A Collision Aware Multi-link Operation for Next Generation WLAN

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Abstract. In a wireless local area network (WLAN), when the contention is fierce, most of the frames are collided and backoff windows are doubled, resulting in a low channel efficiency. 802.11 be introduces multi-link opertaions (MLO) but faces nonsimultaneous transmit and receive (NSTR) problem which limits the prospects of multi-links. In this paper a new multi-link operation scheme is proposed. When a link is transmitting, antennas from the other link usually suffer huge inteference and can't receive properly. In the proposed scheme the interfered antennas are switched to the transmitting link to monitor collisions. If collisions are detected, one of the colliders stops transmitting. Collisions are thus eliminated at the early stage. Simulation shows that using this scheme, the channel efficiency of a highly competitive network stays at a high level compared to traditional solutions. Simulation also shows that the proposed scheme offers better QoS.

Keywords: Multi-link Operation · 802.11be · WLAN · NSTR

1 Introduction

With its simplicity in setting up and high mobility, WLAN has been widely adopted in households, factories and enterprises as LAN solutions. The prevalence of 802.11n/ac/ax in the marketplace has proved its success [1,3]. In 2019, the project of 802.11be was initiated. As a next generation WLAN protocol, 802.11be has adopted MCS of 4096QAM, bandwidth of 320 MHz and up to 16 spatial streams which work together to achieve a bit rate as high as 46.1184 Gbps, leading to a 30 Gbps MAC layer throughput and better quality of service [2]. A paradigm shift made by 802.11be in its protocol family is multi-link operation (MLO) [4]. Before 802.11be, a device has only one radio. Devices in a pre-802.11be BSS work on either 5 GHz or 2.4 GHz frequency band. In 802.11be, multi-link devices (MLD) are introduced which has two or more radios working independently on different frequency bands.

The new generation of WLAN comes with two problems. Firstly, as the bit rate is becoming higher, the time used for transmitting MPDUs in a frame

D.-J. Deng et al. (Eds.): SGIoT 2022, LNICST 497, pp. 266–276, 2023.
https://doi.org/10.1007/978-3-031-31275-5_25

exchange is becoming smaller. However, the time used in backoff procedure, the time used to transmit preamble and the time used to transmit control frames remain constant, which reduces the marginal benefit brought by high bit rate. Secondly, AP MLDs are often considered to have well isolation among their antennas that the antennas of each link in an AP MLD are placed far enough that transmission on one link will not interfere the reception on other links. However, because STA MLDs have higher mobility and smaller volume and sometimes cheaper in cost, they have weak isolation between links. When a STA MLD is transmitting on a link, antennas on other links of the MLD will suffer huge in-device coexistence (IDC) interference [5], resulting a failure of reception.

The IDC interference makes it impossible for links to work independently. If a link just waits for the other to finish before working, it will be a waste of multi-link capability. With the assumption that MLDs have the ability to perform link switching and the ability to detect jitter of energy in the existence of IDC interference, this paper proposed a scheme using the idle link to detect collisions on the transmitting link, which not only reduces the use of control frames but also avoids failures caused by data collision.

The article is organized as follows. In Sect. 2, we review the operation of multi-link and have a brief introduction to existing multi-link operation schemes. Existing problems are analyzed in Sect. 3. In Sect. 4 and 5, the proposed scheme is described. We will see how the proposed scheme keeps the network from congestion even when contention is fierce. Simulation results and analysis are presented in Sect. 6. In Sect. 7 we will discuss more details about implementation and pending work.

2 Review of Multi-link Operation

The standard has offered many types of Multi-Link Operation. For example enhanced multi-link single-radio (EMLSR), Simultaneous Transmit and Receive (STR), and Non-Simultaneous Transmit and Receive (NSTR) including PPDU(PHY protocol data unit) alignment and Wait-Slot. In the mode of EMLSR [4], antennas switch from one link to another to perform MIMO transmission and MIMO reception. In the mode of STR, MLDs can transmit on one link while receiving on the other link. Because the number of links are doubled, the theoretical channel capacity are doubled as well. However, in the mode of NSTR, due to IDC interference mentioned above, MLDs can't transmit on one link while receiving on the other link. The transmission on one link will also affect carrier sensing and energy detection on other links. It's a challenge to coordinate all the links while make the largest use of them. PPDU Alignment aligns the end time of PPDUs on two links to prevent the solicited PPDU (for example block acknowledgment) from interfering the carrier sensing on the other link required by the trigger based PPDU process, if the other link is transmitting a PPDU with trigger [6]. Wait-Slot aligns the beginning of transmission on two links, by letting the link that firstly finished backoff to wait for the other link to finish. When both link reach zero [7], they transmit simultaneously, thus neither of the two links are interfered nor set idle. A threshold can be set for Wait-Slot process that if the remaining backoff slots of the lagging link is above the threshold, the preceding link can skip waiting. PPDU Alignment and Wait-Slot are illustrated in Fig. 1 and Fig. 2.

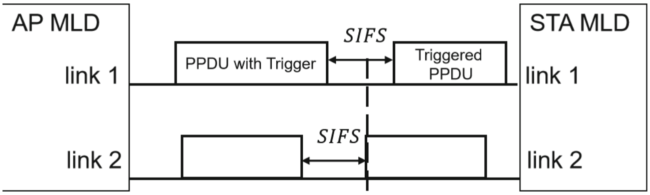

Fig. 1. NSTR PPDU alignment.

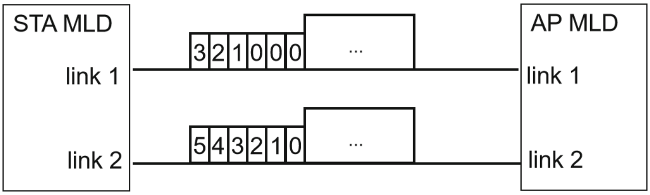

Fig. 2. NSTR wait slot.

3 Problem Analysis

Multi-link operations mentioned above avoid idling by transmitting on two links simultaneously, which do improve the channel efficiency. However, in a dense network where there are many STAs and big uplink traffics, the contention of channel will be fierce [9]. A traditional method may increase backoff windows to mitigate the contention, at the cost of a worse latency and throughput performance. When collision happens, STAs in conflict are not aware of the fact that they are transmitting useless bits, so they keep transmitting till the end, which makes the channel useless for a period of preamble time plus a data time. As the 802.11 protocol evolves, the duration of preamble is getting longer and longer [8,10]. The duration of data is also getting longer with elongated maximal MPDU aggregation. To reduce the span when channel is useless, RTS and CTS mechanism could be used in the contention. However, the frame exchange procedure of RTS and CTS brings an additional overhead of a RTS time plus a CTS time plus two SIFS time, which is comparable to data's length and can't be neglected [11] (Fig. 3).

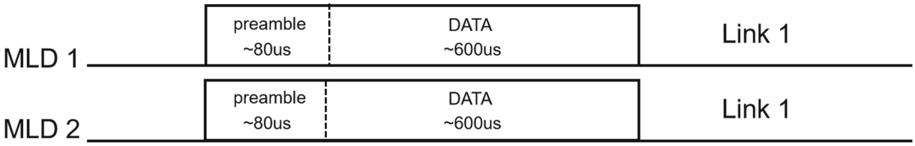

Fig. 3. Collisions make channel useless.

4 Basic Operation of the Proposed Scheme

MLDs using this method are assumed to have the ability to switch the working link of antennas from one to another within a link switching time of microseconds or instantly. After link switch, antennas working on the new link are assumed to have the ability to detect interference from other devices with the presence of self interference from transmitting antennas of this device. The ability to demodulate and receive packages is not required.

The procedure begins when a STD MLD having packages in buffer has updated its backoff counters on both links, and a DIFS or an AIFS of clear channel has been waited (Fig. 4):

Step 1. The MLD performs backfoff on both links. If one of the link is busy, as shown in Fig. 5, only one link needs to backoff.

Step 2. If one link finishes backoff firstly, antennas from the other link should be switched to this link. The bakcoff on the latter link should be paused.

Step 3. MLD begins transmission on the link that firstly finished backoff, while antennas from the other link begins to detect interference.

Step 4. If no interference is detected during a certain period of time, antennas should be switched back to original link.

Step 5. If interference is detected during the detection span, this MLD should stop transmission immediately. And antennas should be switched back to original link. And wait for the channel to be clear to backoff again.

Step 6. When the transmission is finished, go to Step 1.

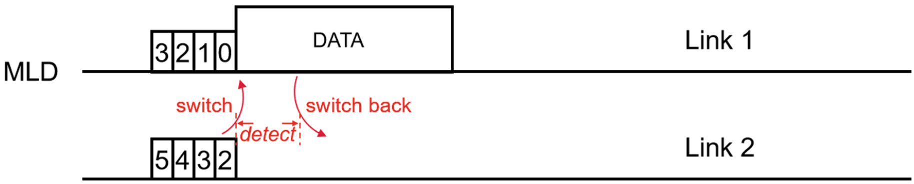

Fig. 4. Basic operation of the proposed scheme, when both links are idle.

The duration of detection should be long enough that other STA MLDs in the same BSS are aware of this transmission.

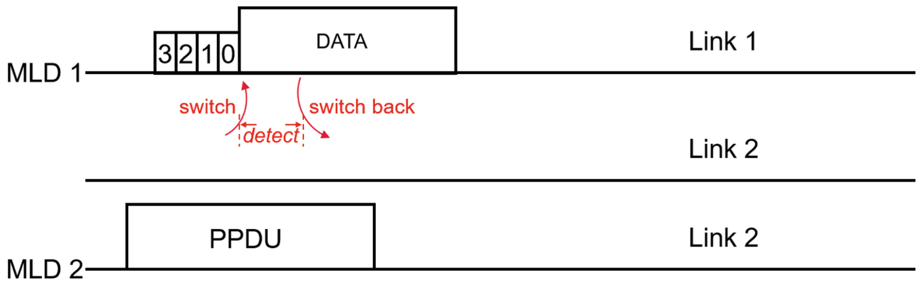

Fig. 5. Basic operation of the proposed scheme, when one link is busy.

5 Collision Awareness Mechanism

Collision happens when two or more devices in the BSS have the same number of backoff slots which is the smallest among all devices. They begein to transmit at almost the same time. Because when they are transmitting, their antennas are set to the receiving state, they can't perceive each other. They don't stop until the end of transmission. Because other devices can't do anything during the collison, the channel is deemed to be wasted.

With the proposed scheme, devices are able to perceive each other in the early stage of a collision. One of the colliders can stop its transmission to avoid interfering the other. In this way, there is always a PPDU being transmitted and decoded correctly, and channel is not wasted.

It's necessary to figure out which device should stop transmission when collision is detected. See Fig 6 and Fig 7. Assume both STA 1 and STA 2 reach the last backoff slot but STA 1 is a bit (microseconds or within a microsecond) earlier STA 2. When STA 1 is transmitting and using the other link detecting, STA 2 hasn't sent a bit. So interference power at STA 1's detection antenna equals to

$$noise \tag{1}$$

Soon STA 2 begins to transmit, and the interference at STA 1's detection antenna becomes:

$$STA\ 2's\ signal + noise \tag{2}$$

From STA 2's view, when STA 1 begins transmission, interference power at STA 2's detection antenna equals to:

$$STA\ 1's\ signal + noise \tag{3}$$

When STA 2's begin to transmit and detect, powers at STA 2's detection antenna is still:

$$STA\ 1's\ signal + noise \tag{4}$$

STA 1 experiences a rise of interference while STA 2 doesn't. We let the device that experiences a rise of interference to stop transmission. In this way, among all the devices that has the same number of backoff slots, the last one wins.

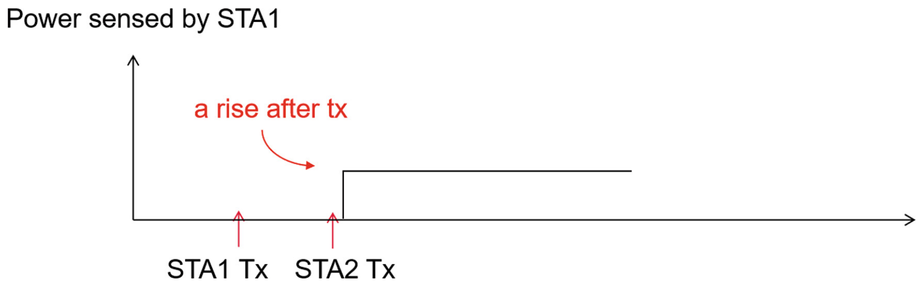

Fig. 6. Channel power sensed at STA 1.

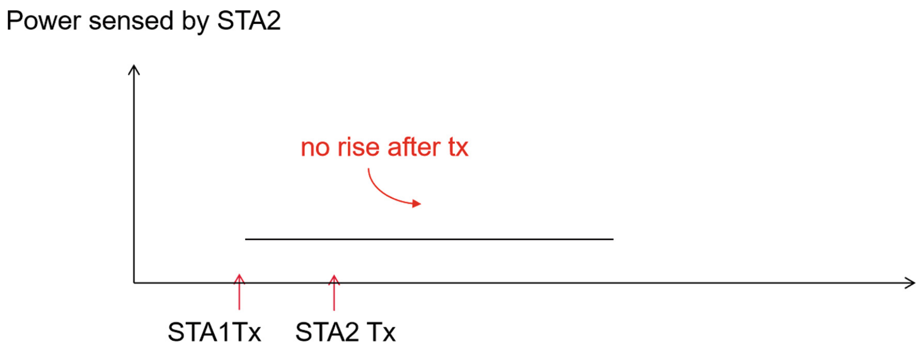

Fig. 7. Channel power sensed at STA2.

6 Simulation Results

The simulation results are carried out with a system-level discrete-event network simulation program. In this program, packages are generated by application layer in a uniform arrival which is dependent on the traffic rate. Upper MAC are designed to coordinates lower MACs and manages a package queue that is shared by its lower MACs. Lower MACs are designed to perform AMPDU assembling and perform frame exchange with peers. Each low MAC works on a link. PHY is in charge of determining packages' durations and energy, and simulate the decoding process by calculating the overlap of PPDUs at the time of receiving. Existence of overlapping PPDUs means happening of collision, then the package is dropped instead of decoded.

This proposed scheme is compared with two basic opeariton and RTS/CTS aided basic operation illustrated in Fig. 8 and Fig 9. In the comparison scheme, the link that firstly finishes backoff transmits, with no coordination with the other link. The other link just stay being interfered.

All devices in the simulation are multi-link devices. STA MLDs are evenly placed as a circle with the AP MLD at center. Power and distance are adequate for devices to listen to each other and hidden-node problem is not considered.

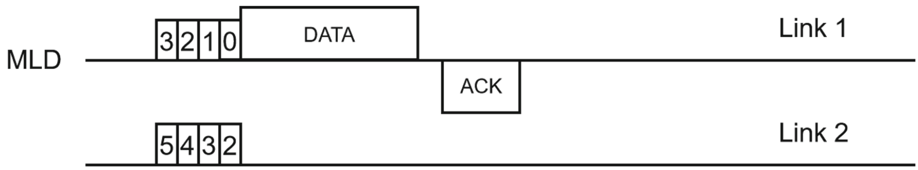

Fig. 8. Comparison scheme 1. The link that firstly finishes backoff performs DATA/ACK, while the other link stays idle.

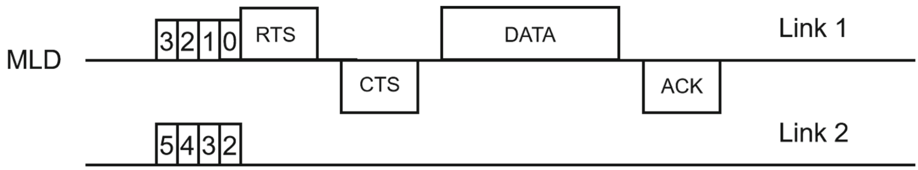

Fig. 9. Comparison scheme 2. The link that firstly finishes backoff performs RTS/CTS, while the other link stays idle.

6.1 Varying Number of STAs

The simulation with varying number of STAs is performed with parameters show in Table 1.

Table 1. Simulation Parameters.

Parameter	Value
Traffic Direction	up link signal user
Traffic Rate (Mbps)	500
Band Width (MHz)	320
MCS (802.11be)	13
Maximal MPDU Aggregation	1024
Package Size (Bytes)	1500
Number of AP	1
Number of STA	1–29
Backoff Window	(7, 15)
Number of Link	2

The simulation results in Fig. 10 show how throughput changes as the number of STA increases. And Fig 11 shows how latency changes as the number of STA increases. As the number of STA increases, the contention becomes fierce. In all cases, throughput firstly increases and then falls, latency keeps increasing. In the case of bare DATA/ACK, the throughput reached a maximum of 2 Gbps, then drops as the number of STAs increases. The RTS/CTS aided case reached a maximum throughput of 5.5 Gbps. The congestion didn't show its effect until the number of STA goes around 15, the maximal backoff window slots. It also suffers a throughput drop because much of the channel time is wasted at collided RTS frames.

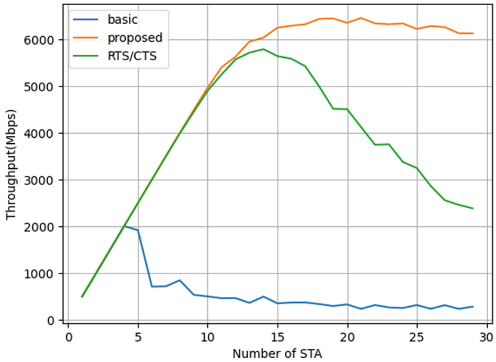

Fig. 10. Throughput performance of proposed scheme and comparison scheme. Varying number of STAs.

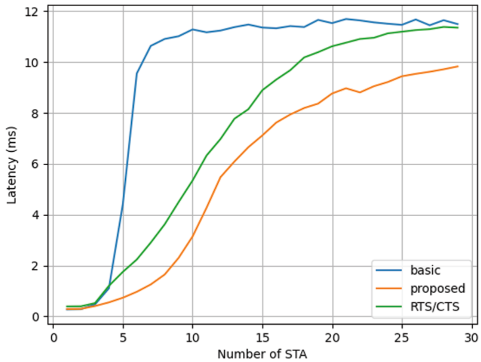

Fig. 11. Delay performance of proposed scheme and comparison scheme. Varying number of STAs.

In the proposed case, the throughput reached theoretical maximum then drops slowly. The comparison cases wasted most of the channel time at the collision of PPDUs, so their throughput is low and latency is high compared to the proposed scheme.

6.2 Varying Traffics

The simulation with varying traffics is performed with parameters show in Table 1 besides that the number of STA is fixed at 25 and the traffic rate varies from 1 Mbps to 1 Gbps. The simulation results are shown in Fig. 12 and Fig. 13 in a log scale.

In all cases the throughput increases as traffic rate increases, then saturated at a certain value. While latency keeps increasing. In the bare DATA/ACK case, as traffic rate increases, the frequency of contention goes up. The throughput drops as contention becomes fierce. In the RTS/CTS aided case, the throughput is higher than the previous case because RTS has a smaller overhead compared with DATA PPDU. However, because of the frequent collision of RTS frames, the throughput didn't reach theoretical maximum. In the proposed case, the throughput reached the theoretical maximum. Although collision happens, one of the conflicting STAs stops while the other remains. The channel is not wasted by transmitting useless bits, so maximum reached.

The proposed scheme has the lowest latency and highest throughput among the compared schemes. Fig. 14 shows the fairness performance of the proposed scheme. Data of Fig. 14 is collected from a 10 STAs simulation. From the pie plot we can see that a BSS using the proposed scheme have nearly the same possibility of successful access for its STAs.

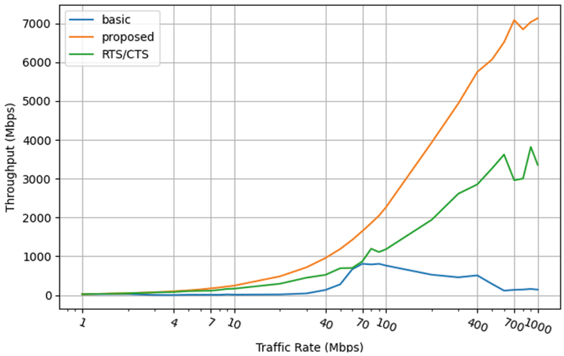

Fig. 12. Throughput performance of the proposed scheme verses comparison. while the other link stay idle.

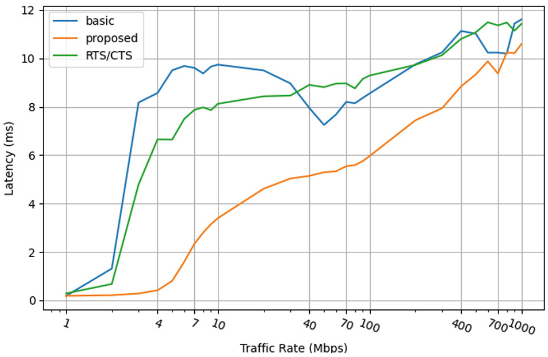

Fig. 13. Delay performance of the proposed scheme verses comparison scheme

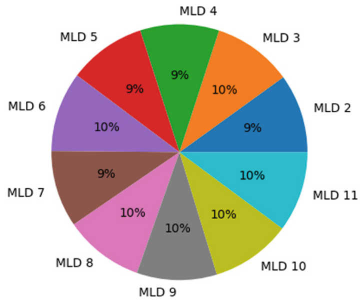

Fig. 14. The percentage of transmitted data of each MLD during the simulation, of all transmitted data during the simulation. The pie plot shows the fairness of the proposed scheme.

7 Conclusion and Future Works

We have proposed a multi-link operation scheme which detects collision at the early stage with the help of antennas from other links. Due to in-device coexistence interference, antennas of a link couldn't receive when other link is transmitting, and couldn't transmit if there are other devices transmitting on current link. We put the interfered link into use by using it to detect power changes on other links. The simulation results shows the proposed scheme has a near theoretical throughput in a dense single BSS, and a relative good latency performance compared with traditional schemes.

There are studies on self interference cancellation showing that dozens of dB of self interference can be suppressed [14,15]. Implementations of full duplex also shows it is possible for antennas to detect power change with the presence of self interference [13]. The detection works at the initial period of preamble. To facilitate power detection, different structures and coding schemes for preamble need to be evaluated.

Fairness with the presence of legacy devices remains to be studied.

Acknowledgment. This work was supported in part by the National Natural Science Foundations of CHINA (Grant No. 61871322, No. 61771390, and No. 61771392), and Science and Technology on Avionics Integration Laboratory and the Aeronautical Science Foundation of China (Grant No. 20185553035 and No. 201955053002).

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