Abstract— In this paper, we discuss some problems related to direct transmissions between QSTAs in an infrastructure 802.11 WLAN with a legacy Access Point (AP). In the infrastructure mode, collisions of data frames caused by hidden terminals interference can be avoided by the RTS/CTS exchange anticipating the data frames, if and only if all data communications between stations are performed via the AP. The interference problem is solved because all terminals are within the transmission range (TX range) of the AP. However, the RTS/CTS exchange is not enough to protect direct transmissions between QSTAs. In this paper, we analyze the state-of-the-art direct transmissions protection approaches, show their limitations, propose and simulate our own protection schemes.

Keywords-IEEE 802.11; direct links; hidden terminals; protection

I. INTRODUCTION

Initially, in IEEE 802.11 infrastructure networks [1], STAs were not allowed to transmit frames directly to other STAs, but only via the AP. However, STAs with QoS facility (QSTAs) introduced in the latest version [2] of IEEE 802.11 standard may exchange frames directly by setting up such data transfer using the Direct Link Support (DLS) mechanism. Direct transmission opportunity relaxes heavy load on the AP and makes network performance more efficient. In this paper, we focus on several issues related to direct transmissions. One of the issues is the protection of direct transmissions from interference caused by hidden terminals.

In the presence of hidden terminals, the legacy IEEE 802.11 specification [1] recommends to protect every data frame transmission by an RTS/CTS exchange. In [2], Block ACK mechanism is introduced to reduce the average overhead (per data frame). It allows sending several data frames in a row with only one RTS/CTS exchange and the only block acknowledgement (Block ACK) following a Block ACK Request (BAR), see Fig. 1.

If an IEEE 802.11 network is deployed in a building, the network topology is most likely multihop, because stations are usually located in several rooms connected with corridors. It is cost-efficient to mount APs at corners and intersections of corridors and flight of stairs: one AP may serve several directions at the same time. However, such AP location makes stations hidden from one another. In this paper, the legacy AP and QSTAs are considered to be located at a corner between two corridors, e.g. see Fig. 3. QSTAs use both the ordinary and block data transmission mechanisms.

The rest of the paper is organized as follows. In the next Section, we present the simulation results showing the problems related to direct transmissions. In Section III, we analyze the state-of-the-art direct transmissions protection approach and discuss its limitations. In Section IV, we propose novel direct transmission protection schemes and compare efficiency of the proposed and legacy direct transmission mechanisms, based on simulation. Section V concludes the paper.

II. DIRECT TRANSMISSIONS ANALYSIS

In this section, we consider possible locations of 4 QSTAs around the AP located at the corner between two corridors, see Figs. 3-9. There are 2 direct links: QSTA1 -> QSTA2 and QSTA3 -> QSTA4. Although the considered scenario looks simplistic, it is enough to show that the channel capacity distribution between direct links is unfair in many cases, and it

![Figure 1. Block data transmission](image1)

![Figure 2. Simulation results](image2)
measured throughput for both links in different cases, considering ordinary and Block data transmission mechanisms: see Fig. 2 for the results. We assume that QSTAs work in saturation, i.e. they always have packets to transmit. Also we assume the packet length is equal to 1 KB, the block size is equal to 15, and 54 Mbps 802.11a PHY [2].

Before proceeding to the analysis and discussion of the simulation results let us define the Carrier Sense (CS) range and Transmission (TX) range of a station. We refer to the CS-range of station A as to the area where other stations are able to detect PHY activity when A transmits; with that, these other stations are unable to decode the frame transmitted by A because the signal is too weak. In contrast, within TX-range of station A, other stations are able to decode correctly frames transmitted by A. Obviously TX-range is embraced by CS-range. In the simplest case with omni-directional antenna, in the absence of obstacles like walls, TX-range is a circle, and CS-range is a ring embracing the TX-range circle.

We start with the simplest case when all QSTAs are in TX ranges of one another, see Fig. 3. In this case, all frames transmitted by any station can be received by any other station and the standard RTS/CTS exchange is enough to protect both direct transmissions from mutual interference. Links 1->2 and 3->4 get equal throughput, which is shown in Fig. 2, see bars related to Case 1.

In Fig. 4, Case 2 is shown. Here, QSTAs 1 and 4 are in CS-range of one another because of obstacle. If QSTA1 transmits, QSTA4 senses some PHY activity at its antenna, but cannot decode the signal correctly. In particular, QSTA4 cannot receive RTS frames from QSTA1 correctly. But QSTA3 can, and RTS/CTS exchange works well. However, QSTA1 cannot receive the ACK frame from QSTA4 to QSTA3 correctly. After the ACK, QSTA1 waits for EIFS before resuming decrementing its backoff counter, while QSTA3 waits only for DIFS<EIFS. This means that QSTA3 has more chances to win in the contention for the channel, making the channel capacity distribution unfair. In Fig. 2, bars related to links 1->2 and 3->4 are of different height, because the links get different throughputs.

In Fig. 5, Case 3 is shown, when QSTAs 1 and 4 are far away from the corner and cannot hear each other at all, but can receive correctly frames from other stations. In particular, when QSTA1 transmits RTS frames, QSTA4 senses the channel clear, while QSTA2 and QSTA3 receive the RTS frames successfully. When QSTA1 and QSTA3 transmit RTS frames simultaneously, QSTA4 receives the RTS frame from QSTA3 successfully, but QSTA2 cannot receive the RTS frame from QSTA1 correctly because of collision. The difference in reaction on collisions leads to different throughputs for the considered links, because: (i) QSTA3 can overcome collisions, and its contention window is always minimal; (ii) QSTA1 increases its contention window after collisions and hence has fewer chances to get the channel. So, link 1->2 throughput is less than link 3->4 throughput (compare the related bars in Fig. 2), i.e. the channel resource distribution remains unfair.

In Fig. 6, Case 4 is shown. QSTAs 1 and 3, as well as 2 and 4, are in CS-range of one another. Let us compare throughputs...
measured in Case 3 and Case 4. With the ordinary data transmission mechanism, the difference in throughputs between the considered two links is. It can be explained in the following way. When QSTA1 transmits its data packet and QSTA2 answers with an ACK, both QSTA1 and QSTA3 receive the ACK successfully. So, they start counting their backoffs simultaneously. However, when QSTA4 replies QSTA3 with an ACK, QSTA1 cannot hear it at all. The latest frame which QSTA1 heard was the DATA frame from QSTA3, and the frame was not decoded correctly, because QSTA3 is in the QSTA1’s CS range. This means that QSTA1 waits for EIFS=94 us after the end of the QSTA3’s DATA frame transmission before starting counting its backoff. In contrast, QSTA3 transmitting its DATA frame starts counting its backoff after SIFS+ACK+DIFS=74 us. Since backoff slot is 9 us, only QSTA3 can start its next transmission in the next three slots after DIFS. The phenomenon increases the difference in throughputs between the considered two links, comparing to Case 3. With the block data transmission mechanism, the difference in throughputs remains the same as in Case 3, because SIFS+BlockACK+DIFS=94 us = EIFS and QSTA1 and QSTA3 always start counting their backoffs simultaneously.

In Figs. 7 and 8 corresponding to Cases 5 and 6, QSTAs 2 and 3 are in TX-range (Case 5) or CS-range (Case 6) of one another, but QSTA1 is absolutely hidden from QSTAs 3 and 4. Similarly, QSTA4 is absolutely hidden from QSTAs 1 and 2. This situation causes severe unfairness between links 1->2 and 3->4. With high probability, STA1 transmits its RTS during STA3-STA4 frame exchange and receives no answer from STA2. It makes STA1’s contention window very long, and STA1 has small chances to access the channel, while the contention window of STA3 is of minimal size because of successful data transmission 3->4. As a result, link 3->4 throughput is by order of magnitude greater than link 1->2 throughput. In Case 6, the RTS/CTS mechanism cannot protect STA1’s data transmissions, which worsens the channel capacity distribution even greater: in Fig. 2, the bars related to link 1->2 are dramatically low, while link 3->4 gets almost all the total throughput.

In Fig. 9, the last case is shown. Here, pairs QSTA1+QSTA2 and QSTA3+QSTA4 are isolated from each other. Links 1->2 and 3->4 does not interfere at all. In this situation, two frames may be transmitted at the same time: one
in link 1->2 and the other in link 3->4. In other words, the channel is reused. Further in this paper, we refer to such a situation as to spatial reuse. As we show below, using benefits from spatial reuse may require special technique.

III. STATE-OF-THE-ART APPROACH AND ITS LIMITATIONS

In March 2007, an approach was proposed to protect direct transmissions, which works as follows. Before sending data frames directly, the direct transmission initiator exchanges RTS/CTS with the AP, but not with the direct transmission receiver. The duration field of the CTS covers the direct transmission duration plus an acknowledgement. As all stations receive the CTS frame broadcasted by the AP, they do not start their own transmissions. Thus, the direct transmission becomes protected from interference caused by hidden terminals.

This approach, which we further refer to as Scheme 0, is very simple and it uses standard frames. Thus, minimal modification of the specification is needed to adopt the approach. It may be easily implemented in real hardware/software. At last, it guarantees the direct transmission protection. All these advantages seem to make the proposed approach a favorable candidate to be incorporated into an amendment to IEEE 802.11 specification.

However, it leads to some limitations. As it is shown in Fig. 2, the total throughput is doubled when two direct links are isolated, i.e. both the transmitters and receivers of the links are out of radio range of one another, e.g. see Case 7 in Fig. 9. Unfortunately, the proposed approach protects one direct transmission, actively prohibiting all other transmissions. In Case 7, two transmissions coexist successfully, but forced overprotection allows only one transmission at a time. It means that all benefits from spatial reuse are wasted.

IV. PROPOSED SOLUTIONS

The advantages of Scheme 0 (using standard frames) turn to be its disadvantages at the same time. It is simple to implement, but it is impossible to include additional features allowing spatial reuse. We propose [5] to introduce a special Direct Link Announcement (DLA) frame. The DLA frame indicates

- direct transmission source and destination
- duration of the planning direct transmission
- DLA expiration time, after which the DLA frame should be ignored
- protection scheme type

The basic idea is the following. The source QSTA shall broadcast/multicast the DLA frame over the AP, setting ToDS bit to 1. For that, the DLA frame header contains the broadcast address in the destination address field, if the AP is collocated with a router. Otherwise, the DLA frame header contains a special multicast address in the destination address field. The multicast address indicates all stations in the 802.11 network. We propose two types of DLA-based protection.

**Scheme 1.** The AP sends out the DLA frame with the protection scheme field set to ‘Scheme 1’. The DLA payload includes a list of neighbors which it may interfere with. The list is collected by means of radio measurements which are out of scope of this paper. QSTAs which are not in the list may communicate during the direct transmission announced by the DLA frame, without sending their own DLA frames. In contrast, the stations in the list can be neither transmitters nor recipients during the pending direct transmission.

**Scheme 2.** After the AP sends out the DLA action frame, the direct transmission initiator starts an RTS/CTS exchange with the direct transmission receiver. The RTS frame is sent after PIFS, i.e. without contention. QSTAs which received DLA with the protection scheme field set to ‘Scheme 2’, but don’t detect PHY activity during the subsequent PIFS+RTS+SIFS+CTS interval, may communicate during the direct transmission announced by the DLA frame, without sending their own DLA frames.

Comparing with Scheme 1, Scheme 2 makes more overhead (additional RTS/CTS exchange), but it doesn’t require the direct transmission initiator to know the list of its neighbors.

When a direct transmission initiator uses any of these two Schemes, the following is guaranteed:

- **Protection:** All QSTAs are informed of the planning direct transmission and its duration and postpone their own transmissions for the duration.
- **Fairness:** All peer-to-peer links appear to operate in the same conditions and so provide the same transmission quality.
- **Spatial reuse:** QSTAs which are not in the TX- or CS-ranges of the direct transmission initiator or receiver may communicate during the direct transmission.

The waiting delay in the AP queue may appear to be too long. If the direct transmission initiator receives no DLA frame back from the AP during the DLA timeout, it shall use Scheme 0 to protect the planning direct transmission. All QSTAs which receive the DLA frame later than the DLA expiration time indicated in the frame shall ignore this DLA. The DLA expiration time shall be set equal to the sum of the DLA frame creation time and the DLA timeout.

To protect direct transmissions from the interference caused by the legacy STAs which don’t respect DLA frames, the DLA-based approach may be combined with Scheme 0 as described in Schemes 3 and 4.

**Scheme 3.** After the AP sends out the DLA action frame, the direct transmission initiator carried out an RTS/CTS exchange with the AP (Scheme 0) after PIFS. (This RTS/CTS exchange prohibits all transmissions of legacy STAs.) QSTAs which received DLA with the protection scheme field set to ‘Scheme 3’ shall ignore the first RTS/CTS exchange. After the exchange, QSTAs which are not in the neighbor list indicated in the DLA may communicate during the announced duration.

**Scheme 4.** First steps of the scheme are the same as for Scheme 3. Then, after the initiator-to-AP RTS/CTS exchange, the initiator starts an RTS/CTS exchange with the direct transmission receiver. QSTAs which received DLA with the protection scheme field set to ‘Scheme 4’, shall ignore the first RTS/CTS exchange, but listen to the second one. QSTAs
which detect no PHY activity during the second RTS/CTS exchange, may communicate during the direct transmission announced by the DLA frame, without sending their own DLA frames.

In order to avoid the unfairness problem caused by using EIFS instead of DIFS (see section II, Case 2) we propose the following two approaches.

**Attached DLA.** After a QSTA transmits a direct data frame or a sequence of direct frames in case of block transmission, it may send a DLA frame to the AP without backoff, i.e., after PIFS (SIFS is not enough because new packets should be prepared), after this direct frame or the sequence of direct frames, if the QSTA has more data to transmit directly.

Let us call the immediate DLA frame described above as 'attached DLA frame'. If a QSTA transmits an attached DLA frame, all stations receive the ACK frame sent by the AP in response to the attached DLA frame. This makes all stations to start decrementing their backoff counters synchronously after DIFS. So, the attached DLA mechanism solves the problem of using EIFS instead of DIFS described in the previous section.

This approach requires for additional changes in DLA mechanism. In the case when spatial reuse is possible (e.g. Case 7 in section II), attached DLAs of 2 direct links will be sent to the AP always concurrently, causing their collision. We propose to allow only the QSTA which the previous DLA is intended for, to attach its next DLA, while the other direct transmission initiator should not send anything during the attached DLA and should send its next DLA after backoff only.

**CCA switching off.** In the second approach, the DLA frame is sent to the AP after backoff. To avoid unfairness connected with using EIFS instead of DIFS, we propose to switch off the CCA function of stations which are in the interference list of DLA frame for the time of the direct transmission announced by the DLA frame. After that, the stations wait for DIFS before resuming counting their backoffs. This makes all stations to start decrementing their backoff counters synchronously after DIFS. So, this approach solves the problem of using EIFS instead of DIFS too.

With Scheme 2 and 4, there is another problem causing unfair channel resource distribution between direct links. For example, consider Case 5 in section II, when QSTA 1 does not sense QSTA3, while QSTA 2 does. When the AP broadcasts the DLA intended for QSTA 3, QSTA 3 and QSTA 4 exchange with RTS and CTS frames before starting direct data transmission. QSTA 1 does not receive the frames and decides to start its direct transmission too. However, QSTA 2 cannot receive frames from QSTA 1, because of their collisions with frames from QSTA 3. QSTA 2 even does not reply to QSTA 1, and QSTA 1 has to retry again and again, increasing its contention window up to CWmax. So QSTA 1 has much less chances to win the contention for the channel, and its performance degrades.

To resolve the unfairness problem, we propose to prohibit the QSTA trying to exploit the spatial reuse possibility (QSTA 1 in the considered case) to increase its contention window and/or to limit the number of its retries by one or another small value.

In a whole, our analysis has shown that Schemes 1 and 3 looks more efficient in terms of achieved throughput, fair channel resource distribution and implementation simplicity than Schemes 2 and 4.

Fig. 10 shows simulation results obtained for the legacy DLS mechanism and for the DLA mechanism with attaching the DLA. With simulation, we make the same assumptions as in section II and use Block transmission technique. One can see that the DLA mechanism provides fair distribution of the channel capacity between these 2 links, in contrast to the current DLS mechanism, and saves the possibility of spatial reuse (see Case 7), in contrast to Scheme 0.

V. CONCLUSIONS

In this paper, we analyze direct transmissions in infrastructure IEEE 802.11 networks. Focusing on the direct transmissions interference problem, we develop a simulation model showing that conventional RTS/CTS exchange is not enough to protect data frames sent by QSTAs directly. We consider the state-of-the-art approach aimed to guarantee such a protection and discuss its limitations. We propose our own schemes to protect direct transmissions, to provide fair distribution of network capacity between several direct links, and to save benefits from possible spatial reuse.

REFERENCES


