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A Novel Scheduler Framework for 802.11ac

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ABSTRACT
Due to the unpredictable nature of the CSMA/CA media access mechanism in WLANs and also, as WLANS operate in the unlicensed band, assuring time bound guarantees for multimedia applications has always been a challenge. Although schedulers have been proposed for WLANs, they have not met with the success witnessed in cellular networks. In this paper, we study the features introduced in IEEE 802.11ac WLANs and investigate if schedulers can be recommended for these wireless networks.
***Keywords**:* Aggregation, IEEE 802.11, LTE, MAC, MU-MIMO, PHY, scheduler, Transmit Beamforming, WiMAX, WLAN

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I. INTRODUCTION

Scheduler has not been defined for WLANs in IEEE standard unlike in Cellular networks. WLANs evolved from wired Ethernet meant for data networks. Cellular networks had to assure QoS guarantees for voice traffic. For this reason, scheduler design was a key component in WiMAX and LTE.

Later, with the highly successful IEEE 802.11 standard and with packet applications like VOIP, voice and video have been used as much as data in WLANs. However, the media access mechanism adopted in WLANs (CSMA/CA) extended from Ethernet, is not predictable compared to time division multiplexing in mobile networks. Time bound guarantees are not possible for multimedia applications. Also, as WLANs operate in the unlicensed bands, interference is a major issue. The protocol 802.11e meant for QoS has also not been extensively used for the same reason. All these factors have been causes for performance issues in WLANs. Although schedulers have been recommended for 802.11n WLANS in the literature, these solutions have not been very satisfactory and issues persist. The various scheduling techniques for WLANs discussed in literature were analyzed in [1]. In this paper a scheduler framework is proposed for 802.11ac.

The paper is organized as follows: The need for a scheduler is expressed in section 2. The performance improvement in 802.11ac is examined in section. Section 3 proposes a scheduler framework. This also draws lessons from schedulers and WiMAX. Also, the components of the scheduler are defined after examining in depth the new features such as transmit beamforming and MU_MIMO. The conclusions are derived in section 4.

II. NEED FOR A SCHEDULER

The need for identifying if QoS guarantees are possible in 802.11ac has been taken up in the conference on “The Future of Wi-Fi Technology: Looking Ahead to the Future” (Osama Aboul-Magd the Chair of IEEE 802.11 ac, IEEE 802.11 HEW SG) as early as 2012. The agenda for the discussion is expressed as follows: “***Improve real world performance in indoor deployments with interference and in moderate to heavy user loaded Access Points. Can WLAN really offer any QoS/QoE guarantees?"***

2.1 Current State of Advanced Applications

With 802.11ac, applications that were used earlier only over wired networks/ laptops are now possible to be used on mobile devices. Wireless displays - Tablets are as capable as laptops, but have smaller screens. As they become increasingly used for business, it should be possible to link wirelessly to LCD displays which are wireless-capable. Time-critical applications such as ERP, CRM, business analytics and stock trading offering real-time updates will be made possible because of the availability of 802.11ac at 5GHz. 802.11ac will be standardized for reliable and distortion free video conference. Special equipment or facility reservations will no more be required. Considering the requirements of these applications, it is advisable to design a scheduler which works with a cross layer approach (say, application layer and PHY layer) to meet the QoS guarantees.

2.2 Vendor Features

While there is no standard defined for a scheduler, most product vendors have added advanced functionality over and above the specifications defined. We shall take the sample case of Cisco and look at features which would have been, otherwise, handled by a scheduler. For Enterprise networks, WLAN Controllers are responsible for QOS, RF Management and mobility functionalities among others by working in conjunction with APs.

Radio Resource Management (RRM) software present in the Cisco Wireless LAN Controller plays the role of a manager to constantly monitor over-the-air metrics and control the RF transmitted. It measures Signal, Interference, Noise, Coverage and instantaneous user load on the network, RSSI and SNR - with which RRM can periodically reconfigure the 802.11 RF network for best efficiency. This is achieved with Radio resource monitoring (for collecting the metrics), Transmit power control (adjusting for optimal power levels) and Dynamic channel assignment—Ensuring that channel assignments do not overlap.

Cisco tool (Clean Air technology) provides IT Managers information on the wireless spectrum in order to handle RF interference and avoid unexpected downtime. Cisco Video Stream technology enhances robustness of voice with CAC. Dynamic Bandwidth Selection (DBS) has the ability to use multiple channels together as a single assignment on a given AP. Bonding channels—using multiple single channels to create a single super channel—has the advantage of providing more usable throughput to a client with the capability to use the channel. DBS assigns appropriate channel widths to APs to dynamically balance the bandwidth selection for the types of clients and traffic that each AP uses. DBS allows appropriately sized bandwidth to be used for the clients being served, avoids wasting multiple channels for devices that likely could not use the added capacity, and avoids the associated interference created by those devices. Therefore, considering that that all the above features can be handled better by designing a framework which holistically addresses the issues, we find a need for a scheduler.

2.3 Performance in 802.11ac

Regarding performance in WLANs, QoS and Interference have been the bottlenecks since years. We shall discuss how 802.11ac improves on these in the next two sections.

2.3.1 QoS

From the results in [2] it is seen that in comparison with 802.11n, even at 40 MHz, marginal improvement is present for QoS parameters at higher values of MCS. With higher bandwidths (80 and 160 MHz), 11ac cannot be compared with 11n, but the real benefits of 11ac are visible now (again with 256 QAM also available) in the case of all parameters - throughput, delay and jitter. Higher BWs and enhanced MCS permit a scheduler to be designed to better regulate QoS. The real controlling power for the scheduler is brought about by having more spatial streams which was one of the reasons why schedulers were not successful with earlier WLANs.

Rate Adaptation mechanisms are not defined in IEEE 802.11ac. Moreover, unlike in cellular networks, where link adaptation and power control is clearly defined, RA schemes are loosely coupled to the main system flow in WLANs. Hence, there is a need to integrate RA with the scheduler for performance improvement.

Transmit Beamforming and MU_MIMO are considered to be major innovations in 802.11ac. Transmit beamforming (TBF): In TBF, an array of antennas are used to transmit with high gain to the 802.11 client, resulting in higher downlink signal-to-noise ratio (SNR), higher data rate over a longer range, and hence better overall system performance. It is demonstrated that if a receiver can be a beamformee, the SNR can be enhanced with transmit beamforming as weighed against transmission with spatial expansion. The increase in received power with beamforming can result in more reliable demodulation or even a higher order MCS can be utilized for the transmission. While Transmit

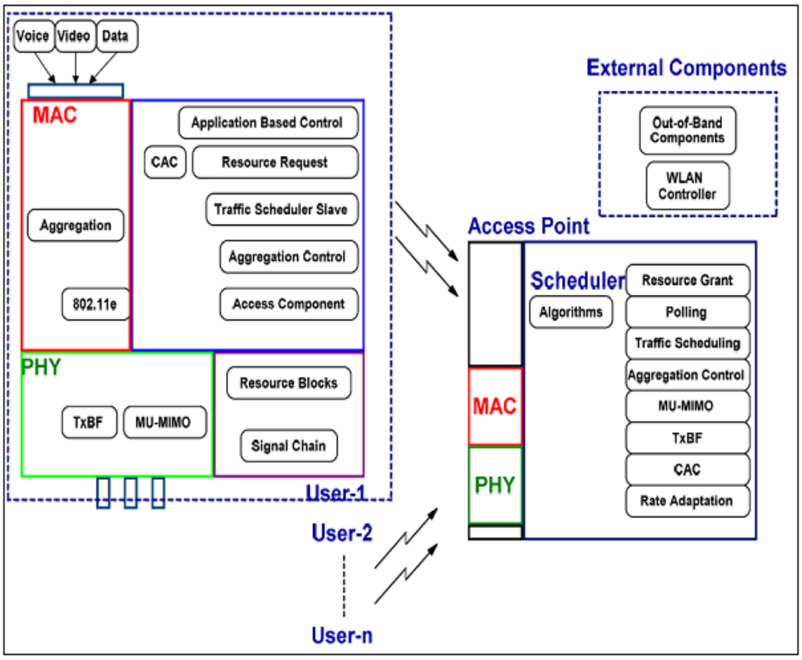

Fig 1 Block Diagram of the Proposed Scheduler

Beamforming has an advantage of increasing the range, this is more pronounced when communication is between devices separated by a distance in the mid to long range. In scenarios where the STA drifts away from the AP, the scheduler can decide on which solution is best suited for the current situation - increasing the transmit power, changing MCS or using beamforming.

MU-MIMO: With 802.11n all data transmission from the AP was only to a single client. When servicing mixed speed clients, service to high speed clients was delayed by the transmission to low speed clients. The MU-MIMO feature in 802.11ac introduces multiple spatial streams (SS) distributed (maximum of four streams) between the clients. Multiple clients can be serviced simultaneously; hence congestion delay is not an issue. Therefore, latency and also throughput can be increased for multimedia applications. The scheduler can, consequently, be better designed to assure QoS for advanced applications and also regulate the spatial streams better – all of which benefits were not available to an 802.11n scheduler.

Thus, 802.11ac has been verified to be superior in performance compared to the existing WLANs. MCS, CBW and SS, TxBF and MU-MIMO features are verified and compared to 802.11n. Thus we can conclude that individual benefits from independent features are good and can aid in working towards QoS improvement. However, recommending a scheduler for 802.11ac which combines these benefits will further assure in providing QoS guarantees.

2.3.2 Interference issues in WLANs

Sources of Interference: Potential interference in WLANs can be classified into two broad categories. First, interference from other WLANs which is experienced by residential users, especially in high-density housing. Secondly, interference from non-WLAN traffic in the bands used by WLANs at 2.4 and 5 GHz. This includes a wide variety of cordless phones (both Wi-Fi and non-WiFi), Bluetooth devices, wireless video cameras, and cordless headsets and other P2P and P2MP links, cordless video-game controllers and microwave ovens. Interference management is quite critical in WLANs as they operate in the unlicensed spectrum.

Interference Mitigation in 802.11ac: 802.11ac, operating exclusively in the 5GHz range, avoids the congested 2.4GHz range that can experience interference from microwave ovens and other devices. 5 GHz band: More channels translate to larger bandwidth and permits the RF link to be flexible to switch channels in event of interference. Globally about 37 channels are defined in the 5-GHz frequency ranges which were not used for wireless either because they are used for applications or they are not permitted for wireless. Now with the advent of 802.11ac Wave-2 these channels have added to the WiFi bandwidth supporting speed and more clients/applications.TBF can thus be thought of as directing a beam using phase shifts towards a particular receive antenna. As the TBF technique can converge or cancel a beam by introducing appropriate phases, it can apply the same concept to cancel interfering signals in the direction of the receiver. TBF, using feedback and precoding, optimizes the communications between APs and clients to counteract interference

III. PROPOSED FRAMEWORK

3.1 Components of the Scheduler

Figure 1 shows the block diagram of the proposed scheduler.

This can be a stand-alone block functioning with the MAC and PHY subsystems and consisting of the following components:

3.1.1 Aggregation control can be used for applying vendor specific aggregation algorithms and more specifically, in combination with other approaches (discussed below).

3.1.2 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 conditions: a) There is bandwidth available to accommodate the new connection, without adversely affecting the connections already admitted. b) Both bandwidth and delay characteristics of the connection can be met. The methodology followed to achieve CAC in WiMAX is discussed.

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 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.

3.1.3 Application based control

i) *QoE based scheduling*: Providing QoE during streaming of video in WLANs is mandatory for good reception at user end. Normally, the scheduler fixes the priority in scheduling of the queued packets before transmission.

Algorithms such as Earliest Deadline First (EDF), gradient-based scheduling algorithm (U'R) and the Modified Largest Weighted Delay First (M-LWDF) mechanism support throughput but not QoE. Hence, they are not the best choice for video streaming. QoEAS or QoE-aware scheduling mechanism [3] is derived from U'R. A factor derived from three parameters discussed in the following is used for scheduling. Packet importance index derived from the slope of video QoE function, and it indicates the importance of the packet in improving quality of video. It is derived at the APP layer and inserted into the IP header's ToS field. Packet delay is a utility parameter defined for streaming of video which is delay-sensitive. Current status of channel is done using a link model. At the MAC layer, the above three factors are all taken into consideration by the scheduler and then a packet is selected from one of the queues followed by transmission.

ii) Synchronized Time: Synchronized time facilitates exact delay measurements in both directions. It is now possible to get this easily as NTP is deployed in a large scale and precise time sources such as GPS receivers are available. As per ITU-T G.114 recommendation, delay in one-way is maximum 150 milliseconds. NTP is deployed at each end and RTCP sender reports link the RTP time stamps to absolute time. RTCP packets also help senders in determining the RTD time. In a round trip, if the environment is time synchronized, then the sender will be able to estimate the received packet delay from the RTCP sender and receiver reports. Hence, with the information of RTD also, it is possible to estimate delays for the to and fro trips. When many VoIP calls are routed through the same AP at the same time, one-way delays normally vary to a great extent. For instance, with calls over long distances with Wired Network Delay (WND) >100ms, the total one-way delay may go beyond150 mS as recommended by ITU-T G.114.

Problem: 802.11e supports to a certain extent functions like VOIP where QoS is critical. Still, it is prone to congestion and packet losses, resulting in delays. All VoIP sessions have dissimilar one-way Mouth-to-Ear (M2E) delays which may also vary. In spite of this, they compete with each other using the equal prioritization AC, as per the 802.11e standard.

Solution: It is proposed in [4] that if delay in one leg, of VoIP session data can be determined for both directions, we can set EDCA parameters in a different way between two VoIP sessions. Basically, priority assignment is done to voice sessions in the VO AC. In sessions where R-factor is high and one leg delay is small, packets waiting time at MAC layer may be more, subject to the fact that they are conveyed within a period that will not reduce their QoS remarkably. Conversely, a VoIP session having long network delay will have a reduced MAC layer contention delay due to prioritization. Hence the voice session will have a reduced one-way delay. Compared to the existing 802.11e EDCA mechanism, an improvement has been shown and one can discriminate between VoIP sessions.

3.1.4 (Medium) Access control component

TXOP: Variety of algorithms has been recommended for schedulers which vary TXOP parameters for improving performance. For example, in [5], based on Queue length, the TXOP limit can be varied for achieving better QoS performance for multimedia services.

TXOP sharing: Algorithms can be designed to enhance this component so that fairness can be assured to multimedia applications for multiple users in a MU MIMO scenario in 802.11ac WLANs [6], [7], [8], and [9]. In [7], it is proposed to enhance the TXOP Sharing mechanism, to obtain improved DL-MU-MIMO transmission and to gain advantages with respect to throughput and channel utilization.

Backoff Mechanisms, NAV: These parameters can also be controlled by the scheduler depending on the scenario. The approaches mentioned in the papers below give an idea of how the standard can be improved and the newer algorithm could be applied to meet the desired requirement of a scenario. In [6], a revised backoff procedure for secondary ACs is discussed. It is seen that the proposed backoff mechanism in [10] performs better, with respect to fairness, as compared to the conventional backoff mechanisms. In [11], a two-level NAV mechanism is proposed with only minor changes to the standard and it is demonstrated that the proposed mechanism achieves better throughput when evaluated against the usual NAV method. In [7], a modified backoff procedure is designed for the primary AC.

3.1.5 Traffic scheduling approaches are discussed in [12].

3.1.6 Polling and 802.11e: 802.11e should be tightly integrated into the scheduler framework and this is a subject matter in itself. An example of how a novel polling technique called Channel Access Throttling (CAT) enhances QoS is described in [13] by enabling scheduled fine-granularity based QoS policy.

3.1.7 Resource Request and Resource grant is one of the principal reasons why cellular networks achieve satisfactory QoS. The BW Request and BW grant mechanism helps in negotiating QoS demands before actual transmission. The decisions are taken to grant BW or admit the connection (CAC) after the scheduler analyzes the resource availability and current status of requests. Again, in the PHY layer, the resource blocks are of fine granularity and hence resources (spectrum, powers, MCS, etc.,) are very optimally utilized. These approaches if taken forward and integrated into the WLANs, will go a long way in assuring QOS guarantees.

***i) 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 on media conditions 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.

***ii) Scheduling in LTE*:** During scheduling in LTE [14], the eNodeB decides which 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 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. ½ ms 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.

***iii) 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. The details on network entry maybe available in literature on WiMAX.

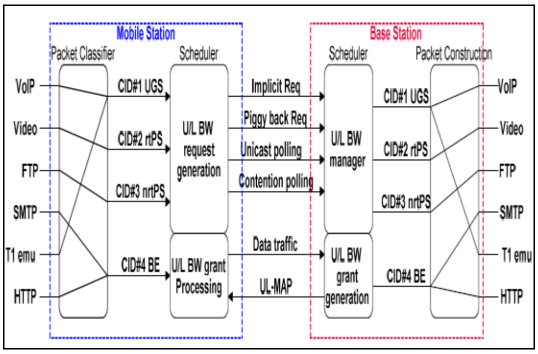

Fig 2: Uplink Data Flow (MS-BS) Process

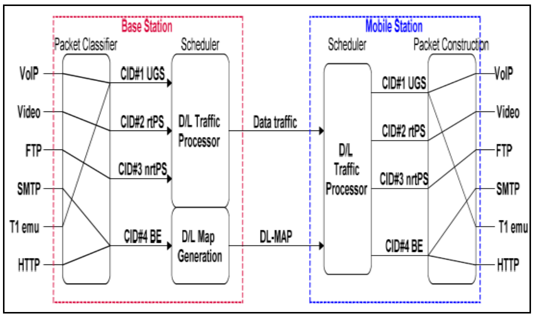

Fig 3: Downlink Data Flow (BS-MS) Process

Figures 2 and 3 show the data flow process in uplink (MS-BS) and downlink (BS-MS) respectively.

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.

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).

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

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.

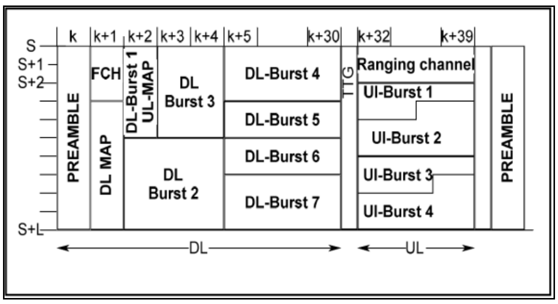

Fig 4: 2D view of the OFDMA Frame

As seen in Figure-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.

iv) PHY layer scheduling in WLANS: In [15], to maximize system performance, a new solution with 802.11 PHY and MAC layers is designed with multiuser channel access and a dynamic sub-channel assignment based on traffic priority. The sub-channel scheduling access can be viewed as choosing the best set of users to allocate subcarriers according to their CSI. Two ways to merge these concepts in WLANs are discussed in Approach-1 and Approach-2 in sections below.

PHY Layer Scheduling

Approach-1: Problem: In DCF all contending stations are offered equal opportunities in a distributed way, and thus it is highly appropriate for BE traffic. Conversely, because of the same contention and unpredictable characteristic, it is inappropriate for transmitting traffic having QoS requirements. As the operational frequency range of WLANs is unlicensed, it is difficult to predict the other existing sources of signals which can cause interference and hence QoS is not assured. However, demand for transmission with QoS guarantee is constantly rising. Issue with DCF is that it inefficiently utilizes radio resources. Here, once a STA gains a TXOP, the STA occupies the radio resource which becomes unavailable to other STAs until released.

Solution: A transmission scheme with multiple-users using OFDMA is introduced [16]. An AP controls all STAs in the BSS. Radio resource is reserved for some time, using DCF. Fine-grained RB or resource blocks are utilized to make access control flexible. Resource block is the radio resource's minimum allocation unit in a 2D plane characterized by time and frequency domains. AP has K back off counters, and none of the stations has a back off counter. Once any of the K back off counter's value becomes zero, Access Point sends in broadcast mode, a RTS frame. The individual STAs respond with CTS as per the sequence in RTS. The CTS from each STA holds CSI of its own STA and the QoS required by the application. Using the CTS information, the AP manages to reallocate the RB for DL transmission, and conveys this by sending DL-ARBI or Down-Link Assigned Resource Block Information frame. Next, the Access Point sends DL data frames to many STAs in the resource blocks allocated. Individual STA responds with a 'DL ACK' to indicate whether the DL-DATA frames are successfully transmitted or not.

The STAs also renews their requirement for QoS and CSI using DL Acknowledge (DL-ACK) frame. This information is utilized by Access Point to allocate resource for UL transmission, and notified in the UL-ARBI or UL Assigned Resource Block Information. The STAs now send UL-DATA frames to Access Point using the RB allocated to them in UL-ARBI. AP now transmits in broadcast mode, UL-ACK frame and then releases the allocated resource.

Resource Allocation Algorithm: A heuristic resource allocation scheme is proposed and implemented for WLANs comprising real-time (RT) and non-real-time (NRT) traffic. The aim is to enhance the spectrum efficiency and simultaneously meeting RT traffic's QoS requirements. A STA having RT traffic and one with NRT traffic are referred to as “RT-STA” and “NRT-STA”. (1) RB generation. (2) Allocation of sub-channels for individual RT-STAs. Data from RT-STA is time-dependent and satisfies time delay criteria normally. Hence, RT-STAs are given priority during resource allocation. Using the EDF algorithm, the Access Point chooses the RT-STA which has a lesser TTL or time-to-live remaining and assigns to this RT STA a sub-channel having largest SNR. (3) Sub-channels not allocated in (2) are allocated to NRT-STAs in (3). Here also the sub-channels having largest SNR are individually assigned to the NRT-STA in order to optimize utilization.

Approach-2: A resource allocation algorithm termed QoS-aware dynamic resource allocation algorithm (QDRA) is recommended [17] for the DL transmission in an OFDMA and WLAN integrated system. A channel comprising numerous sub-carriers within an allocation period is known as a sub-channel. Allocation time slot is the time period for the resource allocation process. While the process of allocation takes place, Access Point assigns sub-channels for delivering frames to STAs and verifies the amount of transmit power permitted. The decision on allocation is done when each time slot starts. It is assumed that the AP has information on the CSI, available spectrum and QoS request of the user.

The aim of the optimization is to achieve maximum data rates and also that both real time and non-real time users have their QoS requirements satisfied. Users are not allocated channel resource based on the highest data rates but according to their needs. The three steps involved are:

(i) QoS requirements convert: All the QoS requirements (BER, time delay and data rate) of each user are converted into various rate requests at the start of the allocation period. *(ii) Priority determination*: Received rate requests are sorted in descending order for users. A user having the highest rate request gets the topmost priority while spectrum is being allocated. For RT user, highest rate request stands for packets which will be sent at the shortest time. *(iii) Sub-channel assignment*: When sub-channels are available, they are assigned

to RT users. For NRT users, as long as there are available sub-channels, they are assigned. When the RT user has to wait for a long while, the user can select sub-channels before the NRT users.

Sections 3.1.8 to 3.1.10 are explained using figure 5.

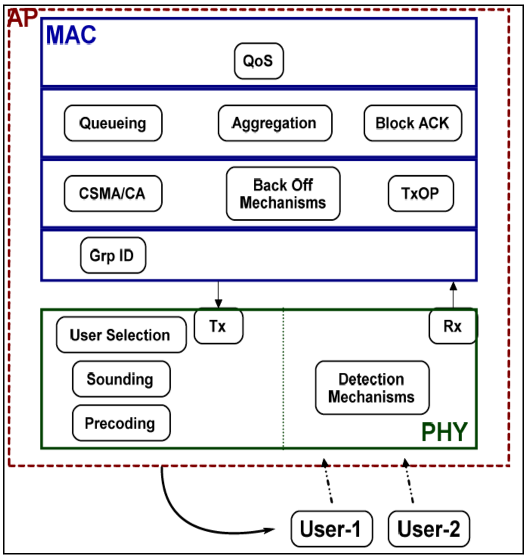

Fig 5 - TXBF/MU-MIMO Subcomponent

3.1.8 Transmit Beamforming: Feedback and quantization algorithms are factors which delay the Transmit Beamforming mechanism. Algorithms can be integrated to the framework and used based on the scenario. Two such examples are mentioned below.

In [18], a technique "time domain quantization" is introduced wherein there is a feedback of time domain parameters which are required to form the beamforming matrix at the transmitting end. It is proved that TD-Q reaches the same sum rate capacity of the conventional Givens rotation quantization GR-Q and requires less amount of feedback.

Reference [19] proposes a method of transmitting precise channel estimation to the transmitter which requires this to enable the calculation of precoding vectors. Since there is a huge amount of channel coefficients that is required for feedback, limited CSI feedback works out to be an advantage. This scheme permits both the feedback accuracy to be better and the amount of feedback to be decreased as well.

3.1.9 MU MIMO - Precoding, Detection and user selection mechanisms: The different mechanisms are BD, RBD, SVD, CI and ZF. The choice of which algorithm to incorporate, needs to be selected by the scheduler based on the situation. The pros and cons of different mechanisms have been verified in the papers below, followed by detection mechanisms.

Precoding: Interference cancellation is the main goal of precoding algorithm. Due to its good performance and low complexity, Block Diagonalization (BD) precoding algorithm is widely used in MU-MIMO schemes. However, it also has obvious defects: the ignoring of addictive Gaussian noise and the restrictions of antenna dimensions (i.e. number of receiving antennas < number of transmitting antennas). In [20], an algorithm called Regularized Block Diagonalization (RBD) with signal space diversity (SSD) is proposed using constellation rotation and Q-component interleavers to optimize the MIMO-OFDM, channel coding and modulation together.

Study of Precoding Mechanisms: In [21], the performance of channel inversion (CI) and BD with limited CSI and compressed feedback are analyzed. The results evaluate the achievable sum-rate between the user selection metrics and present the PER performance. Using the simulations, it is seen that superior data rates are achieved by greedy user selection algorithm and low complexity precoding schemes. BD performs better compared to CI with respect to packet error rate on using compressed feedback. [22] Discusses the maximum capacity that can be obtained with BD and zero forcing (ZF) in MU-MIMO and singular value decomposition (SVD) based precoding in SU-MIMO.

Detection Mechanisms: [23] proposes to detect the SS in 802.11ac device using (2×2), (4×4), (8×8) MU-MIMO systems using some of the MIMO detection algorithms. Here, the objective is to evaluate the effect of Detectors/Interference Canceller (IC) like ZF, MMSE and the proposed ZF-Successive IC (SIC) with Optimal Peak Power Ordering (OPPO), ZF-SIC-OPPO on the performance of 802.11ac. The result of the proposed ZF-SIC-OPPO was weighed against the existing mechanism. The OPPO method for ZF -SIC showed enhanced performance in both the SNR and BER. ZF-SIC-OPPO detector outperformed ZF and MMSE with the lowest BER for a MIMO (8 × 8) 802.l1ac system.

3.1.10 MU MIMO-Sounding: The algorithms (and similar others) described below which overcome inherent limitations in Sounding mechanism can be implemented and controlled by the scheduler, when required.

In practice, the beamformer has to compromise between the frequency of sounding and CSI accuracy. In [24], the evaluation of a downlink MU_MIMO sounding protocol coined Multi-User Transmission enhancer (MUTE) is presented which decouples the sounding set selection (utilized in collecting CSI) from the transmission set selection, thereby helping in reducing the sounding overhead and simultaneously selecting the best users. At the same time, adequately accurate data regarding users' channel statistics is given to the Access Point.

The sounding overhead may severely degrade the performance of a WLAN. In [14], a comprehensive sounding control scheme for IEEE 802.11ac MU-MIMO is proposed which considers broadly the sounding control needs of the network environment, including channel coherence times, nodes' DL traffic loads, DL SNRs, etc.,. The sounding node set and sounding interval to maximize the MU-MIMO throughput are jointly determined.

In MU-MIMO, the AP selects both the user set and the mode and after completing sounding and before commencing transmission. Thus, optimal user groups are selected given full CSI of a set of potential receivers (which is a major overhead) or through intermittent probing. In [25], Pre-sounding User and Mode selection Algorithm (PUMA), an algorithm for selecting user and mode earlier to sounding is designed, implemented and evaluated. After PUMA chooses the suitable mode and user group, the selected protocol's sounding mechanism is applied on the intended user subset for actual data transmission.

3.1.11 Combination approaches: It is seen that MU MIMO and TX BF have finer levels of control which the scheduler makes use of before a feature or combination is derived. For example, when applying TXBF, algorithm using Precoding variants, an improved Sounding and Aggregation scheme may be decided so that the solution will provide optimum QoS for the present flow as also other existing flows. The real need for a scheduler is seen in the cross layer /combination between components approach.

i) Aggregation Related: MU-MIMO in combination with aggregation improves performance considerably. [26] Compares the performance of two DL user multiplexing schemes: MU-MIMO and frame aggregation. If each user's encoded data stream has a similar length, the MU-MIMO achieves better throughput compared to aggregation. Conversely, if different lengths are present, the reverse is true. In a fast-varying channel, because of the overhead of channel feedback, throughput of MU-MIMO is lesser than frame aggregation.

The MU-MIMO combined with aggregation can improve performance considerably. If the frames in different SS have differing transmission times, the space channel time occurs .This is a period wherein data is carried by certain SS whereas the others do not have data. Due to space channel time, DL MU-MIMO channels transmission efficiency degrades. Reference [27] proposes a combination of packet aggregation and MU-MIMO to augment the system performance. WLANs implement multi-rate transmissions using Adaptive Modulation and Coding (AMC) to realize transmission channel adaptation. The paper, in addition to addressing the space channel time also considers AMC and VoIP transmission in aggregation mechanisms.

Aggregation for VoIP: In the proposed scheme in [28], the Access Points uniform the transmission times of frames to the optimum extent on all the SS to the different Mobile Terminals considering their MCS level. Consequently, the scheme can reduce the space channel time for the VoIP packets transmission within the allowable delay limitation.

Combination of Aggregation and MU-MIMO: [27] proposes a combination of packet aggregation and MU-MIMO transmission to improve performance of the system. The technique adopted is: (a) RTS/CTS handshake is used to signal the selected Stations as well as for channel sounding, (b) quantify the gain possible due to aggregation and the influence of the size of the buffer on the attainable throughput (c) decide on buffer size to optimize performance.

If the number of stations is very large, due to the heterogeneity of destinations, complete benefit of packet aggregation is not realized. With a larger queue size, the throughput is enhanced - although it is at the cost of resulting in an increased delay.

Efficient Aggregation Scheme-Problem: To achieve efficient frame aggregation in downlink MU-MIMO transmission, we have to consider transmission efficiency in each SS channel. Different transmission time between frames on different SS causes space channel time for reducing which parameter, the data size based frame aggregation scheme has been proposed. This scheme uniforms the amount of data size carried in the wireless frame on each SS channel. Under multi-rate transmissions, however, wireless frame duration (time length) generally differs between SS, and then, the space channel time arises in this scheme. Solution: [29] has proposed the efficient frame aggregation scheme for DL MU-MIMO transmissions which enhances system throughput and decreases frame error rate. Here, the receiving MT selection gives higher priority to MTs achieving higher throughput in the next MU-MIMO transmission while reducing signaling overhead, resulting in an improvement in throughput. The wireless frame setting in the proposed scheme, introducing hybrid frame aggregation method, provides lower frame error rate than acceptable level by using frame size adaptation. Conclusion: The transmission performance and its fairness between MTs have been evaluated though system-level simulation. From the results, the proposed scheme greatly improves both performances, compared with the conventional frame aggregation schemes.

In [30], a new solution with 802.11 PHY and MAC layers is designed with multiuser channel access and a dynamic sub-channel assignment method based on traffic priority. Here, selection happens, of the best set of users where they are allocated subcarriers according to their CSI. In [30], the authors have offered a distributed solution using which optimal scheduling can be determined in a practical system. The objective of the RA scheme is to choose the optimum set of transmission parameters for a given user bearing in mind the channel quality. In particular, the designed approach can support QoS traffic over an OFDM-based network. Assuming information of the channel gains for all users, an adaptive multiuser OFDM sub-channel allocation and modulation solution is proposed. A smart solution is designed for high-density wireless environments, such as airports, campuses, sports stadiums, etc. In addition, efficient resources are allocated for multiuser OFDMs over frequency selective channels with data and user priorities.

Conclusion: The algorithm was evaluated using NS-3 in a multiuser frequency selective fading environment with different time-delay spread values. It is seen from the results that the recommended solution leads to a RT aggregation model with a stable throughput. It surpasses traditional multiuser OFDM systems with static TDMA or FDMA methods, which use fixed and predetermined time-slots.

***Aggregation for VoIP*:** A frame aggregation scheduler is proposed [31] which manages QoS for RT multimedia applications (for instance - video streaming) by combining 802.11e differentiation and frame aggregation.

Joint urgency delay scheduler and adaptive aggregation technique [32], implemented in the AP realizes a compromise between maximizing throughput and minimizing delay. Frames from voice, video, and streaming sources will be mapped into Access Categories based on Enhanced Distributed Controlled Function scheme defined by IEEE 802.11e. New scheduling metrics defined are urgency delay (UD) and waiting delay (WD). Packets with the least UD are included first in the aggregated frame following which the aggregated frame's payload size will be adjusted.

***ii) Transmit Beamforming*:** As with other 802.11ac features, [33] beamforming also shows modest performance improvement, and it should be combined with other techniques to realize spectacular performance enhancements.

iii) Precoding with Detection Techniques: Selecting the correct combination of precoding and detection mechanism by the scheduler will provide the ideal solution for the appropriate situation. In [34], the performance improvements under realistic channel conditions are measured when BD and CI are paired with various MIMO detection techniques. It is observed that high performance MIMO decoders such as LRA MMSE decoder improve the uncoded BER performance of the BD precoding. On the other hand, it does not improve the uncoded BER performance of the CI precoding. The effective channel matrix of the BD precoding is a block diagonal matrix. Hence MIMO decoders can benefit from the diversity present in the inter stream interference within a single user. The PER performance of each MU-MIMO transmission methods is considered when MIMO decoder is changed. Thus, it is seen that (1) the PER performance of the BD precoding can be improved by the MIMO decoder and (2) the BD precoding is more effective compared to CI precoding.

In [35], a unified performance evaluation of five transceiver configurations implementing MU-MIMO in 802.11ac is done: BD+ZF, BD+MMSE, CI+ZF, CI+MMSE and RI+MMSE. It is seen that while RI-MMSE schemes is optimum for low SNR region, impact on achieved performance parameters when SNR is good, is negligible.

iv) While *STBC feature* is built to operate in open-loop mode, TBF operates in closed-loop mode with AP supporting one STA in the SU-BF mode and many STAs simultaneously in MU-BF mode. If a station cannot perform closed-loop beamforming, data transmission from AP should be by STBC. With SU / MU-BF, variation of channel parameters with time leads to degradation. Sometimes, STBC can yield higher throughput compared to BF even in the absence of feedback in the channel. When the amount of data to be transmitted is not huge, feedback turns out to be an overhead. In such cases, open-loop BF is a better choice compared to the close-loop BF.

3.1.12 Cross layer Approach: Some examples are provided below:

i) In [36], *A multi-traffic scheduler with genetic algorithm (GA)* is proposed, which seeks to improve QoS, taking into account both traffic and status of the channel. The APP layer of AP generates different traffic types which is categorized in MAC and buffered in memory queues in FIFO manner. When the packet wait time in the queue gets larger than the delay limit of the packet, it will be dropped.

When scheduling commences, AP initially detects queue length for every type of traffic. It then offers an opportunity for scheduling the queues that are not empty. Next the AP obtains from STA, feedback of CSI and CQI i.e. channel state and quality information. Prior to scheduling a frame, the scheduler estimates traffic QoS using queue and channel information, traffic QoS requirements and priority. The problem is of selecting the optimal traffic slot in the frame (MAC layer) where delay satisfaction, packet loss and data rate are considered. GA, a widely used random search technique learnt from the principles of evolution (i.e. survival of fittest), is used to reduce the search time for obtaining the optimal solution.

ii) Scheduler for 802.11ac**:** By far, the most complete Scheduler for 802.11ac is explained in [37]. Here, a framework which considers link adaptation in networks supporting MU MIMO-OFDM, with restricted feedback and combines precoding, sounding and mode selection. The link adaptation problem is formulated as a maximization of the sum rate subject to a FER constraint. The two steps involved in the approach are:

Step-1 CSI Acquisition**:** This mechanism is described in the 802.11ac standard .(A) Sounding: Here, the AP sends a VHT NDP announcement control frame (NDPA), which consists of the set of users going to be polled. The frame, in addition, also includes information on the requested feedback (single user or multiuser—SU/MU). The AP next sends an NDP. (B) Quantization and Feedback: The CSI obtained by each user is first quantized. The main pertinent parameters for the MU-MIMO operation are the preferred beamforming matrices which are represented using Givens decomposition. The first user in the NDPA list estimates the channel and transmits quantized feedback information, and the remaining users (if any) transmit their CSI by replying to future beamforming (BF) report polls. Based on the limited feedback obtained, the AP performs link adaptation.

Step-2 Link Adaptation**:** The four blocks of link adaptation are:

(A) Block Diagonalization (BD) Precoding: The precoders are based on BD. This precoding removes the interference between the different users but not the interference between streams associated with the same user. *(B) Quantization*: The presence of limited feedback caused by the quantization procedure generates unknown interference leakage (IL) among the multiple users. As the post-processing SNR is dependent on IL, it is required to estimate this parameter. It is preferable to do this at the transmitter, without the receiver sending feedback. A closed form approximation of the inter-user IL is derived from BD precoding with zero forcing (ZF) receivers. This is simply calculated at the transmitter by means of statistical characterization of the quantization error and is found to be very accurate for different feedback rates. *(C)MCS selection*: Features derived from the channel are classified into the highest MCS that meets the target FER constraint. A supervised machine learning approach is used which includes the following tasks: Feature Extraction and Classification. *(D)User and Mode Selection* is done using a greedy algorithm which makes use of information on the SNRs, the feedback rate and the number of users.

3.2 Description

The procedure described below should be integrated with WLAN Management frames such as Association, Authentication, Probing, etc., During capability exchange, additional information such as Precoding and detection algorithms used, etc., in the STAs should also be conveyed which the scheduler will make use of before arriving at a decision.

Multimedia application requests for granting a flow. Resource request for granting bandwidth is routed through 802.11e and Media Access component (CSMA/CA). Scheduler algorithm will verify the availability of resources (bandwidths-20, 40, 80 and 160 MHz, MCS, spatial streams) and collaborate with polling mechanisms in 802.11e, CAC, Request grant and traffic Scheduling. The output of the activity will be to grant the access, reject the request or queue it. Based on the application (for e.g. Video,), Cross-platform control with application layer (Application based control component), MAC layer (aggregation) and PHY layer (resource blocks fine tuning) the flows are provisional and regulated. When interference occurs, TxBF is applied while deciding on the impact on other SS. In the DL, DL-MU MIMO will be applied for delay based QoS applications when the resources are available for concurrent transmission of multiple users.

The appropriate Sounding algorithms, combination of Precoding and detection schemes, user selection mechanisms are used with Aggregation and VOIP management methods to meet QoS requirements for all users. When the signal is corrupted due to noise, rate adaptation mechanism is invoked which is now designed to be tightly coupled with the scheduler and integrated with MU_MIMO and TX BF mechanisms. The decision of whether STBC, MU_MIMO or SU_MIMO is appropriate for the current situation is also taken.

IV. CONCLUSION

A scheduler has not been defined for WLANs in the IEEE standard. As mobile networks had to assure QoS guarantees for voice traffic, the scheduler design was a key component in WiMAX and LTE. The media access mechanism adopted in WLANs (CSMA/CA), is not predictable compared to time division multiplexing in mobile networks. Hence, time bound guarantees are not possible for multimedia applications. Also, as WLANs operate in the unlicensed bands, interference is a major issue. Although schedulers have been recommended for 802.11n WLANS in the literature in several publications, these solutions have not been very satisfactory and issues persist.

Most WLAN product vendors have added advanced functionality over and above the specifications defined. Considering that all the above features can be handled better by designing a framework which holistically addresses these issues, we find a need for a scheduler.

With higher bandwidths (80 and 160 MHz), the benefits of 11ac are visible (with 256 QAM also available) in the case of all parameters - throughput, delay and jitter. The increase in received power with beamforming can result in more reliable demodulation or even a higher order MCS can be utilized for the transmission. The MU-MIMO feature in 802.11ac introduces multiple spatial streams (SS) distributed (maximum of four streams) between the clients. Multiple clients can be serviced simultaneously; hence congestion delay is not an issue. Therefore, latency and also throughput can be increased for multimedia applications. Thus, 802.11ac has been verified to be superior in performance compared to the existing WLANs. MCS, CBW and SS, TxBF and MU-MIMO features are verified and compared to 802.11n. Thus we can conclude that individual benefits from independent features are good and can aid in working towards QoS improvement. However, recommending a scheduler for 802.11ac which combines these benefits will further assure in providing QoS guarantees.

802.11ac, operating exclusively in the 5GHz range, avoids the congested 2.4GHz range that can experience interference from microwave ovens and other devices. TBF optimizes the communications between APs and clients to counteract interference. Hence, it is seen that a scheduler is advantageous with IEEE 802.11ac WLANs. Next, the scheduler has been designed with the components: aggregation control, CAC, application based control, (medium) access control component, traffic scheduling, polling and 802.11e, resource request and resource grant, transmit beamforming, MU MIMO - precoding, detection and user selection mechanisms, MU MIMO-sounding, combination approaches and cross layer approach.

Detailed discussions about each of these components further reinforces the recommendation for a scheduler for IEEE 802.11ac WLANs.

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