Exploiting Reverse Direction Protocol in Full Duplex WLANs

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***Abstract*—This paper proposes the application of Reverse Direction (RD) protocol to enhance performance in future Full Duplex (FD) Wireless Local Area Networks (WLANs). Full duplex communications in WLANs will be possible when a receiving node has frames ready for the transmitting node. This requires the receiver to decode the frame header for each and every frame in the Transmission Opportunity (TXOP) of the transmitter, in order to obtain the source and destination addresses. It is shown that, in FD-capable WLANs, this procedure may lead to suboptimal performance, reducing the benefits of FD communications. A simple and effective method, based on the usage of RD protocol, is proposed in order to enhance efficiency in future FD WLANs. The performance of the proposed solution is evaluated and compared to the standard method in terms of maximum achievable throughput.**

***Index Terms*—full duplex, reverse direction protocol, transmission opportunity, WLANs**

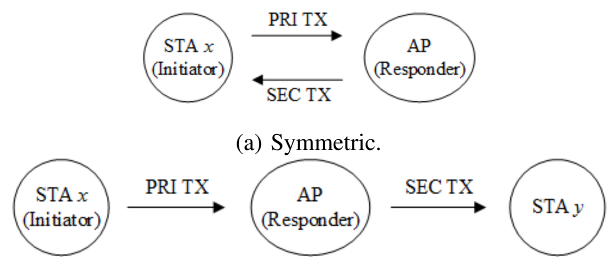
I. Introduction

Commercial WLAN systems operate under a half duplex regime. This means that a wireless station (STA) is not able to transmit and receive at the same time. However, achieving FD wireless communications (i.e., simultaneous transmit and receive radio operation mode) has been proven not only feasible but also practical [1]–[5]. Besides the obvious potential of doubling the network capacity, FD may offer some other advantages too, such as mitigation of the hidden node problem [2], [3] and collision detection in the wireless environment [6].

FD technology was one of the most important technologies initially considered for inclusion in the most recent IEEE 802.11ax amendment [7]. However, it was decided that it was out of the scope of IEEE 802.11ax and was ultimately abandoned [8]. Nonetheless, FD is not completely dismissed as it is expected to be considered in future WLAN technologies [9].

FD communications can be initiated by either an STA or an Access Point (AP) [10], [11]. The node that initiates the FD session holds the *primary transmission* (PRI TX). The transmission that takes place in the opposite direction, triggered by the PRI TX, is called the *secondary transmission* (SEC TX), with which the FD operation ultimately manifests. Throughout this paper the node whose transmission starts the FD communication is called the *FD initiator* while the node that holds the SEC TX is called the *FD responder*.

Depending on the destination address of the Head of Line (HoL) packet in the transmission queue of the responder we can distinguish between two FD modes: symmetric or asymmetric [11], [12]. The former is graphically explained in Fig.1(a) and the latter is depicted in Fig.1(b). Assuming equally sized frames for the FD initiator and the responder, the chronicle of a single frame exchange during FD operation is depicted in Fig.2. The FD responder (AP in this case) requires some time, d, to receive and decode the header of the incoming frame to determine the source and then start the SEC TX towards it, provided that the responder does have frames backlogged destined to it. The time gap incurred is filled with a busy tone signal to protect against hidden terminals and synchronise the Acknowledgment (ACK) transmission, which starts after the necessary Short Inter-Frame Space (SIFS) period [13]. Asymmetrical FD communications require that the transmitting STA (STAx) and the receiving STA (STAy) are far enough so that the transmitted and received signal do not interfere. If this condition is not met, then the interference of the STAx to AP and AP to STAy transmissions will produce a collision event on STAy [12]. In this work, we do not consider asymmetrical FD communication mode. Note that the AP may also assume the role of the FD initiator if it wins channel contention.



(a) Symmetric.

(b) Asymmetric.

Fig. 1: FD communication modes.

However, in modern WLANs each node may transmit multiple frames per channel access for a bounded period known as TXOP. In this case the decoding period, d, dedicated to each frame reception by the receiving node will negatively affect system performance. While several research papers have studied the FD mode in WLANs [6], [10]–[14], none of them have considered its performance under the TXOP protocol operation. Hence, in this paper we investigate the behaviour

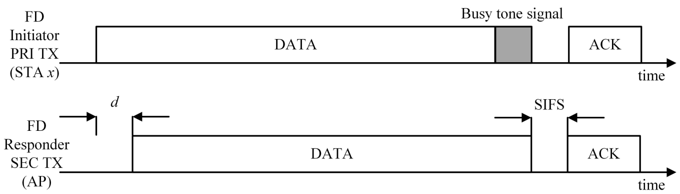


Fig. 2: Single frame exchange during FD operation mode.

of FD mode combined with the standard TXOP mechanism and we show that the decoding period necessary to perform FD communications may limit the system performance. To that direction we propose the usage of the RD protocol to optimise performance in FD-capable WLANs.

The rest of the paper is structured as follows. Section II provides some necessary background information on TXOP and RD protocol operation. Section III includes our study on the performance of FD communications under the standard TXOP and presents our proposal on applying the RD protocol to enhance it. Section IV presents a simple throughput oriented analysis in order to evaluate our proposal and the results are provided in Section V. The paper is concluded in Section VI with concluding remarks.

II. Background

Wireless nodes in existing WLANs employ multiple queues managed by a priority queuing channel access mechanism known as Enhanced Distributed Channel Access (EDCA). There are, typically, four queues per node known as Access Categories (ACs) and each of them accommodates a different traffic type. ACs content for channel access with distinct and predefined MAC-layer parameters. Once an AC gains channel ownership, it may reserve the channel for a specific amount of time known as TXOP, thus allowing for contention-free burst transmissions. The reservation period is known as $TXOP_{limit}$. The values of $TXOP_{limit}$ are AC and PHY-specific and are summarised in Table 1 for the latest IEEE 802.11 amendments. A value of zero denotes that the specific AC is allowed one frame transmission per channel access. Hence, multimedia ACs (i.e., $AC[VO]$ and $AC[VI]$) may transmit multiple frames per channel access, while non-multimedia ACs (i.e., $AC[BE]$ and $AC[BK]$) are refrained from exploiting the contention-free frame burst.

RD protocol was initially defined in the IEEE 802.11n amendment and allows an AC that has won channel contention to sublease a portion of its TXOP to the receiving node. The node that holds channel ownership is called the *RD initiator*

TABLE I: AC-specific $TXOP_{limit}$ values

Priority	**Access Category (AC)**	$TXOP_{limit}$ **(ms)**
Highest	Voice ($AC[VO]$)	1.504
High	Video ($AC[VI]$)	3.008
Low	Best Effort ($AC[[BE]$)	0
Lowest	Background ($AC[BK]$)	0

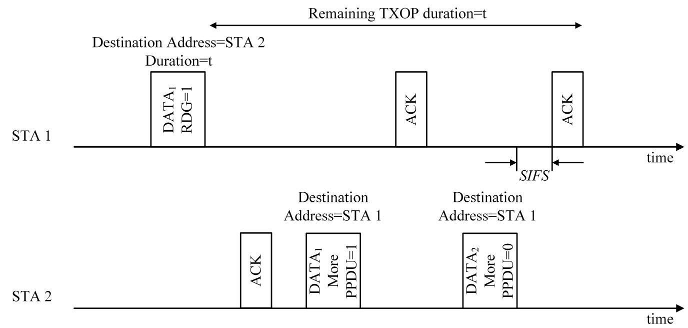


Fig. 3: RD protocol operation.

and the node that is allowed to transmit during the initiator's TXOP is called the *RD responder*. For the RD protocol to work both nodes must support it. This can be indicated in the header of the frames exchanged between the two.

An example of an RD frame exchange between two nodes is depicted in Fig. 3. In the figure, $STA1$ holds the channel ownership and performs a frame transmission towards $STA2$. Having no other frames to transmit, it issues an RD Grand (RDG) to $STA2$ permitting a frame burst transmission in the reverse direction, as long as this burst does not violate the remaining TXOP duration (t) of $STA1$. The FD responder indicates in each of its frames if it has more packets (PPDUs) for transmission in the reverse direction by setting the $MorePPDU$ ($MPPDU$) bit to 0 or 1. If $STA2$ is finished with its burst towards $STA1$ ($MPPDU = 0$), the FD initiator regains its TXOP and may grand it to another STA.

Note that the RD protocol cannot be applied to transmissions from $AC[BE]$ and $AC[BK]$ since their TXOP may include only a single frame transmission, as indicated in Table I.

III. Investigation and Enhancement of FD operation during TXOP

For the analysis that follows, we make the following assumptions:

- all nodes are FD capable (i.e., they employ self-interference cancellation techniques at their PHY layer) and within range (i.e., no hidden terminals are present),
- we consider symmetric FD communications (i.e., the FD responder always has frames destined to the FD initiator)
- channel access is provided by the EDCA mechanism,
- as in [11], we assume that all frames have equal sizes.

Furthermore, let us adopt the notation $TXOP^{init}_{lim}[q]$ to denote the value of $TXOP_{lim}$ of $AC[q]$ at the FD initiator, with $q \in (VO, VI, BE, BK)$.

Now, consider the case where $AC[q]$ at a node (STA or AP) has won channel contention. Hence, it starts the PRI TX for a period limited by $TXOP^{init}_{lim}[q]$. The node that receives the PRI TX (i.e., the FD responder) will first have to check the number of its ACs that have frames ready for transmission. Then, it has to determine how many HoL packets have as their destination the address of the FD initiator. If more than one

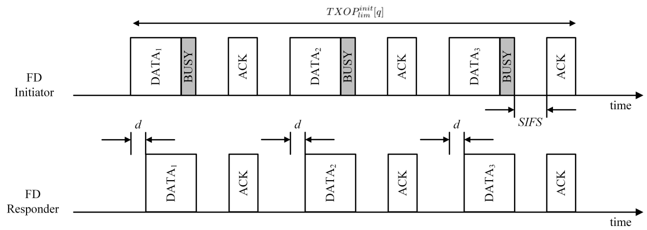


Fig. 4: FD operation during TXOP.

ACs are non-empty and the destination address of their HoL is set to that of the FD initiator, then the node must select the AC that will start the SEC TX. In this case it is logical to assume that the AC with the highest priority should be granted the SEC TX, while the lower priority ACs will remain at their backoff phase.

Once the $AC[q]$ at the FD responder is determined, it will start the SEC TX after the decoding period, d, for each frame received by the FD initiator. The procedure is shown in Fig. 4. It is depicted that for each session of FD frame exchange a busy period, which is equal to d, is incurred. Transmitting busy tones signals is clearly a waste of resources, since they do not contribute to system throughput.

In order to eliminate the busy periods during the $TXOP^{init}_{lim}[q]$, we propose to activate the RD protocol each time the FD initiator starts its HoL frame. The frame exchange in this case would be as presented in Fig. 5. The FD initiator issues and RDG to the FD responder which is revealed to the node after the d period, thus allowing the FD responder to transmit its frame burst in-phase with the rest of the burst transmission by the FD initiator. The busy signal periods for each FD frame exchange are eliminated and substituted by actual data frames transmission. The only busy period that is present, is that of the initial frame of the FD initiator (i.e., the HoL frame of the $AC[q]$ that has won channel contention) which is needed for the RD protocol to function. The use of RD protocol will facilitate the FD operation and can lead to an increased throughput performance.

As mentioned earlier, we consider only symmetrical FD communications which can be either STA or AP-initiated. When an STA acts as an FD initiator the destination address of all of its frames in the PRI TX will be set to that of the AP. However, if the AP initiates the FD, not all of its frames may be destined to the same STA. In this case, each receiving

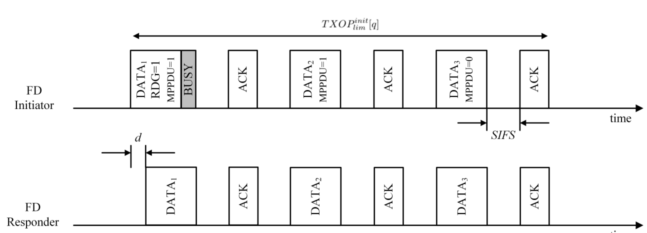


Fig. 5: Proposed FD operation during TXOP with RD.

STA must be able to identify which is the last frame of the FD initiator destined to that STA. This is needed in order for the STA to release the channel and allow the AP to initiate a new FD session with another STA. Hence, we propose that the $MPPDU$ flag be active to the FD initiator's (which is also the RD initiator) frames also. This modification is shown in Fig. 5 where each frame of the initiator indicates if there are more data frames destined to that specific FD responder. As long as the FD responder receives frames with $MPPDU = 1$, it may start SEC TX.

Both Fig. 4 and Fig. 5 reveal an issue, firstly reported in [12], known as ACK timeout. The FD initiator has to wait for $d + T_{SIFS} + T_{ACK}$ to receive the ACK frame for its data frame transmission. This period may be longer than the ACK timeout setting, leading to an unnecessary retransmission by the FD initiator. To counteract this problem, the data frame transmitted by the FD responder should include its expected duration in order for the FD initiator to calculate and update its ACK timeout setting.

IV. Throughput Analysis

In this section we provide a simple throughput analysis in order to evaluate our proposal ($PropFD$) against the standard TXOP ($StdFD$) functionality, and asses its impact on the system throughput.

Let $\nu[q]$ be the maximum number of frames that may be transmitted by $AC[q]$ during its $TXOP_{lim}$, and is given by (refer to Fig. 4 and 5):

$$\nu[q] = \begin{cases} \left\lfloor \frac{TXOP^{init}_{lim}[q]}{d+T_{DATA}+T_{ACK}+T_{SIFS}} \right\rfloor, & StdFD \\ \\ \left\lfloor \frac{TXOP^{init}_{lim}[q]-d}{T_{DATA}+T_{ACK}+T_{SIFS}} \right\rfloor, & PropFD \end{cases} \tag{1}$$

where, T_{DATA}, T_{SIFS} and T_{ACK} are the duration of the transmitted data frame, the SIFS period and the transmission of the acknowledgement frame, respectively. Note that $\nu[BE] = \nu[BK] = 1$ according to Table I.

The contention-free burst period (CFB) for a specific AC at the FD initiator can be expressed as:

$$CFB[q] = \begin{cases} i[q](T_{DATA} + T_{SIFS} + T_{ACK} + d), & StdFD \\ \\ i[q](T_{DATA} + T_{SIFS} + T_{ACK}) + d, & PropFD \end{cases} \tag{2}$$

where, $i[q]$ is the number of data frames included in the CFB by $AC^{init}[q]$, with $i[q] \in [1, 2, ..., \nu[q]]$.

The maximum throughput achieved can be approximated as:

$$S[q] = \frac{2 \cdot i[q] \cdot l}{CFB[q]}, \tag{3}$$

where, l, is the number of data bits included in the data frame. It can be easily seen that for the $StdFD$ case the achievable throughput will be independent of $i[q]$, i.e., the number of frames included in the TXOP. Thus, the throughput achieved will be the same for any number of $i[q]$ for this case.

TABLE II: PHY amd MAC parameters used for numerical results

PHY	MAC
T_{SIFS}=16us	$MPDU$ size=11454bytes
Rate(data,control)=780,48(Mbps)	Header(data, control)=240bits
Preamble(data,control)=68.8,64.8(us)	$TXOP_{lim}$[VO,VI]=1504,3008us

V. Results

To evaluate the performance of the standard FD operation during TXOP and our proposed enhancement, the PHY and MAC parameters depicted in Table II are used.

First, note that $\nu[VO] = 6$ and $\nu[VI] = 13$ for the $StdFD$ case, while $\nu[VO] = 7$ and $\nu[VI] = 14$ in the $PropFD$ case (given the parameters used from Table II). This is a result originating from the reduction of the busy periods induced by the use of RD protocol.

The independence of $S[q]$ from the $i[q]$, for the $StdFD$ case, is also observable in Fig.6, where $S[q]$ is constant for all ACs regardless the value of $i[q]$. The proposed solution obviously outperforms the standard FD case, and the performance difference becomes greater as the number of frames included in the CFB of the FD initiator ($i[q]$) increases.

Note that for $AC[BE]$ and $AC[BK]$ the proposed enhancement performs identically with the standard mechanism, since $i[q] = \nu[q] = 1$.

VI. Conclusions

In this work, the performance of FD communications in modern WLANs is investigated and enhanced by exploiting a modified version of the RD protocol. It is shown that under the current TXOP functionality, the FD potential is limited by the fact that every time an FD-capable receiver receives a frame from an FD-capable transmitter, FD manifests after a decoding period necessary to extract the destination and receiver addresses. Towards optimising performance, we proposed the use of the RD protocol which reduces the decoding periods necessary to achieve FD communications. Numerical results indicate that the proposed mechanism is able to enhance performance in terms of maximum achievable throughput.

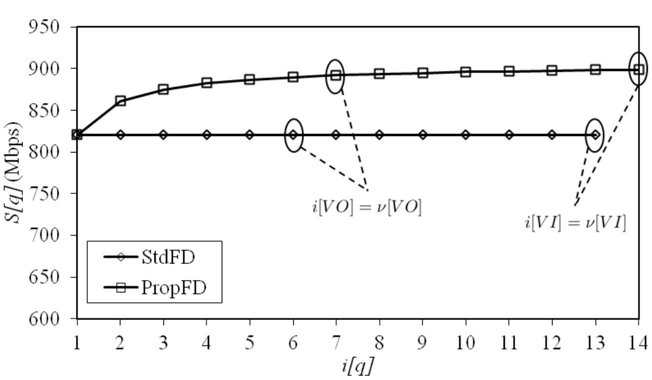


Fig. 6: Maximum throughput achieved for different number of frames included in the CFB.

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