the 6th International Symposium on Power Lines Communications-ISPLC2002, the International Conference on Communications-ICT1998 etc. She is a permanent reviewer for many IEEE/IEE journals. She has published about 80 papers in refereed journals and conferences. She has served as guest-editor on special issues as: Mobile Ad Hoc Networks (MANETs): Standards, Research, Applications in the International Journal of Wireless Information Networks and Power Line Communications and Applications in the International Journal on Communications Systems. She is a senior member of IEEE, currently chairing the joint IEEE VT&AES Chapter in Greece.