CHAPTER-2: CONCEPTS OF 802.11n AND 802.11ac

2.1Enhancements in 802.11n WLANs over Legacy WLANs

2.1.1 Introduction

802.11n protocol [3] [4] builds upon legacy 802.11 standards with enhancements in PHY and MAC layer. Actual speeds would be 100 Mbps (250 Mbps in PHY layer), and so up to 4-5 times faster than 802.11g. The enhanced features are discussed below:

2.1.2 PHY layer enhancements

2.1.2.1 Spatial multiplexing

MIMO is an outstanding innovation that is being assimilated by several non-802.11 wireless standards. It is an adaptable technology that can be utilized in several ways. At one extreme is SM; and at its opposite we have transmitter and/or receiver diversity. The same data streams are sent and received, in diversity, using multiple antennas and this helps in augmenting the robustness of the link. In SM, different data streams are sent and received at the same time over the same bandwidth. Here, the data throughput is enhanced.

Spatial multiplexing (SM) is central to 802.11n. To transmit with more than one spatial stream calls for correspondingly more than one transmitter and receiver and with each stream having independent, uncorrelated paths in the channel. Multiple paths for the streams are realized using physically separate paths (indoor use).

Multipath streams happen, when the signal gets reflected from physical obstructions. When any signal travels through diverse paths to a receiver, the lengths of the path determines its time of arrival at receiver. The shortest path signal arrives first, followed by reflected versions of the signal in the increasing path lengths of the copies. As traveling speed is high (speed of light), the delay between signals is trivial, (order of nanoseconds), yet sufficient to result in substantial distortion of the signal at a single receive antenna. Thus the reflections combine to degrade signal quality at receive end.

In all earlier WLAN standards simultaneous transmission of multiple signals on a common channel was not done due to the receiver's incapability to differentiate them. MIMO based WLANs try to benefit from multipath while the legacy WLANs strive to conquer the consequences of the same. The MIMO concept ensures that multiple signals (called spatial streams) are simultaneously transmitted from multiple dedicated antennas and transmitters. The space between the transmit antennae, results in a different path for each signal and hence aptly called **spatial diversity.**

The multiple signals have dissimilar reflections and change in polarization and ultimately arrive with different amplitudes and phase delays i.e. the signals are uncorrelated. A receiver designed for 'SM' can receive the uncorrelated streams and reconstruct the original signal through processing techniques. Hence the capacity of the channel is multiplied by using multiple spatial streams.

MIMO configuration defines the numbers of (transmitters, receivers) used; for example, 2×1 is two transmitters × one receiver. The different MIMO configurations in 802.11n standard start at 2×1, equivalent to TBF and goes, up to 4×4. Though SNR improves when additional transmitters or receivers are added to the MIMO configuration, the delta change reduces with increasing configuration.

While APs should have two to four spatial streams, the stations can work with even a single spatial stream in 802.11n protocol.

2.1.2.2 Channel bonding

Channel bonding is a technique in which the bandwidth, data rates and hence throughput are doubled by merging two adjoining 20 MHz into a 40 MHz band in

802.11n. Products implementing legacy 802.11 have a channel bandwidth (CBW) of about 20 MHz. While radios using 802.11b/g use one of the eleven (of which channels 1,6 and 11 are non-overlapping) 20 MHz channels in the ISM band, radios using 802.11a protocol use one of the twelve 20 MHz non-overlapping channels in UNII band. Devices having 802.11n protocol are designed for either 20 or 40 MHz CBW in either ISM or UNII band.

As the 5 GHz UNII band has more channels -24 non-overlapping channels with 20 MHz guard, 12 non-overlapping channels with double bandwidth can be created, making channel bonding most effective. The number of 20 MHz non-overlapping channels in 2.4 GHz band is limited to 3, thus making channel bonding very less spectrum efficient. Also, 40 MHz operation risks interference with functional legacy networks.

There is an additional advantage in using the 40 MHz bonded channel. When two 20 MHz channels are bonded to create a 40 MHz channel, the upper guard band of the lower channel and the lower guard band of the higher channel can also be utilized to pack more OFDM carriers, as they are not essential for reducing inter channel interference. The enhanced subcarriers results in increased data rates. By combining the two 20 MHz channels through this method, slightly more than double of the data rate is made possible (for 40 MHz).

2.1.2.3 Maximal Ratio Combining (MRC)

By the MRC technique in 802.11n standard is a receiver activity in which the received multiple signals from multiple receive antennas are suitably combined and reconstructed to form a single spatial stream. With MRC single antenna at the transmitter is sufficient but multiple antennas are mandatory at the receiver.

Client coverage is often restricted by the 'client to AP' connection as clients (for example, smart phones, and laptops) typically include low powered devices. The limitation on the transmitted power in these devices is due to factors such as size, cost and battery. This is further compounded by multipath signals due to which signal strengths of the different frequency subcarriers in the CBW attenuate differently leading to frequency selective fading.

MRC employs multiple receive antennas for reassembling signals, thereby minimizing error probabilities and re-transmissions, and thus improving client coverage. The receive antennas in line-of-sight normally receive signals with same characteristics. But noise and multipath effects may distort the signal to either or both receive antennas. Using MRC, the receiver will process the received signals separately and combine them using suitable weights so that the final received signal (using MRC) is a more exact reproduction of the transmitted signal than if received with one receive antenna. Further, MRC, uses signal processing techniques and effectively enhances the receive sensitivity.

MRC and MIMO techniques are more effective, when the received signals are uncorrelated antennas to the original transmitted signal. This can be realized by setting the antenna spacing to be at least $\lambda/2$.

MRC performance improves if channel is characterized through receiver-feedback. In 802.11n the system is calibrated by conveying an identified sequence of symbols from the transmit to the receive antennas in the long training fields (LTF). As the receiver knows the contents of the LTF it can estimate the effect of the RF channel and channel characteristics from the received signal.

2.1.2.4 STBC - Space-Time Block Coding

Like MRC, this feature is a (diversity) technique used to enhance the SNR of the receive signal when the number of antennas transmitting is more than those receiving. Alamouti coding on the data stream increases the data volume such that a single spatial stream is doubled. Copies of the data stream (after coding) are transmitted through different antennas. Knowledge of the code enables the receiver to decode the data in-spite of channel noise and with better accuracy than if a single transmit antenna were used.

The efficiency of the Alamouti code is established by the fact that, with a less complex transmitter and receiver it is able to achieve more improvement in SNR, even with channel noise and other impairments.

STBC codes can work with a maximum of 4 space-time streams. Both MRC and STBC techniques can be used simultaneously. The conditions are that STBC requires prior knowledge of the characteristics of the channel and also, the transmitter and receiver should have information about the currently used STBC code.

2.1.2.5 Guard Interval

The modulation techniques used in 802.11n is OFDM, in which each OFDM symbol comprises of blocks of coded input data. For reducing inter symbol interference and in aiding proper decoding by the receiver, GI or guard interval separates the symbols. If the GI is shorter than the time delay between the different RF paths, in multipath communication, then inter symbol interference can occur, On the other hand a long GI leads to higher idle time and wastage of communication time. Hence the GI should be chosen judiciously.

GI in 802.11a/g devices is 800 ns and in 802.11n devices GI can be chosen to be 400 or 800 ns which is short or long GI respectively.

Short GI (which is an optional feature) is chosen if the maximum delay between the RF paths is within the Short GI limit. Choice Short GI results in reduction of symbol time (4 μS) and enhancement of symbol rate by 10%. SGI is usually beneficial in indoor environments.

2.1.2.6 Transmit beam forming

Transmit beamforming (TBF), also known as MIMO beam forming or co-phasing is an optional feature in the transmitter to improve the SNR at the receiver.

IEEE 802.11n can be either Implicit or Explicit.

Implicit beamforming is simple and works on the assumption of a reciprocal RF channel. Hence the transmit beam is formed by the beamformer using the received weights. CSI is not sent by beamformee to beamformer. The constraint in this method is that though the channel is reciprocal, the transmitter and receiver aren't so. Moreover their characteristics vary with time and temperature. As these varying parameters are not taken into consideration in the implicit method of TBF, the implicit method is complex, inexact and inadequate.

In explicit beamforming (which is not mandatory in IEEE802.11n) with NTx and NRx(number of transmit and receive antennas respectively), a special sounding packet is transmitted through the NTx antennas and it is received by the receiver through the NRx receive antennas. The beamformee derives information regarding the channel from this sounding packet and sends back this information (Channel State Information or CSI) to the beamformer thus incurring overheads.

There are three methods of explicit beamforming with the basic procedure being the same as described above.

In the first method, the CSI from beamformee indicates how each NRx antenna has heard the sounding pattern. The beamformer utilizes the contents of the CSI matrix to estimate the weights to enhance beam formation. In the next two explicit methods, weight calculation is done by the beamformee itself to optimize the beam and sends the weights in the form of 'V' matrix to beamformer. The CSI and V matrices are large as they include precise data for each OFDM sub-carrier, for each NTx streams, and for each NRx antennas, they can be large. The burden on the channel can be reduced by using compression techniques and hence the 'compressed V matrix' (method 3).

Hence, TBF can be effectively used to improve SNR when NRx=1 and not for broadcast/multicast messages as optimizing phases and calculating the phases for (NTx, NRX) antenna pairs is very complex and data intensive. Also TBF can improve data rates and range but not the field-of-view as the beams are made to point to the specific receiver.

2.1.2.7 MCS -Modulation and Coding Schemes

The PHY rates, in 802.11n APs and stations is dependent on and is a combination of NSS, channel width, guard interval width, modulation and coding rate and MCS is a simple integer assigned to each combination. 802.11a/g/n all use OFDM and a 4 µs symbol. However in 802.11n, the data rate can be increased to 65 Mbps, for a single-transmit radio with 52 sub-carriers instead of 48 sub carriers. 802.11n also supports a maximum of eight data rates and four transmitters leading to 32 modes in a 20 MHz channel. Maximum data rate of 130, 195 and 260 Mbps can be achieved with 2, 3 and 4 transmitters respectively. Similarly in a 40 MHz channel, 108 subcarriers ensure data rates like 135, 270, 405 and 540 Mbps for 1,2,3,4 transmitters, respectively. Also, 4 transmitters and the eight data rates yield 32 modes in 40 MHz CBW. Further using SGI, data rates can be enhanced. For example 40 MHz channels, can cater to 150 Mbps data rate for each transmitter and 600 Mbps for a four-transmitter 802.11n radio.

MCS can take values from 0 to 77. MCS-0 to MCS-31 has same modulation and coding on all 4 Spatial Streams (SS) and MCS-32 to MCS-77 define different combinations of modulation and coding on each stream. As an example, MCS-33 is identified as 16-QAM, QPSK on SS-1 and SS-2, while MCS-77 is configured as 64-QAM on SS-1, 2 and 3 with 16-QAM on SS-4. As per 802.11n protocol APs must, as a minimum, support MCS-0 through MCS-15 and stations, MCS-0 to 7. Support for further MCS values is optional.

Note: 802.11n coding rate is 5/6, higher as compared to 3/4 in 802.11a/g.

2.1.3 MAC layer enhancements

2.1.3.1 Frame aggregation

The details of Frame aggregation and its functionality in 802.11n are discussed in section Appendix A3.3.1.

2.1.3.2 Block ACK

The details of Block ACK and its functionality in 802.11n are discussed in section AppendixA3.3.2.

2.1.3.3 Reduced inter-frame spacing (RIFS)

RIFS mechanism is an 802.11n feature to decrease the overhead time when sending a stream of frames to various receivers.

The overhead time referred to is the gap between frame transmission to access the channel and the time lost in contention for the channel.

During transmit opportunity a transmitter sends data frames in a burst without need for back off to create short inter-frame space (SIFS). RIFS, a reduced IFS is defined in 802.11n. RIFS additionally condenses inter-frame space time and increases time in the TXOP which can be used for transmitting frames. 802.11n defines a RIFS and SIFS periods as 2 and 16 μsec respectively.

RIFS achieves objectives comparable to aggregation in MAC, yet simpler in execution. However, RIFS is employed only in green field situations where 802.11a, b, or g devices are not present.

2.2 Enhancements in 802.11ac WLAN over previous WLANs

802.11ac [5] [6] being a faster version of 802.11n, combines the benefits of wireless and Gigabit Ethernet. Wireless LAN APs can support more clients, with larger bandwidth, more parallel video streams, superior speeds and lesser delays. Band of operation for 802.11ac is only 5-GHz and therefore steers clear of much of the interference generated by other external sources that generally work at 2.4 GHz. Some applications that have benefitted from the 11ac enhanced data rates are wireless display, HDTV, large file transfer between users and servers, campus and auditorium deployments.

The 802.11ac IEEE standard has been introduced in two “waves”.

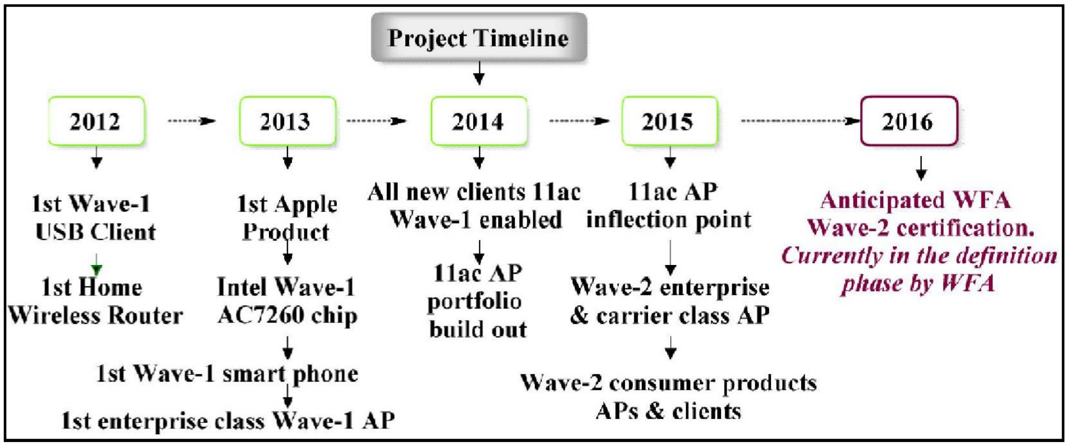

Fig 2.1 Timeline for the development of IEEE 802.11ac Wave-2

The 802.11ac standard permits theoretical speeds touching 6.9 Gbps data rate in 5-GHz band. Refer table2.3.

Table-2.3 Features of 802.11ac and 802.11n

Features	**802.11n**	**802.11n IEEE Spec**	**802.11ac Wave-1 today**	**802.11ac Wave-2 WFA certification process continues**	**802.11ac IEEE Spec**
Band (GHz)	2.4 & 5	2.4 & 5	5	5	5
MIMO	SU	SU	SU	MU	MU
PHY Rate (Mbps)	450	600	1300	2340-3470	6900
Spatial streams	3	4	3	3-4	8
Channel Width (MHz)	20 or 40		20, 40, 80	20, 40, 80, 80-80, 160	
Modulation	64 QAM		256 QAM		

Wave-2 follows Wave-1 with certain prominent enhancement. The need for different features in Wave-2 is explained below:

1) In 5 GHz band -Maximum data rate 2.34 Gbps

This high data rate is required to accommodate the enormous growth of video in mobile networks.

2) Multi-User MIMO

Requirement for MU-MIMO feature came about due to dense wireless communication, end-user mobility, mounting numbers of IoT devices, multiple devices per user and the user experience of an “all wireless office”.

MU-MIMO feature offers simultaneous downlink communication to a number of wireless devices and hence frequency reuse. It also allows the devices to move in and out of the network faster, thus enabling more clients to access the network.

3) 160-MHz channel width

Larger files require higher CBW for High-speed transmission.

The 160 MHz channel has 2.3 Gbps data rates in 802.11ac Wave-2, while it is 450Mbps and 1300Mbps in 11n and 11ac Wave-1.

4) 4th spatial stream

Wave-2 supports 4 antennas each at transmit and receive end while earlier systems supported 3 antennas at receive end.

5) Additional 5-GHz channels

More channels translate to increased bandwidth and feasibility to switch channels, in event of interference.

Globally about 37 channels are defined in the 5-GHz frequency range which was not used for wireless-either because they are used for other 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 more clients/applications.

A nonprofit organization called 'Wi-Fi Alliance' has taken the initiative to create a common platform for vendors and clients of WiFi devices, APs and chipsets to promote, collaborate and define guidelines which vendors are expected to comply, regarding WiFi and related devices. They should also check interoperability so that consumers benefit from interworking of their network devices.

It is anticipated that the 'consumer-' and 'enterprise-' class products implementing Wave 2 features may not comply with inter-operability involving the devices and clients in 802.11ac standard. The introduction of the numerous 802.11ac compatible client devices is expected to hit the market only in 2017.

The enhancements to 802.11n which have resulted in the 802.11ac standard are discussed below.

2.2.1 Modulation and Coding Schemes

256-QAM modulation is an addition to the MCS schemes present in 802.11n.

2.2.2 Channel Bonding

While, in 802.11n, the basic CBW is 20 MHz and with the channel bonding feature used to combine two 20 MHz into one 40 MHz channel, 802.11ac additionally has 80 and 160MHz CBWs additionally and also has backward compatibility supporting 20 and 40MHz CBWs. The data rate is enhanced by 117% when two 40MHz channels bond to form an 80MHz CBW and 333% when two 80MHz channels bond to form a 160 MHz channel respectively with reference to the 20 MHz CBW.

2.2.3 Spatial Streams

While 802.11n has 4 spatial streams at the AP, 802.11ac specifies up to 8.

2.2.4 Transmit Beamforming in 802.11ac

2.2.4.1 Introduction

TBF in 802.11ac [5][6][7] is much simpler than in 802.11n as the various TBF techniques in 802.11n namely implicit, explicit and CSI matrix method and V matrix methods are all replaced by a single method of TBF in 802.11ac - i.e. sounding of null data packet (NDP) which is an **explicit** mechanism.

2.2.4.2 Channel Measurement or Sounding Procedures

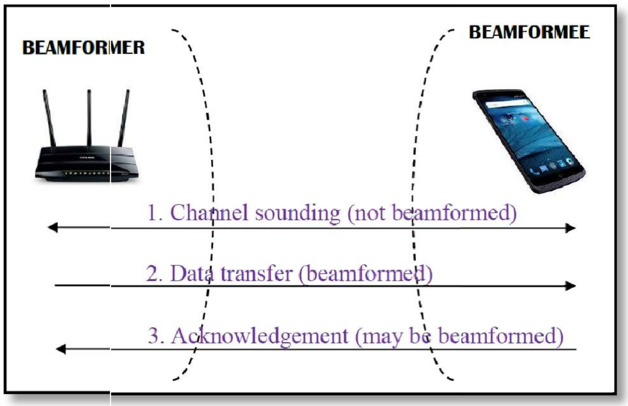

Fig 2.2 Data Transfer Mechanism with Beamforming

Figure 2.2 shows the data transfer mechanism when Beamforming is enabled. The below procedure is implemented in Channel sounding:

Step 1. The NDP Announcement (NDPA) frame from beamformer is to discover beamformees. By responding to the NDPA, the beamformee ensures that channel is not accessed by others until the end of the sounding sequence.

Step 2. An NDP from the beamformer follows the NDPA.

Steps 1 and 2 are explained through Figure 2.3a.

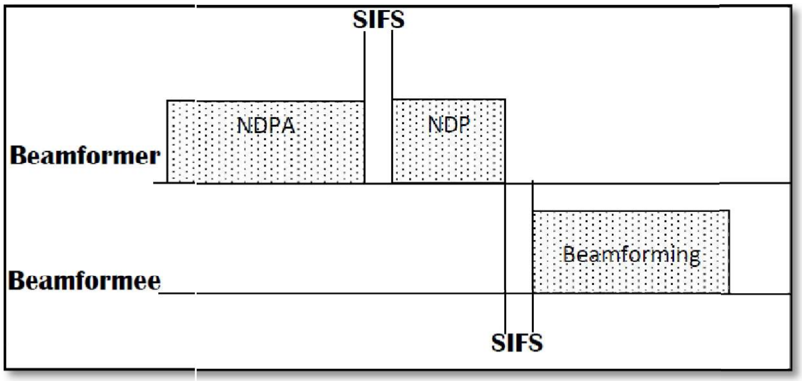

Fig 2.3a Channel Sounding - NDPA and NDP

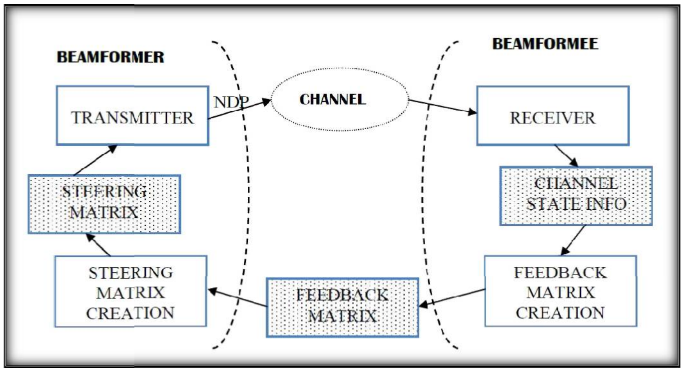

Fig 2.3b Channel Sounding - Feedback and Steering Matrices

Step 3. On receiving the NDP, the beamformee analyses the OFDM training fields, processes the individual OFDM subcarrier associated with each (NTx, NRX) antenna pair and forms the V feedback matrix based on the amplitude and phase of each signal.

The feedback matrix is converted by a series of matrix and mathematical operations to calculate the angles by the beamformee and transmitted to the beamformer as a string of bits in the format specified by the IEEE 802.11ac standard. One of operations performed is compression which results in a smaller frame and hence lesser airtime.

The size of the feedback matrix V is dependent on CBW and (NTx, NRx) pair numbers. CBW in turn decides how many OFDM sub-carriers can be configured.

Step 4. The beamformer forms the steering matrix 'Q' based on the contents of the 'V' feedback matrix. The effect of the steering matrix on the data to be transmitted is to create a pointed beam from an omni-directional beam. The advantage of representing the steering data as a matrix is that, it is convenient to represent data frequency response vs. spatial stream which can be applied to modify the data required to steer the beam for each OFDM subcarrier to the receiver.

The beam, before TBF, with approximately same energy in all directions is manipulated after TBF to have maximum energy only towards the receiver (by constructive addition). The phase data required to converge or cancel the energy is contained in the steering matrix. Figure 2.3b explains the steps 3 and 4.

The local maximum at the receive antenna improves the signal strength and hence SNR, which in turn ensures a sustainable RF link at the desired rate. TBF is thus a concept of forming 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.

On the flip side, if the amount of data exchanged between the beamformer and beamformee to converge the beam and increase the data rate is so much that speed advantage achieved is countered by the time taken to transmit the huge volume of the steering matrix data, then TBF is not attractive as the overall speed will reduce.

Also the advantage of TBF is more pronounced when communication is between devices separated by a distance in the mid to long range. At short range, the advantage gained by TBF is countered by the degradation of the signal due to multipath effects and incorrect estimation of the signal properties. At long ranges, TBF gain is insufficient to increase the speed of transmission.

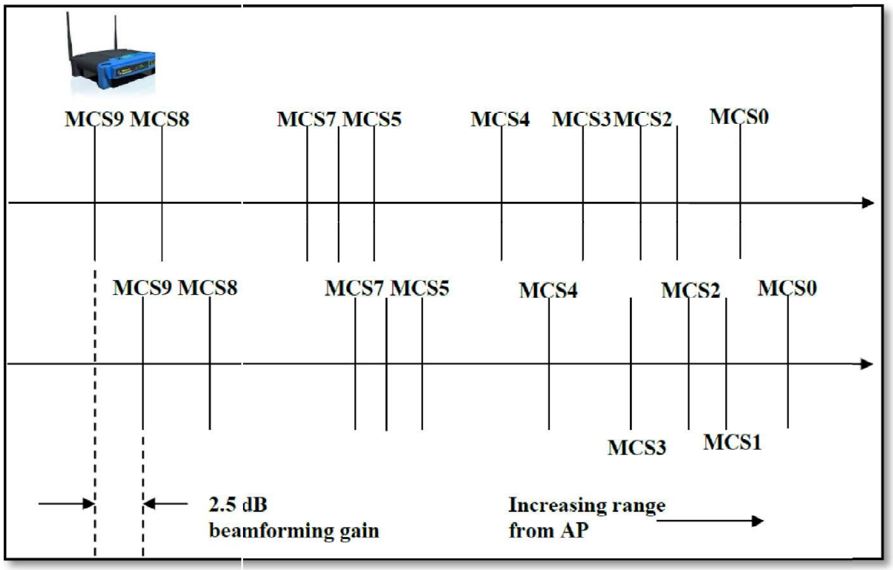

Fig 2.4 Range Improvement due to Transmit Beam Forming

To summarize, TBF gain (of about 3-dB) in the direction of the receiver is best in mid-range.

The figure 2.4 is used to explain the increasing range for a sustainable link from an AP with reducing orders of MCS. The 2 horizontal lines indicate the effect of range improvement at the client device due to gain offered by TBF.

Also there is at least 5-dB change between MCS8 and MCS7.

2.2.4.3 Example Scenarios where Beamforming can be applied

While the Spatial division multiplexing (SDM) technique boosts the throughput, TBF achieves better SNR. As the two end results are contradictory, jointly implementing both mechanisms can happen only as a compromise. The following example discusses the implication of implementing both the mechanisms [8].

A major difference between SDM and TBF is that in SDM data has to be transmitted in multiple streams whereas in TBF a single stream is used. Hence in a 2×2:2 AP/Client MIMO configuration both SDM and TBF cannot be simultaneously implemented.

If the configuration is 3×3:3 AP/Client, theoretically two SDM streams and one TBF stream can be configured. This enhances the SDM stream but the achieved data rate is 300 Mbps only against the expected 450 Mbps as the 3rd antenna is utilized to transmit the other antennas spatial streams in SDM instead of independent data of its own.

Also a 4×4:3 AP MIMO configuration, can theoretically communicate three SDM streams and one TBF stream. This boosts the throughput of the SDM streams but reduces the data that could have been transmitted on the SDM stream and hence the maximum data rate achievable with this mixed implementation is 450 mbps only.

An example to depict the performance of TBF is an application used in interiors (as against outdoor application). In medium big sized house i.e. in medium ranges, TBF enhances the signal strength even in edges of the home or in a closet.

Short ranges do not require this enhancement as the signal strength/SNR is sufficiently high. And at long ranges TBF gain is unable to support increase in data rates.

2.2.5 Multi-User MIMO

MU-MIMO is a mechanism designed for 802.11ac Wave 2, to enable more than one client to receive packets at the same time from the AP leading to frequency reuse of the available spectrum and hence better system performance.

Usage: As per the Wave-2 standard of 802.11ac, data can be streamed simultaneously to a maximum of four clients using at the most 8 SS or a maximum of 4 SS for each client in MU-MIMO configuration transmission. So the AP-to-client(s) combination can be 2 clients with either one (1+1), or four SS each (4+4), or two SS each to four clients, or some unequal combination to 3 clients with 1+2+3 or 2+2+4 SS.

The highest number of SS an AP can transmit is equal to the transmit antennas. Usually the Access Point keeps one antenna as spare too. So the SS combinations supported by an AP with four transmit antennas is 1+1, 1+1+1, and 1+2 combinations.

Modifications to 802.11 standard resulting from addition of MU-MIMO feature are given in Appendix-7.

2.2.5.1 Benefits and Limitations

Benefits:

1) MU MIMO uses the beamforming feature to transmit data simultaneously to receivers spatially separated thus acting like an 802.11 "switch."

2) When both router and client have enabled MU-MIMO, the CBW is very efficiently utilized.

3) Having a network with a better means of handling bandwidth means you'll get faster buffering, lower latency and more consistent and stable download speeds.

These benefits are extremely useful for gaming, full-time HDTV streaming and heavy internet usage.

MU-MIMO can transmit streams in parallel and thereby latency is decreased. RT streaming applications benefit from lower latency.

4) MU-MIMO increases both speed and capacity and thus enhances the number of devices in a home network.

Limitations:

1) MU-MIMO feature is implemented only in downlink i.e. AP to client. But, as traffic is mostly in this direction, so DL-MU-MIMO feature is definitely an advantage. When MU-MIMO is present in UL and DL, then the complete benefits of such a feature can be realized in newer WLAN standards, 802.11ax .

2) Data reception with MU-MIMO is better if the Wi-Fi device does not change its location. So watching a video on your smart phone while walking is not a smart idea as the router may decide to switch over to SU-MIMO, to avoid quality degradation for other stationary MU-MIMO connections.

3) When using multiple streams for communication, because of the manner in which the signal streams are processed, the benefit of MU-MIMO is more noticeable when the two devices (say a laptop and a desktop) are spatially separated in two different rooms rather than on the same study table.

4) MU-MIMO at the router translates to complexity in handling data streams. Hence, the trouble shooting is also complex and involves examining the advanced settings of the router.