Delay Performance of the Enhanced Distributed Channel Access of IEEE 802.11e

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***Abstract*— In the recent years Wireless Local Area Networks of the IEEE 802.11 standard experienced an impressing commercial success. The increasing demand for Quality-of-Service is the motivation for extending this standard through the amendment 802.11e. These enhancements introduce a Hybrid Coordination Function to enable the support of Quality-of-Service. The Hybrid Coordination Function defines two medium access mechanisms: the (1) contention-based channel access and (2) the controlled channel access. The contention-based channel access is referred to as Enhanced Distributed Channel Access and is discussed in this paper. 802.11e introduces four Access Categories that define different parameter sets for the Enhanced Distributed Channel Access that enable the support of Quality-of-Service on a probabilistic basis. This paper evaluates the capabilities of the Enhanced Distributed Channel Access for supporting Quality-of-Service in distributed environments by analytic approximation and simulation.**

***Keywords*— Analytic Approximation, Enhanced Distributed Channel Access, 802.11e, Markov Model**

I. INTRODUCTION

The *Wireless Local Area Network* (WLAN) protocol 802.11 of the *Institute of Electrical and Electronics Engineers, Inc.* (IEEE) is a very popular standard for wireless communication. IEEE 802.11 is a radio standard designed for operation in unlicensed frequency bands at 2.4 and 5 GHz. It is a root standard for a multitude of supplements (amendments) that have been developed or are under development at the time of this paper. This paper concentrates on IEEE 802.11e [1] which is a protocol extension to 802.11 for providing the support of *Quality-of-Service* (QoS). A compilation of the base standard 802.11 and its amendments 802.11a, 802.11b and 802.11d is given in the IEEE Wireless LAN Edition [2]. IEEE 802.11 is in detail described and analyzed in [3, 4] while 802.11e is explained and evaluated in [5]. The version D13.0 of the IEEE 802.11e amendment has been approved by the IEEE Standards Association in September 2005 and is the basis for this paper.

A. Related Work

The contention-based access of 802.11e's EDCA is evaluated in this section with the help of an analytic Markov model of the backoff process. The model used in this paper is based on the approximation analysis of the legacy 802.11 DCF from Bianchi [6]. Bianchi uses a two dimensional Markov model to calculate the saturation throughput of contending legacy backoff entities. A simplification of this well-known model is done in [7]. Hettich [3] extends Bianchi's model for the analysis of the backoff delay of legacy 802.11 and the *High Performance Local Area Network Type 2* (H/2). A Z–transform based analysis of the service time in saturated 802.11 networks is performed in [8] ending up in a linear evaluation of the service time distribution.

The EDCA saturation throughput of competing backoff entities of different ACs is analyzed and discussed by Mangold [5]. In addition, the achievable throughput per AC and the mutual influences of the ACs on each other are evaluated in terms of share of capacity per AC. Xiao [9] also developed a model to analyze the prioritization through contention window size differentiation of the EDCA. The throughput and mean delay is evaluated in neglecting the different AIFS per AC and the virtual collision mechanism as originally specified in 802.11e. Robinson and Randhawa [10] extended Bianchi's model to analyze the saturation throughput performance of the EDCA mechanism similar to Mangold [5] ending up in a complex, difficult to analyze model.

B. Overview

In the following, the saturation throughput analysis of Mangold [5] is briefly summarized with a different set of EDCA parameters as summarized in Table 2. Here, the ACs "AC_VI" and "AC_BK" are evaluated and compared. The default EDCA parameters are defined in the 802.11e standard and are used by QSTAs if no QAP is present. Here, the analytic model of Mangold [5] is extended in a similar way as the extensions by Hettich [3] to Bianchi's model in the case of 802.11. These extensions enable a saturation analysis of the mean service time and the service time distribution. For saturation analysis it is assumed in the following that every contending backoff entity is saturated with traffic load, i.e., all entities have always *MAC Service Data Units* (MSDUs) to deliver and their queues are never empty.

In this paper the MAC enhancements of 802.11e in its final version are briefly described in the Sections II. The capability of supporting QoS in distributed environments with the means of 802.11e is examined through analytic approximation and simulations in Section III followed by a conclusion in Section IV.

II. MEDIUM ACCESS CONTROL IN IEEE 802.11E

The main element of the enhancements of 802.11e is the introduction of a new central entity: The *Hybrid Coordination Function* (HCF). The HCF realizes a contention free, centrally controlled medium access denoted as *HCF Controlled Channel Access* (HCCA) and a contention-based, distributed medium access, in 802.11e referred to as EDCA. Therefore, the HCF is able to schedule in an 802.11e beacon interval that in the following is referred to as superframe a *Contention Free Period* (CFP) and a *Contention Period* (CP) as outlined below. An 802.11e access point forms with its associated stations a *QoS supporting Basic Service Set* (QBSS).

A time interval during which stations have the exclusive right to initiate transmissions is in 802.11e referred to as *Transmission Opportunity* (TXOP). TXOPs can either be allocated in the contention-based EDCA of the CP or are assigned by the HC in the CFP or CP. In the first case, the TXOP is also denoted as EDCA TXOP and in the latter case the TXOP is called a *Controlled Access Phase*. It is protected by a timer referred to as *Network Allocation Vector* (NAV) and is used for reservation of the channel for the indicated time duration. TXOPs obtained by the EDCA have a limited duration named *TXOPlimit*. It is a QBSS-wide parameter which is broadcasted by the HC as part of the information field

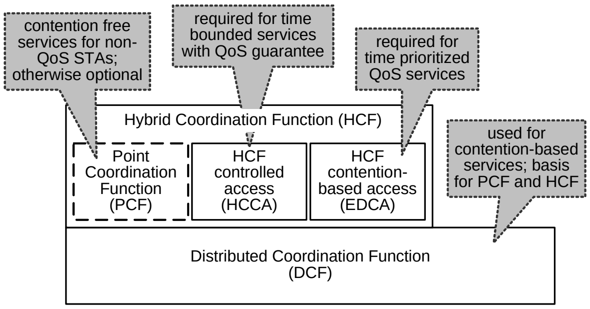


Figure 1: Medium access control architecture of IEEE 802.11e.

of a beacon. The beacon is regularly transmitted by the HC at the beginning of each superframe. Legacy STAs ignore this new information field and consequently do not take this limitation into account. Thus, legacy STAs may have longer transmission durations.

A. Architecture

Figure 1 illustrates the main elements of the 802.11e MAC architecture. The legacy 802.11 *Distributed Coordination Function* (DCF) is the basis for the contention-based access of the HCF and the legacy 802.11 *Point Coordination Function* (PCF). The PCF offers contention free services to legacy STAs and is used by the HCF for polling stations as discussed below. The HCCA introduces the possibility to guarantee QoS, while the EDCA is used for prioritized contention-based QoS support. Both HCCA as well as EDCA use the known 802.11 MAC frames of the DCF to transmit user data on the radio channel, namely the DATA/*Acknowledge* (ACK) frame exchange sequence with an optional preceding *Request to Send* (RTS) / *Clear to Send* (CTS).

B. Enhanced Distributed Channel Access

The EDCA realizes the contention-based access of the HCF as illustrated in Figure 1. It is used to provide differentiated services. In order to support QoS, the EDCA introduces four *Access Categories* (ACs). Each AC has a corresponding backoff entity as illustrated in Figure 2. The four backoff entities of an 802.11e station operate in parallel and realize the contention-based access corresponding to the respective AC. The four ACs of 802.11e, namely AC_BK ("background"), AC_BE ("best effort"), AC_VI ("video") and AC_VO ("voice"), result from a mapping of the user priorities from Annex H.2 of IEEE 802.1D [11], as also illustrated in Figure 2. The prioritization between the four backoff entities is realized through different AC-specific parameters in the following denoted as set of EDCA parameters. These EDCA parameter sets modify the backoff process with individual interframe spaces and contention window sizes per AC introducing a probability-based prioritization as explained next.

The EDCA parameters of each backoff entity are defined by the HC and may be adapted over time. Default values for the EDCA parameters are given in Table 1. Only a QAP may change these parameters according to the traffic within the QBSS. The EDCA parameters are broadcasted therefore via information fields in the beacon frames. Identical EDCA parameters must be used by all backoff entities with the same AC within a QBSS in order to enable this centrally controlled prioritization. In case of an independent QBSS, i.e., in the absence of an access point, the beacon holder is responsible for defining the sets of EDCA parameters.

Each backoff entity within a QSTA individually contends

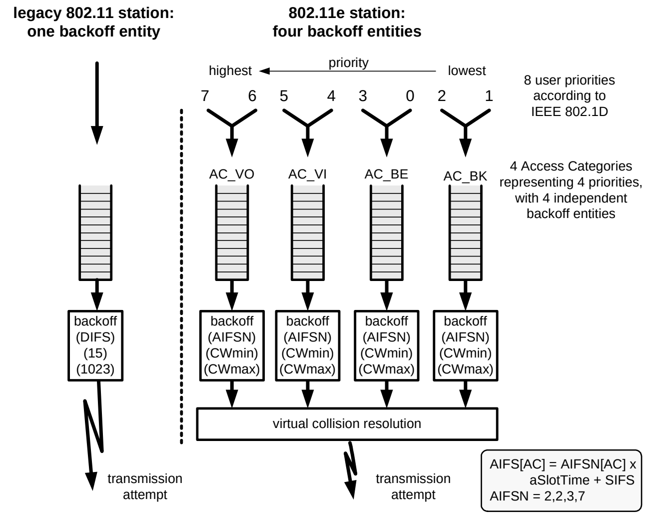


Figure 2: The backoff entity of a legacy 802.11 STA compared to the four parallel backoff entities of an 802.11e QSTA.

for obtaining a TXOP. When multiple backoff entities of a QSTA try a parallel access to the same slot an internal virtual collisions resolution is performed: The backoff entity with the highest AC transmits, while the other backoff entities act as if a collision occurred. Nevertheless, the transmission attempt of the highest AC may collide with frames from other stations.

1) Arbitration Interframe Space

A backoff entity starts decreasing its backoff counter after detecting that the channel is idle for an *Arbitration Interframe Space* (AIFS). The AIFS has at least a duration of *DCF Interframe Space* (DIFS) and depends on the corresponding AC as illustrated in the timing diagram depicted in Figure 3 of the four ACs of 802.11e. To express this dependency, it is denoted therefore in the following as $AIFS[AC]$. The *Short Interframe Space* (SIFS) is the shortest interframe space of 802.11. It is used between the frames of the RTS/CTS/DATA/ACK sequence. The *PCF Interframe Space* (PIFS) is used by the PCF to gain access to the radio channel. The *Arbitration Interframe Space Number* (AIFSN) is defined per AC according to Table 1 and enlarges $AIFS[AC]$. A small $AIFSN[AC]$ implies a high access priority. The earliest channel access time after an idle channel, i.e., the shortest value of $AIFS[AC\_VO]$=DIFS is similar to the legacy DCF of 802.11 which would have an AIFSN of 2. Prioritization is reached in this case through different values of the contention window as described below.

2) Contention Window Size

The *Contention Window* (CW) of the backoff process is also used in 802.11e to introduce priorities. Its minimum $CWmin[AC]$ and maximum value $CWmax[AC]$ depends on the AC as illustrated in Figure 3 and default values are given in Table 1. For the legacy 802.11a PHY, the minimum and maximum value is given by $CWmin = 15$ and $CWmax = 1023$. A small $CWmin[AC]$ leads to a high access priority. Nevertheless increases a small $CWmin[AC]$ the collision probability when multiple backoff entities of the same AC compete for channel access within a QBSS. In case of a failed frame transmission, the contention window increases up to a value of $CWmax[AC]$. A small $CWmax[AC]$ results into a high priority for accessing the channel.

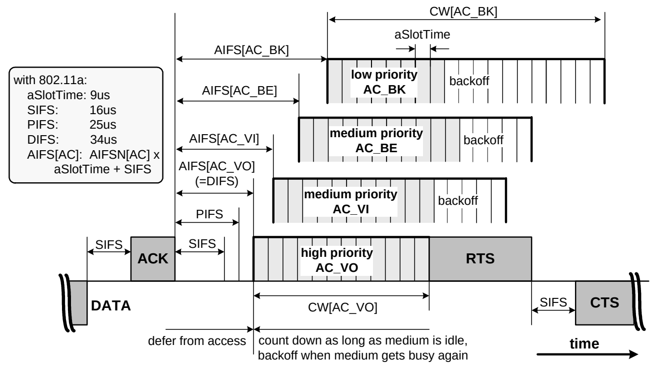


Figure 3: EDCA timing diagram of the four backoff entities defined in 802.11e with different AIFSs and contention window sizes.

The strict prioritization is lost when high priority backoff entities increase their contention window after a collision while low priority backoff entities experience no collisions. The relative difference between the contention windows of different ACs, necessary for prioritization, is lost in such a case. Legacy stations have $CWmin = 15$, $CWmax = 1023$ and an earliest channel access time of AIFS = DIFS =34 µs. An 802.11e QSTA has a higher priority than legacy STAs in setting its $CWmin[AC] < 15$ and $CWmax[AC] << 1023$.

III. Analytic QoS Approximation

This section introduces an analytic approximation of the (i.) saturation throughput, (ii.) the mean service time and (iii.) the service time distribution in saturation.

A. Saturation Throughput

The following analysis of the EDCA's throughput in saturation corresponds to the one of Mangold [5] besides a neglect of the persistence factor. Such an individually per AC defined persistence factor is not part of the standard: In 802.11e, it has a fixed value of 2 for all ACs.

In using the notation of Mangold [5] the size of the contention window $CW_i[AC] = W_i[AC], i = 0...m[AC]$ can be calculated with a recursion according to

$$W_i[AC] = 2^{min(i, m[AC])} \cdot W_0[AC], \quad i \in 0,1,...,m[AC].$$

The variable i defines the backoff stage, $W_0[AC] = CWmin[AC] + 1$ the initial size of the contention window and $m[AC]$ the maximum value of the backoff stages given by

$$m[AC] = log_2 \frac{CWmax[AC]+1}{CWmin[AC]+1}.$$

In legacy 802.11 with the PHY of 802.11a the initial contention window has a size of $W_0[legacy] = 16$ and the maximum backoff stage is defined as $m[legacy] = 6$.

The rest of Bianchi's saturation throughput analysis is summarized in [5] and ends with the following description for the saturation throughput

$$Thrp_{sat} = \frac{P_{success} \cdot P_{CCAbusy} \cdot FrameBodySize}{P_{success} \cdot T_{success} + P_{CCAbusy}\left(P_{coll} \cdot T_{coll} + P_{CCAidle} \cdot T_{CCAidle}\right)} \quad (1)$$

Note that a generic slot in this paper has a different meaning than a backoff slot, analogous to Mangold [5]. A generic slot may be (i.) an idle slot in the contention phase, (ii.) a busy slot during which a frame exchange is completed or (iii.) a slot during which the transmission attempts of backoff entities collide. Therefore, a generic slot can be a backoff slot or a busy phase with a longer duration than the duration of a backoff slot.

The throughput in saturation of multiple backoff entities which operate all according to the same AC can be analyzed with the approximation of Bianchi's model under consideration of the modifications from above.

B. Saturation Mean Service Time

In extending the analytic model of Mangold [5], the service times in saturation can be determined in improving Hettich [3]. In saturation, the mean service time $t_{ServiceTime}$ describes the time of an MSDU that is required for successfully transmitting an MSDU, i.e., the time between being first in the waiting queue and successful transmission. Consequently, the waiting time within the queue required to move to this first position is not considered.

The mean service time $\overline{t}_{ServiceTime}$ can be calculated with the help of the mean number of time slots needed for successful transmission. Therefore, this mean number of time slots needed to reach backoff stage i is multiplied with their occurrence probability. The sum over all backoff stages is than multiplied with the mean time slot length $\overline{T}_{slot}$ which is derived from the Markov model [5]. Thus, the mean service time $\overline{t}_{ServiceTime}$ is given by

$$\overline{t}_{ServiceTime} = \overline{T}_{slot} \cdot \sum_{i=0}^{\infty} p^i (1-p) \cdot \frac{\left(2^{min(i,m[AC])+1} - 1 + max(i - m[AC], 0) \cdot 2^{m[AC]}\right) \cdot W_0[AC] - (1+i)}{2} \quad (2)$$

The parameter p, corresponding to Bianchi's model, refers to the probability that a transmission attempt from a single backoff entity at a particular slot fails due to a collision.

C. Saturation Service Time Distribution

The *complementary Cumulative Distribution Function* (CDF) of the service time can also be derived from the approximation of the backoff window process. Therefore, the probability $P(T = j)$ that a backoff entity waits j time slots before a successful transmission can be calculated to

$$P(T = j) = (1-p) \cdot \sum_{i=0}^{\infty} \left(p^i \cdot N_{j,i} \cdot \prod_{l=0}^{i} \frac{1}{W_0[AC] \cdot 2^{min(l, m[AC])}} \right) \quad (3)$$

$P(T = j)$ is thereby a sum of conditioned probabilities, each given by the product of transition probabilities of spending time in $i+1$ backoff stages. Thereby, m determines again the number of backoff stages per AC. $N_{j,i}$ is the number of possibilities to wait the j time slots in states that are

Table 1: Default values of EDCA parameters based on [1]. The star indicates dependency on the PHY, here 802.11b/802.11a are selected.

AC	CWmin	CWmax	AIFSN
AC_BK	*CWmin**	*CWmax**	7
AC_BE	*CWmin**	*CWmax**	3
AC_VI	(*CWmin**+1)/2-1	*CWmin**	2
AC_VO	(*CWmin**+1)/4-1	(*CWmin**+1)/2-1	2

Table 2: EDCA parameters with 802.11a based on [1].

AC	CWmin	CWmax	AIFSN	AIFS	RetryCnt
legacy	15	1023	2	34 us	N/A
AC_BK	15	1023	7	79 us	N/A
AC_BE	15	1023	3	43 us	N/A
AC_VI	7	15	2	34 us	N/A
AC_VO	3	7	2	34 us	N/A

distributed in total over *i+1* backoff stages. This is related to the different combinations of backoff decrements and collisions implying *j* time slots of waiting before successful initiating transmission.

In general $N_{j,i}$ can be calculated with the following recursion:

$$N_{j,i} = \sum_{n}^{min(j,W_i[AC])} N_{j-n,i-1}\ ,\ N_{j,0} = \begin{cases} 1 & 0 < j \le W_0\left[AC\right] \\ 0 & else \end{cases}.$$

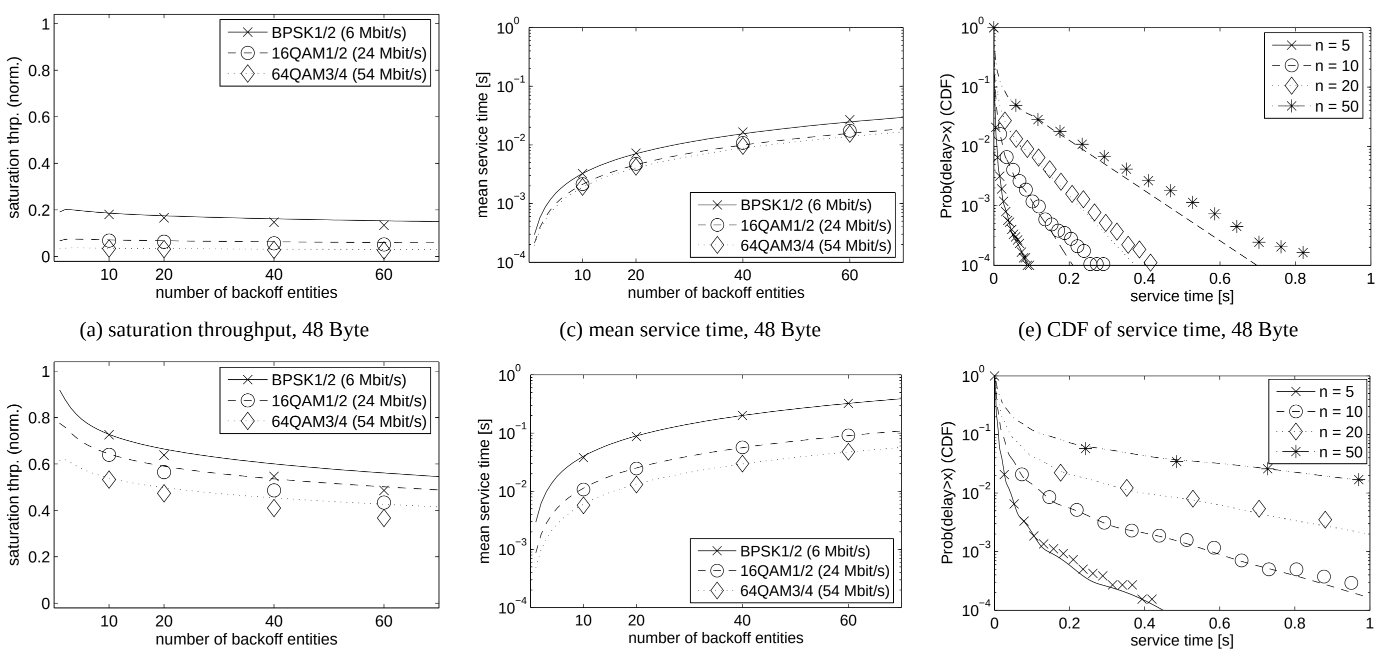
The recursion reflects the dependency of the available number of time slots per backoff stage on the contention window size. Otherwise, $N_{j,i}$ would have a binominal distribution [3] .

IV. QoS Evaluation

This section evaluates the capability of the EDCA to support QoS in a distributed network architecture. The ACs of AC_BK and AC_VI are analyzed with EDCA parameter sets corresponding to Table 2, there highlighted gray. AC_BK has the same contention window size as a legacy backoff entity of 802.11, but a different AIFSN. The analytical results for the throughput, the mean service time and the service time distribution are obtained with Equations (1), (2) and (3) respectively. In each scenario, all backoff entities have the same AC and the dependency of the observed QoS on the number of contending backoff entities is analyzed. In the contention scenarios of Figure 4 and Figure 5 no backoff entity uses RTS/CTS. The frame body size is fixed and has either a value of 48 Byte (the upper subfigures) or 2304 Byte (the lower subfigures). The simulative results are produced with a Matlab™-based implementation of the EDCA‘s backoff procedure that is part of the spectrum sharing simulation tool YouShi2 introduced in [5]. Saturation scenarios are simulated in which every backoff entity has always a packet in its transmission queue. Further, completely overlapping transmission/reception ranges are assumed for all QSTAs. The results show the expected characteristic.

The normalized saturation throughput decreases for an increasing number of contending backoff entities, besides one exception: In AC_BK, for a frame body size of 48 Byte and without using RTS/CTS the throughput increases for a small number of backoff entities as observable in Figure 4(a). In general, the inefficiency of 802.11 for small frame body sizes due to the overhead of the MAC protocol is indicated when comparing the saturation throughputs of subfigures (a) and (b) in all contention scenarios.

The QoS capabilities of AC_VI can be observed in focusing on Figure 5. The small contention window size leads for a high number of backoff entities to multiple collisions and the saturation throughput breaks in. The analytic approximation of the backoff process loses its accuracy for a large number of backoff entities when the size of the contention window is very small. In this case, the Markov characteristic of the stochastic process is lost: The states depend significantly on each other and are not independent anymore. This reasons the difference between simulations and analysis for AC_VI when more than 20 backoff entities contend. Nevertheless, the analytic model is accurate for a small number of backoff entities and it introduces always a conservative lower limit for the QoS that can be supported. The horizontal lines of the analytic CDFs of Figure 5(e) and (f) and the missing upper bound for the analytic mean service time in Figure 5(c) and (d) are reasoned by the inaccuracy of the Markov model. The usage of



(a) saturation throughput, 48 Byte
(c) mean service time, 48 Byte
(e) CDF of service time, 48 Byte
(b) saturation throughput, 2304 Byte
(d) mean service time, 2304 Byte
(f) CDF of service time, 2304 Byte

Figure 4: Observed saturation QoS of AC "AC_BK" with EDCA parameters from Table 2. Without RTS/CTS, no WEP, no Address 4, modulation used in (e) and (f): 16QAM1/2. lines: analytic model – markers: YouShi2 simulation results.

RTS/CTS improves the QoS outcomes but is not depicted here.

The difference between AC_BK and AC_VI due to the different contention window sizes is indicated by a comparison of Figure 4 and Figure 5. For a small number of backoff entities, AC_VI observes service times shorter than the ones of AC_BK. For a large number of backoff entities the results are reversed because of multiple collisions in case of AC_VI coming from the small contention window size. This can be observed when comparing for instance the subfigures (c) and (d) of Figure 4 and Figure 5.

Although the number of backoff stages is limited through the maximum number of retries (RetryCnt), the analytic model is not capable to take this retry limit into account: An unlimited number of retries in backoff stage *m* is assumed. The simulations of this section therefore neglect the limitation of retries to allow a comparison to the analytic results. Especially the CDFs of the service time reflect the impact of this assumption. In case of a retry limit, the observed service times would have a strict maximum value.

Besides the exceptions from above, the simulation results correspond to the outcomes from the analytic approximation through the Markov model.

V. Conclusion

The contention-based medium access of the 802.11e EDCA leads only to a limited capability to support QoS. The number of contending backoff entities determines essentially the level of supported QoS and the differentiability of QoS. This result is independent from the AC of the considered backoff entities, whether all backoff entities have the equal or different ACs. Already the competition between multiple backoff entities of the same AC results into unsatisfying QoS results. The contention between the ACs will lead to even worse QoS outcomes, although prioritization is successful for a small number of competing backoff entities [5]. The maximum number of competing backoff entities should be limited below ten, in order to enable distributed QoS support.

Intelligent communication systems, so-called cognitive radios are a promising approach to QoS support in distributed environments. Cognitive radios are able to share spectrum in mutually coordinating their channel access. In enhancing the channel access of 802.11(e) the contention resolution with the backoff procedure can be avoided.

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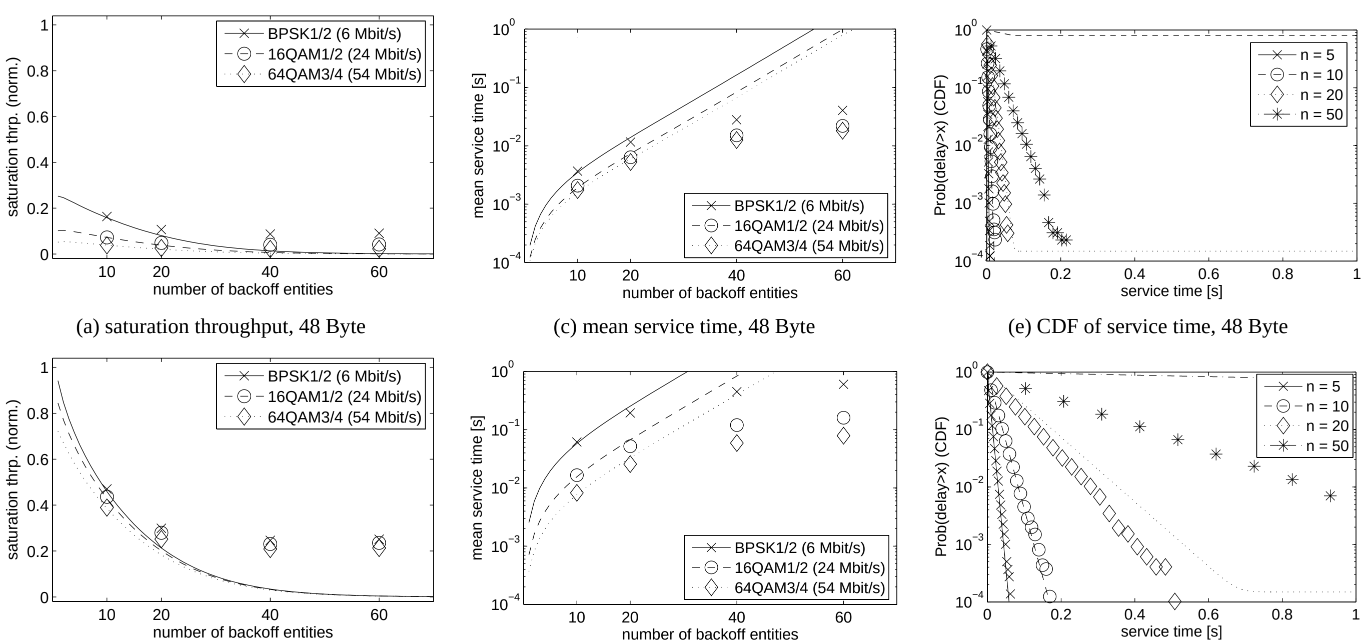

(a) saturation throughput, 48 Byte

(c) mean service time, 48 Byte

(e) CDF of service time, 48 Byte

(b) saturation throughput, 2304 Byte

(d) mean service time, 2304 Byte

(f) CDF of service time, 2304 Byte

Figure 5: Observed saturation QoS of AC "AC_VI" with EDCA parameters from Table 2. Without RTS/CTS, no WEP, no Address 4, modulation used in (e) and (f): 16QAM1/2. lines: analytic model – markers: YouShi2 simulation results