IEEE 802.11E - FAIR RESOURCE SHARING BETWEEN OVERLAPPING BASIC SERVICE SETS

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ERRATA December 2002.

This version of the paper includes a correction in Section V-A, in the description of the simulation scenario:

> "The medium and low priority streams each transmit MSDUs of *1514 bytes and not 200 bytes as stated in the original paper* with exponentially distributed inter-arrival times, each stream with variable rates."

These MSDUs are transmitted with RTS/CTS, and fragmented into several MPDUs (dot11FragmentationThreshold: 512, dot11RTSThreshold: 512). That explains why only one MPDU fits into the TXOPlimit for medium and low priority streams.

Thanks to Dr. Mooi Choo Chuah, Bell Labs, who pointed me to the misleading information in the original text.

Stefan Mangold, Dec. 2002

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Abstract - The upcoming IEEE 802.11e is an extension of the 802.11 Wireless Local Area Network (WLAN) standard. We use this new standard with its priority provisioning mechanism to address fairness issues that occur when geographically co-located WLANs share the radio channel in the so-called Overlapping Basic Service Set environment. By allowing a new mechanism that is part of the 802.11e, called EDCF-TXOP bursting, we show that WLANs will gain from intelligent radio resource control in a fair manner. A WLAN that applies EDCF-TXOP bursting can significantly improve its performance compared to a WLAN that does not utilize EDCF-TXOP bursting.

Keywords – IEEE 802.11e, EDCF-TXOP bursting, Link Adaptation, Radio Resource Control, Coexistence of WLANs, Fairness

I. INTRODUCTION

The IEEE 802.11e is an extension of the 802.11 *Wireless Local Area Network (WLAN)* standard for the Quality-of-Service (QoS) provisioning [10], [11]. This new standard provides the means of prioritizing the radio channel access by different stations and data streams [1]...[4].

This paper focuses on the fairness issues that occur when geographically co-located WLANs share the same radio channel in the so-called overlapping BSS environment. The 802.11 WLANs operate in unlicensed bands and have to share radio resources with other co-existing WLANs, which could be the same kind as we consider in this paper, or a different kind as considered in [2]. By enabling a mechanism that is part of the current draft of 802.11e, called EDCF-TXOP bursting [11], [12], we show that WLANs will achieve the performance enhancement via an intelligent radio resource control, encouraging co-existing WLANs to use the radio spectrum efficiently. The evaluation in this paper will show that, without the EDCF-TXOP bursting, co-existing WLANs will not use the radio spectrum efficiently. The maximum achievable throughputs in a QBSS show undesirable results without the bursting concept, but improved results when the bursting mechanism is enabled.

In this paper, we consider an infrastructure *Basic Service Set (BSS)* of the IEEE 802.11 WLAN, which is composed of an *Access Point (AP)* and a number of stations associated with the AP. A BSS that supports the new priority schemes of the 802.11e is referred to as *Quality-of-Service (QoS)* BSS *(QBSS)*. We consider the IEEE 802.11a 5 GHz *physical layer (PHY)* [5].

The paper is outlined as follows. In the following section, the 802.11 MAC protocol and its extension to support QoS are summarized. We then describe a technique for radio resource control that allows stations to adapt their coding and modulation schemes dynamically to the channel characteristics, i.e., dynamic Link Adaptation. After describing the bursting mechanism, we discuss simulation results with overlapping QBSSs.

II. THE IEEE 802.11(e) MAC

A. The legacy 802.11 MAC protocol [10], [7]

The basic 802.11 MAC protocol is the *Distributed Coordination Function (DCF)* based on *Carrier Sense Multiple Access (CSMA)*. Stations deliver *MAC Service Data Units (MSDUs)* [1] of arbitrary lengths (up to *2304 bytes*), after detecting that there is no other transmission in progress on the channel. However, if two stations detect the channel as free at the same time, a collision occurs. The 802.11 protocol defines a *Collision Avoidance (CA)* mechanism to reduce the probability of such collisions. As part of CA, a station performs a backoff procedure before starting a transmission. It has to keep sensing the channel for an additional random time after detecting the channel as being idle for a minimum duration called *DCF Interframe Space (DIFS)*, which is *34 us* for the 802.11a PHY. Only if the channel remains idle for this additional random time, the station is allowed to initiate its transmission. The additional time period is selected from a *Contention Window (CW)*, counted in slots (*9 us* per slot, min. *15 slots* per CW). The size of the CW is doubled after each unsuccessful transmission from *CWmin=15* slots up to *CWmax=1023* slots, to reduce the collision probability.

For each successful reception of a frame, the receiving station immediately acknowledges the frame reception by sending an *Acknowledgement (ACK)* frame. To reduce the hidden station problem inherent in CSMA networks, the

[1] An MSDU is the unit of data arriving at the MAC from a higher layer. MSDUs are transmitted as *MAC Protocol Data Unit (MPDUs)* over the Wir eless Medium.

802.11 also defines a *Request-to-Send/Clear-to-Send (RTS/CTS)* mechanism, which can be used optionally. Before transmitting data frames, a station may transmit a short RTS frame, followed by the CTS transmission by the receiving station. The RTS and CTS frames include the information of how long it does take to transmit the subsequent data frame and the corresponding ACK response. Thus, other stations close to the transmitting station and hidden stations close to the receiving station will not start any transmission; by receiving either RTS or CTS, their timer called Network Allocation Vector, *NAV,* is set. Between two consecutive frames in the sequence of RTS, CTS, data, and ACK frames, a *Short Interframe Space (SIFS)*, which is *16 us* for 802.11a, gives transceivers the time to turn around. See Fig. 1 for an example of the DCF. It is important to note that SIFS is shorter than DIFS, which gives CTS and ACK frames always the highest priority for the channel access.

B. QoS Supporting Mechanisms of 802.11e [11],[1]

IEEE 802.11 Task Group E is currently defining enhancements to the above-described 802.11 MAC, called the 802.11e, which introduces *Enhanced DCF (EDCF)* and *Hybrid Coordination Function (HCF)*. Stations, which operate under the 802.11e, are called *QoS stations (QSTAs)*, and a QoS station, which works as the centralized controller for all other stations within the same QBSS, is called the *Hybrid Coordinator (HC)*. A QBSS is a BSS, which includes an 802.11e-compliant HC and QoS stations. The HC will typically reside within an 802.11e AP. In the following, we mean an 802.11e-compliant QoS station by a station. The EDCF is the contention-based channel access mechanism of the HCF, and is the access scheme we are considering in this paper. In particular, the HCs do not apply the polling schemes of the HCF, which gives a HC the highest priority in medium access.

With the EDCF, the QoS support is realized through the introduction of *Access Categories (ACs)*. MSDUs are now delivered through multiple backoff instances within one station, each backoff instance parameterized with AC-specific parameters. In the CP, each AC within the stations contends for a TXOP and independently starts a backoff after detecting the channel being idle for an *Arbitration Interframe Space (AIFS)*, which is dependent on each AC. After waiting for AIFS, each backoff sets a counter to a random number drawn from the interval [*0,CW*] in case of *AIFS>=DIFS* and from [*1,CW+1*] in case of *AIFS<DIFS*.

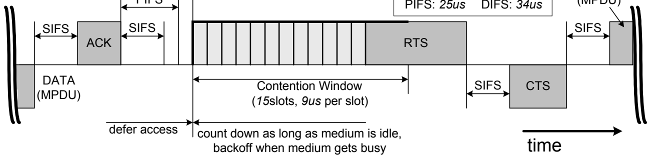

Fig. 1: Timing of the 802.11 DCF.

The minimum size of the CW is another parameter dependent on the AC. See Fig. 2 for an illustration of the EDCF parameters.

As in legacy DCF, when the medium is determined busy before the counter reaches zero, the backoff has to wait for the medium being idle for AIFS again, before resuming the counter count down.

A single station may implement up to eight transmission queues for the ACs, realized as backoff instances inside a station, with individual QoS parameters that define the priorities per AC. If the backoff counters of two or more parallel ACs in a single station reach zero at the same time, two frames of different priorities within a station are to be transmitted at the same time, which is referred to as a virtual collision. However, rather than transmitting two frames, a scheduler inside the station resolves this virtual collision: the scheduler lets the backoff instance with highest priority AC transmit its frame. The other backoff instance acts as if a collision at the radio channel happened. There is then still a possibility that the transmitted frame collides at the wireless medium with a frame transmitted by other stations.

One crucial feature of the 802.11e MAC is the *Transmission Opportunity (TXOP)*. A TXOP is defined as an interval of time when a station has the right to initiate transmissions, defined by a starting time and a maximum duration. TXOPs are acquired via contention (*EDCF-TXOP*) or granted by the HC via polling (*polled-TXOP*). The duration of an EDCF-TXOP is limited by a QBSS-wide *TXOPlimit* distributed by the HC in beacon frames.

III. LINK ADAPTATION IN 802.11a

Link Adaptation (LA) is the process of dynamically selecting a combination of physical layer channel coding and modulation schemes (which is referred to as *PHY mode* for the rest of this paper) for the transmission of frames, under certain conditions such as the channel condition, and required MSDU Delivery throughputs and delays. For example, the throughput optimization of 802.11a WLAN via LA is presented in [6].

In principle, each frame can be transmitted with an individually optimized PHY mode, but in case of control frames under the following restriction.

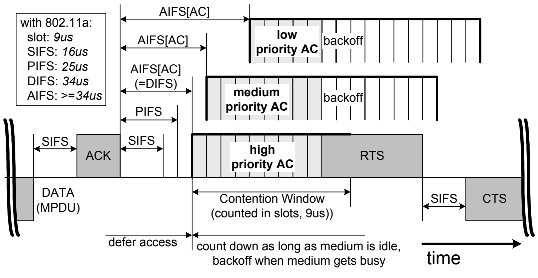

Fig. 2: Multiple parallel backoffs of MSDUs with different priorities.

802.11a PHY at 5 GHz defines mandatory PHY modes. As control frames (e.g., RTS/CTS/ACK) should be received not only by the addressed station but also by other active stations in the area close to the transmitting station, they must be transmitted using one of the mandatory PHY modes, i.e., *6, 12,* and *24 Mbit/s.* Table 1 summarizes the relevant characteristics of the available PHY modes for 802.11a [5],[6].

We use a simple open-loop LA process, which counts the number of successful and failed transmissions and switches the PHY mode after a certain number of transmission successes or failures. A transmitting station that carries data for more than one station selects the PHY mode with respect to the addressed receiving station. Such a station is typically the AP. It has to alternate the PHY mode from frame exchange to frame exchange sequence with high dynamics. Applying this simple LA process, a station ends up transmitting with the PHY mode that optimizes the throughput, by in addition periodically attempting to increase it, i.e., here after 25 successful transmissions. This may then lead to higher probability of failed transmissions which means that the station has to fall back to the original PHY mode, here after 4 unsuccessful transmission attempts.

Finding an optimal algorithm for LA is beyond the scope of this paper. The algorithm presented here is very limited but gives us the opportunity to investigate the combination of EDCF-TXOP bursting with the radio resource control.

TABLE 1: 802.11a PHY LAYER CHARACTERISTICS

PHY Mode	Modulation	Bit rate Mbit/s
1	*BPSK1/2*	*6*
2	*BPSK3/4 **	*9*
3	*QPSK1/2*	*12*
4	*QPSK3/4 **	*18*
5	*16QAM1/2*	*24*
6	*16QAM3/4 **	*36*
7	*64QAM2/3**	*48*
8	*64QAM3/4**	*54*

*) Optional. Only data frames, not control frames are usually sent using the optional PHY modes.

IV. EDCF-TXOP BURSTING

The concept of transmitting more than one MSDU after winning the EDCF contention is called EDCF-TXOP bursting. It is part of the latest 802.11e draft specification [11], and discussed in [12]. With EDCF-TXOP bursting, a station may transmit many pending MSDUs for a duration of not exceeding the maximum allowed duration called *TXOPlimit*, which is announced by the HC as part of beacon frames. The advantage of EDCF-TXOP bursting is the increased maximum achievable throughput at the cost of potentially increased MSDU Delivery delays of other streams, which do not utilize the whole TXOP, because they do not apply EDCF-TXOP bursting. Fig. 3 illustrates the EDCF-TXOP bursting.

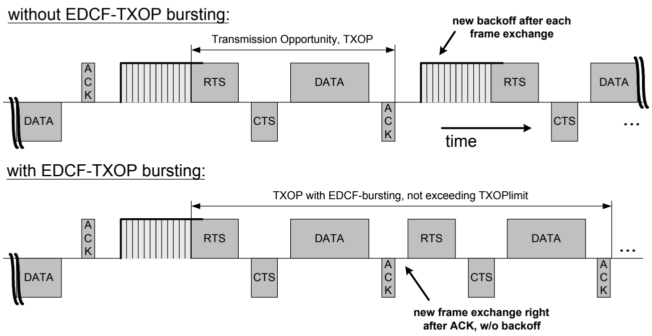

Fig. 3: Single MSDUs per TXOP (top) and EDCF-TXOP bursting (bottom).

V. EVALUATION

We use event-driven stochastic simulations to discuss the efficiency and fairness of our concepts. Simulation campaigns have been performed for the 802.11a physical layer that allows up to *54 Mbit/s* in the 5 GHz license exempt band. For delay results, we give empirical *Complementary Cumulative Distribution Functions (CDFs)* of the resulting stochastic data, using the discrete Limited-Relative-Error (LRE) algorithm that also measures the local correlation of the stochastic data [8]. By measuring local correlations, the accuracy of empirical simulation results can be estimated. All results presented in this paper are within a maximum limited relative error of *5 %*.

A. Scenario: two overlapping QBSSs

Fig. 4 shows the scenario of two overlapping QBSSs with three stations in each QBSS. The two stations QSTA 2.1 and QSTA 1.1 are HCs, which deliver MSDUs to the other stations. Consistent with the 802.11 terminologies, we call this service *MSDU Delivery*. Each HC generates the same mix of offered traffic of three data streams per station, which we label with high, medium and low, respectively, according to their priorities. The HC labeled as QSTA 1.1 transmits three data streams to QSTA 1.2 and three data streams to QSTA 1.3; the HC labeled QSTA 2.1 transmits three data streams to QSTA 2.2 and three data streams to QSTA 2.3. At the high priority AC, MSDUs of *80 bytes* are transmitted. The exponentially distributed inter-arrival time has a mean of *2.5 ms* for the offered traffic of *256 kbit/s*. Note that throughout all simulations, the high priority streams are always offered *256 kbit/s* per stream The medium and low priority streams each transmit MSDUs of *1514 bytes* with exponentially distributed inter-arrival times, each stream with variable rates. The Table 2 shows the EDCF-parameters selected for the three priorities. Because of the overlapping QBSS situation, QSTA 1.1 and 2.1 do not make use of their highest priority as an HC in accessing the medium, but rely on a prioritized random backoff to avoid collisions between them.

Distances between stations are chosen in such a way that each station detects any transmission by another station.

That is, no station is hidden to another. We use the channel model as described in [5]. With an attenuation coefficient $\gamma=3.5$ and constant transmission powers of *200mW*, PHY mode 8 (= *54 Mbit/s*) for the stations close to the HCs and the PHY mode 3 (= *12 Mbit/s*) for the stations far from the HCs optimize the throughputs. The offered traffic in the simulated scenarios includes three streams with different priorities from the two HCs to each of their associated stations.

Only the HC of QBSS 1 is capable of performing the LA described in Section III. However, the PHY modes of control frames are not changed, they are sent at 6 Mbit/s all the time. The stations of QBSS 2 always transmit data frames and control frames at 6 Mbit/s.

Channel errors are very rare with the selected PHY modes. The stations at larger distances (*35 m*) have an error probability at the channel similar to the stations close (*1 m*) to the HCs. For this reason, the throughput results given in the following figures are shown as throughputs per priority stream, where for each QBSS the stream to the close station and the stream to the far station are averaged, without loss of relevant information. There are three resulting throughputs for each QBSS, i.e., one per priority.

TABLE 2: EDCF PARAMETERS USED FOR THREE ACS.

	High	Medium	Low
AIFS [us]	*34*	*52*	*63*
CWmin [slots*]	*7*	*10*	*15*
CWmax [slots*]	*7*	*31*	*255*

*) slot time is *9 us* in 802.11a

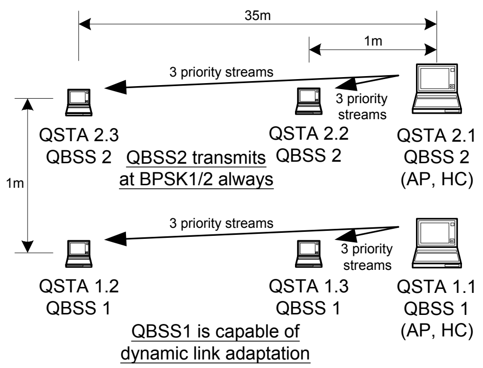

Fig. 4: Simulation scenario. The two larger stations are the HCs that deliver MSDUs with three different priorities to their associated stations. All statio ns are in range to each other (no hidden stations).

B. Throughput results with static PHY mode 1

The resulting throughputs when all stations transmit at *6 Mbit/s*, i.e., PHY mode 1, without EDCF-TXOP bursting, are shown in Fig. 5, left. Here, QBSS 1 does not apply dynamic LA, therefore both QBSSs show equal throughput results. The offer is varied for the medium priority and low priority streams. The offer of the four high priority streams stays at *256 kbit/s* per stream, which can be carried by the two QBSSs at any time. As expected, the low priority streams suffer from the increased offer at medium priority. Note that in the figures we show the average throughput between near and far stations.

C. Unwanted throughput results with LA used in one QBSS and without EDCF-TXOP bursting

An interesting observation can be taken from the right part of Fig. 5. In contrast to before, now QBSS 1 is applying LA. Although only QBSS 1 is applying LA, both QBSSs gain from it. The improved throughput of the medium priority streams within QBSS 2 even exceeds the resulting throughputs of the QBSS 1. The reason for this is as follows. Because of the simplicity of the applied algorithm for LA, the HC in QBSS 1 attempts to transmit to its far station at higher PHY modes than *6 Mbit/s* from time to time. After a number of failed transmissions, it switches towards the basic mode, before trying again to increase the PHY mode. This reduces the throughput of the medium and low priority streams in QBSS 1 compared to QBSS 2. Interestingly, it is still improved compared to static PHY mode 1, which was shown in Fig. 5, left. For the transmissions to the closer station, the HC of QBSS 1 switches to 54 Mbit/s and then transmits very efficiently with a small number of errors. As transmissions at this PHY mode require short times, the radio resources are efficiently utilized. However, both QBSSs can improve their resulting throughput performance. The probability that QSTA 1.1 or QSTA 2.1 wins the contention is still the same.

The fact that QBSS 2 gains from dynamic LA that is applied in QBSS 1 is an undesirable result. There is no motivation to apply spectrum efficient and complicated techniques if the gain from such an effort is shared between co-existing WLANs, i.e., co-existing QBSSs in our simulations. From the regulatory perspective, radio systems that operate spectrum efficiently must benefit from it. To attract vendors to implement dynamic LA or other radio resource control schemes into their radio systems, other co-located radio systems should not gain equally from its usage.

This problem is known as the "tragedy of commons" in ga me theory and especially important for radio systems that sh are unlicensed bands [9].

D. Throughput results with LA applied in one QBSS and EDCF-TXOP bursting applied in both QBSSs

Fig. 6 shows the resulting throughputs when EDCF-TXOP bursting is used by both QBSSs. QBSS 1 is capable of applying dynamic LA. Interestingly, now the throughput of the medium streams in QBSS 1 exceeds the throughput of the medium streams in QBSS 2. The reason is obvious: after a short transmission of an MSDU, the HC of QBSS 1 is allowed to deliver another MSDU without contending for the medium again, as long as the TXOPlimit is not exceeded (here, *TXOPlimit=2.88 ms)*. Therefore, it is now mainly

QBSS 1 that notably improves its performance by applying dynamic LA, compared to the previous scenario. It should be reminded that QBSS 1 improves its performance by utilizing a given *TXOPlimit* better thanks to transmitting frames at *54 Mbit/s* when it is possible.

E. MSDU Delivery delay implications of EDCF-TXOP bursting

Fig. 7 and Fig. 8 show the MSDU Delivery delay distributions for both QBSSs in a lightly loaded scenario, i.e., *320 kbit/s* per medium and low priority streams, *256 kbit/s* per high priority streams. In each figure, the results for one QBSS are shown, where two distributions per priority are given, one for the near station and one for the far station, respectively. It can be observed that the LA within QBSS 1 results in considerable shorter minimum MSDU Delivery delays than in QBSS 2. Due to the higher error probability with the higher PHY modes, retransmissions are more likely in QBSS 1, which is the reason for the higher probability of larger delays in QBSS 1. The near and far stations show different delays in QBSS 1 due to different PHY modes.

Fig. 9 and Fig. 10 present the delays when EDCF-TXOP bursting is applied. It is observed that in a lightly loaded scenario, EDCF-TXOP bursting does have minor implications on the MSDU Delivery delays. As before, QBSS 1 always shows smaller delays than QBSS 2, as the transmission times in QBSS 1 are reduced with the higher PHY modes. Fig. 10 indicates that QBSS 1 fills its TXOPs often up to the TXOPlimit of *2.88 ms*, which is the reason for the shape of the curve of the high priority streams within QBSS 2.

Note that all delay results given here show the MSDU Delivery delays for a lightly loaded scenario, not for the saturation points.

VI. CONCLUSIONS

We have presented simulation results of MSDU Delivery throughput and delay for the emerging 802.11e WLANs with the 802.11a physical layer. Two QBSSs that share a common radio channel were simulated with and without using adaptive radio resource control, i.e., dynamic link adaptation, and EDCF-TXOP bursting. The concept of EDCF-TXOP bursting is an attractive element of IEEE 802.11e in terms of spectrum efficiency, and economically. In overlapping QBSS environments, a radio system takes significant advantage of dynamic link adaptation when EDCF-TXOP bursting is applied. A WLAN that uses bursting can improve its performance compared to other WLANs that operate without bursting.

With EDCF-TXOP bursting, future WLANs will apply dynamic link adaptation in order to achieve higher throughputs. Without EDCF-TXOP bursting, future WLANs will not necessarily apply dynamic link adaptation. Without EDCF-TXOP bursting, co-existing WLANs achieve the same throughput results. The EDCF-TXOP bursting mechanism automatically motivates for the application of link adaptation, which as a result increases the spectrum efficiency of radio systems in the unlicensed 5 GHz band.

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SIMULATION RESULTS

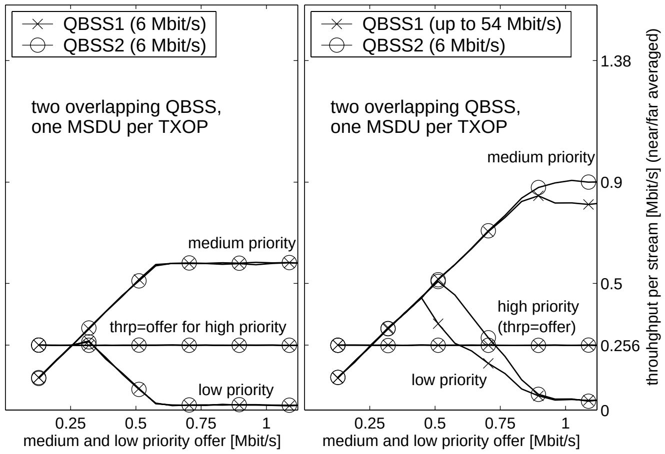

Fig. 5: Resulting throughputs vs. offered traffic. Left: no LA, all statio ns transmit at *6 Mbit/s*. Right: LA applied in QBSS 1.

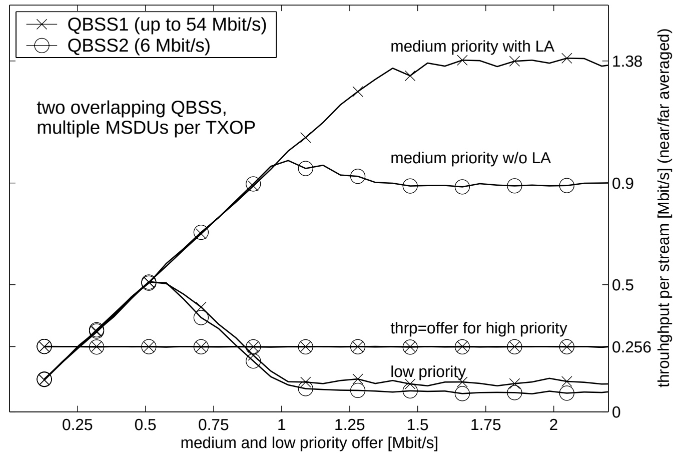

Fig. 6: Resulting throughputs vs. offered traffic. LA applied in QBSS 1. EDCF-TXOP bursting is applied in both QBSSs.

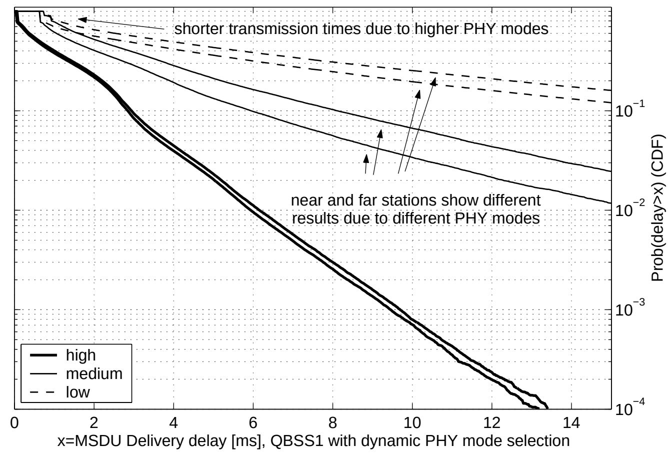

Fig. 7: MSDU Delivery delays in QBSS 1, no EDCF-TXOP bursting. LA applied only in this QBSS.

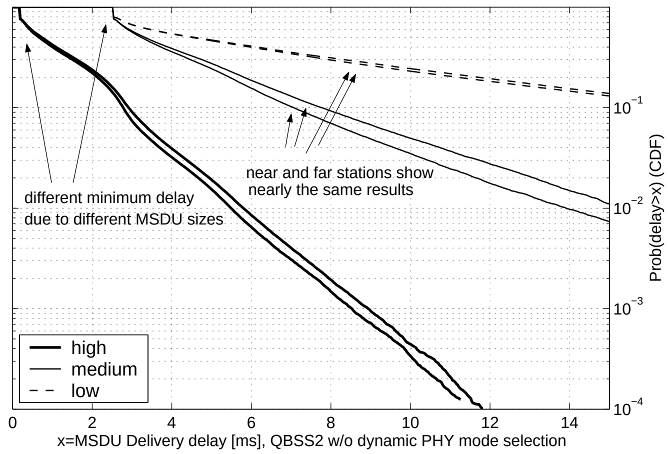

Fig. 8: MSDU Delivery delays in QBSS 2, no EDCF-TXOP bursting. LA applied only in the other QBSS, i.e., QBSS 1.

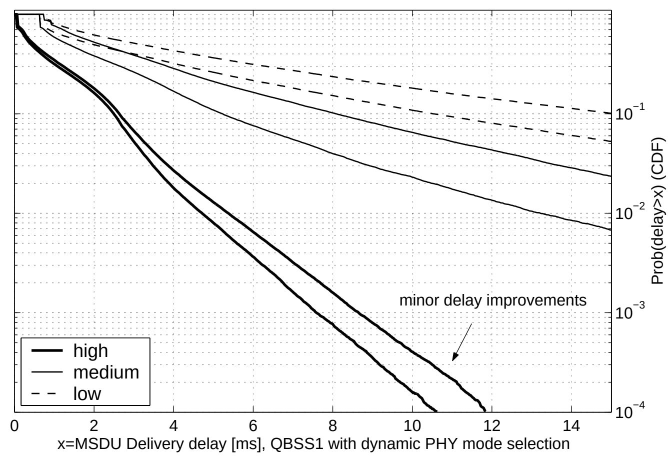

Fig. 9: MSDU Delivery delays in QBSS 1, with EDCF-TXOP bursting in both QBSSs. LA applied only in this QBSS.

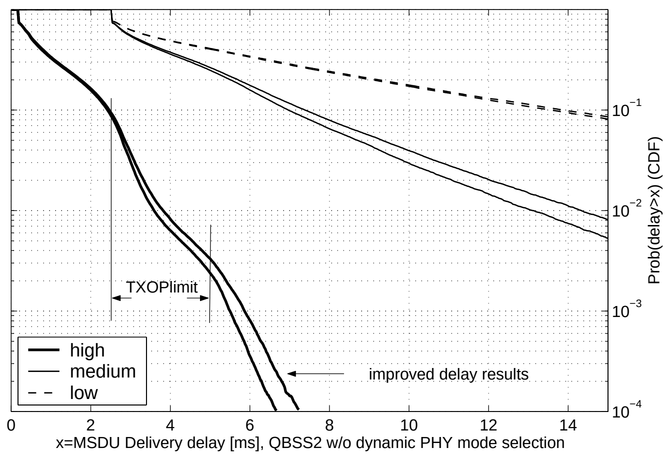

Fig. 10: MSDU Delivery delays in QBSS 2, with EDCF-TXOP bursting in both QBSSs. LA applied only in the other QBSS, i.e., Q BSS 1.