Evaluation of Contention Free Bursting in IEEE 802.11e Wireless LANs

Atul Salhotra
Marvell Semiconductor, Inc.
700 First Avenue,
Sunnyvale, CA 94089, USA

Ravi Narasimhan
Department of Electrical Engineering,
University of California,
Santa Cruz, CA 95064, USA

Rahul Kopikare
Marvell Semiconductor, Inc.
700 First Avenue,
Sunnyvale, CA 94089, USA

***Abstract*— This paper presents a simulation-based study of a MAC protocol, named Contention Free Bursting (also referred to as Enhanced Distributed Coordination Function (EDCF) Bursting) described as an optional mode of operation in 802.11e WLAN networks. A simple recovery mechanism is proposed upon transmission failure during the burst. The new scheme aims to provide better Quality of Service when high throughput applications operate in the presence of low throughput, latency-sensitive applications.**

Index terms — **Medium Access Control, IEEE 802.11, WLAN, Quality of Service, Enhanced Distributed Coordination Function, Hybrid Coordination Function**

I. Introduction

With the tremendous growth of wireless technology, the dream of the wireless home is not far-fetched. It is envisioned that wireless access will be considered as another hop of the communication path. The IEEE 802.11 Wireless Local Area Network (WLAN) [1] is one of the most widely deployed wireless communication technologies in the world today. The commercial success of 802.11 networks owes to their flexibility, simplicity and cost effectiveness. The main goal is to provide ubiquitous communication.

The ever increasing popularity of these networks has led researchers into considering the possibility of multimedia traffic being supported over WLAN. People wish to receive video/ voice/ data at high speeds over the Internet regardless of where they are. Multiple traffic streams with different levels of Quality-of-Service (QoS) requirements in terms of delay, throughput and jitter can potentially over burden the network, even if the bandwidth is sufficient, if the medium access control (MAC) protocol is not designed for efficient bandwidth sharing. QoS is not much of a concern in Ethernet due to enormous bandwidth provided by the sophisticated physical layer (PHY). Contrary to this, guaranteeing QoS in WLAN is a very challenging task due to the challenges that wireless channel has to offer.

With the motive of providing QoS in the WLAN, IEEE formed an 802.11 Task Group, popularly known as 802.11e [2], to enhance the support for QoS sensitive applications like Voice over IP (VoIP), streaming video applications and video conferencing. The original IEEE 802.11 MAC [1] supports two modes of operation: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). The proposed 802.11e standard is intended to enhance the 802.11 MAC to improve and manage QoS, expand support for applications with QoS requirements [3] [4], provide classes of service, and consider efficiency enhancements in the area of the DCF and PCF by providing two new modes of operation, namely Enhanced Distributed Coordination Function (EDCF) and Hybrid Coordination Function (HCF) that can work on the top of existing PHYs (802.11 a/b/g).

In this paper, we will evaluate the Contention Free Bursting (CFB) scheme that is based on the packet frame grouping scheme introduced originally by Tourrilhes in [5]. This scheme mainly extends the concept of burst transmission, wherein a particular station, after gaining access to the medium, transmits small fragments of a big packet. During CFB, on the contrary, a station transmits packets in succession until its allocated transmission opportunity (TXOP) is over. The main idea is to share the contention overhead by transmitting packets in a burst rather than having the station contend for the medium.

CFB promises higher throughput by cutting down on the overhead due to contention. However, the throughput of the network could have a significant impact if the frames in the burst are unsuccessful. It should be noted that in a wireless channel, collision need not be the only cause of a transmission failure. The fades in the channel could be equally responsible for the lost frames. How should a station react in case of transmission failure when employing CFB ? Should the station continue to burst or should it relinquish the medium ? How would hidden nodes impact the performance of CFB ? In this paper, we propose a technique to address this issue.

The organization of the paper is as follows. In Section II, we present an overview of the legacy 802.11 MAC [1], describing in brief the multiple access mechanisms, DCF and PCF. Section III covers the mandatory MAC enhancements as proposed in the 802.11e draft [2]. Various aspects of the CFB scheme are discussed in Section IV, including the proposed modified CFB scheme. Simulation results are presented in Section V. We discuss the impact of hidden nodes on CFB protocol and suggest alternate mechanisms in Section VI. The conclusions follow in Section VII.

II. Legacy 802.11 MAC

The legacy 802.11 MAC layer incorporates two access methods: the mandatory DCF and the optional PCF.

DCF is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. CSMA/CA is analogous to CSMA/CD used in Ethernet, but the half-duplex limitation of wireless transceivers prohibits the use of collision detection.

In CSMA/CA every station senses the medium to ensure that no other station is in the process of transmission. Each station maintains a Contention Window (CW) which it uses to determine the random amount of time (using a backoff counter in multiples of time slots (TS)) the station has to sense the channel idle. The backoff counter begins to decrement when the medium is found idle for a DCF InterFrame Space (DIFS) amount of time, and the stations transmit upon the expiry of the backoff counter. The backoff counter is decremented by unity every time the medium is sensed idle for TS amount of time. In DCF, the collision refers to the instance of the backoff counters of two or more stations expiring simultaneously. In the case of this event, each colliding station expands its CW (in a binary exponential fashion), randomly selects its new backoff period and contends again for the medium.

DCF is used to support asynchronous data transmission and can be used in ad hoc as well as infrastructure mode. Despite performing very well under low traffic conditions, DCF, by no means, provides service differentiation of any sort. All traffic streams are treated alike. This leads to performance degradation when the traffic load increases and makes it unsuitable for real-time applications.

PCF is provided in IEEE 802.11 MAC to support time-bounded multimedia applications in order to provide limited QoS. The PCF can only be used in the infrastructure mode, since it requires the presence of a Point Coordinator (PC), that is collocated with the Access Point (AP). The PCF provides contention-free frame transfer by dividing the time frame (after the beacon is transmitted) into two sections: the Contention Free Period (CFP) followed by Contention Period (CP), which together constitute a superframe. During CFP, the PC gets priority over other stations in terms of having to wait only for PCF InterFrame Space (PIFS), which is smaller than DIFS. The PC polls all the stations in a round robin fashion and provides them guaranteed access to the medium. A station can also request the PC an access to the medium that will be granted during the next polling interval. The CFP is followed by a CP, which is governed by the rules of DCF.

PCF, though seemingly capable of providing limited QoS, is rarely implemented in 802.11 compliant devices for various reasons [3], [6], [7]. The inefficient centralized polling mechanism of PCF in addition to the borne overhead limits its use when the network load increases [7]. The transmission of the beacon frame could be delayed if the CP gets extended due to longer transmissions. The requirement of the AP prohibits the use of an ad hoc mode when operating under PCF. To alleviate these problems and to provide QoS, IEEE task group is working towards a IEEE 802.11e [2], which promises QoS by enhancing MAC features of the legacy 802.11 MAC [1].

III. Enhanced 802.11e MAC

To support QoS, many access mechanisms have been proposed and analyzed [3], [7], [8], [9]. Also, refer to [6] and references therein. MAC enhancements of IEEE 802.11e include two new modes of operation, EDCF and HCF [2].

EDCF, as the name suggests, works on the principles of DCF. Additionally it supports service differentiation by providing different Access Categories (ACs). Every station supports up to 4 ACs, where the packets from different streams get mapped onto different ACs depending on the QoS requirements of the different streams (See Fig. 1).

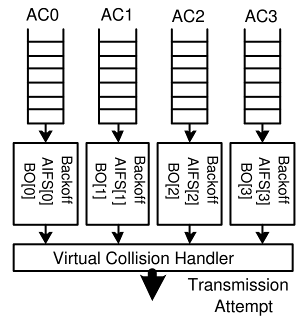

Fig. 1. EDCF implementation: 4 Access Categories (ACs)

Each AC in EDCF starts decrementing its backoff counter after detecting the medium idle for Arbitration InterFrame Space (AIFS). Each AC has its own AIFS[AC], minimum Contention Window ($\mathrm{CW}_{min}[\mathrm{AC}]$), maximum Contention Window ($\mathrm{CW}_{max}[\mathrm{AC}]$) to contend for the medium based on its priority. AIFS[AC] is calculated as follows:

$$AIFS[AC] = SIFS + AIFSN[AC] * SlotTime, \quad (1)$$

where $AIFSN[AC]$ is a positive integer (≥ 2) and Short InterFrame Space ($SIFS$) and $SlotTime$ are Physical Layer (PHY) dependent.

HCF combines the advantages offered by both DCF and PCF. As with PCF, the superframe in HCF also consists of CFP initiated by beacon transmission followed by the CP. During CP, the access rules are governed by EDCF, though the Hybrid Coordinator (HC) can access the medium any time owing to its higher priority. Each transmission opportunity (TXOP), specified by its starting time and the maximum duration, begins when the medium is available to be free under the EDCF rules (EDCF-TXOP). EDCF-TXOP can be obtained from the QoS parameter set element in the beacon frame. During the CFP, the HC issues a polled-TXOP to a particular station by sending a special QoS (+) CF-Poll packet. A TXOP is granted to another station if the first station does not respond to the QoS (+) CF-Poll within SIFS amount of time, thereby making HCF more efficient than PCF.

In this paper we are interested in the contention based HCF mechanism, namely EDCF. EDCF seems very attractive, mainly due to the fact that it can be used in ad hoc scenarios since there is no requirement of an AP.

IV. Contention Free Bursting in the Allocated EDCF-TXOP

As mentioned before in Section I, this paper concerns mainly with the CFB scheme, also referred as TXOP Bursting [10], an optional mode in the 802.11e draft [2].

CFB allows multiple frame exchanges within non-polled TXOP (EDCF-TXOP Bursting). During this mode, a station may transmit multiple frames from the same queue (AC). Successive frame exchange sequences are separated by SIFS amount of time as shown in Fig. 2. In CFB, a station does not give up the medium after executing a frame exchange (DATA + Acknowledgement (ACK)), as long as the allocated TXOP is long enough to complete another frame exchange sequence. If next frame exchange requires more time than is allocated to the station, the CFB mode ends, the station goes into backoff and contends again for the medium as per EDCF rules.

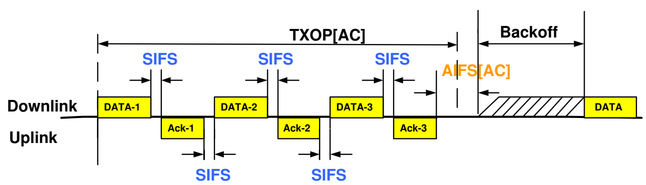

Fig. 2. Illustration of the Contention Free Bursting (CFB) Mode

CFB is very attractive since it reduces the network overhead by eliminating the contention between the successive frames transmitted during the burst. This results in higher efficiency and lower delays according to [5], [10] and [11]. CFB also leads to an increased fairness among the queues with same access parameters, almost independent of the frame sizes. In fact, without CFB, the longer frames occupy the medium for more time. The rules related to carrier sensing and the Network Allocation Vector (NAV) settings are described in [10].

CFB is effective as long as there are no transmission failures, i.e. as long as the transmitter receives an ACK. How should the stations respond in the case of failures ? We try to investigate this issue in this section. We present below two different ways of handling the transmission failures and discuss the advantages and drawbacks of each.

A. Normal CFB

According to [10], the station relinquishes the medium and goes into backoff after a transmission failure occurs, i.e. the station does not receive an ACK within a certain timeout interval, called Recovery TimeOut (RTO) here. This is the usual ACK timeout duration for the standard DCF. We call this mode Normal CFB, represented pictorially in Fig. 3. In the example illustrated, DATA-2 was not acknowledged resulting in the station giving up its TXOP.

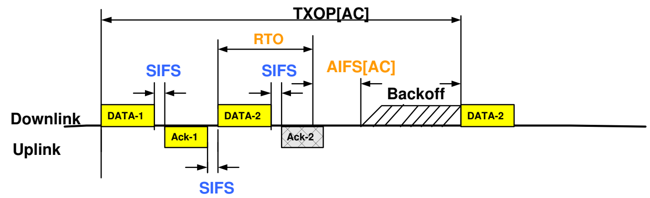

Fig. 3. Illustration of Normal CFB in the case of transmission failure

B. Modified CFB

As mentioned before, collision need not be the only cause of transmission failure in a wireless channel. The received packet could be corrupted due to the noisy environment. In this case, we propose to retransmit instead of releasing the medium. We call this scheme Modified CFB (*m*CFB). The rationale for *m*CFB is described below.

In CFB it should be noted that once a station has grabbed the medium, no other station can attempt to transmit till the transmitting station relinquishes the medium, since the consecutive frame exchange sequences are separated by SIFS amount of time. This is true, of course, when there are no hidden nodes, i.e. perfect carrier sensing is possible. If this is the case, the frames following the first frame in the burst could only be corrupted by the channel, i.e. collision could not possibly be the cause of transmission failure. This idea is used in our *m*CFB approach as follows.

- If the ACK for the first frame in the burst is not received within RTO, the transmitter goes into backoff and contends again for the medium. The rationale is that collisions are possible for the first frame.
- If the frames following the first one are not acknowledged, the transmitter still retains the medium and attempts to retransmit the frame that failed on the medium, after the RTO expires.

The RTO should satisfy the following inequality:

$$SIFS \leq RTO - dur(\text{DATA}) < SIFS + 2 * SlotTime \quad (2)$$

This is to ensure that no other station attempts to gain control of the medium before the failed packet is retransmitted. *m*CFB is illustrated in Fig. 4. In this case, the failure to receive the ACK for DATA-2 resulted due to poor channel conditions, and it is worth trying to retransmit. After the successful frame exchange sequence corresponding to DATA-2, there is not enough time remaining (within its TXOP) to complete the next sequence. So according to the rules of CFB, the station relinquishes the medium.

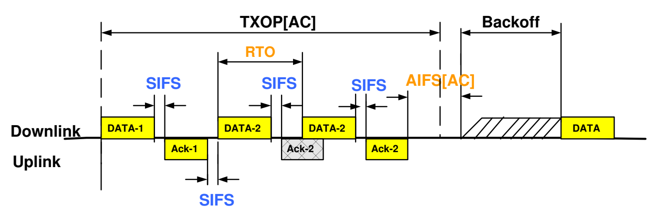

Fig. 4. Illustration of Modified CFB in case of transmission failure

The time out value, RTO, in Fig. 3 and Fig. 4 correspond to the case when the Clear Channel Assessment (CCA) value as observed by the station is low. This implies that the ACK corresponding to the unsuccessful frame was never transmitted. This explains why a station could begin retransmission in Fig. 4 before the expiry of $dur(\text{DATA})+SIFS+dur(\text{ACK})$ amount of time. However, if the CCA is high while the station is awaiting the ACK, it has to wait until the CCA goes low before being able to retransmit. We call this CCA Low TimeOut (CLTO). In this case, the station retransmits the failed packet SIFS time after the CLTO. This is shown in Fig. 5.

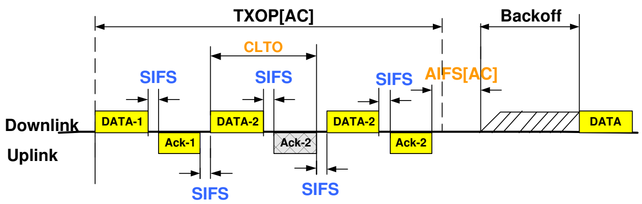

Fig. 5. Illustration of Modified CFB in the case of transmission failure when CCA is high.

This simple extension of CFB can lead to a significant performance improvement. We present simulation results to compare the two schemes in the next section.

V. Simulation Results

The two variants of the CFB protocol were implemented in NS-2 [12] and tested with a simulation scenario (see Fig. 6) in the infrastructure mode. The base EDCF model used in our simulations was developed by the researchers at Planete Group at INRIA Sophia Antipolis, France [13]. We used this model and implemented our CFB protocols.

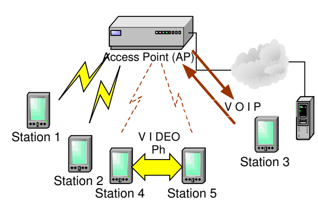

Fig. 6. Simulation Scenario to compare the CFB schemes

- Flow1 – AP → STA1 :: 1500 Bytes, 19.2 Mbps, High Definition TV (HDTV)
- Flow2 – AP → STA2 :: 1500 Bytes, 19.2 Mbps, HDTV
- Flow3 – AP → STA3 :: 100 Bytes, 0.15Mbps, VoIP
- Flow4 – STA3 → AP :: 100 Bytes, 0.15Mbps, VoIP
- Flow5 – STA4 → STA5 :: 512 Bytes, 0.5Mbps, Video-Ph
- Flow6 – STA5 → STA4 :: 512 Bytes, 0.5Mbps, Video-Ph

Note that STA4 and STA5 communicate through the AP in this infrastructure mode.

In terms of providing QoS, latency is very critical to voice and Video-Phone (throughput is not of much concern since their bandwidth requirement is not that significant), but as far as HDTV applications are concerned, latency is bearable as long as the jitter is reasonable (i.e. all the frames are delayed by almost equal extent). The throughput, on the other hand, is very critical to the applications like HDTV and other high bandwidth requirement applications. Keeping this in mind, we assigned the highest priority, i.e. the most aggressive EDCF parameters, to the queue buffering the packets corresponding to Flow3 - Flow6.

We believe that for low data rate applications like VoIP, Video-Phone etc, one can do without bursting. Schemes like CFB could be employed by the queue supporting high throughput applications like HDTV. This can reduce latency and, most importantly, help avoid the undesirable frame drops that could result due to queue overflow, if the VoIP applications are given higher priority. Based on this, we chose the EDCF parameters as follows[1]:

- Flow1 - Flow2: $\text{CW}_{min}[\text{AC}]$ = 15, $\text{CW}_{max}[\text{AC}]$ = 31, AIFS = 4, TXOP = 3ms
- Flow3 - Flow6: $\text{CW}_{min}[\text{AC}]$ = 7, $\text{CW}_{max}[\text{AC}]$ = 15, AIFS = 3, TXOP = 0

All simulations were done with the PHY data rate of 108Mbps[2]. The PHY parameters used for NS-2 simulations were: ‘ PLCP size - 32 μs’, and ‘ basic rate - 6 Mbps’. To compare the performance of the proposed CFB scheme (*m*CFB) with the existing Normal CFB scheme, the Packet Error Rate (PER) was chosen to be 10%, a reasonable number for indoor wireless channels. For simplicity, the simulations were based on the assumption of random frame errors.

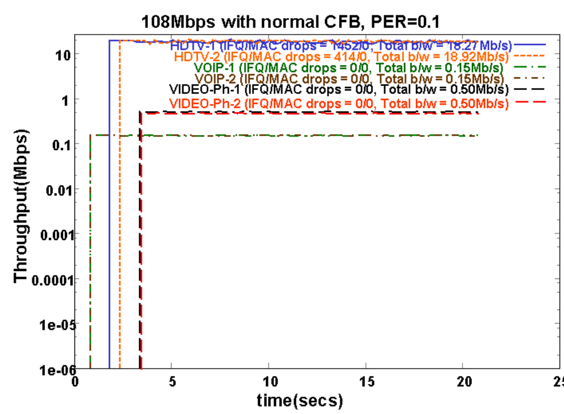

Fig. 7. MAC throughput with 108Mbps with Normal CFB and PER=10%

Fig. 7 and Fig. 8 show the MAC throughput (Mbps) and the latency (ms) distribution, respectively, for each of the flows when employing Normal CFB scheme. The coordinates (10, 40) in Fig. 8 imply that 40 % of the packets corresponding to a particular flow experience latency of 10 ms or less. As seen from the results, Flow3 - Flow6 (VoIP and Video-Phone)

[1]TXOP = 0 implies no bursting.

[2]The usage models proposed by IEEE 802.11n Task Group necessitate the existence of very high over-the-air data rates. One way to achieve such data rates is to use multiple antennas at both the transmitter and the receiver. The discussion of Multi-Input Multi-Output (MIMO) systems is beyond the scope of this paper.

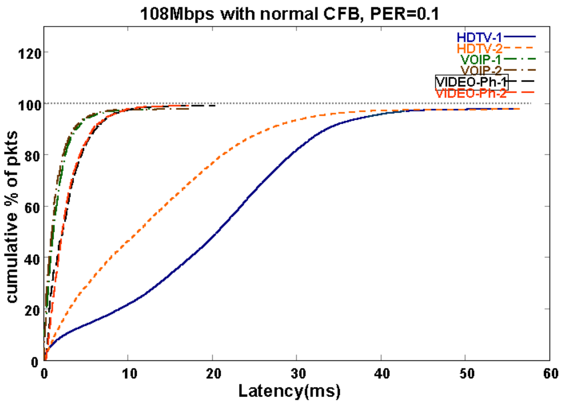

Fig. 8. Cumulative Distribution Function (CDF) of latency with 108Mbps, Normal CFB and PER=10%

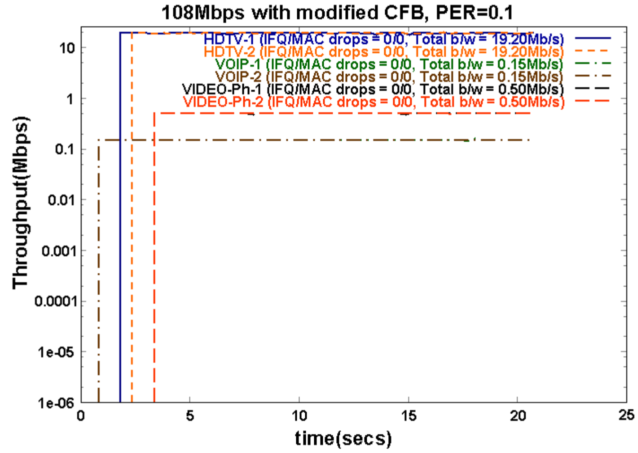

Fig. 9. MAC throughput with 108Mbps with Modified CFB and PER=10%

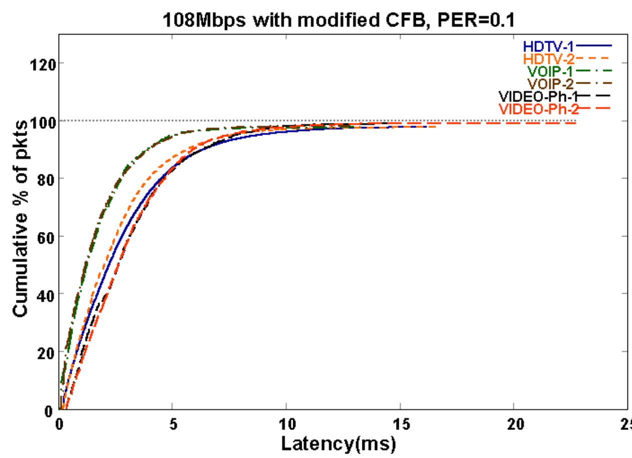

Fig. 10. CDF of latency with 108Mbps, Modified CFB and PER=10%

have no performance degradation in terms of throughput and delay, since these are assigned the highest priority. However, Flow1 (HDTV-1) and Flow2 (HDTV-2) suffer when using Normal CFB. There are significant number of IFQ drops (dropped frames resulting from the overflow of the interface queue between the Link Layer and the MAC Layer) resulting in the throughput loss. The differences in the performance of Flow1 and Flow2, despite the use of same parameters, could be attributed to the fact that the two applications try to access the medium in a random fashion (decided by the random backoff). The jitter experienced by these streams is also significant, as seen from Fig. 8. The jitter is related to the slope of the latency distribution plot. The higher the slope, the smaller is the jitter. These frame drops and the jitter lead to performance degradation for high throughout (HT) HDTV applications operating under Normal CFB mode.

The *m*CFB scheme has quite an impact on the performance of HT applications like HDTV. It can be seen that, in the case of saturated networks, *m*CFB reduces the contention overhead, thereby resulting in the increased network utilization and reduced queueing delays. The plots for bandwidth and delay distribution are shown in Fig. 9 and Fig. 10, respectively.

As seen from Fig. 9, the HDTV streams do not experience any frame drops and there is no loss in the throughput. The slopes of the curves in Fig. 10 are also large for all the flows, implying insignificant jitter. It should be noted that *m*CFB does not affect performance of VoIP and Video-Phone applications.

Note that in the simulation scenario, all the stations are within the carrier sensing range of each other, i.e. there are no hidden nodes. Hidden nodes can potentially make the matters worse if the stations are operating in the *m*CFB mode. We discuss this in the next section.

VI. CFB in the Presence of Hidden Nodes - Multimode Operation

Fig. 11 shows a simulation scenario with two hidden stations, STA1 and STA2 (belonging to the same basic service set (BSS) network) communicating to the AP (uplink traffic). The dotted line indicates that STA1 and STA2 can not hear each other. *m*CFB can result in reduced network efficiency if the packet in a burst from STA1 collides with a packet from STA2. See Fig. 12 for an illustration.

The top figure of Fig. 12 shows the packet exchange sequence between STA1 and the AP, while the lower one illustrates the corresponding frame transfer between STA2 and AP. The hashed out area indicates the state of the medium to be idle, as sensed by a particular station. STA2 pauses its backoff counter while the AP acknowledges DATA-1, since each station can hear the AP, and the STA2 initiates the transmission when its backoff counter expires. If the duration of the transmission from STA2 is longer compared to the one from STA1[3], the use of *m*CFB, in this case, would lead to repeated number of collisions (see Fig. 12). Also, the retry

[3]If STA2 is very far from AP compared to STA1, STA2 might have to transmit at a lower rate, leading to a longer transmission time.

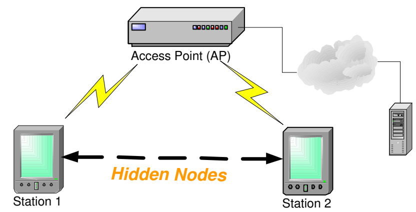

Fig. 11. Simulation Scenario with two hidden nodes

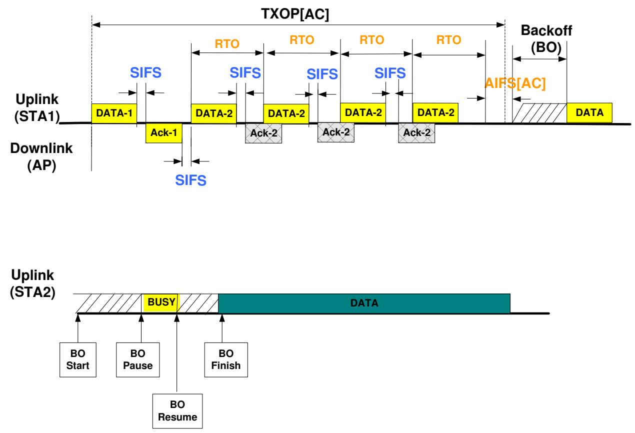

Fig. 12. Illustration of repeated collisions in the case of hidden nodes when using *m*CFB

count[4] would keep getting incremented unnecessarily. This could lead to false link adaptation and possibly a packet drop as well. This situation could have been avoided if STA1 was operating in the Normal CFB mode.

It was pointed out in Section V that the HT applications like HDTV benefit a lot from *m*CFB mode of operation unlike the low throughput applications like VoIP, Video-Phone, etc. Also, most of the practical high throughput applications (HDTV, Standard Definition TV, etc.) are unidirectional and the source is the AP. Based on this observation we suggest the following multimode operation:

- AP should operate in *m*CFB mode for unidirectional downstream applications.
- STAs exchanging bidirectional traffic with AP should operate in Normal CFB mode.

Since EDCF is based on ACs (per queue), multimode operation is feasible. It is also possible to come up with a mixed mode of operations as follows[5]:

- **Intermediate Bail Out CFB** - Keep a separate retry counter for CFB, say CFBrcount, smaller than the ShortRetryLimit, as specified by the IEEE standard [1] for packet retransmissions. Increment this counter on ACK failure and bail out of the CFB mode when the counter expires.
- **Adapt and Bail Out CFB** -
  - Set CFBrcount = 1.
  - If 2nd attempt fails, ⇒ retransmit at a lower rate.
    - If retransmission failure ⇒ bail out of CFB.
    - If retransmission success ⇒ continue in CFB with existing rate adaptation.

VII. Conclusions

In this paper, we have proposed a modification to the existing CFB (EDCF-TXOP Bursting) scheme that is an optional mode of operation in the 802.11e WLAN standard. The variant differs mainly in the error recovery mechanism adopted upon any transmission failure. The CFB mode of operation allows one to distinguish between the frames lost due to collision and the ones lost due to channel errors. This knowledge is exploited to retransmit the frames that are corrupted due to a poor channel. As observed by the performance curves, *m*CFB helps HT applications meet their bandwidth/ delay (jitter) requirements in the presence of low bandwidth VoIP and Video-Phone applications without sacrificing their performance.

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[4] According to IEEE 802.11 MAC protocol, if a transmitted unicast packet is not acknowledged, the station keeps retransmitting the packet until the number of retries exceeds a certain threshold, thereafter dropping the packet.

[5] The performance of these schemes will be reported in a future paper.