Resource Control for the EDCA and HCCA Mechanisms in IEEE 802.11e Networks

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Abstract— **We investigate the problem of efficient resource control for elastic traffic over the EDCA (Enhanced Distributed Channel Access) and HCCA (Hybrid Coordination Function - HCF - Controlled Channel Access) mechanisms of IEEE 802.11e. Our approach considers an economic modelling framework based on congestion pricing that captures how various factors, such as the probability of attempting to transmit a frame, the transmission opportunity (TXOP), and the physical layer transmission rate, contribute to congestion. Additionally, we consider the joint control of the EDCA and HCCA mechanisms, which allows us to determine the optimal sharing of the wireless channel between the two access mechanisms.**

I. INTRODUCTION

In wireless networks, unlike wired networks, there is a limited capability to increase the capacity. Along with the increasing use of wireless networks by users and applications with different requirements, this creates the need for models and procedures that efficiently utilize the wireless channel and support service differentiation. One approach for developing such procedures is based on economic modelling, with the use of utility functions for encoding user requirements and congestion pricing for providing the right incentives for efficient resource utilization through a decentralized control approach.

In this paper we use economic modelling to provide practical ways to derive congestion prices and the values of 802.11e's control parameters in order to efficiently utilize the network resource (wireless channel). The proposed models take into account the specific characteristics and operation of both the contention-based EDCA (Enhanced Distributed Channel Access) and polling-based HCCA (Hybrid Coordination Function - HCF - Controlled Channel Access) mechanisms. In particular, we extend previous work that focused on the EDCA mechanism and resource sharing through the minimum contention window [1]. The extensions involve models that consider the transmission opportunity (TXOP) parameter for controlling resource sharing in the contention-based EDCA and the polling-based HCCA mechanisms, in multi-rate 802.11e systems. Additionally, joint consideration of EDCA and HCCA enables us to determine the optimal sharing of the wireless channel between the contention-free and the contention periods. The proposed models can be applied in a class-based service differentiation framework, where different classes have a different price per unit of time, and a different minimum contention window or transmission opportunity (TXOP).

The rest of the paper is organized as follows. In Section II we present a brief overview of IEEE 802.11e's EDCA and HCCA mechanisms. In Section III we discuss analytical throughput models for multi-rate 802.11e networks. In Section IV we present our framework for efficient resource control for both the EDCA and HCCA mechanisms. In Section V we present experimental results that demonstrate the proposed resource control models. Finally, in Section VI we present a brief overview of related work, identifying where it differs from the work presented in this paper, and in Section VII we conclude the paper discussing the application of the proposed models and identifying future research directions.

II. EDCA AND HCCA

In IEEE 802.11, access to the shared wireless channel is controlled through two MAC layer mechanisms: polling-based PCF (Point Coordination Function) and contention-based DCF (Distributed Coordination Function). DCF is based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). With CSMA/CA prior to a frame transmission the wireless channel must be sensed idle for a time interval called interframe spacing (IFS), which can be different for different frame types; hence, for data frames the interval is a DCF-IFS (DIFS), and for acknowledgements it is a short IFS (SIFS). In wireless networks, unlike in Ethernet LANs, collision detection is not possible or is too costly. For this reason the DCF mechanism uses collision avoidance: Before initiating the transmission of a frame, a station selects a random backoff period from the interval $[0, CW-1]$, where CW is referred to as contention window. The station waits for the channel to be idle for a total time equal to this backoff period, after which it senses the channel to see if it is idle for an interval DIFS, in which case it can transmit a data frame, when the basic CSMA/CA procedure is used, or an RTS frame, when the RTS/CTS procedure is used. The contention window has an initial value CW_{min}, and is doubled when a collision occurs, up to the maximum value CW_{max}.

IEEE 802.11e is a supplement to the 802.11 standard that addresses the issue of QoS support in wireless LANs. The MAC protocol of 802.11e is the Hybrid Coordination

Function (HCF), which supports both contention-based and controlled channel access [2]. The contention-based access of HCF is implemented by the Enhanced Distributed Channel Access (EDCA) mechanism, which is an extension of the DCF mechanism that enables distributed differentiated access to the wireless channel with the support of multiple access categories (ACs). A higher priority access category has a smaller minimum contention window CW_{min}, thus has a higher probability to access the channel. Additionally, different access categories can have different values for the maximum contention window CW_{max} and the interframe spacing interval (IFS). An important addition of EDCA is the capability of a station, once it captures access of the channel, to deliver data up to a maximum time interval called EDCA transmission opportunity (TXOP). The HCCA (Hybrid Coordination Function - HCF - Controlled Channel Access) mechanism is based on polling, similar to the basic PCF mechanism [2]. A difference of the HCCA mechanism is that when a station is polled, it is allowed to transmit packets holding the channel up to a maximum time interval referred to as HCCA or polled transmission opportunity (TXOP). The standard allows the definition of a contention period, where the EDCA mechanism is typically used, and a contention-free period, where the HCCA mechanism is used for channel access.

III. ANALYTICAL MODELS FOR THROUGHPUT

In this section we discuss analytical models that capture the congestion effects that a wireless station has on the throughput of other stations in the same 802.11e wireless network; the models will be used in the next section to compute congestion prices.

A. Throughput model for contention-based access (EDCA)

Several analytical studies have approximated the congestion avoidance procedure of IEEE 802.11 with a p-persistent model [3], [4]. In a p-persistent model, the probability that a wireless station tries to transmit in a time slot is p, and is independent of the success or failure of previous transmission attempts. If $E[CW]$ is the average contention window, then the approximate p-persistent model has transmission probability $p = \frac{2}{E[CW]+1}$ [3]. Although the p-persistent model does not capture the exponential backoff behavior of 802.11's congestion avoidance mechanism, it provides us with a simple expression for the throughput, and is accurate in the range of values that maximize the aggregate utility or the aggregate throughput [1]. If the probability of a frame being involved in more than one collision is very small, then $E[CW] \approx CW_{min}$ [4]. In IEEE 802.11e, different wireless stations can have a different minimum contention window, hence using the same arguments as above [4], the corresponding transmission probability of station i in the p-persistent model is

$$p_i = \frac{2}{CW_{min,i}+1} \, .$$

The MAC operation of IEEE 802.11 can be viewed in time as involving three different types of time intervals: a successful transmission interval, a collision interval, and an idle time interval. Let the length of the first two intervals be T^{suc} and T^{col}, which we assume to be normalized to the duration of the idle time interval. The duration of each time interval depends on the physical layer encoding and the MAC layer operations. The average throughput x_i for station i can be expressed as the ratio of the average amount of data transmitted by that station in one time interval $E[X_i]$ over the average time interval $E[T]$: $x_i = \frac{E[X_i]}{E[T]}$[5], [3], [4]. If we assume that the individual transmission probabilities p_i and the aggregate transmission probability are very small, then the average throughput for station i is approximately

$$x_i = \frac{p_i(1-P_{-i})L}{\sum_k p_k(1-P_{-k})T^{suc} + [P - \sum_k p_k(1-P_{-k})]T^{col} + 1 - P} \, , \tag{1}$$

where L is the frame length, which for simplicity we assume to be the same for all stations, $P = \sum_j p_j$ is the aggregate transmission probability, and $P_{-k} = \sum_{j \neq k} p_j$. Note that the above expression is valid for all versions of 802.11, provided all stations have the same transmission rate. The specific version of 802.11, and whether the CSMA/CA or RTS/CTS procedure is used, will determine the values of T^{suc} and T^{col}, which we have taken to be normalized to the duration of the idle interval.

With the RTS/CTS procedure, the transmission rate does not affect the collision interval, since the latter involves RTS frames which are always transmitted at the basic rate (1 Mbps). Hence, with RTS/CTS and stations having different transmission rate rates, the average throughput is

$$x_i = \frac{p_i(1-P_{-i})L}{\sum_k p_k(1-P_{-k})T_k^{suc} + [P - \sum_k p_k(1-P_{-k})]T^{col} + 1 - P} \, . \tag{2}$$

In the last expression the successful transmission probability will be different for stations with a different physical layer transmission rate.

If T_{CFP} and T_{CP} is the duration of the contention-free period and the contention period, respectively, and we assume that in the contention period only the EDCA mechanism is used, then the above throughput expression is multiplied by the factor $\frac{T_{CP}}{T_{CP}+T_{CFP}}$.

Now consider the case where once a station gains access to the wireless channel, it is allowed to transmit for a time interval o_j (EDCA-TXOP); the throughput for station i is

$$x_i = \frac{p_i(1-P_{-i})R_i o_i}{\sum_k p_k(1-P_{-k})(a+o_k) + [P - \sum_k p_k(1-P_{-k})]T^{col} + 1 - P} \, , \tag{3}$$

where R_i is the physical layer transmission rate of station i[1]. In the last expression, the sum $a + o_k$ is the successful transmission interval, with a being the physical layer and IFS overhead, and the MAC layer acknowledgement transmission time.

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[1] For simplicity, we do not consider the MAC layer overhead.

B. Throughput model for controlled access (HCCA)

According to the HCCA mechanism, a polled station i is allowed to transmit data up to a maximum time interval o_i, referred to as the polled transmission opportunity (polled-TXOP); the polled-TXOP is assigned by a scheduler operating at the access point. If R_i is the physical layer transmission rate of station i, then in time o_i station i can transmit an amount of data $R_i o_i$[1], hence its throughput is

$$x_i = \frac{R_i o_i}{\sum_j o_j} \,. \tag{4}$$

If access to the wireless channel is through both contention-based and controlled (contention-free) access, and the HCCA mechanism is used only in the contention-free period, then the throughput for station i can be approximated by (4) multiplied by the factor $\frac{T_{CFP}}{T_{CP}+T_{CFP}}$.

IV. RESOURCE CONTROL MODEL

In this section, based on the throughput models of the previous section, we present a congestion pricing framework for efficiently utilizing the wireless channel. We consider the case of elastic users, which value the average throughput of data transfer. The utility for such a user i is $U_i(x_i)$, where the average throughput x_i depends on the parameter q_i used for controlling access to the wireless channel; for contention-based access the control parameter is the transmission probability or the EDCA transmission opportunity (TXOP), whereas for controlled access it is the polled transmission opportunity (polled-TXOP).

Consider the global problem of maximizing the aggregate utility in a wireless system with N users

$$\begin{aligned} \text{maximize} \quad & \sum_i U_i(x_i) \\ \text{over} \quad & \mathbf{q} \geq 0 \,, \end{aligned} \tag{5}$$

where $\mathbf{q} = (q_i, 1 \leq i \leq N)$ is the vector of control variables and the throughput x_i is of the form $f(\mathbf{q})$. The necessary conditions for the maximization in (5), if the maximum is achieved for $\mathbf{q} > 0$, are

$$\frac{\partial \sum_i U_i(x_i)}{\partial q_i} = \frac{\partial U_i(x_i)}{\partial q_i} + \sum_{j \neq i} \frac{\partial U_j(x_j)}{\partial q_i} = 0 \quad \forall i \in N \,. \tag{6}$$

A. Resource control for contention-based access (EDCA)

Next we first consider the case where resource sharing is based on the transmission probabilities, and then the case where resource sharing is based on the transmission opportunities.

1) Control of the transmission probability: We present only the case where different wireless stations have different transmission rates, which affect the duration of the successful transmission interval T^{suc}, but not the duration of the collision interval T^{col}; this is the case when the RTS/CTS procedure is used. The throughput for station i is now given by (2). Substituting (2) in (6), and after some mathematical manipulations, we find that the necessary conditions for the global optimization problem are approximately

$$\frac{\partial U_i(x_i)}{\partial p_i} = L \frac{(1-P)^2 T_i^{suc} + P(2-P)T^{col}}{E[T]^2} \sum_j U_j' p_j \,, \quad 1 \leq i \leq N \,, \tag{7}$$

where $P = \sum_j p_j$. If $p_i \ll P$, then we have

$$E[T] \approx (1-P) \sum_j p_j T_j^{suc} + P^2 T^{col} + 1 - P \,.$$

To solve the global optimization problem in a distributed manner we define the following user problem

$$\begin{aligned} \text{maximize} \quad & U_i(x_i) - (\lambda_1 T_i^{suc} + \lambda_2) p_i \\ \text{over} \quad & p_i \geq 0 \,, \end{aligned} \tag{8}$$

where we see that the congestion price can be different for different users, and depends on factors λ_1, λ_2, and the successful transmission interval T_i^{suc}, which depends on the physical layer transmission rate. The necessary condition for the user optimum is

$$\frac{\partial U_i(x_i)}{\partial p_i} = \lambda_1 T_i^{suc} + \lambda_2 \,.$$

From the last equation and (7), the user and global problems coincide if

$$\lambda_1 = \frac{L(1-P)^2}{E[T]^2} \sum_j U_j' p_j \,, \quad \lambda_2 = \frac{LP(2-P)T^{col}}{E[T]^2} \sum_j U_j' p_j \,. \tag{9}$$

The congestion price in (8) has two components: The first component $\lambda_1 T_i^{suc}$ contains the factor λ_1, which depends on the level of congestion in the wireless channel and the duration of a successful transmission T_i^{suc}. The second component λ_2 is related to the level of congestion. The interpretation of the above is that the congestion cost for a wireless station depends, in addition to its throughput, also on the duration of the successful transmission interval, which in turn depends on the station's transmission rate. For stations with the same average throughput, the station with the smaller transmission rate, which will have a longer successful transmission interval, will induce a higher congestion cost.

In the case of proportional sharing, the utility for user i is given by $U_i(x_i) = w_i \log x_i$ [6], where w_i is a weight or willingness-to-pay factor. In this case we have

$$\sum_j U_j' p_j = \sum_j \frac{w_j}{x_j} p_j = \frac{E[T]}{(1-P)L} \sum_j w_j \,.$$

Substituting this equation in (9) we find

$$\lambda_1 = \frac{1-P}{E[T]} \sum_j w_j \,, \quad \lambda_2 = \frac{P(2-P)T^{col}}{(1-P)E[T]} \sum_j w_j \,. \tag{10}$$

From (8), if $p_i \ll P$, we have $\frac{\partial U_i(x_i)}{\partial p_i} = \lambda_1 T_i^{suc} + \lambda_2 \Rightarrow x_i = \frac{E[T]}{1-P} \frac{w_i}{\lambda_1 T_i^{suc} + \lambda_2}$, from which we find

$$p_i = \frac{w_i}{\sum_j w_j} \frac{(1-P)E[T]}{(1-P)^2 T_i^{suc} + P(2-P)T^{col}} \,.$$

2) Control of the transmission opportunity (TXOP): Assume that the sharing of the wireless resource is controlled through the EDCA transmission opportunity (TXOP) o_i; here we assume that the transmission probabilities p_i are fixed. The throughput is given by (3). Substituting this equation in (6) we find that the necessary conditions for the global optimum are

$$\frac{\partial U_i(x_i)}{\partial o_i} = \frac{p_i(1-P)^2}{E[T]^2} \sum_j U_j' p_j R_j o_j \,, \quad 1 \le i \le N \,, \tag{11}$$

where $P = \sum_j p_j$. If $p_i \ll P$, then we have

$$E[T] \approx (1-P) \sum_j p_j (a + o_j) + P^2 T^{col} + 1 - P \,.$$

To solve the above optimization problem in a distributed manner we define the following user problem

$$\begin{aligned} \text{maximize} \quad & U_i(x_i) - \lambda p_i o_i \\ \text{over} \quad & o_i \ge 0 \,. \end{aligned} \tag{12}$$

The necessary condition for achieving the user optimum is $\frac{\partial U_i(x_i)}{\partial o_i} = \lambda p_i$. From this equation and (11), the user and global optimization problems coincide if

$$\lambda = \frac{(1-P)^2}{E[T]^2} \sum_j U_j' p_j R_j o_j \,.$$

The current and previous subsections considered maximizing the aggregate utility over the transmission probabilities and the transmission opportunities separately. Following a similar approach, one can consider maximizing the aggregate utility jointly for both control parameters.

B. Resource control for controlled access (HCCA)

The control variables q_i in (5) are now the polled transmission opportunity o_i, which defines the maximum time interval in which station i can transmit data. Based on the dependence of the throughput x_i on o_i (4), we have $\frac{\partial U_j(x_j)}{\partial o_i} = U_j' \frac{\partial x_j}{\partial o_i} = -\frac{U_j' R_j o_j}{(\sum_k o_k)^2}$. Hence, from (6) the necessary conditions for maximizing the aggregate utility are

$$\frac{\partial \; U_i(x_i)}{\partial o_i} = \frac{1}{(\sum_k o_k)^2} \sum_j U_j' R_j o_j \,, \quad 1 \le i \le N \,. \tag{13}$$

To solve the above optimization problem in a distributed manner we can define the user problem identical to (12). The necessary condition for the user optimum is $\frac{\partial U_i(x_i)}{\partial o_i} = \lambda$. From this equation and (13), the user and global optimization problems coincide if

$$\lambda = \frac{1}{(\sum_j o_j)^2} \sum_j U_j' R_j o_j \,. \tag{14}$$

In the case of proportional resource sharing, the user utility has the logarithmic form $U_i(x_i) = w_i \log x_i$, where w_i is a weight or willingness-to-pay factor. For such a utility we have $\sum_j U_j' R_j o_j = \sum_j \frac{w_j}{x_j} R_j o_j = \sum_j w_j \sum_k o_k$. Substituting the last equation in (14) we have $\lambda = \frac{\sum_j w_j}{\sum_j o_j}$, from which we can find that the optimal values of o_i and x_i are $o_i = \frac{w_i}{\sum_j w_j} \sum_j o_j$ and $x_i = \frac{w_i}{\sum_j w_j} R_i$.

C. Coexistence of contention-based and controlled access

The previous sections focused on optimizing usage of the wireless channel when pure EDCA or pure HCCA is used. IEEE 802.11e allows the interleaving of contention-free periods, with duration T_{CFP}, and contention periods, with duration duration T_{CP}. In this section we discuss how to select the percentage of each type of period in order to efficiently utilize the wireless channel.

Assume both the EDCA and HCCA mechanisms coexist, and let $\mathbf{p} = (p_i, 1 \le i \le N^{\text{EDCA}})$ and $\mathbf{o} = (o_j, 1 \le j \le N^{\text{HCCA}})$ be the vector of control variables for each access method, where N^{EDCA} and N^{HCCA} are the number of stations participating in contention-based and controlled access respectively. The throughput $x_i^{\text{EDCA}}(\mathbf{p}, \rho)$ for a station participating in contention-based access is given by (2) multiplied by $\rho = \frac{T_{CP}}{T_{CP} + T_{CFP}}$, which represents the percentage of time allocated to the contention period; the throughput $x_i^{\text{HCCA}}(\mathbf{o}, \rho)$ for a station participating in controlled access is given by (4) multiplied by $1 - \rho$. The optimal values of $\mathbf{p}$, $\mathbf{o}$, and ρ, can be found from the following optimization

$$\begin{aligned} \text{maximize} \quad & \sum_i U_i^{\text{EDCA}}(x_i^{\text{EDCA}}(\mathbf{p}, \rho)) + \sum_j U_j^{\text{HCCA}}(x_i^{\text{HCCA}}(\mathbf{o}, \rho)) \\ \text{over} \quad & \mathbf{p} \ge 0, \, \mathbf{o} \ge 0, \, 0 \le \rho \le 1 \,. \end{aligned}$$

V. EXPERIMENTS

In this section we present experimental results that demonstrate the models presented in the previous sections. In particular, we investigate the impact of the minimum contention window and transmission opportunity (TXOP) parameters on service differentiation, and the closed-loop interaction between the access point and the wireless stations, when prices are explicitly signalled to the stations, which in turn select the transmission probability to maximize their benefit.

A. Throughput differentiation

In this section we investigate the impact of the minimum contention window and transmission opportunity (TXOP) parameters on throughput differentiation using simulation. The simulation results were obtained using the ns-2 simulator, with the module[2] documented in [7] for implementing the EDCA mechanism. The simulation experiments considered UDP traffic with packet size 1044 bytes, which includes the UDP/IP headers, and the results are the average of 6 runs, each for 500 seconds. The parameters used in the experiments are shown in Table I.

Figure 1 shows the ratio of throughput for wireless stations of two types, with the same $CW_{\min}$ value, but different TXOP values. From this figure we observe that the throughput has an almost proportional dependence on the value of TXOP, as suggested by (3).

Figure 2 shows the ratio of throughput for wireless stations of two types with different $CW_{\min}$ values (128 for type 1 stations and 256 for type 2 stations) and different TXOP

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[2] “An IEEE 802.11e EDCF and CFB simulation model for ns-2”, `http://www.tkn.tu-berlin.de/research/802.11e_ns2/`

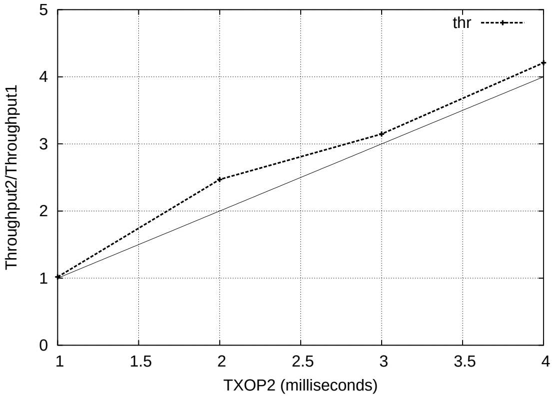


Fig. 1. Simulation results showing the ratio of throughput for stations of type 2 and 1 as a function of ratio of TXOP values for stations of type 2. The experiment considered 5 stations of type 1 and 5 of type 2, both of which had $CW_{\min} = 128$. The value of TXOP for stations of type 1 was 1 milliseconds.

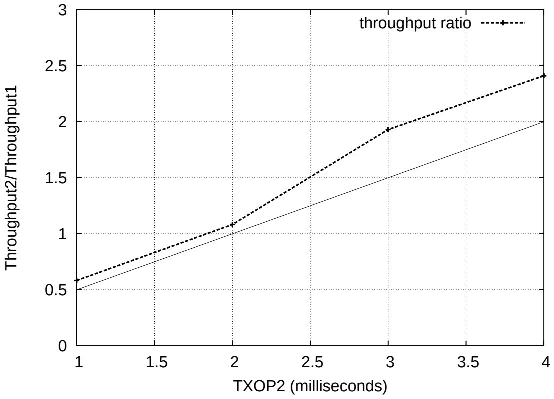
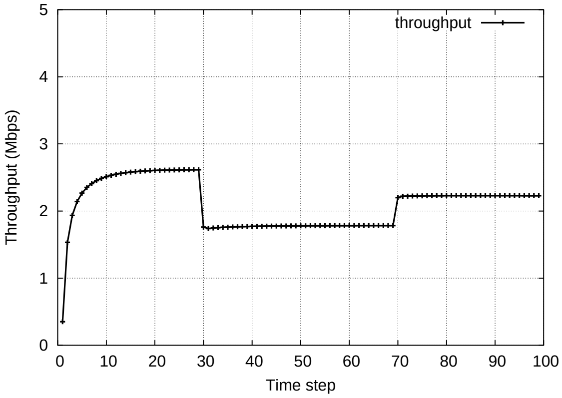


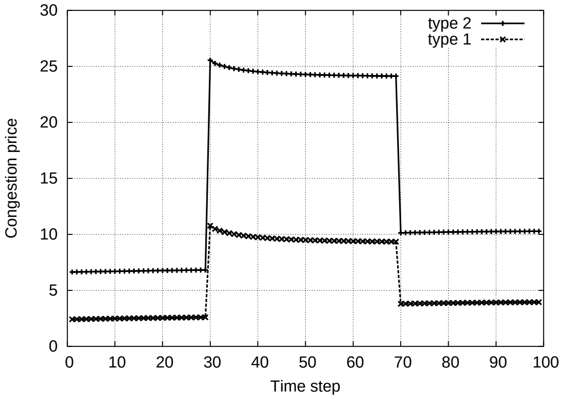
Fig. 2. Simulation results showing the ratio of throughput as a function of ratio of TXOP values for stations of type 2. The experiment considered 5 wireless station of type 1 and 5 of type 2, with $CW_{\min} = 128$ and 256 respectively. The value of TXOP for stations of type 1 was 1 milliseconds.

values. This figure further confirms that the throughput has an almost proportional dependence on the value of TXOP, but also on the value of $CW_{\min}$, as suggested by (3).

B. Closed-loop interaction between access point and wireless stations



(a) Throughput



(b) Congestion price

Fig. 3. Throughput and price as a function of time. Initially $N_1 = N_2 = 5$, at time $t = 30$, $N_2 = 30$, and at time $t = 70$, $N_2 = 10$. $R_1 = 11$ Mbps, $R_2 = 2$ Mbps, RTS/CTS

Next we investigate the closed-loop interaction between the access point and wireless stations, when prices are explicitly signalled to the stations, which in turn respond by selecting their transmission probability, equivalently their minimum contention window. We assume that one user corresponds to each station, and has a logarithmic utility. Access to the wireless channel is controlled through the EDCA and RTS/CTS procedures.

TABLE I

PARAMETERS FOR THE EXPERIMENTS (IEEE 802.11B)

Parameter	Value (in μs)
Slot Time	20
T_{DIFS}, T_{SIFS}	50, 10
T_{PHY}	192
$T_{ACK} = T_{CTS}$, T_{RTS}	112, 160

The access point estimates the congestion price from (10) and communicates it to the end users, which select their transmission probabilities to maximize their net benefit (8). We assume that the access point can accurately estimate the aggregate transmission probability used in (10). Consideration of more complex scenarios, which include asynchronous operation of wireless stations, propagation delays, and measurement errors, is left for future work.

We consider two types of stations with the same utility (logarithmic with the same weight factor), but with different physical layer transmission rates, 11 Mbps (type 1) and 2 Mbps (type 2). Initially, there are 5 stations of each type. Time is assumed to be discrete. At time $t_1 = 30$, we assume that 25 more stations of type 2 (with rate 2 Mbps) enter the network, hence giving a total of 30 stations of type 2. Then, at time $t_2 = 70$, 20 stations of type 2 depart the system, leaving 10 stations of type 2, and 5 stations of type 1. Figure 3(a) shows the aggregate throughput, computed using (2), as a function of time. Observe that the system reacts to changes of the number of users, quickly reaching the equilibrium, where the aggregate throughput achieves its maximum value. Also observe that the aggregate throughput is lower when there are more slow stations of type 2 (with transmission rate 2 Mbps); this is a well known property of 802.11 networks where a low rate station slows down all other stations.

Figure 3(b) shows the behavior of the congestion price $\lambda_1 T_i^{suc} + \lambda_2$ with time. As expected, the congestion price is higher when there are more stations in the network. Moreover, observe that the congestion price is higher for slow stations (type 2), since these occupy the wireless channel for more time to transmit a packet, hence have a higher impact on congestion.

VI. RELATED WORK

The work of [4], [8] proposes an approach for achieving weighted fairness in IEEE 802.11e. The throughput model considered is similar to the model considered in our work. Moreover, the weighted fairness model is similar to the proportional sharing model presented in Section IV-A.1, albeit considering different approximations. The model presented in our work is more general in that it considers both the EDCA and HCCA mechanisms in multi-rate 802.11 networks, and the general case where user requirements are encoded through utility functions. The problem of service differentiation is also investigated in a number of papers, e.g. [9], [10] and the references therein. These works do not quantify the degree of differentiation, nor do they investigate the aggregate efficiency of the network.

The work of [11] investigates the problem of fairness and weighted resource sharing in wireless networks using models based on utility functions, and proposes rate control schemes applied at the end systems to achieve the specific resource sharing model. Although some general characteristics of the wireless channel are taken into account, such as location-dependent contention and inaccurate channel state information, the specific characteristics of the 802.11 MAC operation, such as the EDCA and HCCA mechanisms, are not considered. Also, the utility for each user is taken to be a function of the rate of transmission attempts, rather than the actual throughput that is achieved, as we consider. Our work also differs from [12] which also considers maximizing the aggregate utility, but focuses on the EDCA mechanism in single rate 802.11 networks, and develops a distributed scheme for obtaining the optimal contention window. Finally, the work of [13] applies game theory to investigate the Nash equilibrium in CSMA/CA networks, whereas our work focusing on maximizing the efficiency of such systems through maximization of the aggregate utility.

VII. APPLICATION AND CONCLUSION

We have presented models for efficient resource control of elastic traffic over 802.11e's EDCA and HCCA mechanisms. These models can be used to derive congestion prices, which can be transmitted to the wireless stations through some feedback mechanism, thus providing them with appropriate incentives to guide the system to its optimal operating point. The models assume knowledge of the utilities of wireless stations; in practise this can be achieved through a class-based framework, where different classes correspond to different utility functions, and have a different price per unit of time. Users initially declare their class during the access point association or the authentication phase, and can change their class selection based on the throughput they achieve. The incentive compatibility of such a system, i.e. the fact that users have the incentive for selecting the class that corresponds to their actual utility, is discussed in [1].

With the above approach, a centralized entity located at the access point is responsible for optimally selecting the transmission probabilities (equivalently, the minimum contention windows), the transmission opportunities, and the percentage of time spent in the contention and contention-free periods; these parameters would then be broadcasted to the wireless stations, as defined in the IEEE 802.11e standard.

The work in this paper focused on elastic traffic; an important extension is to consider the case of inelastic (real-time) traffic and traffic with minimum throughput requirements. Another research direction is the extension of the models to multi-hop wireless networks.

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