IEEE 802.11e: Coexistence of Overlapping Basic Service Sets

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Abstract — **A known problem in radio resource management in wireless local area networks using the IEEE 802.11 protocol is the neighborhood capture effect. This effect severely reduces the protocol efficiency when multiple sets of stations are co-located. It is one of the most critical aspects of overlapping and coexisting basic service sets. Here, we discuss the problem with focus on quality of service. By using techniques based on the new upcoming IEEE 802.11e, which is an extension of the IEEE 802.11 for the provisioning of quality of service, the neighborhood capture effect can be reduced, and data throughput and delivery delays can be improved. We show simulation results indicating that in certain scenarios, with a simple synchronization and slotting scheme, the problem is significantly reduced.**

I. Introduction

The efficient radio resource management in uncoordinated *Wireless Local Area Networks (WLANs)* is a complex problem. WLANs include mobile ad-hoc radio networks that rely on the capability of delivering data through multiple hops between radio stations. Co-located stations that operate in the same spectrum require techniques for the support of coexistence. In addition, the reliable operation of WLANs is critical due to the unlicensed nature of the spectrum and the *Quality-of-Service (QoS)* demands of future applications.

Today, the most widely used protocol in WLANs is the *IEEE 802.11 (802.11)* [7],[8]. In an isolated scenario of one *Basic Service Set (BSS)* of the 802.11 WLAN, where each station can detect and receive every transmission from other stations, this protocol operates sufficiently in most cases, as long as the offered traffic is not to high, and QoS is not required. A BSS may be an *Independent BSS (IBSS)*, or may be an infrastructure BSS, composed of an *Access Point (AP)* and a number of stations associated with the AP.

However, in an overlapping scenario of multiple coexisting BSSs, with stations being hidden to each other, there are several drawbacks. One is the so-called neighborhood capture effect. In an overlapping scenario with hidden stations, stations that do not detect each other may transmit in parallel, without noticing any activity of the other stations. This has a dramatic effect on stations that are in detection range of all these active stations, i.e. that are located in the neighborhood. Because stations that operate according to 802.11 perform a listen-before talk with random backoff before initiating any transmission, these stations may not find any sufficient idle time for very long durations, because of the uncoordinated activity of the other stations that captured the channel. This leads to increased delivery delays and reduced throughputs.

Here, we discuss the problem with focus on QoS in the context of the new upcoming *IEEE 802.11e (802.11e)*, which is an extension of 802.11 for QoS support. We discuss modifications of 802.11e that help to support minimizing the capture of radio channel resources by applying techniques based on the solution concept of [10].

In the following, all protocol parameters are defined considering the *IEEE 802.11a (802.11a)* 5 GHz *physical layer (PHY).*

The paper is outlined as follows. In the next section, the 802.11 *Medium Access Control (MAC)* protocol and its extension to support QoS are summarized. Specifically, the *Timer Synchronization Function (TSF)*, which allows distributed synchronization of timers among stations, is summarized. We then describe in Sect. III the neighborhood capture effect and solution concepts. An evaluation of the concepts by means of stochastic simulations is presented in Sect. IV. The paper ends up with conclusions.

II. The IEEE 802.11(e) MAC [1],[2]

This section is a brief summary of the MAC protocol description in [1], [2]. Further details can be found in [8], [9].

A. Legacy 802.11 [8]

The legacy 802.11 MAC protocol is the *Distributed Coordination Function (DCF)* based on *Carrier Sense Multiple Access (CSMA)*. Stations deliver *MAC Service Data Units (MSDUs)* of arbitrary lengths of up to *2304 bytes*, after detecting that there is no other transmission in progress on the radio channel. If two ore more stations detect the radio channel as being idle at the same time, transmissions occur simultaneously, the frames collide. To reduce the probability of such collisions, 802.11 defines a *Collision Avoidance (CA)* mechanism. After detecting the radio channel as being idle for a minimum duration called *DCF Interframe Space (DIFS)*, which is *34 us* for the 802.11a PHY, a station keeps sensing the radio channel for an additional random time. If the radio channel remains idle for this additional random time period, the station will be allowed to initiate its transmission.

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 802.11 also defines a *Request-to-Send/Clear-to-Send (RTS/CTS)* mechanism, which can be used optionally. 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. SIFS is shorter than DIFS, which gives

CTS and ACK frames always the highest priority for the radio channel access. A typical frame exchange sequence in 802.11 is illustrated in Fig. 1. Here, station 4 defers from radio channel access because of the earlier access of station 2. It waits during the channel busy period until the frame exchange sequence between station 2 and station 1 has been finished. After sensing a channel as being idle again, station 4 continues to count down its backoff timer, rather than selecting a new random backoff time. In this manner, stations, that deferred from channel access because their random backoff time was larger than the backoff time of other stations, are given a higher priority when they resume the transmission attempt.

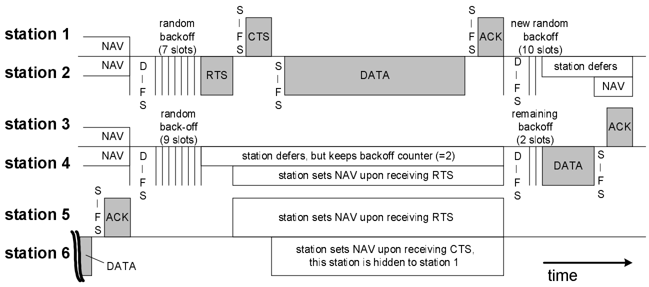

Fig. 1: Timing of the 802.11 DCF. In this example, station 6 cannot detect the RTS frame of the transmitting station 2, but the CTS frame of station 1. Indicated is the virtual carrier sensing by means of the *Network Allocation Vector (NAV)*, a timer that forces a station to remain silent upon receiving a frame from another station indication a following frame exchange for a particular duration.

B. *802.11e for QoS support [9]*

The 802.11e is an extension of the IEEE 802.11 WLAN standard for QoS provisioning [1], [9]. It provides the means of prioritizing the radio channel access within a BSS 802.11 WLAN. A BSS that supports the new priority schemes of the 802.11e is referred to as *QoS supporting BSS (QBSS)*. There are enhancements to the 802.11 MAC currently under discussion, called the 802.11e, which introduce *Enhanced DCF (EDCF)* and *Hybrid Coordination Function (HCF)*. The EDCF is the contention-based channel access mechanism of the HCF, i.e., it is a part of the HCF. Stations, which operate under the 802.11e, are called QoS stations, 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. See [9] for further details, and [1] for an evaluation of the priority schemes.

With the EDCF, QoS support is realized through the introduction of *Traffic Categories (TCs)*. MSDUs are delivered through multiple backoff instances within one station; each backoff instance is parameterized with TC-specific parameters. Each backoff instance within the stations independently starts a backoff after detecting the radio channel being idle for an *Arbitration Interframe Space (AIFS)*, which is dependent on each TC. After waiting for AIFS[TC], each backoff instance sets its backoff counter to a random number, which is dependent of the TC. In EDCF, the minimum size of the *Contention Window (CW)*, i.e., the CWmin[TC], is a parameter that is depending on the TC. Each backoff instance within a station contends for an interval of time that is called a *Transmission Opportunity (TXOP)*. A TXOP is an interval of time during which 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 in the beacon, a frame that is also used for timer synchronization, see next section. The polled TXOPs are allocated with highest priority, without any CA, i.e. without any backoff before the poll. The polling scheme requires that there is one HC coordinating the radio channel, without any other HC in the range of this HC.

C. *Timer Synchronization Function (TSF)*

The TSF of 802.11 is important for the discussion of the capture effect below. Therefore, in this section we outline the concept of updating the local timers. The TSF's original function is to support various PHYs that require synchronization, and management functions such as a station joining a BSS, and saving power through sleep modes. All stations within a BSS are synchronized to a common clock by maintaining a local timer. This local timer is mutually updated by information received from other stations as part of a beacon.

As beacons are transmitted periodically, every station that received an earlier beacon knows when the next beacon will arrive; this time is called *Target Beacon Transmission Time (TBTT)*. The TBTT of each beacon is announced in its previous beacon. In order to give beacon transmissions highest priority of radio channel access, stations stop initiating frame exchanges upon reaching a TBTT. 802.11e-compliant QoS stations are not allowed to transmit across the TBTT, i.e. those stations do not initiate frame exchanges if they cannot finish it before the TBTT.

In QBSS and IBSS, the synchronization is maintained by broadcasting the TSF timer in the beacon. The decision about if the local timer in a station has to be updated or not upon reception of the beacon, is different for QBSS and IBSS.

Fig. 2 illustrates the TSF in an IBSS. In an IBSS, the TSF is distributed over all stations. All stations take part in the generation of beacons. The beacon generation is distributed using a mechanism similar to the backoff. At the TBTTs, stations that are part of an IBSS attempt to transmit a beacon in contention, with small CWmin and interframe space that is smaller than DIFS, but larger than SIFS (*Point Coordination Interframe Space, PIFS,* which is *25 us* in 802.11a). Stations will discard their own attempt of beacon transmission when they receive a beacon from another station. As in the (E)DCF, beacons may collide, which is allowed as part of the standard. Upon receiving a beacon, a station updates its local timer with the information from the beacon only if the received value is greater than the value currently maintained in the local timer. This distributed synchronization results in the shared information about the fastest running clock, with which the complete IBSS will synchronize.

Fig. 3 illustrates the TSF in an infrastructure BSS of legacy 802.11 or, equivalently, in a QBSS of 802.11e. In a QBSS, only the HC generates beacons. At each TBTT the

HC schedules a beacon as the next frame to be transmitted. If the medium has been idle for at least PIFS before TBTT, the HC transmits the beacon right at TBTT, otherwise the beacon is transmitted PIFS after the current transmission, without contention. All stations associated to this HC are required to update their local timers with the information from the beacon, regardless of the values that are currently maintained in the local timers.

Among the timing information needed to synchronize stations, the beacon delivers other parameters related to the protocol and to radio regulations. Depending on the type of the BSS not all information elements may be included in the beacon.

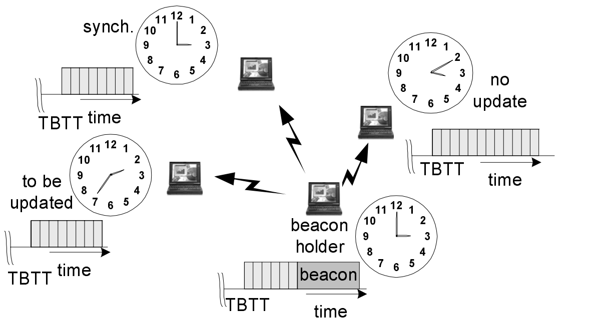

Fig. 2: Timer Synchronization Function in an IBSS. Only received timer values that greater than the local values are used for updating local timers.

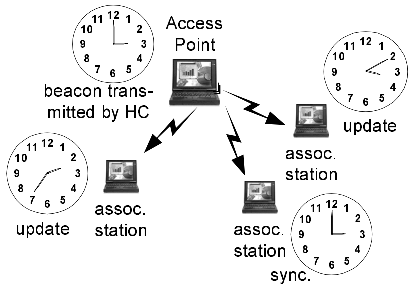

Fig. 3: Timer Synchronization Function in a QBSS. All stations associated to this HC are required to update their local timers with the information from the beacon.

III. The Neighborhood Capture Effect and Solution Concepts

A. The Problem: Channel Capture by Hidden Stations

Stations that are hidden to each other operate simultaneously, without mutually coordinated transmissions and backoff procedures. The DCF can only work if all stations are in detection range of each other. However, this is also a strict requirement for the priority support of the EDCF. If the channel gets idle at a particular time, stations will start their backoff procedures synchronously, and the station that first counts down its backoff counter will initiate its transmission, the other stations will defer from channel access. A station that is located in the detection range of other stations that are hidden to each other can only initiate a transmission, if all of the uncoordinated stations that are hidden to each other are idle at the same time. However, this is a very rare event, especially in hot spot scenarios at times of high offered traffic. The station cannot transmit for long durations, the channel is captured by stations in the neighborhood. This leads to increased delivery delays and reduced throughputs.

To reduce the unwanted effects of the neighborhood capture, [10] proposes an efficient and simple solution based on synchronous time division, i.e. slotting. In the next section we present a way to introduce such a slotting in 802.11(e), and combine it with a technique called EDCF-TXOP bursting as means to improve throughput performance in the slotted protocol.

B. Mutual Synchronization across QBSSs and Slotting in Overlapping scenarios

Two modifications of the 802.11e protocols are required in order to enable coexisting QBSSs as well as coexisting IBSSs to synchronize. Fig. 4 illustrates the two changes. One modification is that beacons are transmitted in contention by all stations of a QBSS, as it is the case in an IBSS. Stations that are associated to an HC are allowed to transmit a beacon. It is not necessary for such stations to deliver all information a HC usually transmits with its beacon. For the purpose of synchronization only the TSF information is required.

The second modification in the standard is the requirement that all stations, regardless if AP or part of a QBSS or IBSS, must update its timer value according to the rules of the IBSS. By applying these two simple modifications in 802.11, it is possible to mutually synchronize overlapping QBSSs without loosing any functionality of the protocol.

Now, slotting is possible by defining a slot dwell time. With such a slot dwell time, frame exchanges are initiated only if they can be finished before the end of the respective slot, i.e., without exceeding the slot dwell time. After that periodic time, stations content for the next frame exchange. In the simulations we discuss below, a slot duration of *4 Time Units (TUs)*, i.e., *4.096 ms*, was used.

An immediate drawback of the slotting is the obvious throughput degradation. To mitigate this, we apply a concept called EDCF-TXOP duration, as explained in the next section.

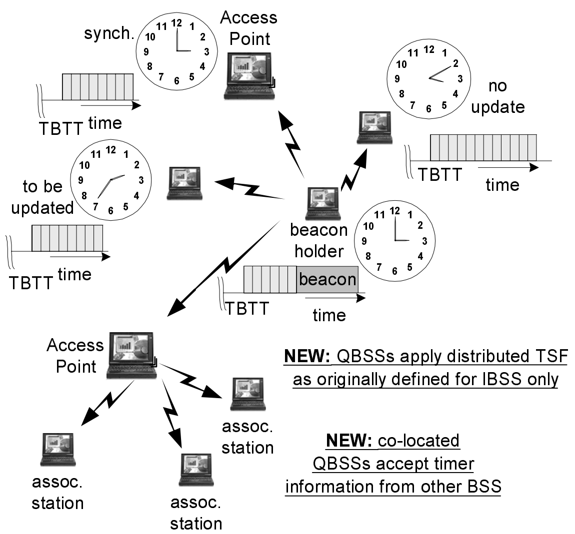

Fig. 4: Two modifications in 802.11e to allow mutual synchronization for the reduction of the neighborhood capture effect and to support multi-hop traffic.

C. EDCF TXOP Bursting

The concept of transmitting more than one MSDU after winning the EDCF contention is called EDCF-TXOP bursting [11]. With EDCF-TXOP bursting, after winning the contention, a station may transmit more than one pending MSDUs for a duration of not exceeding the maximum allowed duration called *TXOPlimit*. According to the current 802.11e draft, a station can transmit a single MSDU during an EDCF-TXOP. 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 EDCF-TXOP bursting due to their traffic characteristics. However, the parameter *TXOPlimit* and the slot dwell time limit the time a single station occupies the radio channel.

IV. EVALUATION

We use event-driven stochastic simulations to evaluate the performance of 802.11e EDCF for the 802.11a physical layer at 5GHz that allows up to *54 Mbit/s*. In all simulations, a radio channel error model as described in [5],[6] is used. For the delay results, we give empirical Complementary Cumulative Distribution Functions (*CDFs*) of the resulting stochastic data, using the discrete Limited-Relative-Error (*LRE*) [11].

A. Scenario

A symmetric scenario has been selected to investigate the effects of slotting and EDCF-TXOP bursting in 802.11e. A circle of *12* stations forms a QBSS where all stations operate according to EDCF, see Fig. 5. All frames are transmitted with *12 Mbit/s* PHY mode. Each station generates the same mix of offered traffic of three single-hop data streams, which we label with high, medium and low, according to their priorities. Within these streams, stations deliver MSDUs to one neighbor station, and in parallel, receive three other streams from the other neighbor station. In total, $12 \cdot 3 = 36$ data streams are simulated. All MSDUs arrive with Poisson inter-arrival times.

The three priorities are always offered the same traffic. At the different backoff instances, MSDUs with a size of *600 bytes* or *128 bytes* arrive such that the queues are always full. We further simulated using an Ethernet trace file that offers *1 Mbit/s* with typical Ethernet frame sizes of up to *1514 bytes* as traffic source for each individual backoff instance.

The following Table 1 shows the EDCF-parameters selected for the three priorities, summarizing the EDCF parameters we mainly use.

Table 1: Used EDCF parameters for the three TCs.

	high, TC6	medium, TC5	low, TC0
AIFS[us]	*34us*	*34us*	*34us*
CWmin[us,slots]	*7*	*14*	*15*
CWmax[us,slots]	*127*	*175*	*255*
PF	*2*	*2*	*2*

RTS/CTS is used for MSDUs larger than *512 bytes*. MSDUs are delivered in single *MAC Protocol Data Units (MPDUs)*, i.e. MSDUs are not fragmented. The TXOPlimit is larger than the slot dwell time.

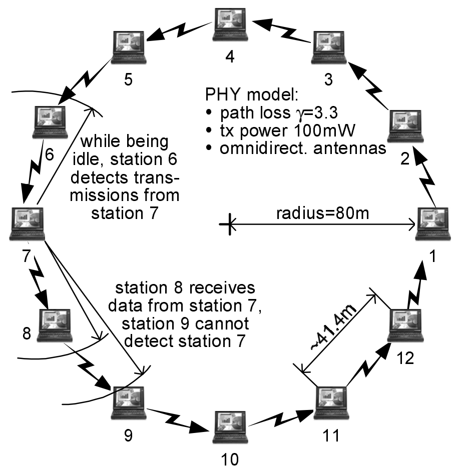

Fig. 5: Symmetric hidden station scenario. Each station detects only its two direct neighbors. Each station carries three parallel streams of data with high, medium, low priority, respectively.

B. Evaluation

The three configurations that were simulated are the standard configuration labeled as "*with capture*", the slotted configuration labeled as "*slotted*", and the slotted configuration with EDCF-TXOP bursting, labeled as "*bursted*". Table 2 illustrates the maximum achievable throughput in a scenario, where one station transmits to its neighbor and all other stations remain idle. Thus, no collisions occur at the radio channel. The results are given for the three configurations and three different types of traffic load. It can be seen that the slotting reduces the throughput compared to the standard configuration, whereas the EDCF-TXOP bursting increases the throughput again, which is very significant with short MSDU sizes.

Table 2: Max. achievable thrp. (all TCs) with two isolated stations [kbit/s].

MSDU size	600 bytes	200 bytes	Ethernet trace
with capture*	*7153.5*	*4213.7*	*=offer(1Mbit/s)*
slotted	*6831.8*	*2998.2*	*=offer(1Mbit/s)*
bursted	*6977.9*	*4987.1*	*=offer(1Mbit/s)*

*) although labeled as "with capture", captures do not occur here, as this is an isolated scenario where no hidden stations exist.

Table 3 shows the maximum achievable throughput in the hidden station scenario of Fig. 5. It can be seen how severe the throughput is degraded in 802.11 by contention and hidden stations.

Table 3: Max. achievable thrp. saturation throughput (all TCs) [kbit/s].

MSDU size	600 bytes	200 bytes	Ethernet trace
with capture	*236.1*	*162.4*	*220.3*
slotted	*232.2*	*160.3*	*205.6*
bursted	*285.0*	*201.1*	*267.8*

Fig. 6 and Fig. 7 show the resulting backoff delays for the three TCs as CDF. Here the MSDU size is *600 bytes*. All stations together are evaluated, as the scenario is symmetric. The advantage of the slotting is clearly visible. For all TCs, the backoff times are reduced. As expected, the bursting increases the delays compared to the slotting, by at the same time increasing the throughput. The shapes of the curves in both figures further indicate the slotting with a duration *4.096ms*.

Fig. 8 and Fig. 9 show resulting backoff delays for the Ethernet trace files. Here, the positive effect of the slotting is again visible, although the advantage is not as high as before. In general, the longer the MPDUs, the more likely is a channel capture, and thus, the more efficient is the slotting.

V. CONCLUSIONS

We have presented simulation results that indicate the efficiency of the EDCF-TXOP bursting together with a slotting scheme. A way to achieve the synchronization among overlapping BSSs was discussed. The results indicate that the occurrence of the neighborhood channel captures by coexisting BSSs is efficiently reduced when applying the slotting scheme together with EDCF-TXOP bursting. This has great potential for multi-hop scenarios and the efficient forwarding of MSDUs across multiple (Q)BSSs under QoS constraints.

All presented delay results are within a maximum limited relative error of *5 %*.

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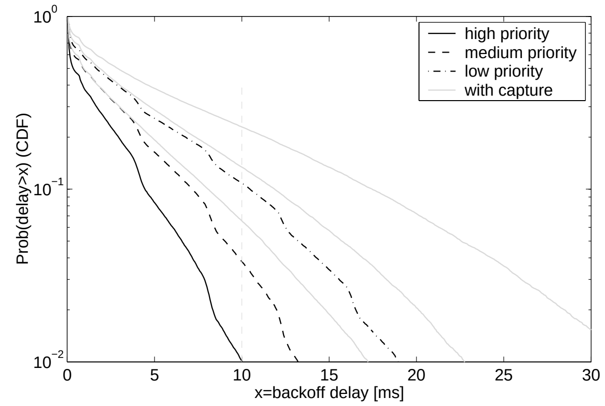

Fig. 6: "*Slotted*" scenario, backoff delay compared to "*with capture*". The MSDU size is *600 bytes.*

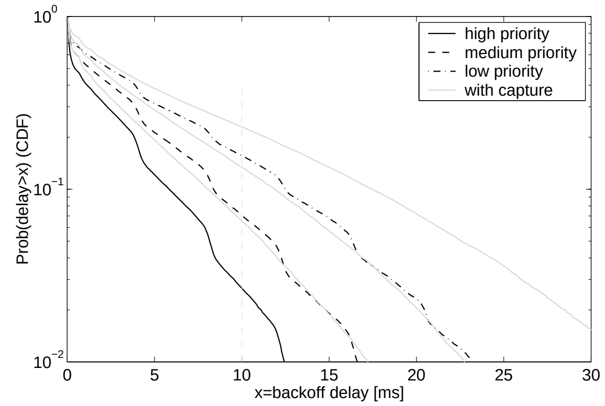

Fig. 7: "*Bursted*" scenario, backoff delay compared to "*with capture*". The MSDU size is *600 bytes.*

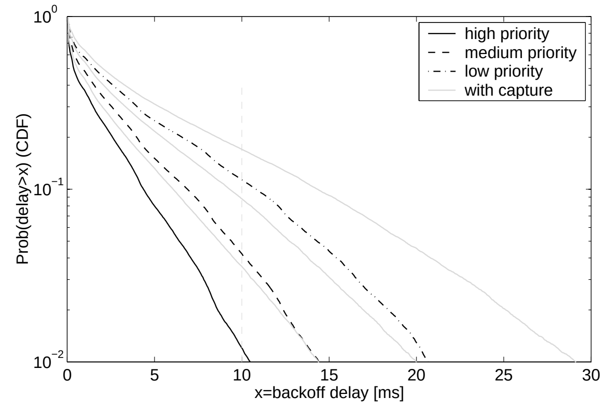

Fig. 8: "*Slotted*" scenario, backoff delay compared to "*with capture*". Results are shown for the Ethernet traces.

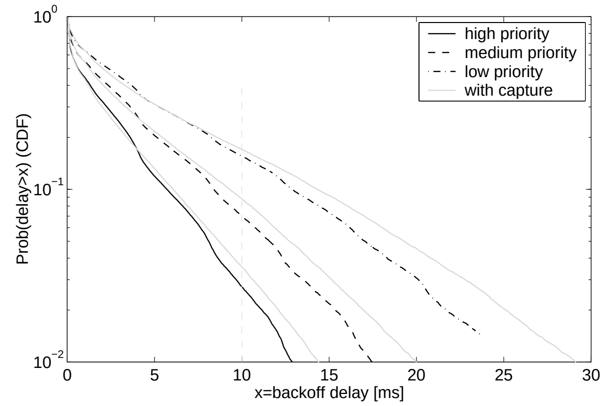

Fig. 9: "*Bursted*" scenario, backoff delay compared to "*with capture*". Results are shown for the Ethernet traces.