APPENDIX-1: SIMULATION TOOLS

A1.1 OMNeT++-4.6

This is written in C++. It is used to simulate both the wired and the wireless networks and also to build the network simulator. As it uses C++ it is both modular and object oriented.

A1.2 OPNET 17.5.A

OPNET is a commercial tool. It is used to study communication networks. The processes in this simulator are based on FSM - finite state machines. Its wireless model simulator has a pipelined architecture. It can simulate and determine the network connectivity and also the propagation between the nodes in the network.

A1.3 QualNet (2014)

QualNet is again a commercial network simulator used by Scalable Network Technologies (SNT) for their defense projects and research

A1.4 NS3

Ns-3 provides an extensible network simulation platform, for study and research in the networking field. The tool is available in the public domain. And helps to simulate a discrete event simulator for networks. Ns-3 provides models to demonstrate functioning of packet data networks, and offers a simulation engine for users to simulate and experiment. Ns-3 is written in multiple languages (C++/OTcl). The ns3-3.25version of ns-3 released in March 2016 is used for the analysis in this paper, has a Wi-Fi module with enhanced support for broader channel widths (up to 160 MHz) and multiple SS (up to 4).

A1.5 MATLAB

MATLAB R2016a version has incorporated a WLAN System Toolbox with provision to design, configure the physical layer in 802.11ac WLAN standard and also to simulate, analyze and test performance of WLAN communications systems.

APPENDIX-2: BACKGROUND OF WLANs

A2.1 Background

Tables A2.1 and A2.2 have been used to trace the progress of new WLAN standards. Table A2.1 shows the major IEEE 802.11 standards and Table 2.2 next generation standards. The main improvement in WLANs has been in data throughput. This has been possible through enhanced modulation schemes in the PHY and is shown in Table-A2.1.

Table A2.1 Major Standards

Std	Year introduced	Data rate (Mbps)	Modulation	Freq	Remarks
802.11	1997	1	FHSS,2 level GFSK	2.4 GHz	Disadvantages: Need high data rates
		2	FHSS,4 level GFSK	2.4 GHz	Disadvantages: Security through WEP (an insecure protocol)based on RC4 stream cipher a) Static keys are not changed often b) RC4 not properly implemented c) IV (initialization vector) is only 24 bits long and tends to get used quickly d) It is possible to obtain the key by sniffing a large no. of packets
		1	DSSS,DBPSK	2.4 GHz	
		2	DSSS,DQPSK	2.4 GHz	
		1	Diffused IR, 16 PPM	850-950 nm	
		2	Diffused IR, 4 PPM	850-950 nm	
802.11b	1999	5.5	DSSS	2.4 GHz	Disadvantages: Overcrowded 2.4 GHz band because of Bluetooth, microwaves, cordless phones, in same band

		11	CCK	2.4 GHz	Disadvantages: Permits only 3 non-overlapping channels
802.11 a	2001	54	OFDM	5 GHz	Advantages : a) 5 GHz less crowded b) More channels (up to 8 non overlapping) Disadvantages: a) Reduced range (due to higher frequency) b) Regulatory issues c) Not backward compatible with 802.11b and 802.11
802.11 g	2003	54	OFDM	2.4 GHz	Disadvantages: Interoperability issues with 802.11b. Hence, needs to send a Protection signal based on CCK
		5.5/11	CCK		Advantages: Backward compatible with 802.11b
		22	CCK,OFDM, PBCC		

Table A2.2 Next Generation Standards

Standard	Year of Introduction	Data rate	Modulation scheme	Frequency
802.11n	2009	600 Mbps	OFDM	2.4 / GHz
802.11ac	2013	6.77 Gbps	OFDM	5 GHz
802.11ad	2012	6.75 Gbps	OFDM with one carrier and low power.	60 GHz

As WLANs were designed with the motivation of substituting Ethernet based LANS, the MAC scheme of CSMA/CD was replaced with CSMA/CA. However, while CSMA/CA ensures fairness to all users, it was not designed with QoS in mind. As long as data was the primary focus (as in LANs), CSMA/CA was adequate for satisfying needs of best effort traffic which data traffic essentially is. However, the high throughputs obtained with WLANs, compared favorably with upcoming cellular technologies. So, there arose a desire to have voice and video traffic with WLANs. The cellular technologies were developed with suitable

MAC schemes to handle multimedia applications, as they were mainly meant to handle such applications.

However, when the same multimedia applications were included with WLANs, it gave rise to certain issues. The QoS of multimedia applications required stringent control of parameters like delay and jitter for which CSMA/CA is not fit enough. Earlier WLANs were conceived with PCF to meet this requirement. As PCF was highly unsuccessful, 802.11e standard was planned. We shall study these in the following sections with respect to modifications in MAC mechanisms and QoS.

Medium access layer details

Access to PHY is through MAC layer which is divided by functionality into Lower MAC and Upper MAC. CSMA/CA, RTS/CTS mechanisms are in the lower MAC which interfaces with the PHY layer. Management frames (described below), security and QoS are functionalities of upper MAC which interface with the data from higher layers.

CSMA/CA used by 802.11 is a MAC protocol, according to which the nodes in the network sense the medium for traffic and then access it, thereby avoiding simultaneous access of the medium by two nodes and reducing data collisions.

The original 802.11 standard proposed 2 mechanisms for medium access: DCF and PCF.

DCF (Distributed coordination function) implements CSMA/CA with binary exponential back off algorithm.

Point Coordination Function or PCF resides in a centralized point coordinator (PC) in the AP which coordinates communication within the WLAN. The PC sends a 'CF Poll frame' to the STA which is capable of PCF, and thus allowing frame transmission. The AP gains channel access after only PIFS duration and not DIFS duration which is more than PIFS. This results in PC having precedence over DCF at all times.

In the absence of frames to transmit, a null frame is transmitted. As PCF has a higher priority, stations utilizing only DCF might be deprived of opportunities to access the medium. This situation is avoided by a repetition period covering both CFP i.e. PCF and Contention Based - CP i.e. DCF traffic. This repetition period commences with a Beacon Frame. On hearing the beacon, the STAs begin their network allocation vector (NAV) for the CFP period.

PCF had several limitations and was not eventually implemented as it was not a mandatory feature for Wi-Fi certification.

There are 3 main frames used in WLANs: Management, Control and data frames. As newer standards evolved, additional subtypes were included to the base frames. For example, 802.11 had RTS, CTS and ACK frames.802.11e had CFP_ POLL added and 802.11n had BLOCK ACK added to support new features.

A2.1.1 Management Frames

Management frames are messages used for purposes of maintenance.

(i) Authentication frame: When STA transmits an authentication frame including its identity, and then AP gives its acceptance or rejection in a reply authentication frame.

(ii) Association request frame: This frame has the STA information like data rates capability and SSID of the preferred network.

(iii) Association response frame: On receiving the 'Association request frame' the AP responds with either approval or rejection of the association request. In the event of approval, the response frame includes association ID and data rate capability.

(iv) Beacon frame: The AP transmits periodic 'Beacon frames' containing SSID and other information to announce its existence to STAs.

(v) De-authentication frame: This frame is used by an STA to end link with another STA.

(vi) Disassociation frame: This frame is transmitted by an STA to disassociate a connection.

(vii) Probe request frame: Sent from an STA for data from AP.

(viii) Probe response frame: On receiving probe request frame, the AP transmits the 'Probe response frame' indicating its features.

(ix) Re-association request frame: When the STA moves, it sends 're-association request frame'. It then locates an Access Point having better signal in a new location.

(x) Re-association response frame: The AP conveys approval or dismissal to an STA through the re-association request frame.

A2.1.2 Control Frames

These frames assist in the process of exchange of data frames amongst STAs. For examples:

(i) ACK frame

(ii) RTS / CTS frames: The RTS/CTS frames provide a means to reduce collision for APs with hidden STAs. STA-1 first transmits 'RTS' frame. CTS is sent by STA-2 in response to RTS. This CTS frame is an indication to STA-1 to transmit data frames.

A2.1.3 Data Frames

A2.1.4 QoS provision in 802.11e

802.11e has a HCF or hybrid coordination function that enhances both PCF and DCF. HCF has two methods of accessing the channel:

(i) Enhanced DCF channel access: EDCA differentiates traffic into high and low priorities. Shorter arbitration inter-frame space (AIFS) is used for packets which have more priority. Contention-free access is also given to the medium by EDCA for a duration referred to as Transmit Opportunity (TXOP). Providing

TXOPs decreases the setback in the legacy 802.11 DCF MAC where STAs with lower rates obtain an unreasonable amount of media or channel duration.

Access categories (ACs) are the priority levels in EDCA. The contention window (CW) is configured depending on the traffic in each AC, wherein ACs with larger traffic are allotted a wider CW. Thus QoS protects HP data from LP data.

(ii) **HCF Controlled Channel Access HCCA:** In PCF, the time gap in the middle of consecutive beacon frames is split into - CP (Contention Period) and CFP (Contention Free Period). During a CP, the AP initiates a Controlled Access Phase (CAP) every time a frame is desired to be transmitted / received to/from a STA in a contention-free mode. During this phase, access to the medium is controlled by the AP, acting as a Hybrid Coordinator (HC). During the CP, all STAs operate in EDCA. The STAs give information regarding the queue lengths for each TC or Traffic Class. The HC avails this information to provide priorities to different STAs, or fine-tune its scheduling scheme. During the CFP, the HC permits STAs to transmit data by issuing CF-Poll frames.

APPENDIX-3: MECHANISMS FOR QoS ENHANCEMENT

A3.1 Queueing

The policies established for the management of the buffer, decide the packets to be rejected when network is congested at data link layer. Based on these policies, packets are disposed under the control of a drop policy and memory is allocated for egress queues. Drop policies can be active or passive. The simplest drop policies are passive wherein packets are dropped after queue is full. Active queue management (AQM) policies regulate the packets arriving at the AC queues (in WLANs). Random Early Detection (RED) is an example of AQM.

A3.2 Call Admission Control

Traffic volume in WLANs is controlled by Call admission control (CAC) by regulating the number of calls, the overall utilized bandwidth, or the rate of packet transfer. When the count reaches a configured upper bound, a new call is not allowed until at least one existing call ends. In the absence of a CAC mechanism, the allowed call session number may go beyond the capacity of the network, resulting in undesirable quality of communication. CAC also ensures that as many call sessions as possible get accepted to achieve efficient utilization of available resources. CAC algorithms can be complicated, as the traffic in communications networks is "bursty," and such traffic bursts are unpredictable.

A challenge for CAC mechanism is -numerous transmission rates and Rate Adaptation (RA) mechanisms. STAs adopt different rates which are also dynamically varied. This adds to the randomness and hence makes the process of estimation of the accessible resources tougher. Generally, in 802.11 WLANs networks, CAC is implemented in the AP.

A3.3 Aggregation

This technique introduced in 802.11n MAC layer (and is also present in 802.11ac [5]) enhances the channel utilization efficiency by decreasing the overheads.

A3.3.1 Frame Aggregation

Whenever a frame needs to be sent a STA (or AP) contends for the channel, which leads to collisions and backoff delays i.e., in wasted time which would have been otherwise utilized in data transmission.

A station merges a number of frames and forms an aggregate frame called MAC MPDU. Because of aggregation, the frame has fewer headers and hence lesser overhead. As the frames sent are lesser and bigger, the medium contention time decreases.

Aggregation is of two types: (1) Aggregated MSDU (A-MSDU) - In this more efficient type, combining the LLC packets (MSDUs) into one unit, results in each frame now being a sub frame within the aggregated frame. This implies that only frames with identical source & destination and MSDUs with identical priority can be selected for aggregation. In other words, sub frames must be of equal QoS level and one cannot, for example, mix video with best-effort frames and (2) Aggregated-MPDU (A-MPDU)..

In the second type (A-MPDU aggregation), MPDUs are concatenated into an aggregate MAC frame and this method should use the new Block Acknowledgement function of 802.11n. Here, we can encrypt each sub-frame independently. The low efficiency of MPDU aggregation, due to additional overhead, is decreased even more when encryption is used.

Frame aggregation and block ACK protocols (explained in the next section) offer substantial efficiency gains. Legacy ACKs can be used to confirm Aggregated MSDUs, but Block ACKs must be used to confirm Aggregated MPDUs.

A3.3.2 Block ACK

In the legacy 802.11 a/b/g systems, the receiving station almost immediately returns to the transmitter an acknowledgment to confirm reception of each non-multicast/broadcast frame. If an ACK is not obtained by the transmitter, the frame is retransmitted until an ACK is received.

The block ACK scheme that transmits one block ACK frame to acknowledge reception of multiple frames aids in improving throughput and hence efficiency of the protocol. Block ACK accumulates the ACKs of each sub-frame in one frame and this permits an accelerated mechanism to achieve selective retransmission of only the unacknowledged sub-frames. When the channel is highly erroneous, block ACK mechanism used with MPDU aggregation can provide better throughput in the WLAN as compared to MSDU aggregation.

A3.4 Rate Adaptation

RA is a key factor that influences 802.11 WLAN performance. In networks that are congested, conventional RA algorithms select lower data-rates for packet transmissions and acknowledgements are used to make decisions regarding enhancing or lowering the rate. Some of the existing RA schemes are:

A3.4.1 ARF or Automatic Rate Fallback) and AARF or Adaptive ARF

ARF implements a simple history-based RA algorithm. After the successful transmission of N consecutive frames or on the expiry of a timer meant to search for the subsequent PHY rate which is greater, the PHY rate is incremented by a step at the sender station. PHY rate is decremented by a step in the event that two consecutive frames are lost / the first frame sent with enhanced rate is unsuccessful. In ARF the retransmissions are huge when the channel is slowly varying. AARF a more adaptive algorithm (as suggested by the name itself) is proposed, with dynamically altered adaptation intervals. Unlike ARF in which the rate increase threshold is kept constant (N), with ARRF, this threshold is adaptively adjusted. A transmitter enhances its data rate r_{old} to a new rate r_{new} after N consecutive transmissions are successful. When the first transmission using this new rate r_{new} is unsuccessful, the transmitter uses the previous rate r_{old} and increases the threshold to 2N when the next rate is raised. Otherwise, i.e., if the first transmission using the r_{new} is successful, the threshold is reset. The time interval between rate increases is enhanced, using such adaptive threshold updates, over a stable channel and generates lesser rate fluctuations than ARF [84].

A3.4.2 CARA - Collision-Aware Rate Adaptation and MiSer

These are able to differentiate between collision and channel errors and allow a reduction in the PHY rate only when the latter occurs. In CARA, after noticing frame transmission failure, the WLAN station enables RTS transmission. The STA can determine which type of error had actually caused the loss in the previous frame from RTS transmission results and from the frame succeeding RTS.

MiSer attempts to improve the power consumed, by varying or adapting transmission rate and power by making the nodes choose the best combination of maximum rate and minimum power possible from a look-up table when the algorithm is running.

A3.4.3 RRAA-Robust Rate Adaptation Algorithm

RRAA uses lossy data to identify channel conditions. RRAA constructs a table for each PHY rate which holds the following: (1) Limits for enhancing or reducing rates and expressed as FER and (2) ewnd or estimation windows expressed in number of frames. A station sends ewnd frames at a particular rate, estimates the FER, and measures it with reference to the rate limits in the table. Based on the comparative value of FER and limit / threshold, the STA increments or decrements the PHY rate suitably by one step. A-RTS of RRAA is an adaptive RTS mechanism (as in the adaptive usage of RTS by CARA) which is very useful in performance enhancement in the presence of hidden terminals.

A3.4.4 SampleRate

PHY rate is chosen by the SampleRate mechanism from FER statistics. It calculates approximately the probable time for transmission and retransmission for the (PHY rate, frame size) combination. The PHY rate which achieves the desired throughput with minimum time is chosen.

A3.5 Scheduler

After packet classification and admission control, packets are scheduled and queued into the memory buffers. Schedulers are implemented in the AP. Varieties of algorithms exist for scheduling purposes.

A3.6 Additional Mechanisms for handling QoS

QoS solutions which control devices external to WLAN (such as routers, centralized servers, etc.,) and which improve QoS with focus on PHY layer (such as interference handling and multi beam antennas) are discussed in this section.

APPENDIX-4: SCHEDULING IN CELLULAR NETWORKS

A4.1Introduction

Sub-Channel Scheduling –In the existing WLANs, the MAC layer randomly assigns the whole channel to a single user, which decreases its efficiency. A method of enhancing the performance of WLAN is by decreasing channel bandwidth besides creating multiple sub-channels. Depending media condition of the user and QoS requirements, PHY layer resources may be assigned dynamically to multiple users simultaneously.

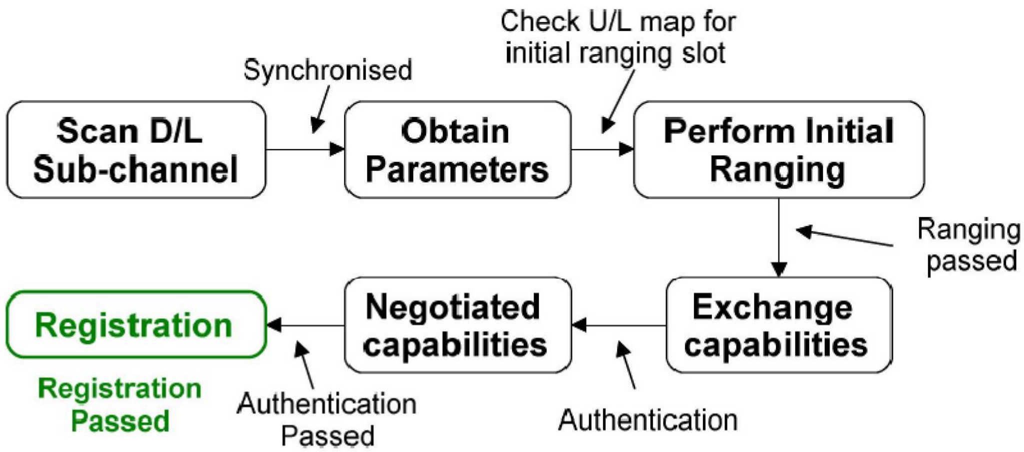
Diverse applications need different QoS requirements. This necessitates design of protocols in higher-layer to consider design of PHY layer also to achieve optimum performance in WLAN. BER or SNR are the parameters used to characterize QoS for dependable communication over lossy wireless medium in the PHY layer. OFDM partitions a given spectrum into multiple bands (termed as subcarriers) that are narrower and overlapping partially. The frequency of the subcarrier is selected to be mutually orthogonal. Hence, the OFDM concept can group subcarriers in sub channels (also called sub-channelization) closely while avoiding inter-carrier interference. Frequency reuse ratio is more by sub-channelization.

Sub-channel assignment to users can be either static or a dynamic. Mapping of subcarriers to sub-channels is known as permutation.

A4.2 Scheduling in WIMAX

The operations involved in WiMAX (802.16e) before the MS exchanges information with a remote user are: (a) network entry (b) creation of connections (with a specific QOS class) for data transmission to or from the BS. These are discussed below.

A4.2.1 Network entry



FigA4.1 Network Entry

MS first needs to synchronize with the Downlink channel. It scans for the channels in the defined frequency list, and tries to synchronize at the PHY level (detect periodic PHY preamble).Following certain operations defined by the PHY layer, MS waits till it gets opportunity in the Uplink for ranging.

It then sends initial ranging request on the uplink sub frame. Once ranging is completed, BS assigns two connections to MS for management message exchange. These are the Basic and Primary management CIDs which is conveyed to the MS through the ranging response. After ranging, the MS sends its set of capabilities (Authentication, modulation levels, coding schemes, etc.). The BS can accept or reject the MS based on its capability, and also choose a specific capability from the set proposed by the MS. After authentication, the MS registers with the network. The MS sends its parameters (ARQ, IP Version, managed/not, Classification support etc.). The BS can choose the final set of parameters and conveys to the MS in the response message.

A4.2.2 Create Connections

802.16 MAC being a connection oriented protocol requires a connection between the MS and BS before data can be exchanged. Each connection uniquely identified by a connection identifier (CID), carried in the header of the message.

Connections used for transport of user data between the BS and MS, should be created using MAC management message.

A4.2.3 QOS

Each connection between the MS and BS belongs to specific Service classes which are as follows:

(i) **Unsolicited Grant Service or UGS** is aimed to provide RT constant bit rate service (e.g. Voice) and provides periodic data transfer opportunities.

(ii) **Real Time Polling Service or rtPS** is aimed to provide RT services, with variable bit rate requirements (MPEG Video) and provides periodic unicast request opportunities.

(iii) **ertPS (Extended rtPS)** combines both the UGS and rtPS features. BS provides periodic grants which can be used to transfer data and also alter the bandwidth.

(iv) **Non real time Polling Service or nrtPS** is aimed for non-RT service requiring variable length grant regularly (FTP) and offers unicast request opportunities on regular basis.

(v) **Best Effort (BE)** is designed for low priority and bursty traffic (http) Uses contention opportunities for bandwidth request.

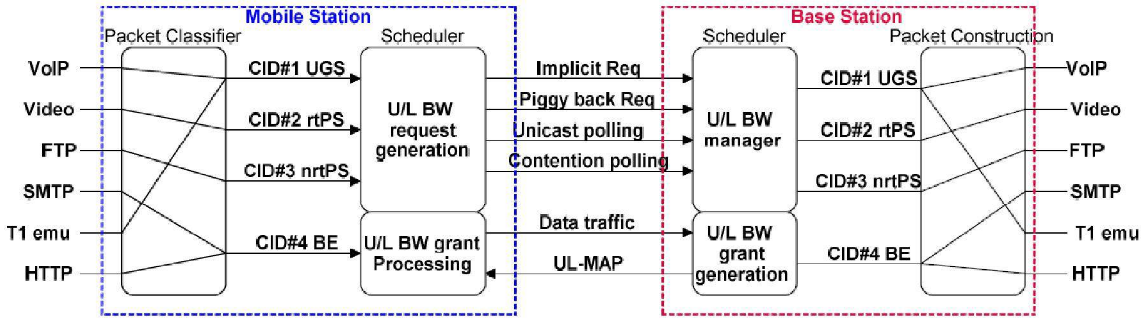
The packet scheduler prepares proposals indicating those connections that need to be scheduled in the current frame to meet their QoS requirements, while optimally utilizing the resources of the air link. Air link scheduler is run on the BS to schedule the air link to the various MS. For scheduling the data for specific MS, the scheduler determines the contents of the DL and UL sub frames.

The connections are scheduled as listed below in the decreasing order of the priority:

UGS >ertPS> MRR of rtPS> MRR of nrtPS> MSR of rtPS= MSR of nrtPS = BE

The scheduler guarantees the MRR for all connections with in the packet latency, if any, and then looks to service MSR of each connection in a round robin fashion. Jitter is considered for UGS and ertPS connection, traffic priority for rtPS, nrtPS connection and latency for UGS, ertPS and rtPS connections.

Refer FiguresA4.2 and A4.3.



FigA4.2 Uplink Data Flow (MS-BS) Process

Connection service class and traffic queued up for the MS decide the bandwidth required for the MS. This decision is taken by BS. For DL scheduling, BS observers the data queues in its own station. To decide the MS UL requirement, BS utilizes mechanisms such as polling, unsolicited bandwidth request, class of service etc.

The Packet Scheduler is responsible for the actual data grants of different flows that are active in the downlink side. This picks up the data from the various CID queues, and schedules them so that the QoS of the various flows are maintained. This module is also responsible for creating CID queues.

On the uplink side, the scheduler is responsible for processing the bandwidth requests and processing of grants and polling.

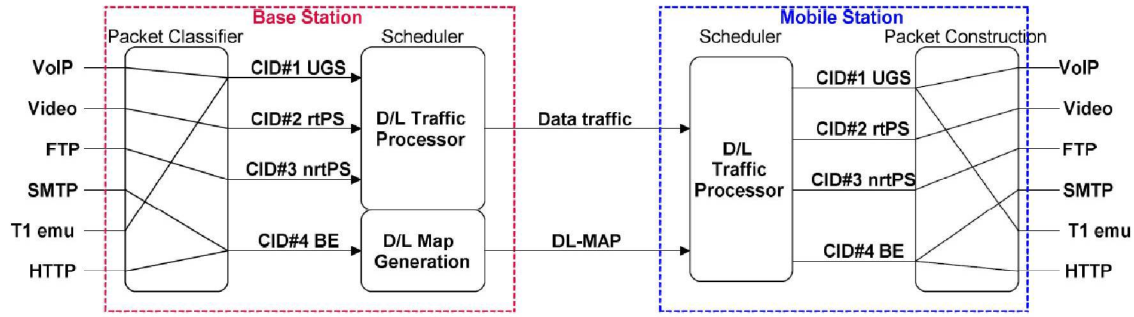


Fig A4.3 Downlink Data Flow (BS-MS) Process

Link adaptation: The BS should monitor the SNR and determine the appropriate burst profile for each MS i.e., increase or decrease the coding and modulation to optimize the throughput while maintaining a specified BER.

Connection Admission Control (CAC): is responsible for admitting a connection based on the QoS parameters specified at the setup time, and the current estimate of the bandwidth available for the MS. The connection is admitted only under the following conditions:

- There is bandwidth available to accommodate the new connection, without adversely affecting the connections already admitted.
- Both bandwidth and delay characteristics of the connection can be met.

Once a connection is admitted, the scheduler for UGS, eRTPS, rtPS and nrtPS service flows guarantees the QoS (bandwidth + delay + jitter) agreed at the connection setup time.

The CAC module does the following processing:

- The CAC module is invoked by the service flow module when a new service flow is setup or if the parameters of the existing service flow are changed or a service flow is deleted.
- The module examines the QoS characteristics of the new service flow being setup or change in parameters of the current service flow and determines the class of QoS it belongs to. Connections with UGS, eRTPS, rtPS and nrtPS QoS class service flows need to go through the CAC

module. The BE connections need not go through the CAC module because no bandwidth is reserved for such service flows.

- The module then invokes the air resource manager module to get the current estimate of the bandwidth that is available for a particular zone and the burst profile. The bandwidth available is calculated based on the maximum bandwidth available for a burst profile in a particular zone minus the reserved bandwidth for the burst profile in that zone.
- The CAC module admits / readmits a service flow if the available bandwidth is greater than the bandwidth requested by the service flow and the delay characteristics for the connection can be honored. This is done by queue size estimation.
- If the connection is admitted the reserved bandwidth is updated by the bandwidth of the admitted connection.
- In case the service flow is getting deleted the CAC module updates the reserved bandwidth for the connection and deletes any resources that have been allocated by the CAC for the service flow.

OFDMA Frame

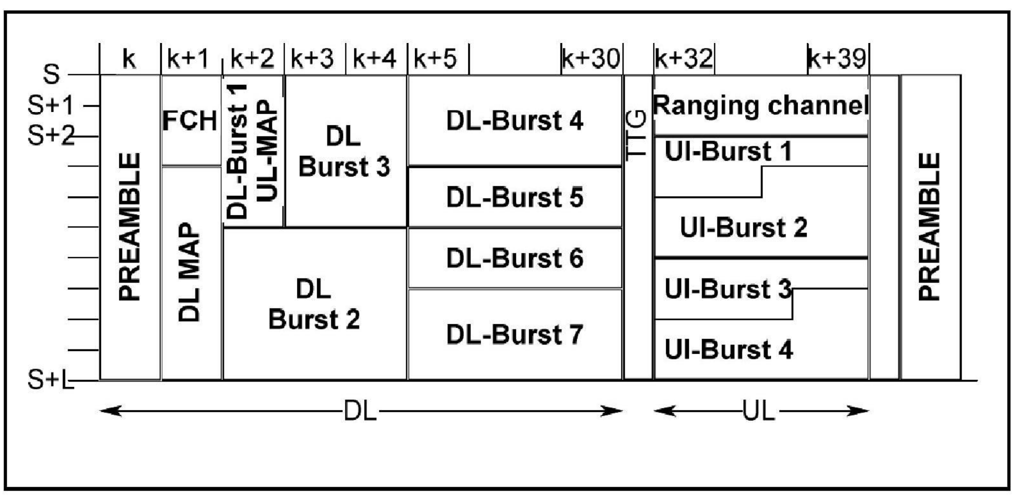


Fig A4.4 2D view of the OFDMA Frame

As seen in Figure-A4.4, the preamble is the start of every DL sub frame. The fixed pilot sequence contained in the preamble eases the task of estimating phase and frequency errors by the receiver and also to harmonize with the transmitter.

FCH (Frame Control Header): Contents describe (a) sub channels used (b) DL-MAP length that will trail and (c) coding parameters of the DL-MAP.

The Downlink MAP (DL-MAP) describes the position of the bursts in the DL zones. It contains number of bursts along with, their offset and length in frequency and time domains.

The Uplink or UL-MAP is the first burst in the DL and contains the position of the uplink burst for various users.

- **Frame**: One set of complete DL and UL transmissions
- **Sub channel**: Smallest logically assigned unit in frequency domain and has minimum one physical carriers.
- **Symbol**: Smallest assigned unit in the time domain.
- **Slot**: Minimum possible data assigned unit within OFDMA frame.

A4.3 Scheduling in LTE

During scheduling in LTE [72], the eNodeB decides which user elements (UEs) should be given bandwidth resources to send or receive data and how UL and DL channels are used by both eNodeB and UEs. In the LTE standard, scheduling is performed at sub-frame level and on cell basis.

Data is allocated as Resource Blocks (RBs) by the eNodeB to the UEs. ½ms of RB is a slot in a frame. RB length is 180 KHz. When the sub-carriers are spaced 15 kHz apart, there are 6 symbols in a slot in normal cyclic prefix and 7 for extended cyclic prefix.

To decide regarding resource allocation, the Scheduler gets the following information:

1) QoS rules/data from the PCRF (Policy and Charging Rules Function) e.g., least guaranteed and highest allowed bandwidths, relative priority of users, packet loss

rates and latency acceptable for various connections to UE. These parameters are application based.

2) UE computes CQI value from downlink channel and sends it to the eNB as a feedback on the signal strength.

3) Receiver measurements about media quality, interference and noise.

4) Upper layers buffer status regarding length of the queue of data for transmitting. Using BSR (Buffer Status Report), the UE informs the network that it requires grants to send this data.

Based on the above values, eNodeB computes MCS (Modulation and coding scheme) value and PRB mapping information and transmits it to the UE in the downlink.

Scheduling involves a tradeoff between maintaining fairness among the different users and on providing higher cell throughput through resource allocations. There are correspondingly different scheduling methods as discussed below.

a) Round Robin (RR) scheduler assigns to users, resources in a cyclic fashion without independent of media conditions. RR meets the fairness criterion –i.e. each user gets identical transmission time. But it does not utilize the known downlink SNR to fix the bit length transmitted. Hence throughput degrades.

b) Proportional fair (PF) is usually preferred in commercial networks. This algorithm attempts to optimize the cumulative throughput of the wired/wireless networks while simultaneously providing every user minimal transmission time. This is made possible by scheduling such that priority varies inversely as its expected resource consumption. As cell throughput and fairness are present PF is comparatively a good option.

c) **Best CQI** is utilized to allocate resource blocks to the user having best media situations (CQI). In downlink, the eNodeB transmits reference pilot signal to the UEs. This is used by the latter for the calculation of CQI and providing this CQI feedback to the eNodeB.

APPENDIX-5: GENERAL CHARACTERISTICS OF VoIP TRAFFIC

1) For VoIP, an analog voice signal is sampled and encoded using a voice codec such as ITU-T G.711/729. Further details on the characteristics of VoIP are given in [85] [86] [87].

2) The ITU-T recommendation G.107 planning tool is a subjective measure of end-to-end service performance from a network point of view. The five categories of quality levels defined by QoS for speech in telecommunications networks is described in [89]. E-model tool measures the parameters and categorizes speech [88] [89] based on transmission quality. The E-model output - transmission rating R-Factor is calculated as follows:

$$R = R_o - I_S - I_d - I_e - A$$

Where Ro = basic SNR

Is = Combined losses because of voice signal

Id = Impairments caused by delay

Ie = Low bit rate codecs caused losses.

A = Advantage factor due to compensation of loss factors due to other advantages to user.

Considering delay, impairments and G.711codec R-Factor is calculated as:

$$R = 93.2 - I_d - I_e$$

where Id = Total delay and losses due to Talker/listener echo

Ie = packet loss ratio factors

If R> 80R the VoIP session has a decent QoS. According to E-model, packet loss rate has a greater impact on voice quality as compared to a mouth to-ear delay <150 mS. Packet losses and latency < 35 ms in current internet. Hence managing the packet losses is critical to assure high QoS [85], [86] for VoWLANs solution.

APPENDIX-6: EVALUATION OF PERFORMANCE PARAMETERS

Throughput (Short GI)

	CBW=20MHz	CBW = 40MHz	CBW = 80MHz	CBW = 160MHz
MCS=0	5.55474	10.536	18.9782	28.9431
MCS=1	10.2039	17.9443	28.8971	38.8219
MCS=2	14.0664	23.3966	34.6591	44.1364
MCS=3	17.505	27.5405	38.8137	46.9839
MCS=4	22.8325	33.5369	44.021	50.9206
MCS=5	27.0754	37.894	46.8697	52.7624
MCS=6	28.9077	39.3695	48.463	53.7386
MCS=7	30.3774	40.997	49.3603	53.7339
MCS=8	33.1294	42.834	50.9218	54.8114
MCS=9		44.0893	51.7967	55.7323

Throughput (long GI)

	20MHz	40MHz	80MHz	160MHz
MCS=0	6.10586	11.4792	20.3996	30.4892
MCS=1	11.133	19.2985	30.5281	40.2256
MCS=2	15.2311	24.8933	36.2018	45.3188
MCS=3	18.8652	29.1209	40.2798	48.0072
MCS=4	24.3952	35.1149	45.3706	51.8274
MCS=5	28.631	39.2459	47.9754	53.5325
MCS=6	30.4998	40.7532	49.3885	54.285
MCS=7	32.0013	42.3771	50.1045	54.2744
MCS=8	34.6485	44.0528	51.7991	55.3755
MCS=9		45.2446	52.6022	56.1562

Mean-Delay (mS) long GI 10m

	20MHz	40MHz	80MHz	160MHz
MCS=0	0.488019	0.402464	0.228581	0.153469
MCS=1	0.414747	0.241406	0.153297	0.116506
MCS=2	0.304865	0.187596	0.129411	0.103411
MCS=3	0.246906	0.160557	0.11635	0.097725
MCS=4	0.191531	0.133393	0.103333	0.0904934
MCS=5	0.163347	0.119356	0.0977684	0.087615
MCS=6	0.153337	0.114949	0.0949672	0.0863953
MCS=7	0.146216	0.110648	0.0935578	0.0864297
MCS=8	0.135081	0.106446	0.0922774	
MCS=9		0.103586	0.188837	

Mean-jitter (UI) long GI 10m

	20MHz	40MHz	80MHz	160MHz
MCS=0	0.000163497	8.96350E-05	6.25943E-05	5.44712E-05
MCS=1	9.34254E-05	6.40479E-05	5.43782E-05	5.13448E-05
MCS=2	7.26250E-05	5.75599E-05	5.26571E-05	5.15430E-05
MCS=3	6.40214E-05	5.48114E-05	5.17455E-05	5.08966E-05
MCS=4	5.78925E-05	5.27749E-05	5.09941E-05	5.01501E-05
MCS=5	5.57090E-05	5.17730E-05	5.08475E-05	5.02216E-05
MCS=6	5.43232E-05	5.18876E-05	5.06348E-05	5.03814E-05
MCS=7	5.41811E-05	5.14102E-05	5.06680E-05	5.01973E-05
MCS=8	5.31901E-05	5.09727E-05	5.78926E-05	
MCS=9		5.11747E-05		

APPENDIX-7: MODIFICATIONS TO 802.11 STANDARD RESULTING FROM ADDITION OF MU-MIMO FEATURE

Modifications to the WLAN standard have been studied with respect to MAC and PHY layer.

A. MAC

1) CSMA-CA and Existing Backoff Mechanism

A CSMA/CA is a medium access mechanism that needs an STA to invoke a specific backoff procedure based on the event leading to backoff [71] [8]. The backoff is activated when more than one station attempts to simultaneously access the channel. The situations which trigger the backoff mechanism are:

(i) When a station wishes to transmit data (with a specific AC), it senses the channel and finds it busy. The value of backoff timer = 0 for that AC.

(ii) The last transmission for the Access Category set off during the time when TXOP met with success and the timer for TXNAV or Tx Network Access Vector has terminated.

(iii) TXOP's first frame does not succeed in getting transmitted.

(iv) It is noted that internal collision occurs for that EDCAF.

Timer values for CW and backoff are tuned for the various events on initiating backoff procedures, as explained below.

When the backoff occurs

a) Due to (i), the value of contention window should be left unchanged.

b) Due to (ii), contention window CW = aCWmin

c) Due to (iii) or (iv) or the lack of success in transmission by TXOP holder even if it is not the first frame, CW [AC] shall become two folded until CW [AC] equals aCWmax of that Access Category (i.e. exponential backoff).

2) The Enhanced Backoff Scheme in 802.11 ac

This section explains changes made to improve the backoff scheme to support downlink MU-MIMO, event by event. No critical changes are made by TGac specification to event (i) definition or to its corresponding backoff method. Event(ii) is redefined as:

(ii) Transmission of every MPDU in the last PPDU sent by that Access Category's TXOP holder met with success during the TXOP as mentioned in the sub clause and the TXNAV timer has terminated.

The variations for this event are trivial; it highlights that "all MPDUs in the final PPDU" are successfully sent.

But, the respective backoff procedures are improved to cover primary and secondary. Secondary AC backoff process is different (as described below), whereas it remains the same for the primary AC:

If backoff occurs due to (ii) and also if the AC is a Multi User secondary AC, then the backoff timer and CW values should both be left unchanged.

As per the new backoff process, secondary AC will continue timer count-down from the existing CW and timer value. It is presumed that when TXOP sharing begins, timer value is logged. Simulations prove enhanced fairness with this approach:

1) Amongst AP and different STAs for same AC

2) Amongst various ACs in the AP, with reference to the original approach designed for SU.

Event (iii) definition is modified to indicate the fact that multiple ACK or Block ACK frames are returned to the AP post successful reception of data frames by receiver.

(iii) The anticipated instant response to the first frame of that Access Category's TXOP is not obtained. "Anticipated instant response " implies the first of a series of ACKs/Block ACKs transmitted by multiple STAs that are receiving, for each downlink PPDU sent.

Event (iv) definition is also revised so that backoff will be triggered if AC(s) with lower priority are unable to share the TXOP earned by .

3) ***TXOP, Queuing and QoS [51][7]:*** Transmit Opportunity (TXOP) was an enhancement in 802.11e to existing Distributed Coordination Function (DCF) scheme to provide access to medium without contention, for the ACs - Voice (VO), Video (VI), Best effort (BE) and Background (BK). As TXOP permits uninterrupted access to voice and video frames for a bounded period and also blocks low priority users from obtaining excessive channel duration, it is considered a major QoS mechanism. 802.11ac has enhanced TXOP with TXOP sharing for DL-MU-MIMO feature.

Operation of TXOP sharing

- **Initiation of TXOP after gaining access to the medium.**

Initially, every EDCAF contends for TXOP with its own parametric values. On winning TXOP, it assumes ownership of the TXOP and its AC becomes 'primary' and the remaining ACs turn into secondary ACs.

- **Sharing of TXOP**

If the primary AC shares the TXOP with secondary ACs to send data streams in parallel, then this TXOP is termed multi-user or MU TXOP. The primary AC can share the TXOP selectively to secondary AC(s), and also select the destinations to transmit streams.

Queuing, however, becomes more difficult as high priority frames maybe mixed with low priority ones in one MU transmission. For example, say, voice frames are scheduled to be sent using MU link to a single stream phone. When the VO_AC in an AP gains access to the medium and the voice queue has large amount of data to send to the phone, this AC is the primary AC. The AP then begins constructing an MU frame by adding low priority frames during the same transmission duration.

- **Multiple and simultaneous frame exchange sequences**

Secondary AC frames can be transmitted in parallel with the Primary AC frames until their length is within the overall frame length. For example, suppose there are frames waiting to be transmitted in 2 queues in the AP- one for data and another for video and they are meant for two users. Within the overall frame length, if one video frame and two BE data frames (low priority) can be sent, the low priority frames have gained early access (compared to SU MIMO) as they are piggybacked onto the video transmission.

The secondary ACs will stop sending their frames (even if incomplete) as soon as the primary AC finishes transmitting at the end of MU-TXOP.

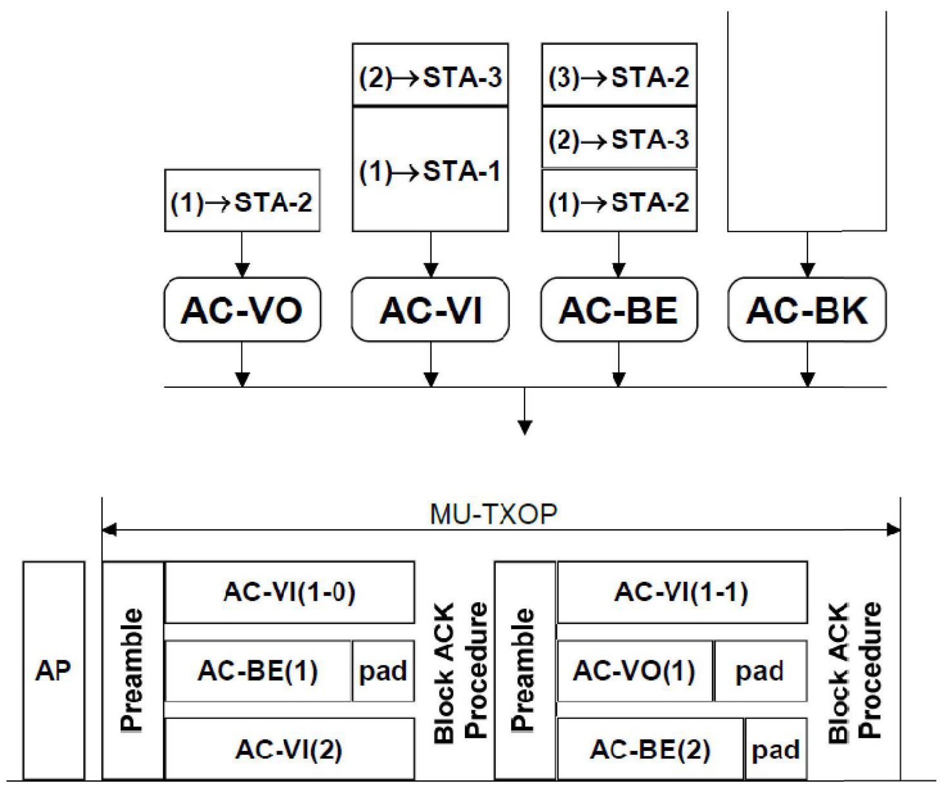


Fig A7.1: Example OF EDCA TXOP Sharing

Refer Figure-A6.1. Here, the Access Point has frames in queues of AC-VO /-VI /-BE. Suppose that AC-VI gets EDCA TXOP, shares it with AC-VO & AC-BE with the aim of targeting three Stations. AC VI (1-0) as well as AC VI (1-1) frames are AMPDUs containing a Very High Throughput single MPDU.

4) ***GROUP IDENTIFIERS FOR DL MU-MIMO [45]:*** As presented in Figure-A7.2, the various subsets of the sent frames are meant for different destinations.

On getting permit to the wireless channel the Access Point begins the first DL transmission of three frames. Frame in position-1 is to STA-1, frame in position-2 is to STA-3, and the frame in position-3 is to STA-2. The next (2^{nd}) DL transmission too has three frames. But here, frame in position-2 is to STA-2 and the frame in position-3 is to STA-3. The final DL transmission is a Single User transmission for STA-2. ACKs are sent in order of the STAs position. Padding is done end of frame alignment.

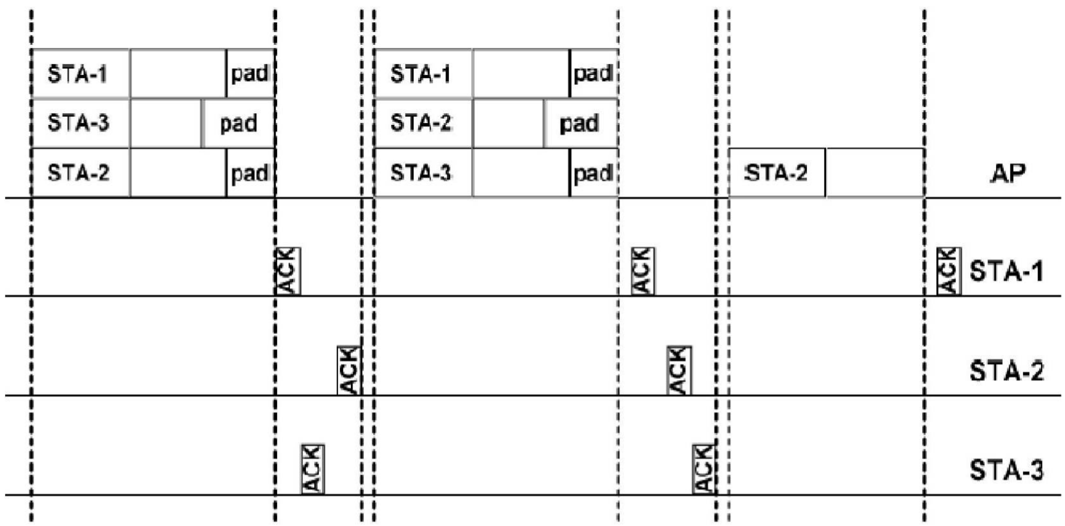


Fig A7.2: Downlink MU-MIMO Transmission

The transmission parameters which need to be identified are whether the transmission in SU or MU, identity of the destination stations with their positions and number of SS to each destination.

Group ID for 802.11ac WLAN: 802.11ac WLAN takes along DL data with data frames. Figure-A7.3 depicts VHT preamble emphasizing the fields for DL MU-MIMO communication. Group ID is utilized to indicate SU/MU type transmission and STA's location, and NSTS field conveys the number of SS for each probable receiver. In 802.11ac, in a DL MU-MIMO transmission there can be maximum four STAs with again a maximum of four streams each, and the aggregate streams cannot exceed 8.

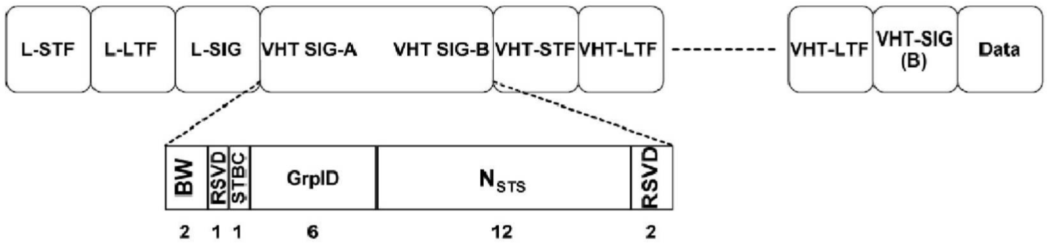


Fig A7.3 VHT Preamble

As indicated in figure-A7.3 Group ID is 6-bit field with which a maximum of 64 groups can be defined. Every Group ID is not utilized for DL MU-MIMO. Some can be earmarked to show SU transmissions or for any other explicit reason like power saving which when enabled by Group ID, the STAs which are not meant to receive the transmission can be in power saving mode for the duration of the transmission.

5) ***Aggregation*****:** In 'A-MPDU with Compressed Block Ack' (announced in 802.11n) many MPDUs are in one A-MPDU. This reduces overheads (like protocol headers backoff procedures, Acknowledgements, inter-frame spacing) and enhances the MAC efficiency. Every MPDU in an A-MPDU is intended for the same receiver with same TID or Traffic ID. Fragmented MPDUs cannot be in an A-MPDU even if the MSDU length which is a part of MPDU is more than fragmentation threshold. The Compressed BlockAck scheme is utilized as acknowledgement for A-MPDU. Their frame structures are depicted in Figure-A7.4.

As per 802.11ac amendment, "a VHT single MPDU is an MPDU which is the lone MPDU in an A-MPDU carried in a VHT PPDU". In such scenario, A-MPDU is eligible to have only one fragmented VHT single MPDU, with same guidelines as for a normal MPDU. Even if having the A-MPDU boundary to share EDCA TXOP is beneficial, fragmented MPDUs in A-MPDU is disallowed. This leads to medium wastage as the worthless A-MPDU pads have to fill up to the A-MPDU boundary.

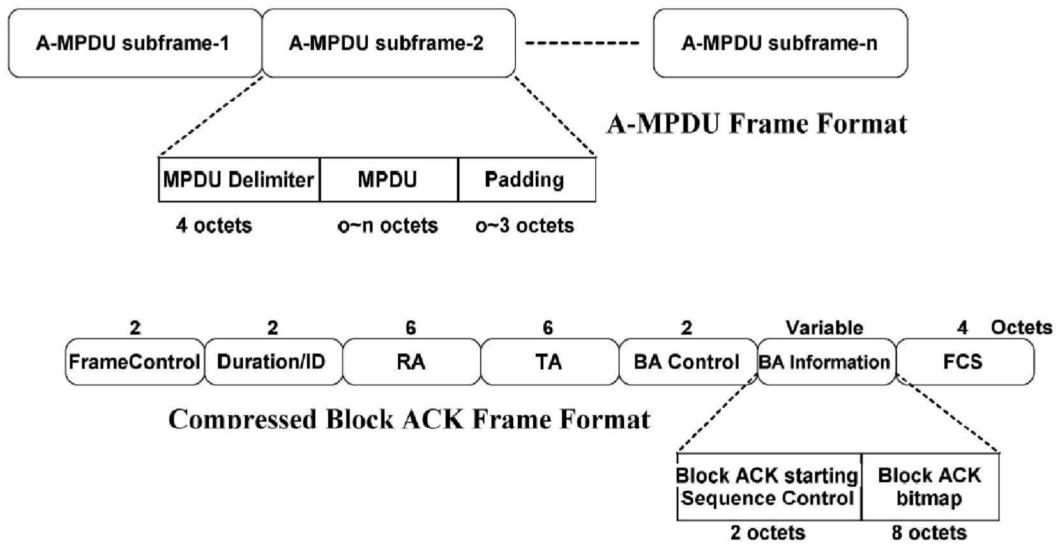


Fig A7.4: Frame Format of A-MPDU & Compressed Block ACK

B. ***PHY***

1) ***Transmission and reception of MU data streams***: The block schematic representation of VHT PHY layer with MU-MIMO support is shown in Figure-A7.5.

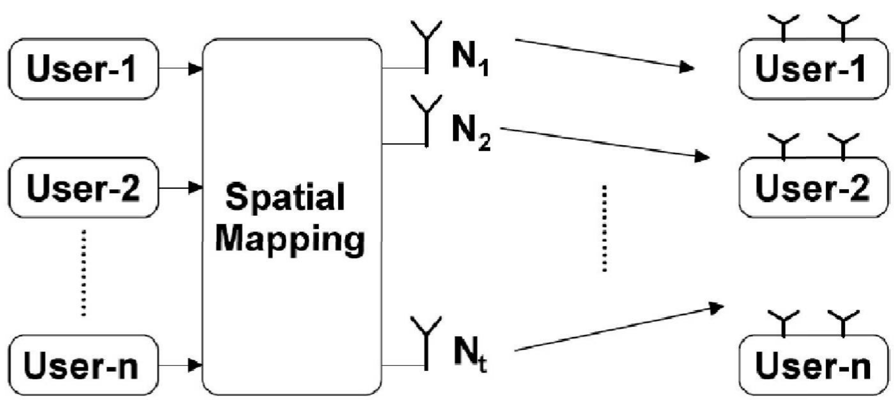


Fig A7.5: Structure of VHT DL MU-MIMO

Figure-A7.6 shows a simplified block diagram of a 2 user MIMO system.

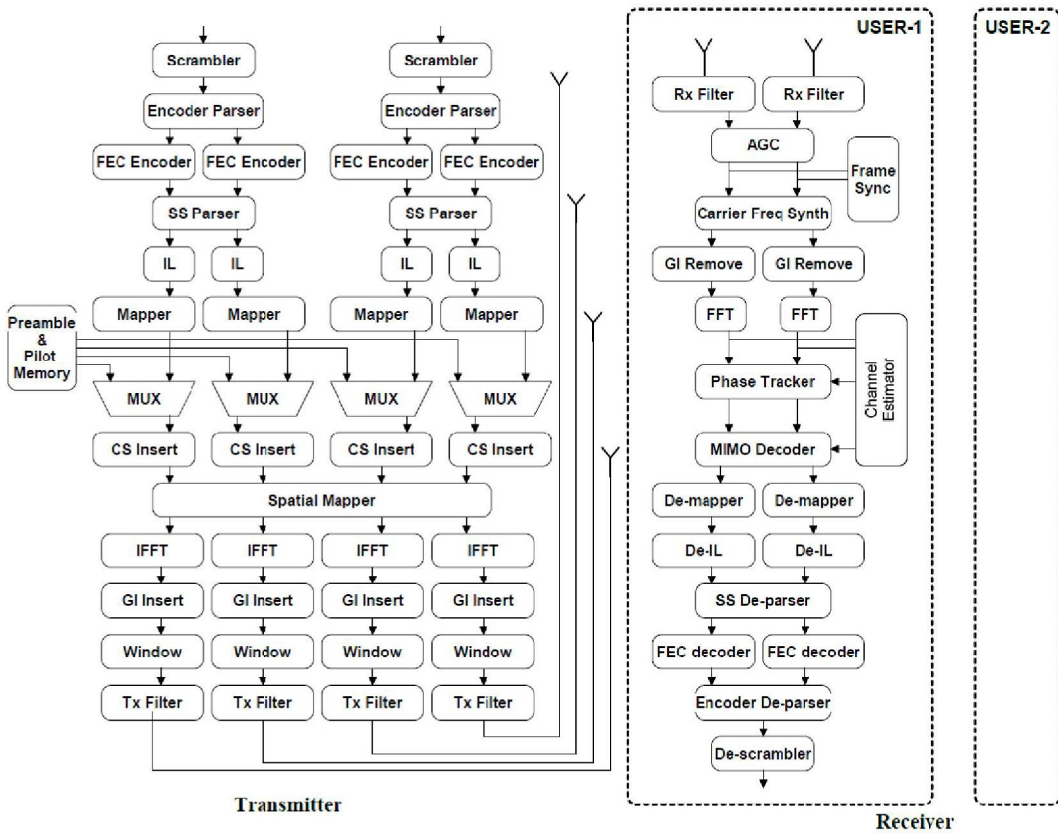


Fig A7.6: 802.11ac WLAN System architecture for 2-user case

- **Transmitter Structure**

Refer figure-6. During transmission, 802.11ac processes each user independently until the analog front end in the spatial mapper where these signals get joined. At this point, the steering matrix is applied.

- **Receiver Structure**

The figure-6 can be used while referring receiver details in the sections which follow.

2) ***VHT Packet Format [61]:*** The packet format of 802.11ac is shown in Figure-A7.7. The area that is not shaded is always one-stream and is transmitted omni-directionally. Multi stream is represented by the shaded area and it is precoded for DL MU-MIMO beamforming.

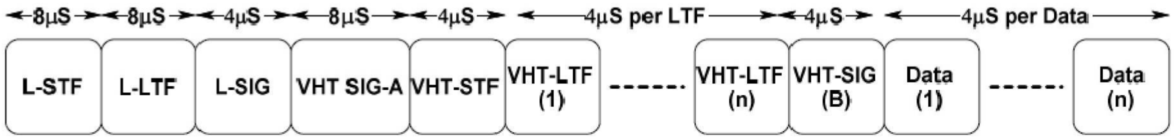


Fig A7.7: VHT Packet format for 802.11ac WLAN Systems

Legacy fields (LSTF, L-LTF and L-SIG) are all used for compatibility with legacy 11a/n devices.

VHT-STF: Used for MIMO data power computation.

VHT-LTFs: Used to compute the MIMO Channel. This information is either sent back to the AP during sounding or used for symbol detection when receiving a MU transmission.

VHT-SIG A: Used to notify participating STAs of the parameters of the directional portion of the packet in MU-MIMO beamforming.

VHT-SIG B: Information regarding user specific MCS value and DATA field lengths.

3) *Channel calibration/Sounding for MU-MIMO*: CSI is obtained from every related user, with the aim of identifying beamformees with orthogonal channel vectors. This results in total suppression of interference between the multiple streams directed towards the various users.

Figure-A7.8 shows the channel sounding and MU-MIMO transmission protocols defined in 802.11ac. When the AP performs channel sounding at a given time, it announces the beginning of a sounding process by transmitting an NDPA or null-data packet announcement. Post SIFS or short inter frame space the AP sends a null-data packet (NDP), in which each AP antenna sequentially transmits a known signal for channel estimation.

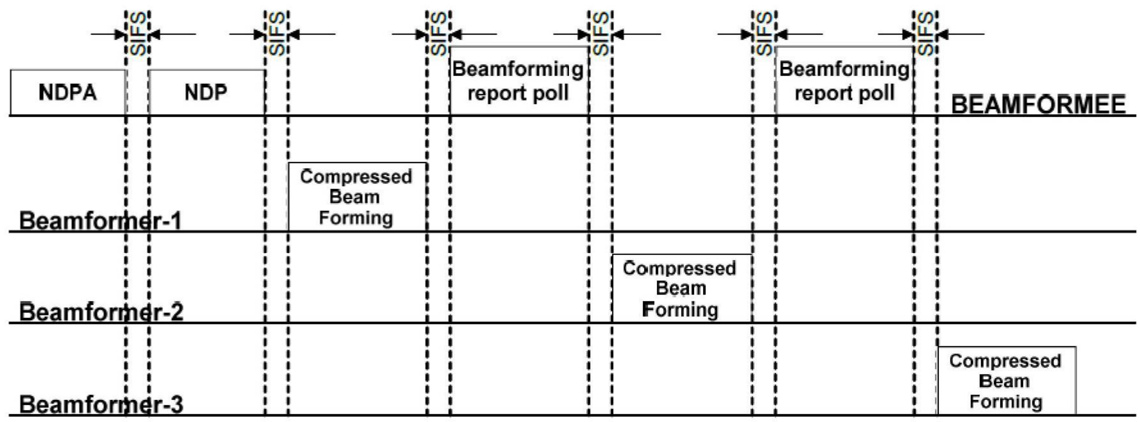


Fig-A7.8: Channel sounding in MU-MIMO Transmission

As shown in the figure, the multi-user mechanism necessitates a response from all beamformees, for which purpose, the Beamforming report poll frame is added. After a SIFS, a pre-destinated node feeds back the CSI. After a SIFS again, the AP polls a next node, and the polled node feeds back the CSI after a SIFS until there is no remaining node to be polled for CSI feedback. The multiple responses are combined by the beamformer resulting in a master steering matrix.

The NDP announcement frame, NDP frame and compressed beamforming action frame are same as in Transmit Beamforming. The 802.11ac MAC protocol defines capability (number of SS, MCS,..) negotiation for all the transmissions happening in parallel.

After the AP transmits packets to the primary and secondary users, the primary user transmits a block acknowledgement (BA) after a SIFS. Then, the AP transmits a BA request (BAR) for one of the secondary users after a SIFS, and the polled node transmits a BA after a SIFS until there is no remaining node to be polled. This is shown in figure-A7.9.

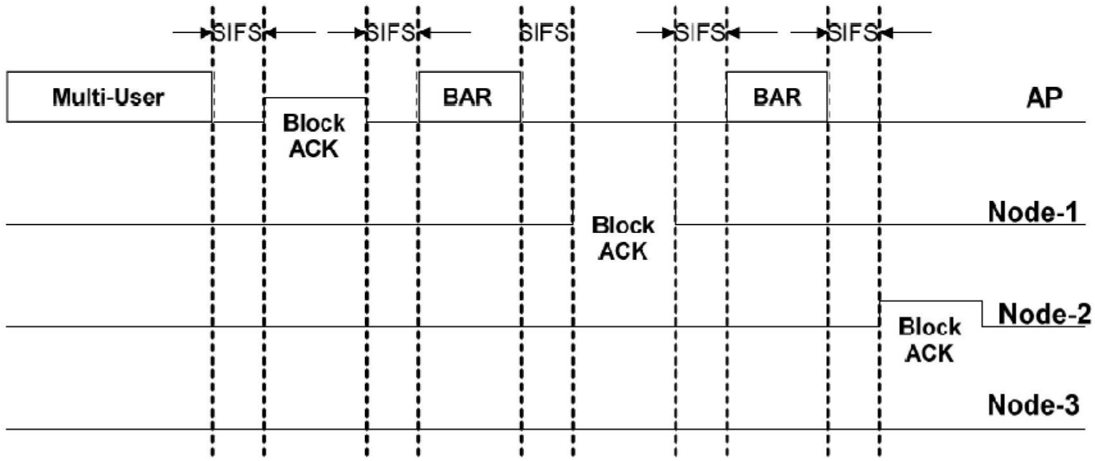


Fig A7.9: MU-MIMO Transmission

4) ***Precoding [61] [60] [59]:*** Precoding techniques majorly affect performance of MU-MIMO transmission. In this regard, there are two major classes of precoding namely, (1) non-linear (2) linear precoding.

(1) Non-linear precoding techniques are recognized to be useful for obtaining the maximum throughput possible. Examples are Tomlinson-Harashima precoding (THP), Vector Perturbation (VP) and Lattice Reduction Aided (LRA) methods. However, these techniques have a very high level of complexity due to the added processing required at the receiver and are also not supported by 802. 11ac.

Linear precoding techniques (Dirty Paper Coding (DPC), Zero Forcing and Block Diagonalization (BD)) on the other hand are low-complexity transmission techniques and are supported by 802.11ac. DPC accomplishes maximum capacity region in Gaussian MIMO medium. The MIMO broadcast medium's total capacity is the total of the capacity of individual users. DPC is capable of the best gain theoretically but its implementation in real time is complicated.

Zero forcing technique for MU-MIMO, does not necessitate knowledge of other users' media. It utilizes pseudo inverse of the existing user's media. This technique is uncomplicated compared to Block Diagonalization, but it is not the best one, because it does not annul the interferences from other users efficiently. However, Zero forcing technique is superior to BD when SNR is low.

BD, which is derived from zero forcing precoding, is a simple algorithm that can reach an aggregate capacity which is equivalent to what is achieved by DPC - with an implementation that is much easier than DPC. Here, the precoding matrix of individual user lies is in the unoccupied space in the channel of another user. A precise knowledge of channel matrix at transmit end enables zero interference at the receive end.

5) ***User selection*****:** Since user numbers are generally more than those that can be supported at Access Point, if users with worthy CSI are selected MU-MIMO system throughput will enhance. Favourable user may be identified by extensive investigation, although it necessitates computational intricacy for large number of users. Greedy user selection, a less complex algorithm, chooses a user per iteration. Complication of the algorithm and its output depend on user selection metrics like Frobenius norm (FN) or Chordal distance (CD).

6) ***Detection Mechanisms*** [61 Independent signals at the receiver will need to be identified using MIMO detection. Traditional methods include the well-known linear MMSE as well as the "vertical-Bell laboratories layered space-time" (V-BLAST) and Lattice Reduction Algorithm (LRA) decoders. V-BLAST and LRA techniques improve the performance of the simple MMSE-MIMO decoder. Another high performance MIMO detection algorithm is called the Maximum Likelihood Detection (MLD) algorithm. MLD algorithm has a very high level of complexity and is hence impractical.

APPENDIX-8: PUBLICATIONS BASED ON THIS THESIS

1. Ravindranath N S, Inder Singh, Ajay Prasad, Sambasiva Rao V, "Performance Evaluation of IEEE 802.11ac and 802.11n using NS3", Indian Journal of Science and Technology, July 2016, Vol 9(26),DOI: 10.17485/ijst/2016/v9i26/93565

2. Ravindranath N S, Inder Singh, Ajay Prasad, Sambasiva Rao V, "Study of Performance of Transmit Beamforming and MU-MIMO Mechanisms in IEEE 802.11ac WLANs", International Conference on Inventive Communication and Computational Technologies (ICICCT 2017), To be published in IEEE Explore, 978-1-5090-5297-4/17/©2017 IEEE

3. Ravindranath N S, Inder Singh, Ajay Prasad, Sambasiva Rao V, "Evaluation of the Effect of Rate Adaptation Techniques on IEEE 802.11ac and 802.11n", First International Conference on Smart Technologies in Computer and Communication, (SmartTech-2017), 27-29 March, 2017. Accepted for publication in International Journal of Computing and Applications - Serials Publications.

4. Ravindranath N S, Inder Singh, Ajay Prasad, Sambasiva Rao V, "Evaluation of the Contribution of Transmit Beam Forming to the Performance of IEEE 802.11ac WLANs", 1st International Conference On Smart Systems, Innovations And Computing" (SSIC-2017).

5. Ravindranath N S, Inder Singh, Ajay Prasad, Sambasiva Rao V, "Review of Scheduling Approaches used in WLANs", International Conference On Contemporary Engineering And Technology 2017 (ICCET 2017).

6. Ravindranath N S, Inder Singh, Ajay Prasad, Sambasiva Rao V "Study on MU-MIMO feature in 802.11ac using MATLAB", Approved for publication in International Journal of Engineering and Technology (IJET)

7. Ravindranath N S, Inder Singh, Ajay Prasad, Sambasiva Rao V "Proposal scheme for Scheduling in 802.11ac WLANs ", proposed to be submitted to SCOPUS indexed journal.