IEEE 802.11e Wireless LAN - Resource Sharing with Contention Based Medium Access

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***Abstract*—Controlling medium access priorities in wireless networks is difficult when multiple radio stations operate according to the popular IEEE 802.11 contention-based protocol. Although the new standard 802.11e defines enhancements for controlling priorities in this distributed medium access control protocol, it does not provide algorithms for the calculation of the achievable throughput per station, when different stations operate with the different priorities. Such an algorithm is discussed in this paper. The evaluation by means of simulation indicates that the algorithm approximates the achievable throughput in many different scenarios.**

Keywords—IEEE 802.11e; Enhanced Distributed Coordination Function (EDCF); saturation throughput; quality of service

I. Introduction

The *Institute of Electrical and Electronics Engineers, Inc. (IEEE)* develops the *IEEE 802.11e (802.11e)* as an extension of the IEEE 802.11 wireless *Local Area Network (LAN)* standard. 802.11e is defined for the provisioning of priorities in medium access, to enable wireless LANs to achieve data throughput and delay constraints, hence, to support *Quality of Service (QoS)*. By applying 802.11e, stations are able to support multimedia and Internet applications that require QoS. Home networks with their characteristic applications such as audio/video streaming and interactive data, typically require QoS.

The 802.11e contention based medium access, the so-called *Enhanced Distributed Coordination Function (EDCF),* is discussed in this paper. For this coordination function, a method to approximate the achievable throughput is presented, which was developed and evaluated in Mangold (2003).

The EDCF is briefly described in the next section. In Section III, the achievable throughput of an arbitrary number of stations in 802.11e, the so-called saturation throughput, is calculated. This saturation throughput is calculated for scenarios where all stations operate with the same *Medium Access Control (MAC)* parameters (later in this paper referred to as EDCF parameters per *Access Category (AC)*). Section IV provides the analytical approximation of the share per AC, which is evaluated in Section V for a large number of scenarios. The share per AC is the achievable saturation throughput per AC when stations operate with different MAC parameters. The paper ends with a conclusion in Section VI.

II. IEEE 802.11e Contention Based Medium Access

We assume that the reader is familiar with the legacy 802.11 protocol[1]. See for details about legacy 802.11 for example IEEE 802.11 WG (1999), Hettich (2001), and Walke (2001). The basic 802.11 MAC protocol is the *Distributed Coordination Function (DCF)* that works as a listen-before-talk scheme, based on the *Carrier Sense Multiple Access (CSMA)*. Stations deliver MAC Service Data Units (*MSDUs*) of arbitrary lengths, after detecting that there is no other transmission in progress on the radio channel. This is called the backoff process. The QoS support in EDCF is realized with the introduction of *Access Categories (ACs)* and parallel backoff entities per station. MSDUs are delivered by multiple parallel backoff entities within one 802.11e station, each backoff entity parameterized with AC-specific parameters, the so-called EDCF parameter sets. There are four different ACs, thus, four backoff entities exist in every 802.11e station, with four priorities AC 0…3. An earlier version of the EDCF is described and analyzed in Mangold et.al. (2002).

The EDCF parameter sets define the priorities in channel access by modifying the backoff process with individual interframe spaces (*Arbitration Interframe Space*, *AIFS*), contention windows and many more parameters per AC. See Figure 1 for an illustration of the EDCF parameter sets. The *Persistent Factor (PF)* can be used to control the increase of the contention window after failed transmissions. The positions of the contention windows relative to each other, as defined per AC by the EDCF parameter sets, are the important factors to define the relative priority in channel access per AC. This relative priority is focus of the analysis in this paper. See IEEE 802.11 WG (2002) for more details about the 802.11e protocol.

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[1] "Legacy 802.11" refers to the IEEE 802.11 Distributed Coordination Function that does not provide QoS support. The Point Coordination Function legacy 802.11 is not considered here due owing to its inefficiency.

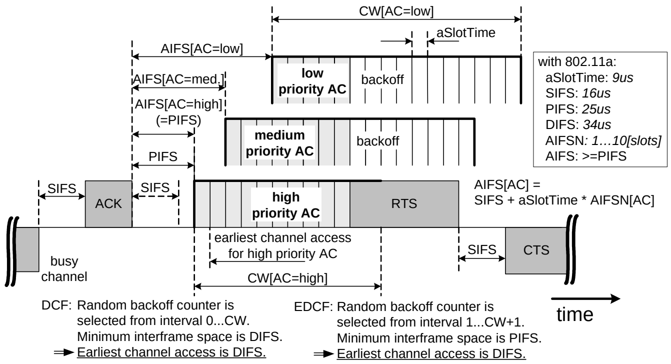

Figure 1: EDCF backoff for three different priorities (three different EDCF parameter sets).

III. Saturation Throughput

The system saturation throughput $Thrp_{sat}$ is defined as expected sum of all throughputs of MSDUs delivered by contending backoff entities when all entities attempt to transmit at any time (all backoff entities have MSDUs to deliver, the queues are never empty). An analytical approximation that allows the analysis of the saturation throughput $Thrp_{sat}$ of a number of contending backoff entities is given in Bianchi (1998a, 1998b, 2000) and here referred to as Bianchi's legacy 802.11 model. Hettich (2001) uses Bianchi's legacy 802.11 model and extends it for the analysis of not only the throughput, but also the backoff delays.

To evaluate the concepts of the EDCF contention window, Bianchi's legacy 802.11 model will be modified in the following.

A. Modifications of Bianchi's Legacy 802.11 Model

To model the saturation throughput of an EDCF backoff entity rather than a legacy station, some modifications of Bianchi's legacy 802.11 model are required.

The parameter *i* is the backoff stage, and *m* is the maximum value of the backoff stage. The contention window sizes $W_i, i=0\ldots m$ and the maximum number of backoff stages m are dependent on the EDCF parameter set, individually defined per AC. Further, since the *Persistence Factor (PF)* has to be included in the modified model as well, although it is not part of 802.11e, this parameter needs to be considered in the equation. The modifications are as follows. The size of the contention window in 802.11e is calculated by

$$W_i[AC]=PF[AC]^{\min(i,m[AC])}\cdot W_0,\quad i\in 0,1,\ldots m[AC].$$

The probability that transmission attempts of a single backoff entity at a particular generic slot are unsuccessful due to collision is denoted by p. As in the approach to model the legacy 802.11, it is in the following assumed that this probability is independent of the contention window size. Bianchi's legacy 802.11 model is modified as described in the following equations.

$$1=\sum_{i=0}^{m}\left(b_{i,0}\cdot\sum_{k=0}^{W_i-1}\frac{W_i-k}{W_i}\right),\quad W_i\ge 1\quad \forall\, 0\le i\le m, m\ge 0\;\Rightarrow$$

$$1=\frac{1}{2}\cdot\sum_{i=0}^{m} b_{i,0}\cdot\left(W_i+1\right)=$$

$$=\frac{b_{0,0}}{2}\cdot\left[W_0\cdot\sum_{i=0}^{m-1}\left(PF[AC]\cdot p\right)^i+\frac{1}{1-p}+W_0\cdot\frac{\left(PF[AC]\cdot p\right)^m}{1-p}\right]$$

with $m\ge 0, W_0\ge 1$.

The stationary distribution $b_{0,0}$ in Bianchi' legacy 802.11 model is now calculated as given in the following three equations. The stationary distribution can be calculated as

$$b_{0,0}=\frac{2\cdot(1-p)}{W_0\cdot(1-p)\cdot m\cdot\left(PF[AC]\cdot p\right)^{m+1}+W_0\cdot\left(PF[AC]\cdot p\right)^m+1},\quad (1)$$

if $p=\left(PF[AC]\right)^{-1}, m>0$, and

$$b_{0,0}=\frac{2\cdot(1-p)}{W_0\cdot(1-p)\cdot\dfrac{1-\left(PF[AC]\cdot p\right)^m}{1-PF[AC]\cdot p}+W_0\cdot\left(PF[AC]\cdot p\right)^m+1},\quad (2)$$

if $p\ne\left(PF[AC]\right)^{-1}, m>0$, and further

$$b_{0,0}=\frac{2}{2+(1-p)\cdot(W_0-1)}\quad (3)$$

for any p and $m=0$. The probability τ that a backoff entity is transmitting in a generic slot is calculated by the summation of all stationary distributions $b_{i,0}$, as in Bianchi's legacy 802.11 model, given by

$$\tau=\sum_{i=0}^{m}b_{i,0}=\begin{cases}1, & p=1,\\ b_{0,0}\cdot\dfrac{1}{1-p}, & else.\end{cases}$$

All the rest of the calculations of the saturation throughput $Thrp_{sat}$ when all backoff entities operate with the same EDCF parameters can be taken from Bianchi's legacy 802.11 model, as described in detail in Mangold (2003).

A generic slot is different from a backoff slot. A generic slot may be an idle generic slot during the contention phase, or a busy generic slot during which a frame exchange is completed, or, alternatively, during which a collision occurs. It is referred to as generic slot to differentiate it from the backoff slots, because a generic slot can be a backoff slot or a busy phase with a longer duration than the backoff slot duration.

IV. Analytical Approximation of the Share per Access Category

A method to approximate the channel access priorities between the different ACs is presented in the following. With this method, the achievable saturation throughput per AC can be approximated for scenarios where backoff entities operate in parallel, and according to different ACs.

This is referred to as share of capacity per AC and more relevant for a QoS analysis than the saturation throughput in isolated operation. The saturation throughput in isolated operation, where all contending backoff entities operate with the same EDCF parameter set, i.e., according to the same AC, is discussed in the previous section. In contrast, in this section the achievable throughput per AC (share of capacity per AC) and the mutual influences between the ACs are investigated for the shared operation. In shared operation, backoff entities operate with different EDCF parameter sets, according to the different ACs.

A. Share of Capacity per Access Category

A method to quantify the mutual influences between the ACs is discussed in the following. This method is based on the expected idle time duration when operating in saturation.

1) Expected Idle Time Duration (Expected Contention Window Size)

The probability that the channel is busy in a generic slot time is given by

$$P_{CCAbusy} = 1 - P_{CCAidle} = 1 - \left(1 - \tau\left[AC\right]\right)^{N[AC]}, \quad (4)$$

where $N\left[AC\right]$ is the number of backoff entities of a particular AC and $\tau\left[AC\right]$ is the probability that a backoff entity of this AC transmits at a generic slot time.

The number of consecutive idle slots in this model depends on the expected duration of the idle backoff phase, i.e., the expected contention window length, $E\left[CW\left[AC\right]\right]$, given in slots, until the first backoff entity attempts its resource allocation by initiating a transmission. Its expected value can be calculated to

$$E\left[CW\left[AC\right]\right]\Big/_{slot} = P_{CCAbusy} \cdot \frac{P_{CCAidle}}{\left(1 - P_{CCAidle}\right)^2}.$$

As a result, with Equation (4), the expected number of consecutive idle slots, i.e., the expected size of the contention window is written as

$$E\left[CW[AC]\right]\Big/_{slot} = \left(1 - P_{CCAidle}\right) \cdot \frac{P_{CCAidle}}{\left(1 - P_{CCAidle}\right)^2} = \frac{\left(1 - \tau\left[AC\right]\right)^{N[AC]}}{1 - \left(1 - \tau\left[AC\right]\right)^{N[AC]}}.$$

The τ is the probability that a backoff entity is transmitting at a generic slot, $N[AC]$ is the number of backoff entities.

2) σ-persistent CSMA

The σ-persistent CSMA (Kleinrock and Tobagi, 1975) results in the following expected duration of the idle phase, when N backoff entities operate at the same time:

$$E\left[CW[AC]\right]\Big/_{slot} = \frac{\left(1 - \sigma\right)^N}{1 - \left(1 - \sigma\right)^N}.$$

This is confirmed by Calì et al. (2000b). In persistent CSMA, MSDUs arriving while the channel is busy have to wait for the channel to become idle again (backlogging), before being delivered immediately. In σ-persistent CSMA, MSDUs that collided before and are waiting for retransmission while the channel is busy, and MSDUs arriving while the channel is busy are delivered with different probabilities, once the channel becomes idle again.

3) Binary Exponential Backoff CSMA

In Calì et al. (2000a, 2000b), the 802.11 DCF is approximated by σ-persistent CSMA. The difference between the 802.11 (E)DCF and the σ-persistent CSMA lies in the selection process of the backoff interval, i.e., the size of the contention window. Whereas 802.11 EDCF uses a binary exponential backoff, the size of the contention window in σ-persistent CSMA is calculated from a geometric distribution with the parameter σ (Calì et al., 2000b).

4) Approximation

Calì et al. (2000a, 2000b) show that in the case the system of contending backoff entities is in saturation, the throughput results of the σ-persistent CSMA approximate the achievable throughput of the 802.11 EDCF, if the average backoff intervals, i.e., the expected size of the contention window, $E\left[CW[AC]\right]$, of the two different CSMA types are equal. For this reason, the mutual influences between the different ACs in the 802.11 EDCF are evaluated based on the assumption that the saturation throughput of the EDCF can be approximated with the saturation throughput of σ-persistent CSMA. In the following, the mutual influences of σ-persistent CSMA backoff entities with different σ-parameters are analyzed instead of the mutual influences of backoff entities that operate with the binary exponential backoff CSMA. The results of this analysis will be compared to 802.11 EDCF simulation results with binary exponential backoff.

For each individual AC, the expected size of the contention window, i.e., $E\left[CW\left[AC\right]\right]$, is used to parameterize σ-persistent CSMA per AC:

$$\underbrace{E\left[CW\left[AC\right]\right]\Big/_{slot} = \frac{1}{\sigma\left[AC\right]}}_{\sigma\text{-persistent CSMA with N contending backoff entities per AC}} \overset{!}{=} \underbrace{\frac{\left(1 - \tau\left[AC\right]\right)^{N[AC]}}{1 - \left(1 - \tau\left[AC\right]\right)^{N[AC]}} = E\left[CW\left[AC\right]\right]\Big/_{slot}}_{\text{Bianchi approximation with N contending backoff entities per AC}}. \quad (5)$$

The left side of this equation shows the expected value for the contention window from the geometric distribution in σ-persistent CSMA, and the right side shows the expected value for the contention window as calculated from Bianchi's model.

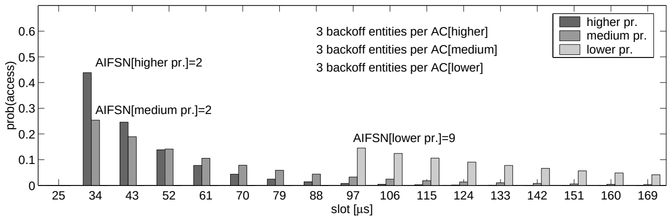

Figure 2: Slot access probabilities for 3 backoff entities per AC. Three ACs with EDCF parameters as defined in Table 1.

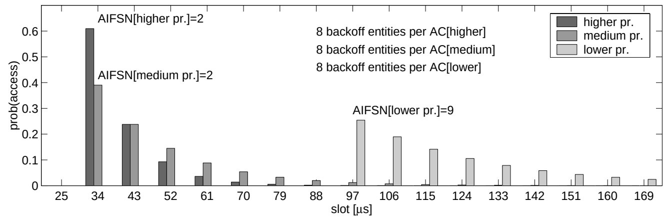

Figure 3: Slot access probabilities for 8 backoff entities per AC. Three ACs with EDCF parameters as defined in Table 1.

This approximation is used in the following to calculate the relative priorities between the different ACs. As an example, Figure 2 and Figure 3 illustrate the access probabilities the three ACs that are parameterized according to Table 1, for 3 and 8 backoff entities per AC, respectively. The geometric distributions are clearly visible. As expected, with a higher number of backoff entities (*8+8+8=24* instead of *3+3+3=9*), the expected size of the contention window decreases; as a result, the probability of access at earlier slots increases.

B. Calculation of Access Priorities from the EDCF parameters

It is now possible to derive a method to determine the access priorities from the EDCF parameters. A scenario of three ACs is used. The ACs are labeled with “High”, “Medium”, and “Low”, according to their priorities. A fundamental approximation taken here is that, once the characteristics of the backoffs of the ACs are found with the modified Bianchi model, these characteristics are assumed to remain constant even in contention with other ACs. For example the expected size of the contention window per AC are as found in the isolated scenario, mutual influences between the ACs are in this case neglected. Note that this assumption is taken for all ACs. What is determined here is the access priority, not the actual resulting capacity share (throughput). This capacity share, however, is a result of the mutual influences between the three ACs, and calculated by considering all ACs.

When calculating the access priorities, care must be taken about the fact that the different ACs start their backoffs at different slots, according to the AIFSN parameter. As a first step, the contention windows are therefore shifted by the AIFSN parameters, hence,

$$E\left[AIFS\left[AC\right]+CW\left[AC\right]\right]=AIFS\left[AC\right]+\frac{1}{\sigma\left[AC\right]}.$$

Table 1: EDCF parameter sets for the three ACs, as selected for the analysis. The TXOPlimit per AC is not used in this thesis; one value is used for all ACs.

AC (priority):	higher	medium (=legacy)	lower
AIFSN[AC]:	*2*	*2*	*9*
CWmin[AC]:	*7*	*15*	*31*
CWmax[AC]:	*1023*	*1023*	*1023*
PF[AC]:	*24/16*	*32/16*	*40/16*
RetryCnt[AC]:	*7*	*7*	*7*

1) Slot Access Probabilities

The access probability of the backoff entities of an AC at a certain slot is in the following referred to as $\xi_{slot}\left[AC\right]$ with $1\leq slot\leq max\left(CWmax\left[AC\right]\right)+1$. The largest value of the maximum size of the contention window defines over how many slots the access probabilities are calculated. Usually this is the value of the lowest priority AC.

The access probability ξ_{slot} for $slot<AIFS\left[AC\right]$ is $\xi_{slot}\left[AC\right]=0$, because for slots earlier than $AIFS\left[AC\right]$, backoff entities of this AC will not access the channel. However, the access probability for $slot>CWmax\left[AC\right]+AIFS\left[AC\right]$ is also given by $\xi_{slot}\left[AC\right]=0$, because for slots later than $CWmax\left[AC\right]$, backoff entities of the respective AC will not access the channel neither. It is again emphasized that $CWmax\left[AC\right]$ is here defined by more than the QoS-parameters known from 802.11e. That means, $CWmax\left[AC\right]$ depends on a number of parameters such as the $RetryCnt\left[AC\right]$, the $PF\left[AC\right]$, and the initial contention window size, $CWmin\left[AC\right]$. For any other slot, with $AIFS\left[AC\right]\geq slot\geq CWmax\left[AC\right]$, the access probability at a particular slot is calculated with the help of the geometric distribution to

$$\xi_{slot}\left[AC\right]=1-\left(1-\left(\sigma\left[AC\right]\cdot\left(1-\sigma\left[AC\right]\right)^{slot-AIFS\left[AC\right]}\right)\right)^{N\left[AC\right]},\quad(6)$$

with $AIFS\left[AC\right]<slot\leq CWmax\left[AC\right]$. As stated above, for any other slot, $\xi_{slot}\left[AC\right]=0$.

2) CSMA Regeneration Cycle

The access priorities of the three ACs, and thus the share of capacity can now be derived with the help of a Markov model. The model is illustrated in Figure 4. It represents the process $s(t)$ of all contending backoff entities of the three priorities. In what follows, this process is referred to as *CSMA regeneration cycle*. The system state alternates between idle phases during which the backoff phase is ongoing and busy phases during which at least one backoff entity transmits a frame. Takagi and Kleinrock (1985) call this a regeneration cycle. Each alternation is a “probabilistic replica” (Takagi and Kleinrock, 1985) of the previous alternation.

Four states “C”, “H”, “M”, and “L”, represent the system while ongoing transmissions (busy phase), and a number of states “1”, “2”,... “CWmax+1” represent the system during the backoff (idle phase). There is one state for each slot of the backoff, beginning with $slot=1$, which is equivalent to $AIFSN=1$ and thus $AIFS=PIFS=25\mu s$. Note that according to 802.11e, the earliest time when backoff entities access the channel is one slot after *AIFS*. Thus, the second slot represents the first possible access time $SIFS + 2 \times aSlotTime$ for backoff entities that operate according to the HCF contention-based channel access, without regard to the individually selected $AIFSN[AC]$ parameter. The access probability per slot of the set of backoff entities of one *AC* is given by Equation (6), The access probability for $slot \le AIFSN[AC]$ is *0*.

The last slot is determined by the value of $\mathrm{CWmax}+1$, it is calculated as the maximum of all contention window sizes per ACs. Typically, but not necessarily, $CWmax = CWmax[Low]$, since a large value implies a lower priority in channel access. If the backoff entities of one AC operate with a smaller value for $CWmax[AC]$, then the access probability for this slot is set to *0*. If at least one backoff entity of the AC "High" attempts to transmit by accessing the channel as the first backoff entity, for example by accessing the channel at the first slot, and if no other backoff entity from the other ACs accesses the channel at this slot or earlier, then the system changes from state *slot* to state "H." At least one transmission of priority "High" is then ongoing. Note that this includes collisions of frames transmitted by backoff entities that belong to this priority "High." The states "M" and "L" are equally defined for the ACs "Medium" and "Low", respectively. However, if more than one backoff entities of different ACs start their transmission attempts at the same slot, a collision of frames transmitted by backoff entities that belong to different ACs occurs and the system changes to the state "C." From the four states "C", "H", "M", and "L", the system changes back to state "1."

3) *Transition Probabilities*

Let

$$P\{s(t+1) = AC \mid s(t) = slot\} = P_{slot,AC}, \quad AC \in H, M, L,$$
$$P\{s(t+1) = C \mid s(t) = slot\} = P_{slot,C},$$
$$P\{s(t+1) = slot+1 \mid s(t) = slot\} = P_{slot,slot+1},$$

with $slot = 1 \ldots CWmax+1$, be the transition probabilities, and

$$\lim_{t\to\infty} P\{s(t) = AC\} = p_{AC}, \quad AC \in H, M, L,$$
$$\lim_{t\to\infty} P\{s(t) = C\} = p_C,$$
$$\lim_{t\to\infty} P\{s(t) = slot\} = p_{slot}, \quad slot = 1 \ldots CWmax+1$$

be the stationary distributions of all states of the backoff process $s(t)$.

The transition probabilities in this model can be easily derived from the definitions given earlier in this section. At a particular generic slot, the probability that the system changes to one of the three states "H", "M", "L" is given by the probability that at least one backoff entity of this AC accesses the channel at this slot, and none of the backoff entities of the other ACs access this same slot, which results in the following three state transition probabilities.

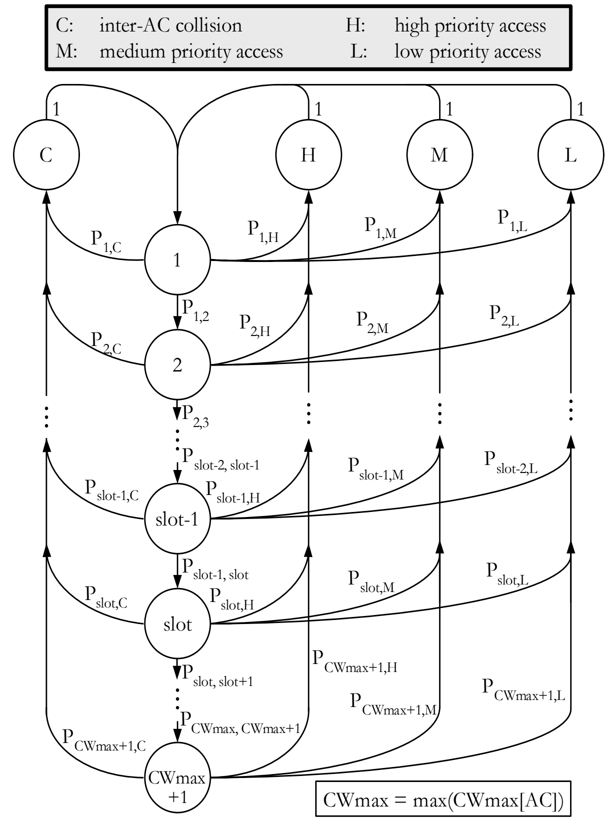

Figure 4: State transition diagram for the CSMA regeneration cycle.

$$P_{slot,H} = \xi_{slot}[High] \cdot (1 - \xi_{slot}[Medium]) \cdot (1 - \xi_{slot}[Low]),$$
$$P_{slot,M} = \xi_{slot}[Medium] \cdot (1 - \xi_{slot}[High]) \cdot (1 - \xi_{slot}[Low]),$$
$$P_{slot,L} = \xi_{slot}[Low] \cdot (1 - \xi_{slot}[High]) \cdot (1 - \xi_{slot}[Medium]).$$

The probability that at a particular slot, a collision of frames transmitted by backoff entities of different ACs occurs, is given by

$$\begin{aligned} P_{slot,C} = {} & \xi_{slot}[High] \cdot \xi_{slot}[Medium] \cdot (1 - \xi_{slot}[Low]) + \\ & \xi_{slot}[High] \cdot \xi_{slot}[Low] \cdot (1 - \xi_{slot}[Medium]) + \\ & \xi_{slot}[Medium] \cdot \xi_{slot}[Low] \cdot (1 - \xi_{slot}[High]) + \\ & \xi_{slot}[High] \cdot \xi_{slot}[Medium] \cdot \xi_{slot}[Low]. \end{aligned}$$

Finally, the probability that the system changes from one slot to the next slot is derived from the probability that no backoff entity attempts to transmit at this slot:

$$P_{slot,slot+1} = \begin{cases} 0, & slot > CWmax \\ 1 - (P_{slot,H} + P_{slot,M} + P_{slot,L} + P_{slot,C}), & else. \end{cases}$$

4) *The Priority Vector η*

From the definitions of the stationary distributions, the transition probabilities from state "0" to the states "H", "M", "L", and "C" can be derived. These four transition probabilities will define the actual priority in channel access. The stationary distribution of state "H" is given by

$$p_H = \underbrace{\left\{ P_{1,H} + \sum_{slot=2}^{\text{CWmax}+1} P_{slot,H} \cdot \prod_{i=1}^{slot-1} P_{i,i+1} \right\}}_{\substack{=:\eta\left[AC=High\right] \\ \text{(this defines the relative priority of the AC "High")}}} \cdot p_1 . \quad (7)$$

In this equation, a new parameter is defined, which determines the relative priority of the AC "High." This is referred to as $\eta\left[High\right]$. The stationary distributions of the states "M", "L", and "C" are equally defined:

$$\begin{aligned} p_M &= \left\{ P_{1,M} + \sum_{slot=2}^{\text{CWmax}+1} P_{slot,M} \cdot \prod_{i=1}^{slot-1} P_{i,i+1} \right\} \cdot p_1 =: \eta\left[Medium\right] \cdot p_1 , \\ p_L &= \left\{ P_{1,L} + \sum_{slot=2}^{\text{CWmax}+1} P_{slot,L} \cdot \prod_{i=1}^{slot-1} P_{i,i+1} \right\} \cdot p_1 =: \eta\left[Low\right] \cdot p_1 , \\ p_C &= \left\{ P_{1,C} + \sum_{slot=2}^{\text{CWmax}+1} P_{slot,C} \cdot \prod_{i=1}^{slot-1} P_{i,i+1} \right\} \cdot p_1 . \end{aligned} \quad (8)$$

The priority vector η is found as

$$\begin{aligned} \eta &= \left(\eta_H , \eta_M , \eta_L \right) = \\ &= \frac{1}{\sum_{AC} \eta\left[AC\right]} \left(\eta\left[High\right], \eta\left[Medium\right], \eta\left[Low\right] \right) \cdot \end{aligned} \quad (9)$$

The priority vector η determines the relative priorities between the three ACs. Once the system changes from ongoing transmission to contention, the system will change to one of the states "H", "M", "L", according to the priority vector η. With the help of the priority vector η, the saturation throughput $Thrp_{share}$ (or the share of capacity) that an arbitrary number of backoff entities of each of the three ACs may achieve when all backoff entities operate in parallel, can be calculated. Any number of backoff entities per AC is possible in this model, and any setup of the EDCF parameters. The achievable saturation throughput $Thrp_{share}$ for the three ACs is approximated by

$$Thrp_{share} = Thrp_{sat} \cdot \eta = \begin{pmatrix} Thrp_{sat}\left[High\right] \cdot \eta_H \\ Thrp_{sat}\left[Medium\right] \cdot \eta_M \\ Thrp_{sat}\left[Low\right] \cdot \eta_L \end{pmatrix} . \quad (10)$$

Note that Equation (10) neglects the mutual influences the shared operation implies on the individual changes of maximum saturation throughput per AC.

V. Results and Discussion[2]

The simulation results discussed in the following are generated with the simulation environment presented in Mangold et.al. (2002). The radio channel is error-free, and all backoff entities operate in saturation (the queues are never empty).

The example with the three ACs as defined in Table 1, and illustrated in Figure 2 and Figure 3, is used for evaluating the approximation of the saturation throughput in a shared scenario, $Thrp_{share}$. Here, backoff entities of the three ACs operate in parallel at the same time. The backoff entities of one of the three ACs operate with different EDCF parameters in different scenarios: the EDCF parameters are changed gradually from the higher to the lower priority. The backoff entities of the two other ACs operate according to the legacy and lower priority EDCF parameter setups. Many different situations can be studied with such a wide-range of scenario combinations. The EDCF parameters of the higher, legacy, and lower priority ACs are defined in Table 1. A constant frame body size of *512 byte* for all ACs is selected here, RTS/CTS is not used. Note that the parameters *CWmax* and *RetryCnt* remain constant for all ACs at any time and are not varied over the scenarios.

The following three subsections discuss the resulting throughput per AC as a result of simulation and analytical approximation. Different numbers of backoff entities per AC are analyzed in the different figures. Figure 5 shows the results for the scenarios with 4 backoff entities per AC, i.e., 12 backoff entities in total. Figure 6 shows results for scenarios with 10 backoff entities with variable EDCF parameter setup, 2 legacy priority backoff entities, and 4 lower priority backoff entities. Therefore, 16 backoff entities in total share a common channel in these scenarios. Figure 7 shows results for scenarios with 2 backoff entities with variable EDCF parameter setup, 10 legacy priority backoff entities, and 4 lower priority backoff entities. Hence, 16 backoff entities in total are again assumed here.

A. 4 Backoff Entities against 4 Legacy and 4 Low Priority Backoff Entities

Figure 5 shows simulation and analytical results for 28 configurations, in which the EDCF parameters of one AC (used by 4 of 12 backoff entities) are varied from higher (left hand side in the figure) to legacy priority, and down to the lower priority (right hand side in the figure), according to Table 1. The other 8 backoff entities of the other ACs operate with legacy and lower priority. It can be seen that the analytical results approximate all priorities with a sufficient accuracy. This figure indicates that the model for the regeneration cycle can be used to sufficiently approximate the saturation throughput, i.e., the share of capacity, of different ACs that share a common channel.

It can be observed from the left hand side of Figure 5 that the AC with the variable priority observes the largest throughput (share of capacity) in scenarios with higher priority EDCF parameters (*AIFSN=2, CWmin=7, PF=24/16*). However, this share decreases with changed EDCF parameters towards legacy priority.

If the 4 backoff entities of the AC with the variable EDCF parameters operate according to the legacy priority, then the observed share of capacity is the same as for the 4 legacy backoff entities. This is indicated by the simulation results, and

[2] Figure 5 ... Figure 7 can be found on the last page of this paper, after the list of references.

confirmed by the analytical approximations (center of Figure 5, *AIFSN=2, CWmin=15, PF=32/16*). As expected, when changing the EDCF parameters down to the lower priority, the share of capacity of this AC decreases down towards the share that is observed by the backoff entities of the lower priority AC (right hand side of Figure 5, *AIFSN=9, CWmin=31, PF=40/16*). In parallel, the legacy priority backoff entities observe an increased share. This is expected: the legacy priority AC is parameterized such that the 4 legacy backoff entities access the channel with highest priority relative to the other 8 backoff entities, because those backoff entities operate with the lower priority EDCF parameters. This is confirmed by simulation and the analytical approximations.

B. 10 Backoff Entities against 2 Legacy and 4 Low Priority Backoff Entities

A different number of backoff entities per AC is assumed in the following, as shown in Figure 6. Simulation and analytical results for configurations with 10 backoff entities with variable EDCF parameter setup, 2 legacy priority backoff entities, and 4 lower priority backoff entities are shown. Hence, 16 backoff entities operate in parallel here. The main difference to the previous scenario is that now the backoff entities that slowly reduce their priority from configuration to configuration (i.e., from the left to the right in the figure), keep their maximum share a longer time (for more configurations).

After some more configurations, an immediate reduction of the share within a small number of configurations (indicated in the center of the figure) can be observed in the figure. This is an obvious result. The 10 backoff entities are more dominant than the 4 backoff entities of the previous scenario. As before, the analytical results and the simulation results confirm each other with sufficient accuracy.

C. 2 Backoff EntitiEs against 10 Legacy and 4 Low Priority Backoff Entities

Figure 7 shows results for a scenario with 2 backoff entities with variable EDCF parameter setup, 10 legacy priority backoff entities, and 4 lower priority backoff entities. Although the 2 backoff entities operate with highest priority at the beginning (indicated in the left of the figure), they do not observe a considerable share. However, the share per backoff entity is larger for any of the 2 backoff entities than the share observed by any of the 10 legacy backoff entities.

It must be noted that with such configurations the analytical results and the simulation results deviate from each other, although the approximations show qualitatively the same share. The analytical results overestimate the achievable share of the legacy stations in the first scenarios. The reason for this deviation is the assumption that there is no mutual influence on the size of the contention windows of the different ACs. With reduced priority (towards right in the figure), the 10 dominating legacy backoff entities obtain the largest throughput, other backoff entities are entirely suppressed.

VI. CONCLUSION

An analysis of the HCF contention-based 802.11e protocol (EDCF) is provided in this paper. The saturation throughput is calculated analytically, and the results are confirmed with the simulation. A model to approximate the resulting share of capacity per AC, i.e., the relative priority between different ACs when backoff entities operate with different EDCF parameters, is provided. The model sufficiently approximates the simulation results in nearly all cases. Further work will be to include loss and delivery delay in the model.

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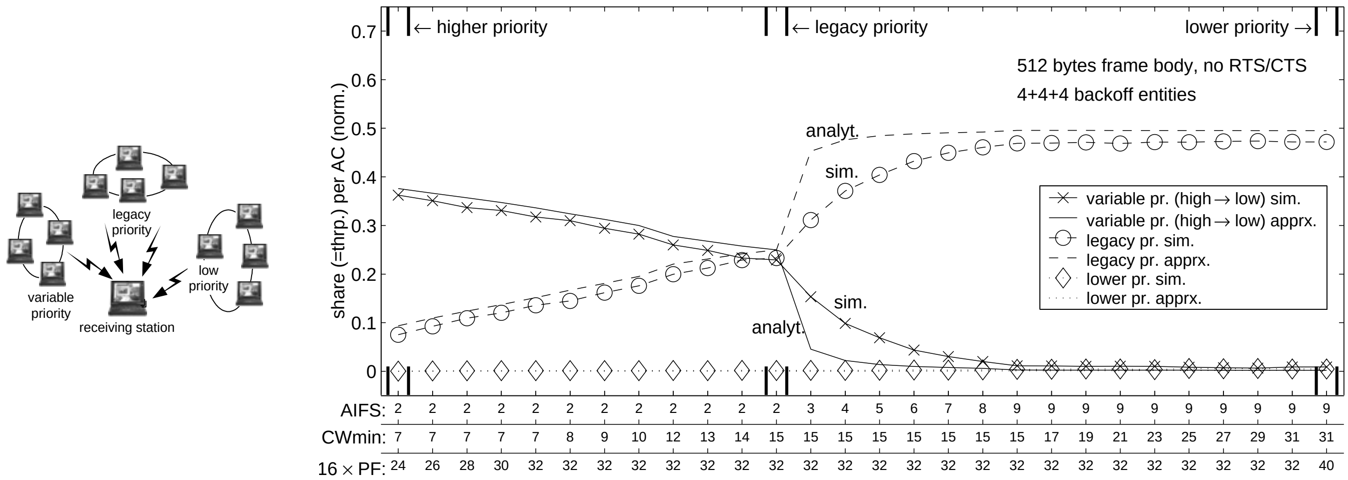

Figure 5: Scenario (left) and resulting saturation throughput per AC (right). 4 backoff entities per AC, 1 backoff entity per station. In this and all other scenarios, all stations detect each other. If two or more stations transmit at the same time, a collision occurs.

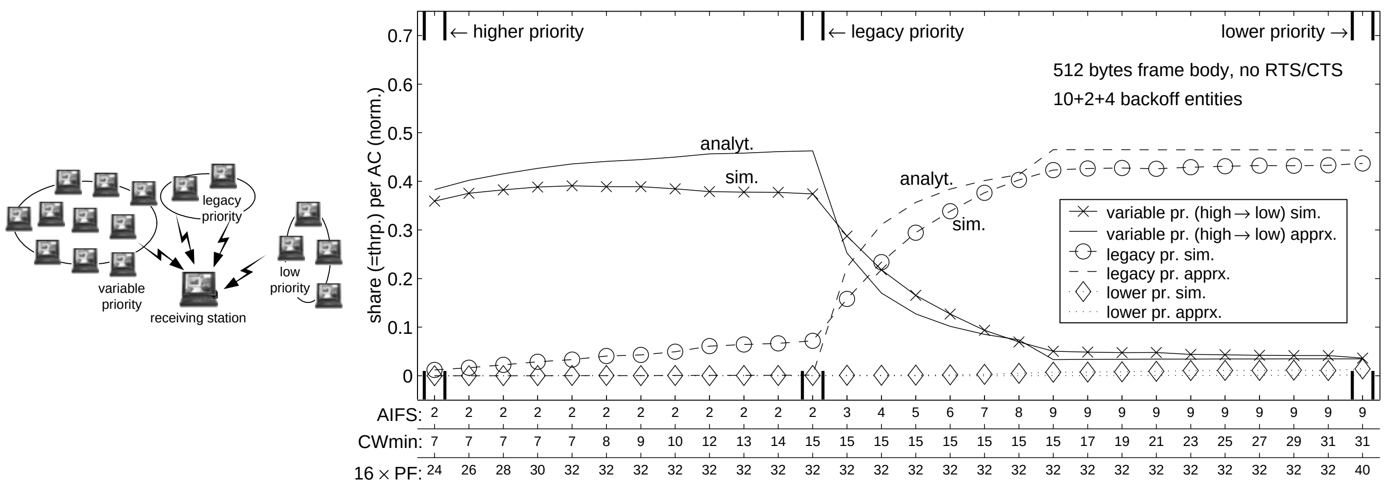

Figure 6: Scenario and resulting saturation throughput per AC. 10 backoff entities with varying EDCF parameters contend with 2 legacy and 4 lower priority backoff entities.

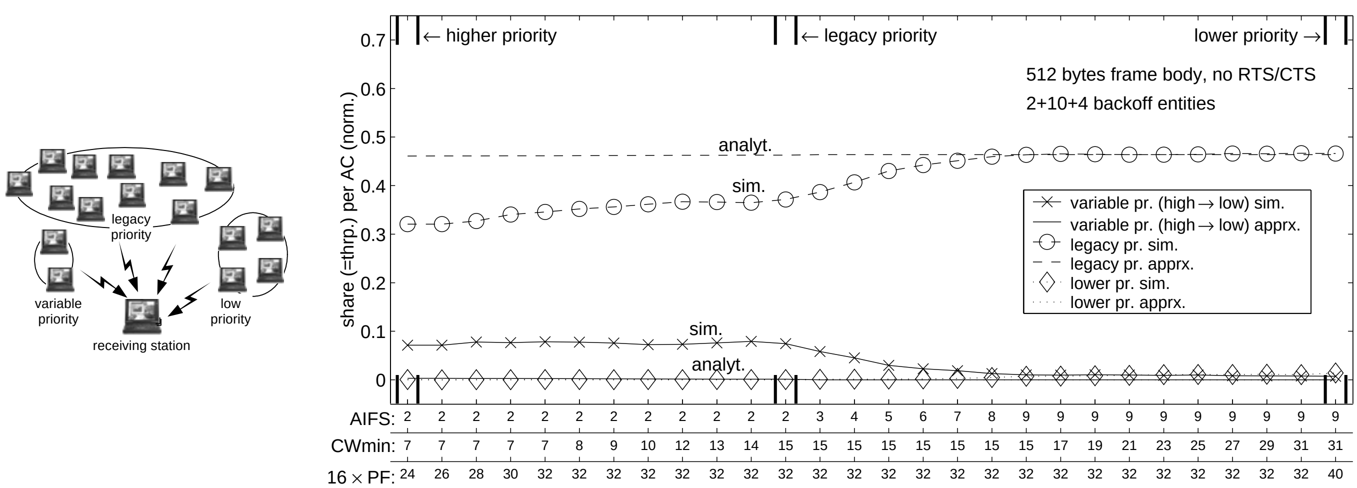

Figure 7: Scenario and resulting saturation throughput. per AC. 2 backoff entities with varying EDCF parameters contend with 10 legacy and 4 lower priority backoff entities.