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Distributed directional cooperative MAC (DD-CoopMAC) protocol for improving VBR throughput in IEEE 802.11ad WLAN

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Abstract. The IEEE 802.11ad-based wireless local area network (WLAN) has emerged out as a promising network technology that is capable of operating on millimetre wave spectrum. This network is being used in many applications and can be extended to serve many different streams of the networking industry. However, the network still has some glitches with respect to throughput, overhead, etc., which need to be handled to make it more reliable and efficient. In this paper, distributed directional cooperative medium access control (DD-CoopMAC) protocol for improving variable bit rate (VBR) throughput in IEEE 802.11ad WLAN is proposed. In this protocol, information about network stations is intelligently collected; based on this, the relay stations are selected for transmission. Simulation results illustrate that this protocol aids in enhancing the throughput and reducing the related overhead. Also, simulation results show that the proposed DD-CoopMAC has given high throughput and less MAC delay compared with D-CoopMAC and IEEE 802.11ad.

Keywords. IEEE 802.11ad; DD-CoopMAC; access point; relay station; VBR.

1. Introduction

1.1 *802.11ad wireless networks*

Nowadays, many new applications like high-speed device synchronization and wireless display in wireless local area networks (WLANs) make use of multi-gigabit wireless communications based on 60-GHz mm wave spectrum. IEEE 802.11ad is a new physical and medium access control (MAC) layer modification for WLAN under mm wave spectrum. The main features of mm wave spectrum are short wavelength, high bandwidth and high interaction with atmospheric components. In IEEE 802.11ad, large steerable arrays are packed in small components that are involved in beamforming (BF), resulting in significant gains. The use of directional communication increases the spatial reuse due to the multiple communication links operating simultaneously in the same domain, causing no interference [1]. The current 802.11ad draft utilizes directional multi-gigabit (DMG) ability to achieve a theoretical maximum throughput of up to 7 Gbit/s [2]. Unfortunately, 802.11ad channels have high signal attenuation. To increase the coverage without increasing transmission power, 802.11ad uses directional communications, which complicates random access. To achieve the best performance, both a transmitter and a receiver must adjust their antennas and directional transmission makes us rethink on the hidden and exposed station (STA) problems. To address these issues, 802.11ad introduces a new schedule-based channel access controlled by a coordinator [3].

1.2 *MAC protocol for IEEE 802.11ad*

In IEEE 802.11ad, time is divided into beacon interval (BI) by the personal basic service set (PBSS) control point (PCP)/access point (AP). The BI is again sub-divided into access periods. As shown in figure 1, the BI includes the following access periods [2]: beacon transmit interval (BTI), association BF training (A-BFT), announcement transmission interval (ATI) and data transfer interval (DTI).

As IEEE 802.11ad draft considers the directional transmission technique, each STA with directional antennas has an individual network environment [4, 5].

1.3 *Problem identification and objectives*

Intelligent listening algorithm (ILA) has been designed during A-BFT [2]. It abolishes the need for BFT during

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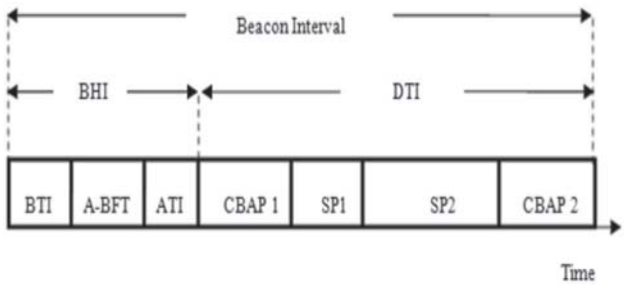

Figure 1. BI structure in IEEE 802.11ad.

communication among STAs. During A-BFT, all STAs perform BF with AP using various time slots. The beam direction is used in STA–STA BF.

In directional cooperative medium access control (D-CoopMAC) [4] a relay STA is selected based on the weight factor, which consists of data rate of the links. This technique is centralized as the PCP/AP is responsible for selecting the best relay STA. However, apart from improving the uplink throughput of variable bit rate (VBR) flows, the packet delivery time (PDT) and packet loss ratio (PLR) should be minimized [3]. Moreover, the channel utilization (CU) must be improved during the contention-based access period (CBAP). During BFT, the BF overhead for communication among STAs will be high [2]. In [6], authors have presented a detailed description about the assumptions for IEEE 802.11ad standard along with the mechanisms designed to mitigate its challenges.

In [7], the authors have proposed a new analytical model for performance analysis of IEEE 802.11ad considering all the features of IEEE 802.11ad MAC.

A distributed spatial reuse (DSR) MAC protocol has been designed by Shih *et al* [8] to increase bandwidth utilization and reduce power consumption. DSR allows the maximum number of interference-free communication pairs for collision-free transmission.

Joshi *et al* [9] have presented an in-depth quantitative evaluation of IEEE 802.11ad devices by forming a 60-GHz WLAN with two docking STAs acting as APs.

A novel group beam training scheme [10] has been proposed that enables simultaneous beam training of all the user devices. Compressed sensing is adopted to further reduce the beam training overhead.

Another directional MAC protocol TrackMAC has been proposed by Satchidanandan *et al* [11]. It continuously tracks the direction of every associated mobile STA.

Hence, the main objective of this work is to design a distributed directional cooperative MAC (DD-CoopMAC) protocol that should provide the following: (i) distribution of relay STA, (ii) satisfy the PDT and PLR constraints of VBR, (iii) improve the CU or normalized throughput and (iv) reduce the BF overhead. In order to fulfil these objectives, a DD-CoopMAC protocol for IEEE 802.11ad WLAN is proposed in this paper.

The organization of the paper is as follows: Section 2 presents the detailed description of the proposed DD-CoopMAC protocol, Section 3 illustrates the simulation experiments along with the results and Section 4 concludes the paper.

2. DD-CooPMAC protocol

2.1 *Overview*

The paper develops a DD-CoopMAC protocol for improving VBR traffic throughput. Figure 2 shows a block diagram of the protocol. In this protocol, each STA knows the best sector ID of all the other STAs using intelligent listening [2] during A-BFT. During that time, by exchanging this gathered information among them, each STA builds a table of candidate STAs with their best sector ID. During an uplink transmission to the PCP/AP, a source STA selects a relay STA based on a combined weight factor (CWF) and a utility function (UF). Later the STA that maximizes both the UF and CWF is selected as the relay STA.

2.2 *System model*

As per the IEEE 802.11ad draft, the PBSS has a PBSS control point (PCP) or AP with non-PCP or non-AP DMG STAs. The PCP performs beacon control and channel access scheduling so that each STA positions its antennas to the suitable directions at suitable time.

2.3 *A-BFT phase in IEEE 802.11ad*

BF Training (BFT) is a bidirectional process in which the transmitting and receiving STAs determine the appropriate antenna settings for the best transmission direction. In IEEE 802.11ad the STA–AP BF is performed during the BTI and A-BFT access periods, whereas the STA–STA BF is

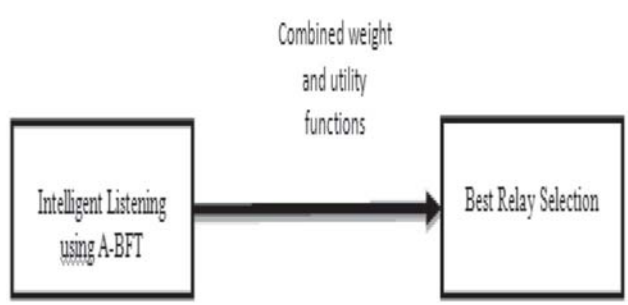

Figure 2. Block diagram of DD-CoopMAC.

performed during the DTI access period. BFT of STAs may comprise a sector level sweep (SLS) and a beam refinement protocol (BRP) phases. A-BFT phase is slotted as shown in figure 3. All the STAs that receive the initiator sector sweep (SSW) randomly choose a time slot in the A-BFT. During this A-BFT time slot, the STA performs responder SSW and receives SSW feedback from the PCP/AP. It confirms the successful SSW phase of BF and also informs the responder of its best sector. The STA that fails to receive this feedback waits until the next A-BFT.

2.4 *ILA*

The aim of intelligent listening mechanism is to collect the information via listening to the channel when STAs beamform with the AP during A-BFT. The collected information is used to decrease the overhead of BF between STAs. All the nodes/ STAs in the WLAN intelligently collect the details of their neighbouring STAs to determine the best sector ID of the neighbouring nodes and the collected details are recorded in their database table to ensure that it is updated with the network topology.

This process is described in Algorithm-1.

Algorithm-1

1. *During the A-BFT phase, initially PCP/AP performs the initiator SSW.*
2. *The PCP/AP keeps listening in order to collect information of all the responding STAs.*
3. *Each STA randomly selects a timeslot for itself.*
4. *Until the timeslot of each STA arrives, it keeps listening in quasi-omni direction.*
5. *During an STA's timeslot, i.e., during S_1's timeslot, it performs the responder SSW.*
6. *All the surrounding STAs: S_2, S_3 and S_4 listen to it and store the best sector ID of the responding STA, S_1.*
7. *During the next timeslot, S_1 stops responding and S_2 starts performing the responder SSW.*
8. *The surrounding STA collects the best sector ID of S_2.*
9. *This process is followed by remaining STAs, which perform responder SSW.*
10. *All STAs intelligently determine the best sector ID of each of their surrounding STA.*
11. *After the timeslots allocated to each STA are elapsed, all the STAs exchange the collected best sector ID among the remaining STAs.*
12. *Based on the received information, each STA builds a table of candidate STAs with their best sector ID.*

In this way, each STA in the WLAN builds a table as a database with the neighbouring node information. This table is referred to by the STA whenever it needs some information about its neighbour STAs.

Since the traditional method of all STAs BF with AP is avoided by this algorithm, the BF overhead becomes naturally less.

Consider the scenario shown in figure 4. In this figure, STA B gets to know the best sector of STA A (sector ID=20) and STA C gets to know the best sector of STA A (sector ID=28). After the SSW phase, in the same timeslot, PCP/AP sends the SSW feedback to STA A. Similarly STA B performs an SSW in a different timeslot, resulting in STA A knowing STA B's best sector (sector ID=10) and STA C knowing STA B's best sector (sector ID=5). Similarly, after

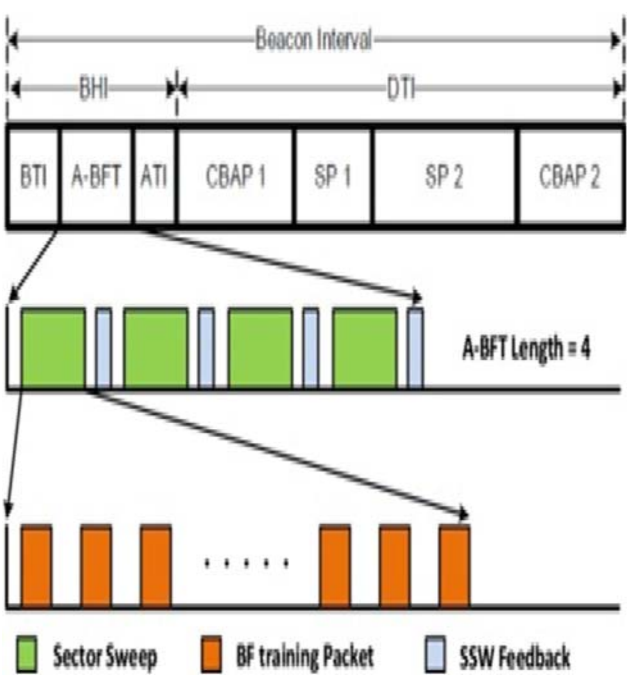

Figure 3. A-BFT phase in 802.11ad.

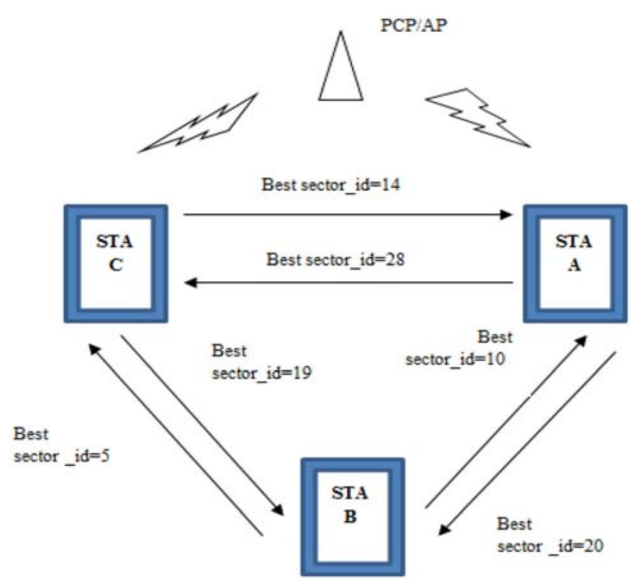

Figure 4. PBSS architecture with intelligent listening.

STA C's SSW, STA A would know STA C's best sector (sector ID=14) and STA B would know STA C's best sector (sector ID=19).

2.5 *Relay STA selection*

When an STA wants to communicate with its PCP/AP, it needs other STAs to relay its data. This selection of relay STA is performed in a distributed manner. The STA intending to perform data transmission selects its relay STA, ensuring that the throughput is enhanced and the overhead is minimized. It is assumed that all the relay STAs are within the communicating range of AP.

In order to enhance the throughput, a combined weight factor (*CWF*) is estimated based on the utilization of the channel k (CU_k) and data rate of two-hop link (DR_{HL}) as

$$CWF = \mu_1.DR_{HL} + \mu_2.CU_k \tag{1}$$

The channel utilization CU_k can be given by [7]:

$$CU_k = [P_{suc}.E[P]]/[P_{idle}.T_{idle} + P_{suc}.T_{suc} + P_{col}.T_{col}] \tag{2}$$

To satisfy the PDT and PLR constraints of VBR, a utility function (UF) is formed as

$$UF = 1 - (\propto .PLR + \beta.PDT) \tag{3}$$

where ∝, β are predefined constants.

The values of the weighted constants μ_1, μ_2, ∝ and β are determined during experimental evaluations. Hence, the objective function is to determine the relay station STA_{relay} such that

$$STA_{relay} = \text{maximize } \{CWF, UF\} \tag{4}$$

This process is described in Algorithm-2.
Algorithm-2

1. *STA_{up} checks its $STA_{tab(i)}$*
2. *For each pair of {STA_{up}, STA_j}, $STA_j \in STA_{tab(i)}$*
3. *If period is CBAP, Then*
4. *Estimate CWF_j of STA_j using (1)*
5. *End if*
6. *Estimate UF_j of STA_j using (3)*
7. *If STA_{relay} with Max{CWF,UF} is found, then*
8. *Select STA_{relay} = STA_j*
9. *End if*
10. *End For*
11. *If STA_{relay} is selected, Then*
12. *STA_{up} transmits the data through STA_{relay} to PCP/AP*
13. *Else*
14. *STA_{up} transmits the data directly to PCP/AP*
15. *End if*

In algorithm-2, STA_{up} considers each STA present in its table. During CBAP, the CU_k of the STA in the table is estimated according to Eq. (2). On the basis of the data rate of two-hop link and the CU_k, the *CWF* is estimated according to Eq. (1). The *UF* is estimated for the STA under consideration from the table as depicted in Eq. (3). In this way, the STA_{up} estimates *CWF* and *UF* of all the STAs present in the table. After the estimation of *CWF* and *UF* details of all STAs, $STA_{tab(i)}$ are considered as a pair and its corresponding pair <*CWF*, *UF*> is computed. The pair (STA_{up}, $STA_{tab(i)}$) that has the maximum {*CWF*, *UF*} is chosen as the relay node. The selected STA is used as the relay STA for transmission of data to the PCP/AP. If a suitable STA satisfying the constraint (4) cannot be determined, then STA_{up} directly transmits the data to PCP/AP.

This distributed method of relay node selection enhances the normalized throughput of uplink VBR flows and minimizes the BF overhead.

2.6 *Complexity analysis*

Let m be the number of $STA_{tab}()$ for any STA_{up}. Let T_{CU} be the time taken for estimating CU. The total time taken for estimating CWF is T_{CU} (as the DR_{HL} is known to STAs). Similarly time taken for estimating *UF* is *PDT* (as the PLR estimation time is negligible). Hence, total time involved in estimating *CWF* and *UF* is ($T_{CU} + PDT$) andthe complexity of the algorithm for m $STA_{tab()}$ will be

$$O[\log(m(T_{CU} + PDT))]. \tag{5}$$

3. Simulation results

The proposed DD-CoopMAC is implemented in NS-3. The IEEE 802.11ad model was designed in NS-3 [12]. This model consists of IEEE802.11ad techniques such as channel access periods, BFT, relay operation, fast session transfer, etc. The IEEE 802.11ad architecture in NS-3 contains 4 layers: MAC high layer, MAC low layer, physical layer and channel layer.

3.1 *Simulation settings*

In this simulation, a maximum of 20 DMGs STAs are deployed and connected to an AP. The Single Carrier (SC) Modulation and Coding Schemes (MCS) 1 and 6 are applied. The MAC Service Data Unit (MSDU) size is varied from 512 to 7096 bytes. In this experiment, the proposed DD-CoopMAC is compared to the D-CoopMAC [4] and standard IEEE 802.11ad MAC protocols. The performance-metric-normalized network throughput and MAC delay are measured. Since MCS 1 and 6 comprise, respectively, the lowest and highest SC data rates, these values are considered for all experiments. The experimental parameters have been summarized in the table 1.

The results are presented and explained in the next section.

3.2 *Results*

3.2a *Varying the number of STAs for MCS=1*: In our first experiment the number of STAs is varied as 4, 8, 12, 16 and 20 (table 1), keeping the MSDU size as 4096 bytes for MCS=1.

Figure 5 shows the throughput measured for DD-CoopMAC, D-CoopMAC and IEEE 802.11ad when the number of STAs is varied. From the figure, it is seen that the throughput of DD-CoopMAC and D-CoopMAC increases from 3.78 to 4.72 and 3.5 to 4.32 Gb/s, respectively. However, throughput of IEEE 802.11ad decreases from 3.25 to 3.01 Gb/s. This is due to the fact that 802.11ad protocol does not predict the best sector accurately; the chances of error rate will be more in case of large number of STAs.

D-CoopMAC considers only the data rate of two-hop links while estimating the normalized throughput whereas DD-CoopMAC considers the channel utilization along with data rate. Hence the throughput of DD-CoopMAC is 6% higher when compared with D-CoopMAC and 26% higher when compared with IEEE 802.11ad.

Figure 6 shows the MAC delay measured for DD-CoopMAC, D-CoopMAC and IEEE 802.11ad when the number of STAs is varied. From the figure, it is seen that the MAC delay of DD-CoopMAC, D-CoopMAC and IEEE 802.11ad increases from 1.33 to 2.17, from 1.25 to 2.62 and from 2.53 to 4.91 ms, respectively. This is due to the time involved in BFT procedure before the communication.

Since D-CoopMAC and IEEE 802.11ad did not handle the PLR and PDT constraints, the delay involved in transmitting and retransmitting the data will be high. Hence, the MAC delay of DD-CoopMAC is 18% lesser when compared with D-CoopMAC and 53% lesser when compared with IEEE 802.11ad.

3.2b *Varying the number of STAs for MCS=6*: In this experiment the number of STAs is varied as 4, 8, 12, 16 and 20, keeping the MSDU size as 4096 bytes for MCS=6. In MCS 6, the SC data rate is 1540 Mbps and is implemented using QPSK modulation with rate ½ code with a symbol repetition of one.

Figure 7 shows the throughput measured for DD-CoopMAC, D-CoopMAC and IEEE 802.11ad when the number of STAs is varied. As seen in the figure the throughput of DD-CoopMAC and D-CoopMAC increases from 5.74 to

Table 1. Summary of experimental parameters.

Parameter	Value
Number of AP	1
Number of stations	4–20
MCS schemes	MCS 1 and 6
Modulation at MCS 1	BPSK
BPSK modulation rate and symbol repetition	½ and 2
Modulation at MCS 6	QPSK
QPSK modulation rate and symbol repetition	½ and 1
Data rate at MCS1	385 Mbps
Data rate at MCS 6	1540 Mbps
MSDU size	512–7096 bytes
μ_1 and μ_2	0.4 and 0.6
α and β	0.5

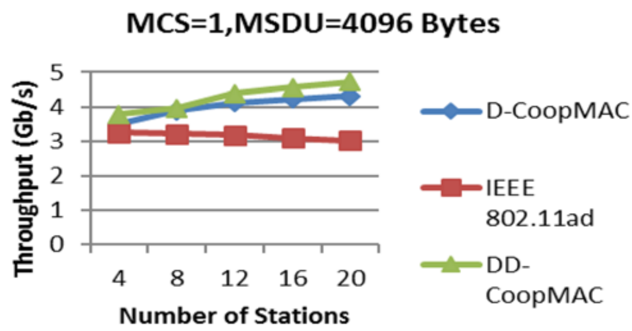

Figure 5. Number of stations vs throughput (MCS=1, MSDU=4096 bytes).

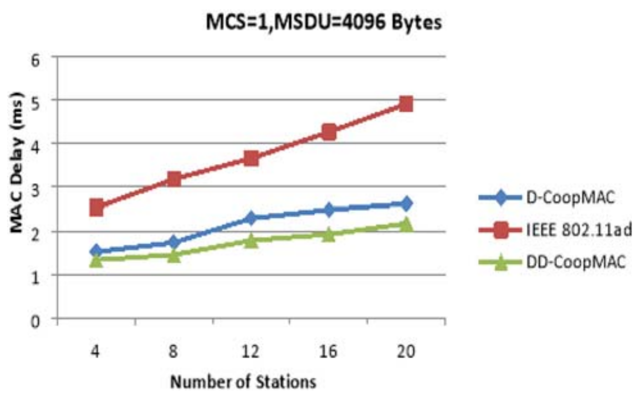

Figure 6. Number of stations vs MAC delay (MCS=1, MSDU=4096 bytes).

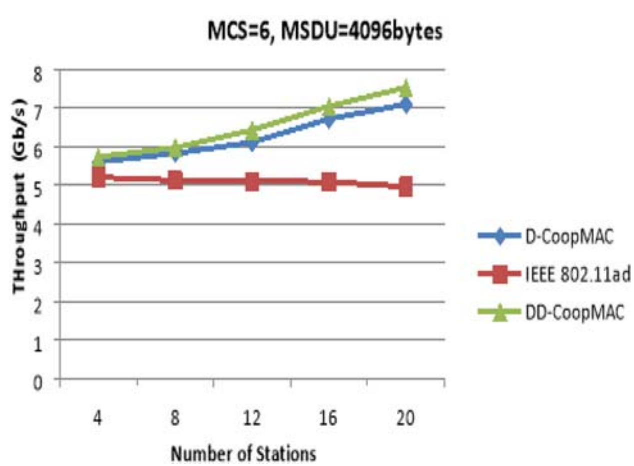

Figure 7. Number of stations vs throughput (MCS=6, MSDU=4096 bytes).

7.55, and 5.61 to 7.11 Gb/s, respectively. However, in IEEE 802.11ad it decreases from 5.21 to 4.97 Gb/s. This is due to the fact that 802.11ad protocol does not predict the best sector accurately; the chances of error rate will be more in case of large number of STAs.

D-CoopMAC considers only the data rate of two-hop links while estimating the normalized throughput whereas DD-CoopMAC considers the channel utilization along with data rate. Hence, the throughput of DD-CoopMAC is 4% higher when compared with D-CoopMAC and 21% higher when compared with IEEE 802.11ad.

Figure 8 shows the MAC delay measured for DD-CoopMAC, D-CoopMAC and IEEE 802.11ad when the number of STAs is varied. As seen in the figure, the MAC delay of DD-CoopMAC, D-CoopMAC and IEEE 802.11ad increases from 2.25 to 4.07, from 2.72 to 4.52 and 3.21 to 5.47 ms, respectively. This is due to the time involved in BFT procedure before the communication.

Since D-CoopMAC and IEEE 802.11ad did not handle the PLR and PDT constraints, the delay involved in transmitting and retransmitting the data will be high. Hence, the MAC delay of DD-CoopMAC is 13% lesser when compared with D-CoopMAC and 26% lesser when compared with IEEE 802.11ad.

3.2c *Varying the MSDU size for MCS=1*: In this experiment the MSDU size is varied as 512, 1024, 2048, 4096 and 7920 bytes, keeping the STA as 20 for MCS=1.

Figure 9 shows the throughput measured for DD-CoopMAC, D-CoopMAC and IEEE 802.11ad when the MSDU size is varied. It is trivial that the throughput will increase when the MSDU size becomes larger. From the figure it is seen that the throughput of DD-CoopMAC, D-CoopMAC and IEEE 802.11ad increases from 0.88 to 8.49, from 0.72 to 8.19 and from 0.45 to 5.98 Gb/s, respectively.

D-CoopMAC considers only the data rate of two-hop links while estimating the normalized throughput whereas DD-CoopMAC considers the channel utilization along with data rate. Hence, the throughput of DD-CoopMAC is 11% higher when compared with D-CoopMAC and 37% higher when compared with IEEE 802.11ad.

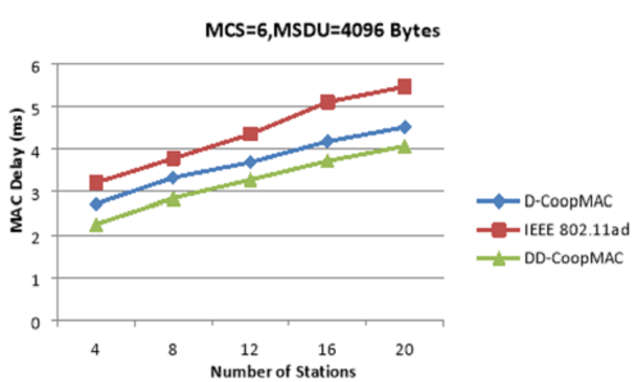

Figure 8. Number of stations vs MAC delay (MCS=6, MSDU=4096 bytes).

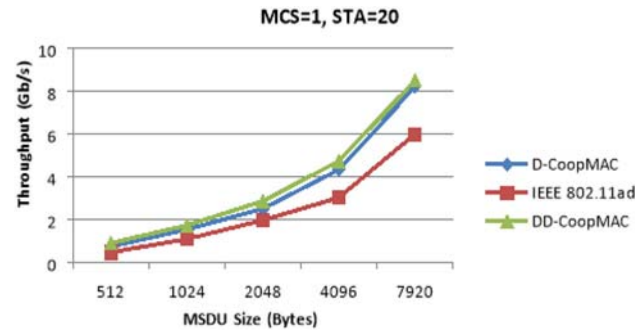

Figure 9. MSDU size vs throughput (MCS=1, STA=20).

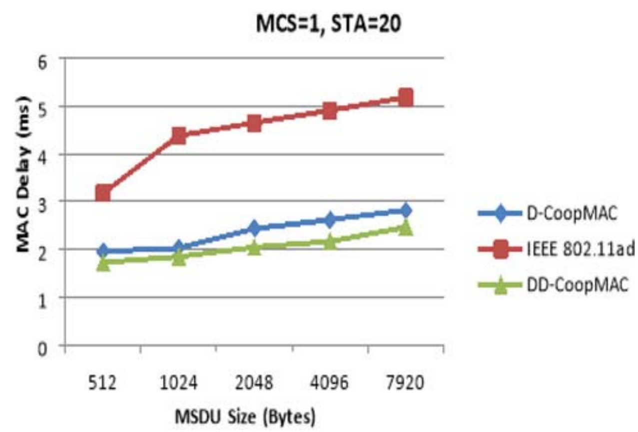

Figure 10. MSDU size vs MAC delay (MCS=1, STA=20).

Figure 10 shows the MAC delay measured for DD-CoopMAC, D-CoopMAC and IEEE 802.11ad when the MSDU size is varied. It is trivial that the transmission delay will increase when the MSDU size becomes larger. From the figure it is seen that the MAC Delay of DD-CoopMAC, D-CoopMAC and IEEE 802.11ad increases from 1.73 to 2.47, from 1.96 to 2.82 and from 3.17 to 5.18 ms, respectively.

Since D-CoopMAC and IEEE 802.11ad do not handle the PLR and PDT constraints, the delay involved in transmitting and retransmitting the data will be high. Hence, the MAC delay of DD-CoopMAC is 13% lesser when compared with D-CoopMAC and 53% lesser when compared with IEEE 802.11ad.

3.2d *Varying MSDU size for MCS=6*: In this experiment the MSDU size is varied as 512, 1024, 2048, 4096 and 7920 bytes, keeping the STA as 20 for MCS=6.

Figure 11 shows the throughput measured for DD-CoopMAC, D-CoopMAC and IEEE 802.11ad when the MSDU size is varied. It is trivial that the throughput will increase when the MSDU size becomes larger. As seen in

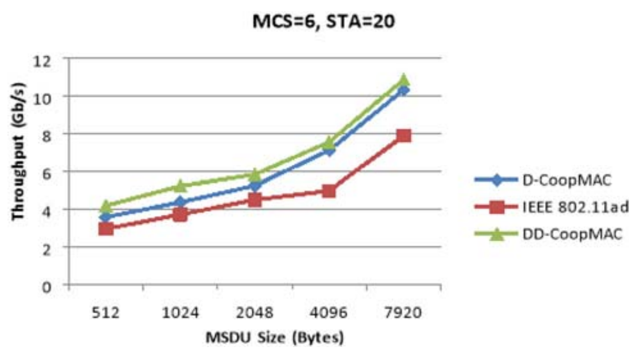

Figure 11. MSDU size vs throughput (MCS=6, STA=20).

the figure the throughput of DD-CoopMAC, D-CoopMAC and IEEE 802.11ad increases from 4.18 to 10.87, from 3.57 to 10.33 and from 2.94 to 7.88 Gb/s, respectively.

D-CoopMAC considers only the data rate of two-hop links while estimating the normalized throughput whereas DD-CoopMAC considers the channel utilization along with data rate. Hence, the throughput of DD-CoopMAC is 10% higher when compared with D-CoopMAC and 29% higher when compared with IEEE 802.11ad.

Figure 12 shows the MAC delay measured for DD-CoopMAC, D-CoopMAC and IEEE 802.11ad when the MSDU size is varied. It is trivial that the transmission delay will increase when the MSDU size becomes larger. As seen in the figure the MAC delay of DD-CoopMAC, D-CoopMAC and IEEE 802.11ad increases from 2.91 to 4.89, from 3.22 to 5.28 and from 4.07 to 6.11 ms, respectively.

Since D-CoopMAC and IEEE 802.11ad do not handle the PLR and PDT constraints, the delay involved in transmitting and retransmitting the data will be high. Hence, the MAC delay of DD-CoopMAC is 9% lesser when compared with D-CoopMAC and 26% lesser when compared with IEEE 802.11ad.

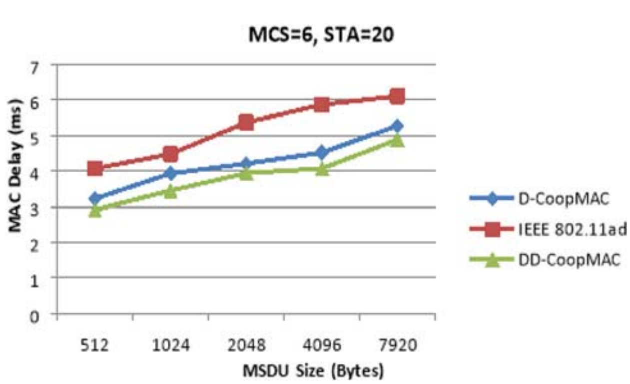

Figure 12. MSDU size vs MAC delay (MCS=6, STA=20).

4. Conclusions

In this paper, we have proposed a DD-CoopMAC protocol for improving VBR throughput in IEEE 802.11ad WLAN. This protocol aims at enhancing channel usage, minimizing the BF overhead and selecting a relay STA. Based on the *UF* and *CWF* values, the best STA is selected from the table and employed as a relay STA. In this way the distributed relay selection is achieved by each STA in the WLAN, which ensures enhanced channel usage as well as minimized BF overhead. Simulation results show that DD-CoopMAC enhances the throughput and reduces the MAC delay, when compared with D-CoopMAC and traditional IEEE 802.11ad MAC protocols.

List of symbols

SSW	Sector sweep
S_1	STA performing responder SSW
S_2, S_3, S_4	Stations surrounding S_1
CU_k	Utilization for channel k
DR_{HL}	Data rate of two-hop link d
μ_1, μ_2	Weight values ranging in [0, 1]
CWF	Combined weight factor
P_{suc}	Probability of successful transmission
P_{idle}	Probability of slots being idle
T_{idle}	Duration of idle time slot
T_{suc}	Duration of successful transmission
P_{col}	Probability of collision
T_{col}	Duration of failed transmission
E[P]	Average duration of a payload packet
UF	Utility function
STA_{relay}	Relay station
PDT and *PLR*	Packet delivery time and packet loss ratio
α, β	Predefined constants
STA_{up}	STA performing uplink transmission
$STA_{tab(i)}$	STAs included in the table

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