IEEE 802.11e/802.11k wireless LAN: spectrum awareness for distributed resource sharing

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Summary

Coordinating priorities in wireless medium access is difficult when radio networks operate with contention-based medium access. Contention-based medium access protocols such as listen-before-talk are widely employed today, and for example used in the popular IEEE 802.11 protocol. Contention-based protocols are used for wireless communication in unreliable radio environments such as the unlicensed frequency bands with their typically irregular and unpredictable interferences. However, to support time-bounded traffic with a certain quality of service (QoS) support is extremely difficult, because it requires the knowledge of how aggressive other radio stations, which also contend for radio resources, access the medium. In this contribution, we discuss a new measurement in the IEEE 802.11k draft standard, together with the IEEE 802.11e draft standard for coordinating priorities. By combining the two extensions of IEEE 802.11, we develop an algorithm that allows radio stations to estimate the achievable throughput per radio station (the saturation throughput) in the presence of other radio stations. Our algorithm further allows predicting the saturation throughput per radio station in the presence of other non-802.11 radio networks, because it only relies on the information about how the medium is used by other stations, i.e. for what duration other stations have to sense the medium as idle before initiating transmissions. The algorithm does not require knowledge about the contention-parameters (like, e.g. minimum contention window sizes) used by other radio stations, and only relies on medium sensing information. For this reason, we refer to spectrum awareness in this work. We modify an existing model that was originally developed for calculating the saturation throughput in IEEE 802.11, to calculate the saturation throughput for IEEE 802.11e with one single priority. We then describe a new measurement, which is part of the IEEE 802.11k draft standard. The measurement provides information about medium access probabilities of other radio stations per contention window slots. These probabilities provide the information about how aggressive the medium is utilized by other stations. The probabilities are used in our model for approximating the saturation throughput per station and priority in the presence of other radio stations. As a result, with the help of the new model, a radio station is able to estimate its own expected saturation throughput. The comparison of the model with stochastic simulation stations indicates that our model approximates the saturation throughput per station and priority sufficiently in many scenarios, and hence allows to predict expected saturation throughputs per radio station. Copyright © 2004 John Wiley & Sons, Ltd.

1. Introduction

The Institute of Electrical and Electronics Engineers, Inc. (IEEE) developed the IEEE 802.11e (802.11e) draft standard as an extension of the IEEE 802.11 wireless local area network (LAN) standard. 802.11e is defined for support of medium access priorities, to enable wireless LANs to achieve data throughput and
delay constraints, hence, to support quality of service (QoS). With 802.11e, stations can support multimedia and internet applications that require QoS. Typically, home networks with their characteristic applications such as audio/video streaming and interactive data require QoS.

Further, the IEEE develops IEEE 802.11k (802.11k) draft standard as another important extension of the IEEE 802.11 wireless LAN standard. 802.11k is defined for the provisioning of radio resource measurement results, to allow radio stations to request and exchange information about the usage of the wireless medium. Although not primarily developed for support of QoS, in this contribution we use 802.11k measurements to collect information about the medium usage, and hence allow radio stations to estimate their expected throughput when operating with the 802.11e contention-based medium access. The 802.11e contention-based medium access is referred to as enhanced distributed channel access (EDCA). The problem, we are trying to solve is the question of how to set the EDCA parameters per priority in the presence of other radio stations, which also operate with contention-based medium access, but may not/do not operate according to EDCA. Hence, we rely on information provided by 802.11k measurements, and not on EDCA parameters like the contention window sizes.

For the EDCA coordination function, an algorithm to approximate the achievable throughput per station and priority is used, which was originally developed and evaluated in Reference [13]. A short version was published in References [14,15]. With this algorithm, we introduce to wireless LANs means for spectrum awareness. With the new type of measurements, information about how the spectrum is being used by other radio networks will be made available to a radio station. Hence, radio stations become aware of the radio spectrum usage.

The EDCA is briefly described in the next section. In Section 3, the 802.11k draft standard is summarized, and a specific measurement, the Medium Sensing Time Histogram is described in detail. Section 4 provides a detailed analysis of the achievable throughput of an arbitrary number of 802.11e stations that all operate with the same priority, the so-called saturation throughput in an isolated case. We describe apparent modifications of an existing model, which is summarized in Appendix A. In Section 4, the saturation throughput is calculated for scenarios where all stations operate with the same medium access control (MAC) parameters (later in this work referred to as EDCA parameters per access category (AC)).

The problem becomes more challenging when stations operate with arbitrary contention parameters. Section 5 provides the analytical approximation of the share per AC, which is evaluated in Section 6 with the help of stochastic simulation for a large number of scenarios. The share per AC is the achievable saturation throughput per AC when stations operate with different EDCA parameters. The approximation makes use of information that can be provided through 802.11k measurements. The conclusions can be found in Section 7.

2. IEEE 802.11e Contention-Based Medium Access

We assume that the reader is familiar with the legacy 802.11 protocol. See for details about legacy 802.11 for example IEEE 802.11 WG [8], Hettich [6] and Walke [18]. 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 medium. This is performed as part of the so-called backoff process. The QoS support in EDCA is realized with the introduction of 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 EDCA parameter sets. There are four different ACs, thus, four backoff entities exist in every 802.11e station, with four priorities. The EDCA parameter sets define the priorities in medium 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 EDCA 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

§'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 in this work.

*The persistence factor has been discussed during earlier stages of the standardization.
each other, as defined per AC by the EDCA parameter sets, are the important factors to define the relative priority in medium access per AC. See Reference [9] for more details about the 802.11e protocol. An earlier version of the EDCA is described and analyzed in Reference [12] and an updated analysis is given in Reference [15].

The effects of the EDCA parameters AIFS, CW_{min}, CW_{max} and PF can be summarized as follows.

1. The smaller the AIFS (or AIFSN), the higher the medium access priority. However, AIFS cannot be smaller than DIFS.
2. The smaller the CW_{min}, the higher the medium access priority.
3. The smaller the CW_{min}, the higher the collision probability.
4. The smaller the CW_{max}, the higher the medium access priority and collision probability, in scenarios where collisions often happen. However, the effect of CW_{max} in general is less relevant compared to CW_{max} in typical scenarios.
5. The smaller the PF, the higher the medium access priority and collision probability, in scenarios where collisions often happen.

3. IEEE 802.11k Medium Sense Time Histogram

IEEE 802.11 Task Group k (TGk) develops an extension to IEEE 802.11 wireless LAN specification for radio resource measurements. This extension specifies types of radio resource information to measure and the associated request and report mechanism and frame formats through which the measurement requests and results are communicated among stations.

3.1. Overview

The goal of this new extension of the existing standard is to provide tools by which a radio station can measure and assess the radio environment and take corresponding actions. To fulfill this goal, the current IEEE 802.11k draft defines different types of measurements [10], as briefly summarized in the following. With the beacon report, a measuring station reports the beacons or probe responses it receives during the measurement period. With the frame report, a measuring station reports information about all the frames it receives from other stations during the measurement period. With the channel load report, a measuring station reports the fractional duration over which the carrier sensing process, i.e. CCA, indicates that the medium is busy during the measurement period. In the noise histogram report, a measuring station reports non-802.11 energy by sampling the medium only when CCA indicates that no 802.11 signal is present. With the hidden node report, a measuring station reports the identity and frame statistics of hidden nodes detected during the measurement period. In station statistic report, a measuring station reports its statistics related to link quality and network performance during the measurement period. The key measurement for our work is the medium sensing time histogram report, which was developed by the authors of this contribution.
measuring station reports the histogram of medium busy and idle time observed during the measurement period. The states busy and idle are typically defined through the CCA process, but may vary depending on what the requesting station attempts to deduce from the measurement. More details are discussed in the Subsection 3.2.

The 802.11k extension of the standard with the variety of measurements allows an IEEE 802.11 radio network to collect information of neighboring access points (via beacon report) and information on link quality to neighbor stations (via frame report, hidden node report and station statistic report). 802.11k also provides methods to measure interference levels (via noise histogram report) and medium load statistics (via channel load report and medium sensing time histogram report). The medium load statistic is discussed in the next section.

It is highlighting to discuss the optimal measurement durations, confidence of measurement results and relevance of the measurement results for the events that follow after the measurement result were obtained, for example not always improves increasing measurement durations the accuracy of the results. 802.11k does not specify a default measurement duration, but allows a station that requests a measurement to specify its duration along with the request. Of course, if a measurement is performed without a previous request, the measuring station itself determines the duration. Similar to the decision about the actual time when the measurement request is issued, and eventually similar to the decision about the interval after which requests may be repeated, it is a local decision of the requesting station how long to measure and whether or not to repeat it after a certain time. The local time-correlation of the medium usage (e.g. the pattern of busy and idle times) is the important information to optimize such parameters. In a conventional homogeneous scenario, in which only 802.11 stations operate, the characteristic frame durations and transmission times for this protocol allow some a priori assumptions about the local time-correlation of medium access patterns. However, it depends generally on the individual scenario and types of radio system that operate in the medium, as well as on the offered traffic (e.g. packet sizes, arrival rates), what the optimal measurement parameters are, and how long reported results are valid and relevant for future events.

Please see Reference [16] for some simulation results of the medium sensing time histogram, and a discussion about the measurement parameters.

3.2. Medium Sensing Time Histogram Details

The interval durations during which no transmission occur, referred to as idle durations, depend obviously on the activities of the communicating radio stations. The more medium accesses occur, the shorter are the idle durations. Idle durations can be measured, and stochastically evaluated, with the help of the medium sensing time histogram. Specifically, the CCA idle report will indicate the duration of idle times of the medium. Figure 2(a) illustrates the structure of the report. A so-called density vector is used to report indicators (referred to as bins that are represented by one byte, therefore the values for a density varies between 0 and 255) for the probability of occurrence of specific medium idle durations. The size of the vector (the number of bins) is variable and for example defined by a measurement request from another station. Indicated in the figure is a vector with six bins.

Which bin corresponds to which duration is also a variable parameter and may have been defined by a measurement request that was received prior to the measurement. Figure 2(a) illustrates an example with CCA idle durations that correspond to slots of the 802.11 medium access protocol (SIFS, PIFS, DIFS, . . .).

The other three subfigures (b–d) of Figure 2 illustrate typical measurement results for this configuration. In Figure 2(b), a typical result is shown which would occur if the medium is relatively idle, when stations access the medium only from time to time. Longer idle durations would occur in this case, and no relevant tendency of the histogram can be expected (usually, randomly distributed idle times). Figure 2(c) and (d) illustrate the resulting histogram of typical idle duration that would occur when the medium is very busy, and frame exchanges are separated by backoff processes only. In this case, as will be explained in the next chapters, the resulting histogram would show a clear tendency towards a specific distribution. The more busy the medium is, the higher is the probability of earlier medium access, hence, earlier slots show higher probabilities of medium access (which means in the language of 802.11k, a higher bin density). The difference between the two subfigures in (c) and (d) is that in subfigure (c) all stations operate according to the same EDCA parameter set, but in (d) two different EDCA priorities are used, and two different earliest medium access times (AIFS) can be identified.

In Section 5, we will use the probabilities that are reported by the CCA idle medium sensing histogram, for the estimation of the share of capacity per station.
4. Saturation Throughput

The system saturation throughput $\text{Thrp}_{\text{sat}}$ is the expected sum of all MSDU throughputs of contending backoff entities that are saturated with traffic load so that all entities have always MSDUs to deliver at any time. In Appendix A, an approximate analysis is summarized to calculate the saturation throughput of a number of contending backoff entities. This approximation is taken from References [1–3] and in this contribution referred to as Bianchi’s legacy 802.11 model.

To evaluate the concepts of the EDCA contention window, Bianchi’s legacy 802.11 model is modified in the following Subsection 4.1. When all backoff entities operate with the same EDCA parameter set, the same AC is used by all backoff entities. In Subsection 4.2, this modified model is evaluated and results are compared to simulation results. In Section 5, the model is extended to approximate the saturation throughput per AC in scenarios where an arbitrary number of backoff entities operate in parallel, but with different EDCA parameter sets. When backoff entities operate with different EDCA parameter sets, multiple ACs are used and the resources are shared among backoff entities of different ACs according to their relative priorities. The model relies on information that is provided by 802.11k measurements.

4.1. Modifications of Bianchi’s Legacy 802.11 Model

To model the saturation throughput of an EDCA backoff entity instead of 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 EDCA parameter set, individually defined per AC. Further, since the PF has to be included in the modified model as well, the model is more general. Although it is not part of 802.11e, this parameter is considered in the equation. Hence the 802.11 or 802.11e can be easily analyzed by setting $\text{PF} = 2$. The modifications are as follows. The size of the contention window in 802.11e is calculated by

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

The probability that transmission attempts a single backoff entity at a particular generic slot are unsuccessful due to collision, is denoted by $p$. The
stationary distribution $b_{0,0}$ in Bianchi’s legacy 802.11 model is calculated as given in the following three equations:

$$b_{0,0} = \frac{2 \times (1 - p)}{W_o \times (1 - p) \times m \times (PF[AC] \times p)^{m+1} + W_o \times (PF[AC] \times p)^{m+1}}$$

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

$$b_{0,0} = \frac{2 \times (1 - p)}{W_o \times (1 - p) \times (1 - (PF[AC] \times p)^m) / (1 - PF[AC] \times p) + W_o \times (PF[AC] \times p)^m + 1}$$

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

$$b_{0,0} = \frac{2}{2 + (1 - p) \times (W_o - 1)}$$

for any $p$ and $m = 0$. All the rest of the calculations of the saturation throughput $Thr_{P_{sat}}$ when all backoff entities operate with the same EDCA parameters can be taken from Bianchi’s legacy 802.11 model, as described in detail in Reference [13]. 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 a 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.

### 4.2. Throughput Evaluation for Different EDCA Parameter Sets

The modifications of the previous Subsection 4.1 are evaluated in the following and compared to simulation results. We use the simulation environment described in Section 6. In addition to the in the draft standard as default values defined EDCA parameters, two other EDCA parameter sets are defined in the following. One is referred to as the ‘higher priority AC’ and the other as the ‘lower priority AC’, as they will allow higher and lower priority in medium access than the legacy priority respectively. The legacy priority AC is in the following also referred to as ‘medium priority AC’.

Whereas the approximation for the saturation throughput of the medium priority AC can be found in Appendix A, the approximation for the higher and lower priority AC are discussed in this section. Table I summarizes the EDCA parameter sets selected for the three ACs. The medium priority AC follows the legacy DCF protocol. The higher priority AC operates with a smaller $CW_{min}[AC]$ and a smaller $PF[AC]$, the lower priority AC operates with a larger $CW_{min}[AC]$ and a larger $PF[AC]$ than what is defined for the legacy DCF. All other EDCA parameters remain equal to the medium priority EDCA parameters. The contention window sizes for the three priorities for the first backoff stages are presented in Figure 3.

Note that depending on the number of retries, there are more backoff stages than shown in the figure. It can be seen that the parameter PF has a considerable impact on the resulting contention window sizes.

We will later see that the relative large value of AIFSN for the lower priority (AIFSN[lower] = 9) together with the larger contention window sizes will give the lower priority AC only a very limited priority in medium access.

### Table I. EDCA parameter sets for the three ACs, as selected for the analysis.

<table>
<thead>
<tr>
<th>AC (priority)</th>
<th>Higher</th>
<th>Medium (= legacy)</th>
<th>Lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIFSN[AC]</td>
<td>2</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>$CW_{min}[AC]$</td>
<td>7</td>
<td>15</td>
<td>31</td>
</tr>
<tr>
<td>$CW_{max}[AC]$</td>
<td>1023</td>
<td>1023</td>
<td>1023</td>
</tr>
<tr>
<td>$PF[AC]$</td>
<td>24/16</td>
<td>32/16</td>
<td>40/16</td>
</tr>
<tr>
<td>(Short and long)</td>
<td>7</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

The $TXOP_{limit}$ per AC is not used. Note that the legacy DCF backoff is assumed.
In Figure 4 the probability $\tau$ that a backoff entity transmits successfully in a generic slot is shown versus the number of backoff entities. The figure illustrates also the probability $p$ that transmission attempts at a particular slot are unsuccessful due to collision, as function of the number of backoff entities. The larger the number of backoff entities, the larger the collision probability. Further, the probability that a backoff entity is transmitting at a generic slot decreases with increasing number of backoff entities.

Remarkably, with any number of backoff entities, the collision probability is higher for the higher probability AC than for the legacy and lower probability ACs, which is a result of the large contention window sizes.

With a small number of backoff entities, the probability that a particular backoff entity is transmitting at a generic slot is higher for the higher priority AC than for the other ACs.

Figure 5 illustrates three other probabilities of the modified model as functions of the number of backoff entities. The probability that a generic slot is idle is labeled with $P_{CCA\text{idle}}$, the probability that a collision occurs is labeled with $P_{\text{collision}}$ and the probability that a frame exchange is successful is labeled with $P_{\text{success}}$.

These probabilities are defined in the appendix as $P_{CCA\text{idle}}$, $P_{\text{collision}}$ and $P_{\text{success}}$ respectively. The index ‘CCA’ refers to CCA, which is the carrier sense process in the 802.11 protocol. It can be observed from Figure 5 that with increasing number of backoff entities the probability that a generic slot is idle, $P_{CCA\text{idle}}$, decreases, as expected.

In addition, the collision probability $P_{\text{collision}}$ increases with increasing number of backoff entities, which is again an expected result. An interesting observation is that the probability $P_{\text{success}}$ shows maxima for all ACs, which are at different numbers of backoff entities for the different ACs. The higher the priority, the smaller the number of backoff entities that define the unique maximum, which is an expected result.

In the next two sections, Subsections 4.2.1 and 4.2.2, the saturation throughput calculated for the two priorities ‘lower’ and ‘higher’ are discussed and evaluated. The figures can be compared also to the figures that show the results for the legacy AC, see Figure A.1 and Figure A.2.
4.2.1. Lower priority access category saturation throughput

Figures 6 and 7 illustrate the resulting saturation throughput obtained through simulation and analytical approximation with the modified model for the lower priority AC. Shown is the saturation throughput for different PHY modes, and a varying number of backoff entities for the frame body sizes 48, 512, 1514 and 2304 byte. The EDCA parameters are as defined in Table I are used. Figure 6 shows the saturation throughput for scenarios without use of RTS/CTS and Figure 7 shows results for the same scenarios, with the use of RTS/CTS. The results show the expected characteristics.

The throughput increases with increasing frame body sizes. The higher the number of backoff entities, the lower the saturation throughput. The higher the PHY mode, the smaller the efficiency of the carrier sense protocol.

RTS/CTS increase the saturation throughput for long frame body sizes, but not for short frame body sizes. The prize of RTS/CTS usage is an increased overhead. For small numbers of backoff entities, the saturation throughput increases with increasing number of backoff entities.

This is an expected result for the lower priority AC with its large initial contention window: as long as the collision probability is not too high, more contending backoff entities result in shorter idle phases and thus higher saturation throughput. Comparing the figures to the results of the legacy priority

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**Fig. 5.** Probability that a generic slot is idle, busy with an collided frame or busy with a successfully transmitted frame, as functions of the number of backoff entities.

**Fig. 6.** Normalized saturation throughput for different PHY modes, and a varying number of backoff entities, for lower priority (AC = lower). EDCA parameters are as defined in Table I. RTS/CTS are not used. The respective legacy saturation throughput is illustrated in Figure A.1. (a) 48 byte frame body size. (b) 512 byte frame body size. (c) 1514 byte frame body size. (d) 2304 byte frame body size.

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AC (Figures A.1 and A.2), the saturation throughput is higher for the lower priority than for the legacy priority, which again is an effect resulting from the lower collision probability at the lower priority AC.

4.2.2. Higher priority access category saturation throughput

Figures 8 and 9 illustrate the resulting saturation throughput for the same scenarios as discussed in the last section, but now for the higher priority AC. As before, results for scenarios without the usage of RTS/CTS and results with the use of RTS/CTS are given in the two figures.

When comparing the results with the lower and legacy priorities, it can be observed that the higher priority AC shows a larger saturation throughput for a smaller number of backoff entities. However, with an increased number of backoff entities, the saturation throughput for the higher priority AC decreases considerably, because of the higher collision probability.

It is worth noting that for this AC with its high probability of collisions, simulation results and analytical approximation do not always show the same saturation throughput. For a larger number of backoff entities, simulation results and analytical approximation deviate from each other and show not the same results with the accuracy as observed for the lower and legacy priority AC.

This effect results mainly from assumptions taken in the model: the Markovian property of the original model is violated when contention windows are small. Also, for smaller contention windows, the assumption that the collision probabilities are constant for all slots is less valid.

Further, the collision duration in Bianchi’s legacy 802.11 model, the collision time $T_{coll}$, is defined without considering the ACK timeout. This is a valid assumption only for the backoff entities that are not transmitting the colliding frames, but not accurate enough for backoff entities that are transmitting colliding frames. When transmitted frames of two or more backoff entities collide, the transmitting backoff entities detect the collision after a timeout of PIFS plus ACK duration, while waiting for the ACK response from the addressed stations. Any other contending backoff entity, however, observes the collision as busy time as they are not able to detect and decode

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one of the colliding frames. It is assumed here that colliding frames cannot be detected by any station, due to the ideal medium conditions. The other contending backoff entities observe the collision time a PIFS duration earlier than the two or more transmitting backoff entities. The other stations do not wait for an acknowledgement, as the collision is observed as noise-like interference. Note that the model assumes that any capture of preambles during collisions that may happen in real life scenarios do not occur. Thus, they immediately start contention after the medium is idle again, not at the ACK timeout. This is the reason why the duration of collisions, $T_{coll}$, is here defined without the PIFS timeout duration.

The higher the collision probability, the less accurate is the approximation. However, it can be observed from Figures 8 and 9 that the analytical approximation and the simulation results show qualitatively the same saturation throughput.

The system saturation throughput $\text{Thr}_{sat}$ 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 $\text{Thr}_{sat}$ of a number of contending backoff entities is given in References [1–3] and here referred to as Bianchi’s legacy 802.11 model. Reference [6] 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 EDCA contention window, Bianchi’s legacy 802.11 model will be modified in the following Section 6.

5. Analytical Approximation of the Share per Access Category

A method to approximate the medium 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 EDCA parameter set, i.e. according to the same AC, was discussed in the previous Section 4. In contrast, in the following, the achievable throughput per AC (share of capacity per AC) and the mutual influences between the ACs are investigated for shared operation. In shared operation, backoff entities operate with different EDCA parameter sets, according to the different ACs, at the same time. Depending on the EDCA parameter sets, different backoff entities will achieve different saturation throughputs.

5.1. Share of Capacity per Access Category

We approximate the mutual influences between the ACs in the following. Our approximation makes use of the expected idle time duration and the probability of slot access in contention. These values can be obtained with the help of the medium sensing time histogram in 802.11k, as described previously in Section 3.

5.1.1. Expected idle time duration (expected contention window size)

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

\[ P_{\text{CCAbusy}} = 1 - P_{\text{CCAidle}} = 1 - \left(1 - \tau[AC]\right)^{N[AC]} \]  

(4)

where \(N[AC]\) is the number of backoff entities of a particular AC and \(\tau[AC]\) 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, \(E[\text{CW}[AC]]\), given in slots, until the first backoff entity attempts its resource allocation by initiating a transmission. Its expected value can be calculated to

\[ E[\text{CW}[AC]]_{\text{slot}} = P_{\text{CCAbusy}} \times \frac{P_{\text{CCAidle}}}{(1 - P_{\text{CCAidle}})^2} \]

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

\[ E[\text{CW}[AC]]_{\text{slot}} = (1 - P_{\text{CCAbusy}}) \times \frac{P_{\text{CCAidle}}}{(1 - P_{\text{CCAidle}})^2} = \frac{(1 - \tau[AC])^{N[AC]}}{1 - (1 - \tau[AC])^{N[AC]}} \]
The $\tau$ is the probability that a backoff entity is transmitting at a generic slot, $N_{[AC]}$ is the number of backoff entities.

5.1.2. $\sigma$-persistent CSMA

The $\sigma$-persistent CSMA [11] results in the following expected duration of the idle phase, when $N$ backoff entities operate at the same time:

$$E[CW[AC]]/\text{slot} = \frac{(1 - \sigma)^N}{1 - (1 - \sigma)^N}$$

This is confirmed by Reference [5]. In persistent CSMA, MSDUs arriving while the medium is busy have to wait for the medium to become idle again (backlogging), before being delivered immediately. In $\sigma$-persistent CSMA, MSDUs that collided before and are waiting for retransmission while the medium is busy, and MSDUs arriving while the medium is busy are delivered with different probabilities, once the medium becomes idle again.

5.1.3. Binary exponential backoff CSMA

In References [4,5] the 802.11 DCF is approximated by $\sigma$-persistent CSMA. The difference between the 802.11 (E)DCF and the $\sigma$-persistent CSMA lies in the selection process of the backoff interval, i.e. the size of the contention window. Whereas 802.11 EDCA uses a binary exponential backoff, the size of the contention window in $\sigma$-persistent CSMA is calculated from a geometric distribution with the parameter $\sigma$ [5].

5.1.4. Approximation

References [4,5] show that in the case the system of contending backoff entities is in saturation, the throughput results of the $\sigma$-persistent CSMA approximate the achievable throughput of the 802.11 EDCA, if the average backoff intervals, i.e. the expected size of the contention window, $E[CW[AC]]$, of the two different CSMA types are equal. For this reason, the mutual influences between the different ACs in the 802.11 EDCA are evaluated based on the assumption that the saturation throughput of the EDCA can be approximated with the saturation throughput of $\sigma$-persistent CSMA. In the following, the mutual influences of $\sigma$-persistent CSMA backoff entities with different $\sigma$-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 EDCA simulation results with binary exponential backoff.

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

$$E[CW[AC]] = \frac{1}{\sigma[AC]} = \frac{1}{1 - (1 - \tau[AC])^{N[AC]}} = E[CW[AC]]$$

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

This approximation is used in the following to calculate the relative priorities between the different ACs. As an example, Figures 10 and 11 illustrate the access probabilities of the three ACs that are parameterized according to Table 1, for three and eight 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 idle times during contention decreases; as a result, the probability of access at earlier slots increases. Simulation studies of the medium sensing time histograms in Reference [16] further support our assumptions, and indicate that slot access probabilities show the anticipated distributions.

5.2. Calculation of Access Priorities from the EDCA Parameters

It is now possible to derive a method to determine the access priorities from the EDCA 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). However, this capacity share, 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,

$$E[AIFS|AC] + CW[AC]| = AIFS[AC] + \frac{1}{\sigma[AC]}$$

5.2.1. slot access probabilities $1 \leq slot \leq max (CW_{max}[AC]) + 1$

The access probability of the backoff entities of an AC at a certain slot is in the following referred to as $\xi_{slot}[AC]$ which corresponds to the reported probabilities of slot access in the medium sensing time histogram report, as explained in Subsection 3.2. 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 $\xi_{slot}$ for slot $< AIFS[AC]$ is $\xi_{slot}[AC] = 0$, because for slots earlier than AIFS[AC], backoff entities of this AC will not access the medium. However, the access probability for slot $> CW_{max}[AC] + AIFS[AC]$ is also given by $\xi_{slot}[AC] = 0$, because for slots later than $CW_{max}[AC]$, backoff entities of the respective AC will not access the medium neither. It is again emphasized that $CW_{max}[AC]$ is here defined by more than the QoS-parameters known from 802.11e. That means, $CW_{max}[AC]$ depends on a number of parameters such as the Retry[Cnt][AC], the PF[AC], and the initial contention window size, $CW_{min}[AC]$. For any other slot, with $AIFS[AC] \geq slot \geq CW_{max}[AC]$, the access probability at a particular slot is calculated with the

Figure 10. Slot access probabilities for three backoff entities per AC. Three ACs with EDCA parameters are as defined in Table I.

Figure 11. Slot access probabilities for eight backoff entities per AC. Three ACs with EDCA parameters are as defined in Table I.
help of the geometric distribution to
\[
\xi_{\text{slot}[AC]} = 1 - \left( 1 - \left( \sigma[AC] \times (1 - \sigma[AC])^{\text{slot-\text{AIFS}[AC]}} \right) \right)^{N[AC]}
\]  
(6)

with \(\text{AIFS}[AC] < \text{slot} \leq \text{CW}_{\text{max}}[AC]\). As stated above, for any other slot, \(\xi_{\text{slot}[AC]} = 0\).

5.2.2. CSMA access 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 12. 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 access 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. Reference [17] discuss in this context the regeneration cycle. Each alternation of a regeneration cycle is a ‘probabilistic replica’ [17] 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,’ \(\ldots\), ‘\(\text{CW}_{\text{max}} + 1\)’ 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. Note that according to 802.11e, the earliest time when backoff entities access the medium is one slot after AIFS.

Thus, the second slot represents the first possible access time SIFS + 2 x aSlotTime for backoff entities that operate according to the HCF contention-based medium 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 \(\leq\) AIFSN[AC] is 0.

The last slot is determined by the value of \(\text{CW}_{\text{max}} + 1\), it is calculated as the maximum of all contention window sizes per ACs. Typically, but not necessarily, \(\text{CW}_{\text{max}} = \text{CW}_{\text{max}}[\text{Low}]\), since a large value implies a lower priority in medium access. If the backoff entities of one AC operate with a smaller value for \(\text{CW}_{\text{max}}[AC]\), 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 medium as the first backoff entity, for example by accessing the medium at the first slot, and if no other backoff entity from the other ACs accesses the medium 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’.

5.2.3. Transition probabilities

Let
\[
P\{s(t + 1) = \text{AC} \mid s(t) = \text{slot}\} = P_{\text{slot,AC}}
\]
\(\text{AC} \in \text{H, M, L}\)

\[
P\{s(t + 1) = \text{C} \mid s(t) = \text{slot}\} = P_{\text{slot, C}}
\]
\(P\{s(t + 1) = \text{slot + 1} \mid s(t) = \text{slot}\} = P_{\text{slot, slot + 1}}\)

with slot = 1 \ldots \text{CW}_{\text{max}} + 1, be the transition probabilities, and let
\[
\lim_{t \to \infty} P\{s(t) = \text{AC}\} = p_{\text{AC}}, \quad \text{AC} \in \text{H, M, L}
\]
\[
\lim_{t \to \infty} P\{s(t) = \text{C}\} = p_{\text{C}}
\]
\[
\lim_{t \to \infty} P\{s(t) = \text{slot}\} = p_{\text{slot}}, \quad \text{slot} = 1 \ldots \text{CW}_{\text{max}} + 1
\]

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 medium 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.

\[
P_{\text{slot, H}} = \xi_{\text{slot}[\text{High}]} \times (1 - \xi_{\text{slot}[\text{Medium}]}) \times (1 - \xi_{\text{slot}[\text{Low}]})
\]
\[
P_{\text{slot, M}} = \xi_{\text{slot}[\text{Medium}]} \times (1 - \xi_{\text{slot}[\text{High}]}) \times (1 - \xi_{\text{slot}[\text{Low}]})
\]
\[
P_{\text{slot, L}} = \xi_{\text{slot}[\text{Low}]} \times (1 - \xi_{\text{slot}[\text{High}]}) \times (1 - \xi_{\text{slot}[\text{Medium}]})
\]
These state transition probabilities can be understood as follows. If the system is in an idle state, with the probability $P_{\text{slot}, X}$ the system changes to state $X$, $X$ representing transmission attempts of at least one backoff entity of the respective AC, but no transmission attempt of any backoff entity of the other ACs.

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

$$P_{\text{slot,C}} = \xi_{\text{slot,High}} \times \xi_{\text{slot,M}} \times (1 - \xi_{\text{slot,Low}}) + \xi_{\text{slot,High}} \times \xi_{\text{slot,Low}} \times (1 - \xi_{\text{slot,M}}) + \xi_{\text{slot,M}} \times \xi_{\text{slot,Low}} \times (1 - \xi_{\text{slot,High}}) + \xi_{\text{slot,High}} \times \xi_{\text{slot,M}} \times \xi_{\text{slot,Low}}$$

This state transition probability can be understood as follows. If the system is in an idle state, with the probability $P_{\text{slot,C}}$ the system changes to state $C$. 

---

Fig. 12. State transition diagram for the CSMA access cycle. The states C, H, M, L represent a busy system, and all other states 1, 2, \ldots, $\text{CW}_{\text{max}} + 1$ represent an idle system. Time is progressing in steps of generic slots. The system state changes with the indicated state transition probabilities.
which means that backoff entities of different ACs attempt to transmit, and a collision occurs.

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:

\[ P_{\text{slot,slot+1}} = \begin{cases} 0, & \text{slot} > \text{CW}_{\text{max}} \\ 1 - (P_{\text{slot,H}} + P_{\text{slot,M}} + P_{\text{slot,L}} + P_{\text{slot,C}}), & \text{else} \end{cases} \]

### 5.2.4. The priority vector \( \eta \)

The priority vector \( \eta \) 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 \( \eta \). With the help of the priority vector \( \eta \), the saturation throughput \( \text{Thrp}_{\text{share}} \)

(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 EDCA parameters. The achievable saturation throughput \( \text{Thrp}_{\text{share}} \) for the three ACs is approximated by

\[ \text{Thrp}_{\text{share}} = \text{Thrp}_{\text{sat}} \times \eta = \left( \frac{\text{Thrp}_{\text{sat}}[\text{High}] \times \eta_H}{\text{Thrp}_{\text{sat}}[\text{Medium}] \times \eta_M} \right) \left( \frac{\text{Thrp}_{\text{sat}}[\text{Low}] \times \eta_L}{\text{Thrp}_{\text{sat}}[\text{High}] \times \eta_H} \right) \]

We need this final step in our approximation to model the effects of the backoff processes. The priority vector \( \eta \) however only determines the relative priorities between the three ACs. If a large number of backoff entities operates according to one ACs, the priority vector would then indicate that this AC achieves a high relative priority. However, a large number of backoff entities also implies a higher probability of unsuccessful transmission attempts because of collisions. This effect is modeled by \( \text{Thrp}_{\text{sat}} \).

As a result, \( \text{Thrp}_{\text{share}} = \text{Thrp}_{\text{sat}} \times \eta \) models the expected saturation throughput in a sharing scenario.

Note that Equation (10) neglects the mutual influences the shared operation implies on the individual changes of maximum saturation throughput per AC. This means that for some EDCA parameter sets, the approximation is more accurate than for others. In general, for a set of backoff entities (e.g. set A) that operate with the same EDCA parameter sets, the more aggressive the EDCA parameters are (smaller values for \( \text{CW}_{\text{min}}, \text{AIFS}, \text{PF}, \text{CW}_{\text{max}} \)) compared to the parameters of other backoff entities (e.g. set B of backoff entities), the smaller the influence of the set B backoff entities on the results of set A backoff entities. However, if the number of set B backoff entities is

In this equation, a new parameter is defined, which determines the relative priority of the AC ‘High’. This is referred to as \( \eta[\text{High}] \). The stationary distributions of the states ‘M’, ‘L’ and ‘C’ are equally defined:

\[ p_M = \left( P_{1,M} + \sum_{\text{slot}=2}^{\text{CW}_{\text{max}}+1} P_{\text{slot,M}} \times \prod_{i=1}^{\text{slot}-1} P_{i,i+1} \right) \times p_1 \]

\[ p_L = \left( P_{1,L} + \sum_{\text{slot}=2}^{\text{CW}_{\text{max}}+1} P_{\text{slot,L}} \times \prod_{i=1}^{\text{slot}-1} P_{i,i+1} \right) \times p_1 \]

\[ p_C = \left( P_{1,C} + \sum_{\text{slot}=2}^{\text{CW}_{\text{max}}+1} P_{\text{slot,C}} \times \prod_{i=1}^{\text{slot}-1} P_{i,i+1} \right) \times p_1 \]

The priority vector \( \eta \) is found as

\[ \eta = (\eta_H, \eta_M, \eta_L) = \frac{1}{\sum_{\text{AC}} \eta[\text{AC}]} (\eta[\text{High}], \eta[\text{Medium}], \eta[\text{Low}]) \]

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larger than the number of set A backoff entities, the influence will be more remarkable.

6. Numerical Results and Evaluation with Simulation Results

The example with the three ACs as defined in Table I, and illustrated in Figures 10 and 11, is used for evaluating the approximation of the saturation throughput in a shared scenario, Thrp\textsubscript{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 EDCA parameters in different scenarios: the EDCA 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 EDCA parameter setups. Many different situations can be studied with such a wide-range of scenario combinations. The EDCA parameters of the higher, legacy and lower priority ACs are defined in Table I. A constant frame body size of 512 byte for all ACs is selected here. RTS/CTS is not used. Note that the parameters \( CW_{\text{max}} \) and \( \text{Retr}_{\text{Cnt}} \) remain constant for all ACs at any time and are not varied over the scenarios.

The simulation results discussed in the following are generated with the simulation environment called ‘WARP2,’ as presented in Reference [12]. The radio environment is error-free, and all backoff entities operate in saturation (the queues are never empty). WARP2 stands for wireless access radio protocol. The simulator was developed as simulation environment for WLAN protocols. In WARP2, the protocols are specified in the graphical representation of the system description language (SDL) and the abstract syntax notation (ASN.1) with the usage of the commercial tool Telelogic TAU SDT\textsuperscript{TM}. The WARP2 simulator includes a complete specification of the 802.11 MAC protocol including the relevant 802.11e QoS enhancements, and a model of the 802.11a PHY with the OFDM radio transmission scheme. The traffic generators used for this work allow the application of differently distributed inter-arrival times of the generated packets, which is not relevant because of saturation. Generated packets are fed into the MAC layers as part of the frame body of MSDUs. With WARP2, event-driven, stochastic simulation is used to calculate long runs of realistic scenarios. The discrete limited relative error (LRE) algorithm that measures the local correlation of the stochastic data can be used. By measuring local correlations, the accuracy of empirical simulation results can be estimated with the LRE algorithm. Typical, results should be within a maximum limited relative error of 5% as the level of confidence results are calculated with.

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 13 shows the results for the scenarios with four backoff entities per AC, i.e. 12 backoff entities in total. Figure 14 shows results for scenarios with ten backoff entities with variable EDCA parameter setup, two legacy priority backoff entities and four lower priority backoff entities. Therefore, 16 backoff entities in total share a common medium in these scenarios. Figure 15 shows results for scenarios with two backoff entities with variable EDCA parameter setup, ten legacy priority backoff entities and four lower priority backoff entities. Hence, 16 backoff entities in total are again assumed here.

6.1. Four Backoff Entities against Four Legacy and Four Low Priority Backoff Entities

Figure 13 shows simulation and analytical results for 28 configurations, in which the EDCA 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 I. The other eight 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 medium.

It can be observed from the left-hand side of Figure 13 that the AC with the variable priority observes the largest throughput (share of capacity) in scenarios with higher priority EDCA parameters (\( \text{AIFS}_\text{N} = 2, \text{CW}_{\text{min}} = 7, \text{PF} = 24/16 \)). However, this share decreases with changed EDCA parameters towards legacy priority.

If the four backoff entities of the AC with the variable EDCA parameters operate according to the legacy priority, then the observed share of capacity is the same as for the four legacy backoff entities. This is indicated by the simulation results, and confirmed by the analytical approximations (center of Figure 13, \( \text{AIFS}_\text{N} = 2, \text{CW}_{\text{min}} = 15, \text{PF} = 32/16 \)). As expected,
Fig. 13. Scenario (left) and resulting saturation throughput per AC (right). Four backoff entities per AC, one 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.

Fig. 14. Scenario and resulting saturation throughput per AC. Ten backoff entities with varying EDCA parameters contend with two legacy and four lower priority backoff entities.

Fig. 15. Scenario and resulting saturation throughput per AC. Two backoff entities with varying EDCA parameters contend with ten legacy and four lower priority backoff entities.
when changing the EDCA 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 13, \( \text{AIFS} = 9, \text{CW_{min}} = 31, \text{PF} = 40/16 \)). In parallel, the legacy priority backoff entities observe an increased share. This is expected: the legacy priority AC is parameterized such that the four legacy backoff entities access the medium with highest priority relative to the other eight backoff entities, because those backoff entities operate with the lower priority EDCA parameters. This is confirmed by simulation and the analytical approximations.

6.2. Ten Backoff Entities against Ten Legacy and Ten Low Priority Backoff Entities

A different number of backoff entities per AC is assumed in the following, as shown in Figure 14. Simulation and analytical results for configurations with ten backoff entities with variable EDCA parameter setup, two legacy priority backoff entities and four 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 ten backoff entities are more dominant than the four backoff entities of the previous scenario. As before, the analytical results and the simulation results confirm each other with sufficient accuracy.

6.3. Two Backoff Entities against Ten Legacy and Four Low Priority Backoff Entities

Figure 15 shows results for a scenario with two backoff entities with variable EDCA parameter setup, ten legacy priority backoff entities and four lower priority backoff entities. Although the two 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 two backoff entities than the share observed by any of the ten legacy backoff entities.

It is 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 ten dominating legacy backoff entities obtain the largest throughput, other backoff entities are entirely suppressed.

7. Conclusion and Outlook

This work discusses the combination of IEEE 802.11e and IEEE 802.11k for the estimation of the share of capacity. The saturation throughput is calculated analytically, results are confirmed with the simulation. An algorithm to approximate the resulting share of capacity per AC is presented. With this algorithm, the relative priority between different ACs when backoff entities operate with different EDCA parameters can be approximated under some assumptions like for example specific distributions for slot access probabilities. We note that simulation studies of the medium sensing time histogram in Reference [16] indicate that slot access probabilities show the anticipated distributions.

Our work can only be an initial step towards a better understanding of how to gain from combining 802.11k and 802.11e. Evaluating the model with more simulation of other scenarios, or real life measurement may help to further improve the model.

IEEE 802.11k will introduce a step toward spectrum awareness in wireless local area networks. We refer to spectrum awareness in particular because with the new type of measurements, information about how the spectrum is being used by other radio networks will be made available to a radio station. Hence, radio stations become aware of the radio spectrum usage. IEEE 802.11e, together with our algorithm, will introduce a step towards self-awareness. With self-awareness, we refer to the ability of radio stations to support their individual requirements, i.e. radio stations that attempt to achieve their individual level of satisfaction, autonomously.

In autonomous radio resource sharing, the decision making of which radio station achieves what level of satisfaction is distributed across the radio networks that are competing for the radio spectrum. Actions that are taken by radio networks, or radio stations, may have
implications on other radio networks. Hence, a third level of awareness may be considered, which we refer to as the society awareness. We will use the concept of society awareness for our future work, which focuses on spectrum agile radios, which organize the usage of the radio spectrum based on policies.

Appendix A: Legacy 802.11 Saturation Throughput Analysis

For the contention of legacy 802.11 backoff entities, Bianchi [1–3] presents an analytical approximation (here referred to as ‘Bianchi’s legacy 802.11 model’) that allows the analysis of the saturation throughput. A similar approach for the analysis of legacy 802.11 is presented in Reference [7]. The system saturation throughput 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). Coli, Conti and Gregori [4] refers to this throughput as achievable throughput in asymptotic conditions. Hettich [6] uses Bianchi’s legacy 802.11 model and extends it to analytically approximate not only the expected saturation throughput, but also the backoff delays, which are not evaluated in our work.

Bianchi [1–3] considers a finite number of \( N \) contending backoff entities and develops an approximation for the transmission attempt at a generic slot of one backoff entity, \( \tau \). If more than one backoff entity transmit, frames collide. If there is an ongoing transmission, regardless if it collided or not, the medium is busy, and the carrier sense mechanism in 802.11, CCA, will detect the medium as busy (CCAbusy). Equivalently, without ongoing transmission, the medium is idle (CCAidle). The probability \( P_{\text{CCAbusy}} \) that there is a transmission of at least one backoff entity in a generic slot time, and the probability \( P_{\text{CCAidle}} = 1 - P_{\text{CCAbusy}} \) that there is no transmission, as well as the probability \( P_{\text{success}} \) that the transmission
attempt leads to a successful frame exchange (conditioned by the probability of transmission, $P_{\text{CCAIdle}}$), are obtained to

\[
\begin{align*}
P_{\text{CCAIdle}} &= (1 - \tau)^N \\
P_{\text{CCAbusy}} &= 1 - P_{\text{CCAIdle}} = 1 - (1 - \tau)^N \\
P_{\text{success}} &= \begin{cases} 
\frac{1}{P_{\text{CCAbusy}}} \times N \times \tau \times (1 - \tau)^{N-1}, & \text{else} \\
0, & \text{if } P_{\text{CCAbusy}} = 0
\end{cases}
\end{align*}
\]

The collision probability $P_{\text{coll}}$ is given by $P_{\text{coll}} = 1 - P_{\text{success}}$.

In each generic slot, the system is in one of the three states, no transmission (CCAIdle), successful transmission (success), or collision (coll). The carrier sense indicates CCAbusy during transmission and during collision. The state durations $T_{\text{CCAIdle}}$, $T_{\text{success}}$, $T_{\text{coll}}$ of the three respective states depend on many PHY and MAC parameters. The state duration $T_{\text{CCAIdle}}$ is given by a slot duration $a\text{SlotTime}$ that is defined by the standard ($a\text{SlotTime} = 9\mu s$ for 802.11a). The state durations $T_{\text{success}}$ and $T_{\text{coll}}$ depend on the duration of a transmission. The state durations are given by

\[
\begin{align*}
T_{\text{success}} &= T_{\text{RTS}} + T_{\text{SIFS}} + T_{\text{CTS}} + T_{\text{SIFS}} \\
&\quad \text{only with RTS/CTS} \\
&\quad + T_{\text{MSDU}} + T_{\text{SIFS}} + T_{\text{ACK}} + T_{\text{DIFS}} \\
T_{\text{coll}} &= T_{\text{RTS}} + T_{\text{DIFS}} \quad \text{or} \quad T_{\text{PPDU}} + T_{\text{DIFS}} \\
&\quad \text{only with RTS/CTS} \quad \text{without RTS/CTS} \\
T_{\text{CCAIdle}} &= a\text{SlotTime}
\end{align*}
\]

The normalized system saturation throughput of legacy 802.11 is finally given as

\[
\text{Thrup}_{\text{sat}} = \frac{\text{time used for successful transmission}}{E[\text{length of renewal interval}]} = \frac{P_{\text{CCAbusy}} \times P_{\text{success}} \times \text{FrameBody}[\text{Mbyte}]}{P_{\text{success}} \times T_{\text{success}}[s] + P_{\text{CCAbusy}} \times (P_{\text{coll}} \times T_{\text{coll}}[s] + P_{\text{CCAIdle}} \times T_{\text{CCAIdle}}[s]) \times \frac{1}{\text{Mbyte}/s}}
\]

The saturation is normalized relative to the applied PHY mode, i.e. $\text{Thrup}_{\text{sat}} \in 0 \ldots 1$. Figure A.1 and Figure A.2 show the saturation throughput obtained through simulation and analytical approximation with Bianchi’s legacy 802.11 model.

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