CHAPTER-4: PERFORMANCE EVALUATION

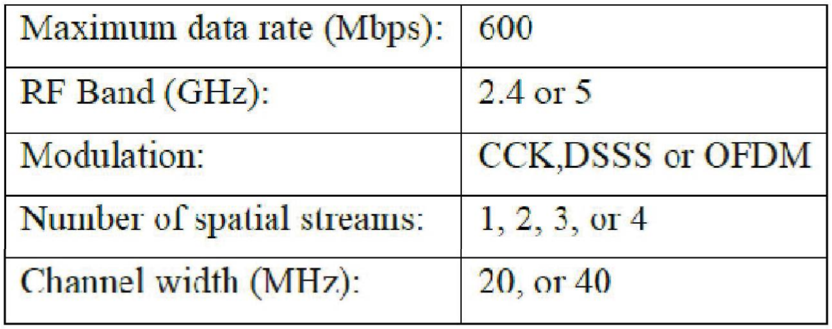
4.1 Introduction to performance evaluation features

In this chapter, all features of 802.11ac are evaluated with respect to 802.11n. The base performance of 802.11ac is compared to 802.11n in section 4.2 where features verified are spatial streams, channel bonding, guard interval and MCS while performance is measured with parameters such as jitter, throughput and delay. Next, the performance of 11ac and 11n with Ideal and Minstrel RA algorithms is evaluated in section 4.3. The performance of 802.11ac with transmit Beamforming is evaluated in section 4.4 while MU_MIMO is evaluated in section 4.5.

The results of the tests in this chapter will permit a decision to be taken if as a new standard, consolidated with all the features, 802.11ac can show advancement in performance compared to earlier WLANs and if so, what is the approach which should be employed.

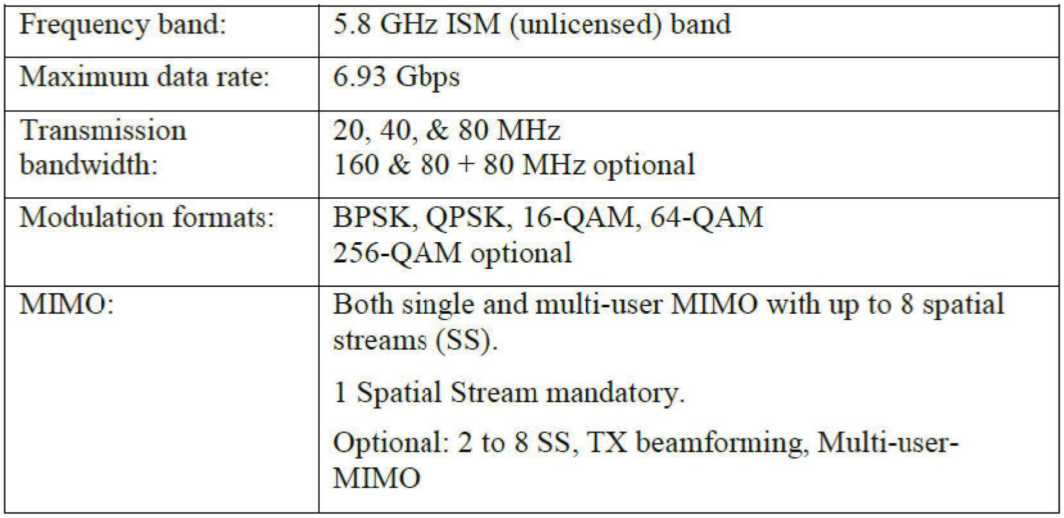
The main parameters of 802.11n and 802.11ac are summarized below:

802.11n Parameters



Maximum data rate (Mbps):	600
RF Band (GHz):	2.4 or 5
Modulation:	CCK,DSSS or OFDM
Number of spatial streams:	1, 2, 3, or 4
Channel width (MHz):	20, or 40

802.11ac Parameters



Frequency band:	5.8 GHz ISM (unlicensed) band
Maximum data rate:	6.93 Gbps
Transmission bandwidth:	20, 40, & 80 MHz 160 & 80 + 80 MHz optional
Modulation formats:	BPSK, QPSK, 16-QAM, 64-QAM 256-QAM optional
MIMO:	Both single and multi-user MIMO with up to 8 spatial streams (SS). 1 Spatial Stream mandatory. Optional: 2 to 8 SS, TX beamforming, Multi-user-MIMO

4.2 Performance Evaluation of IEEE 802.11ac and 802.11n

4.2.1 Introduction

In this chapter, using NS3 simulator, we demonstrate the performance improvements in 802.11ac as compared to 802.11n. Features verified are channel bonding, guard interval and MCS while performance is measured with parameters like jitter, throughput and delay. Results of the analysis are published in, "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.

4.2.2 Performance Test

The ns3-3.24.1 [68] version of ns-3 released in September 2015 is used for analysis in this chapter.

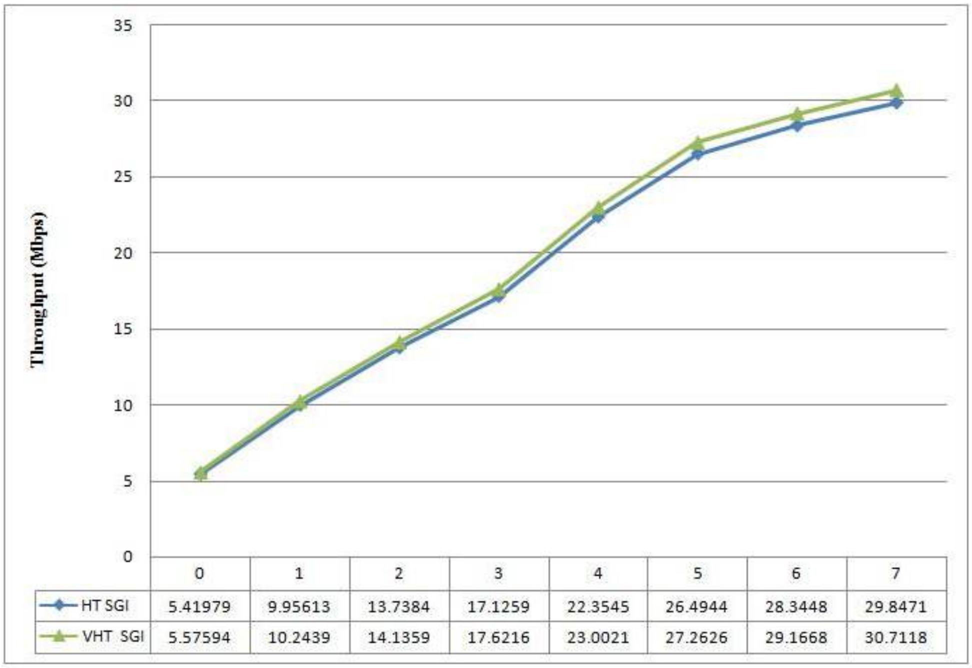
In the scenario, an Access Point or AP and STA are connected in an infrastructure WLAN. The output of the test case is the UDP throughput, jitter and delay for every HT/VHT bit rate value, which depends on the MCS value (0 to 7)/(0 to 9), the channel width (20 or 40 MHz)/(20,40,80 or 160 MHz) and the guard interval (long or short). The PHY bit rate is constant over the complete simulation run.

Table 4.1 - Configuration Parameters for simulation of QoS parameters

Simulation Time	10 seconds	
Mobility Model	Constant position mobility model	
Payload Size	1472 bytes	
Rate Manager	Constant Rate WiFi Manager	
Standard	802.11n	802.11ac
SCI	Short GI, Long GI	Short GI, Long GI
Channel bonding	20,40 MHz	20,40,80,160 MHz
MCS	MCS-0 to MCS-8	MCS-0 to MCS-6

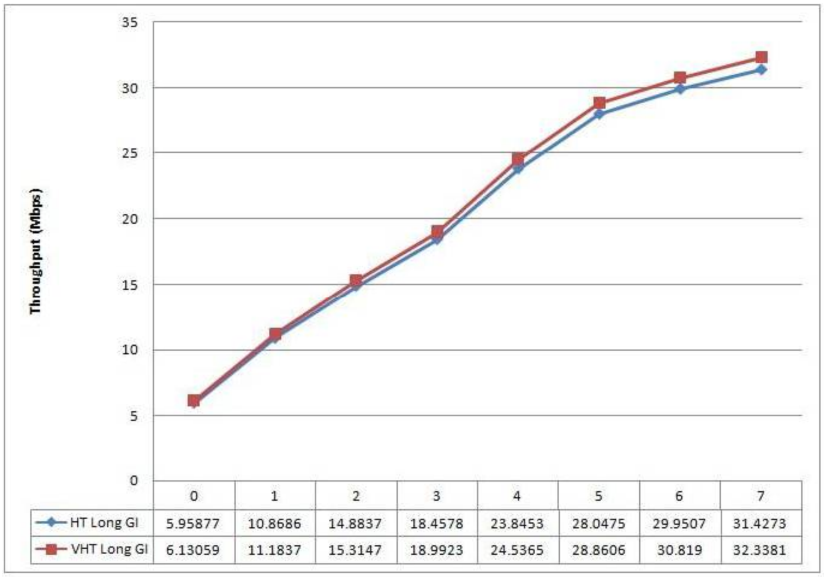
4.2.3 Results and Discussion

4.2.3.1 Results



	0	1	2	3	4	5	6	7
HT SGI	5.41979	9.95613	13.7384	17.1259	22.3545	26.4944	28.3448	29.8471
VHT SGI	5.57594	10.2439	14.1359	17.6216	23.0021	27.2626	29.1668	30.7118

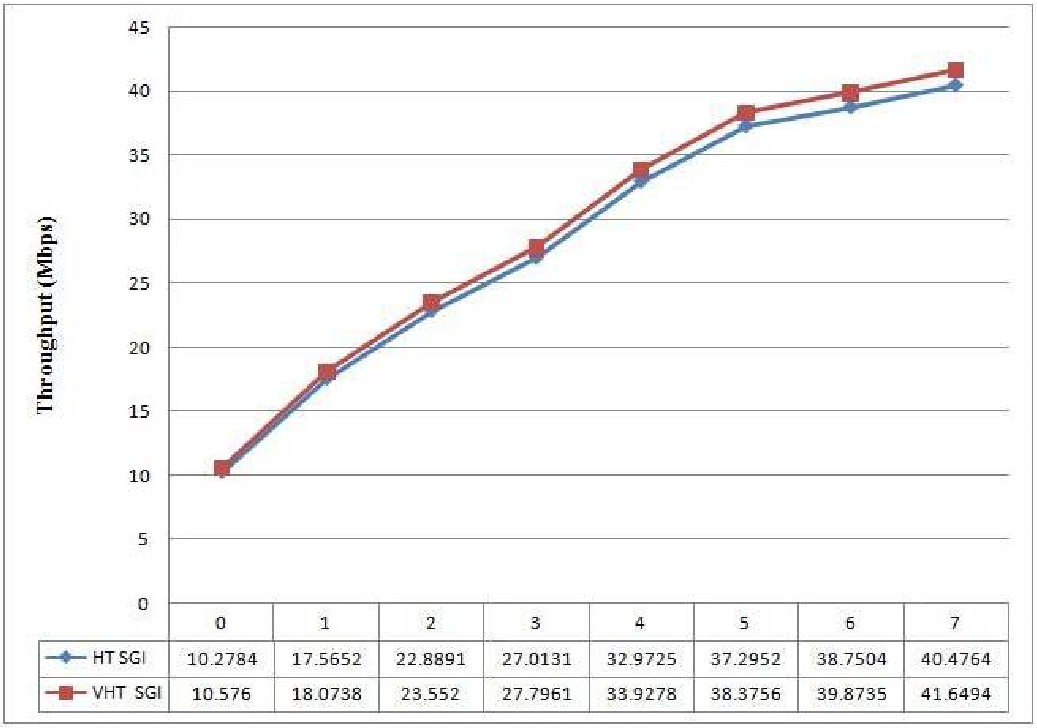
Fig 4.1 Throughput vs. MCS; SGI and 20 MHz Bandwidth



	0	1	2	3	4	5	6	7
HT Long GI	5.95877	10.8686	14.8837	18.4578	23.8453	28.0475	29.9507	31.4273
VHT Long GI	6.13059	11.1837	15.3147	18.9923	24.5365	28.8606	30.819	32.3381

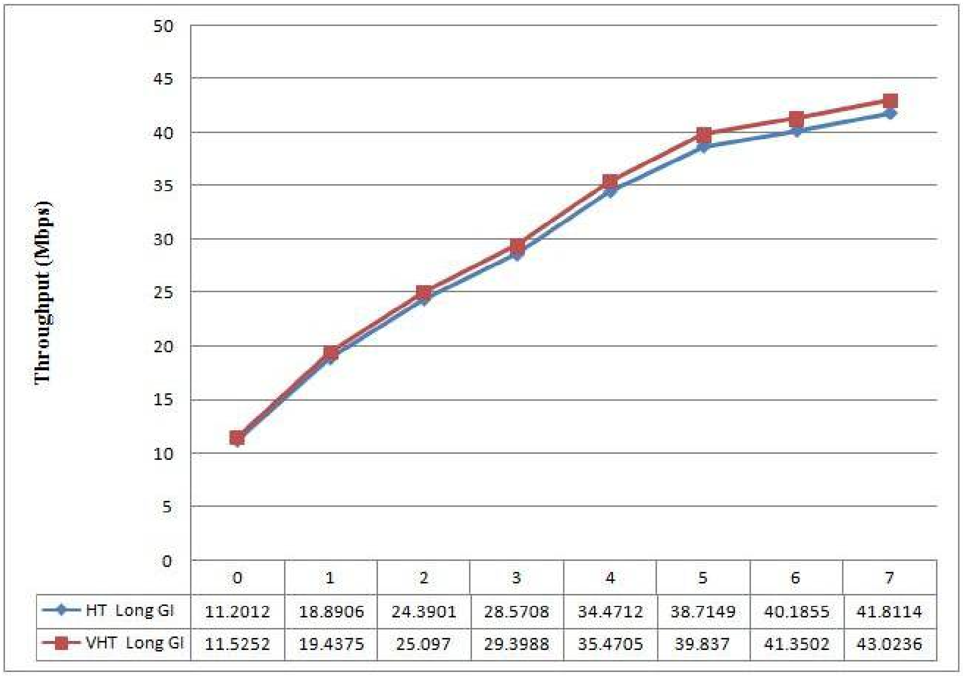
Fig 4.2 Throughput vs. MCS; Long GI and 20 MHz Bandwidth

Throughput in 802.11ac and 802.11n protocols is plotted for MCS values 1 to 8 for SGI and LGI in figures-4.1 & 4.2 with channel bonding when BW is 20 MHz.



	0	1	2	3	4	5	6	7
HT SGI	10.2784	17.5652	22.8891	27.0131	32.9725	37.2952	38.7504	40.4764
VHT SGI	10.576	18.0738	23.552	27.7961	33.9278	38.3756	39.8735	41.6494

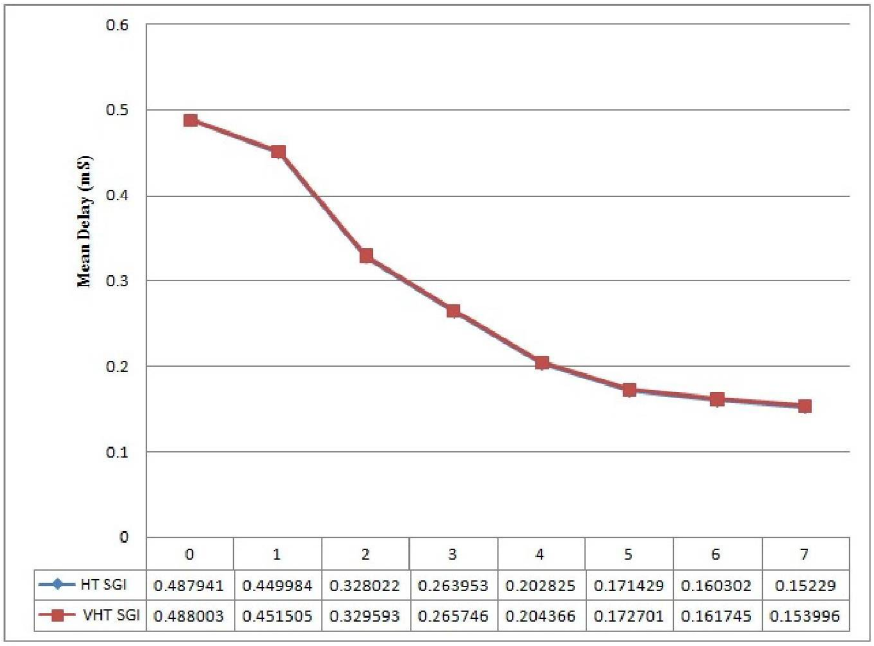
Fig 4.3 Throughput vs. MCS; SGI and 40 MHz Bandwidth



	0	1	2	3	4	5	6	7
HT Long GI	11.2012	18.8906	24.3901	28.5708	34.4712	38.7149	40.1855	41.8114
VHT Long GI	11.5252	19.4375	25.097	29.3988	35.4705	39.837	41.3502	43.0236

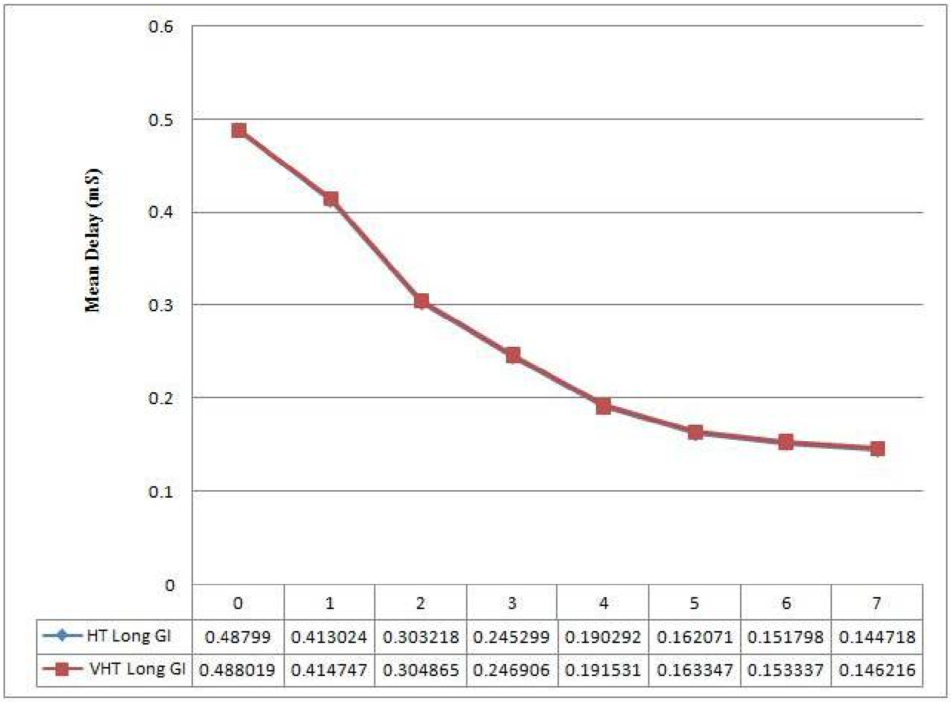
Fig 4.4 Throughput vs. MCS; Long GI and 40 MHz Bandwidth

Throughput in 802.11ac and 802.11n protocols is plotted for MCS values 1 to 8 for SGI and LGI in figures-4.3 and 4.4. Channel bonding is when BW is 40 MHz.



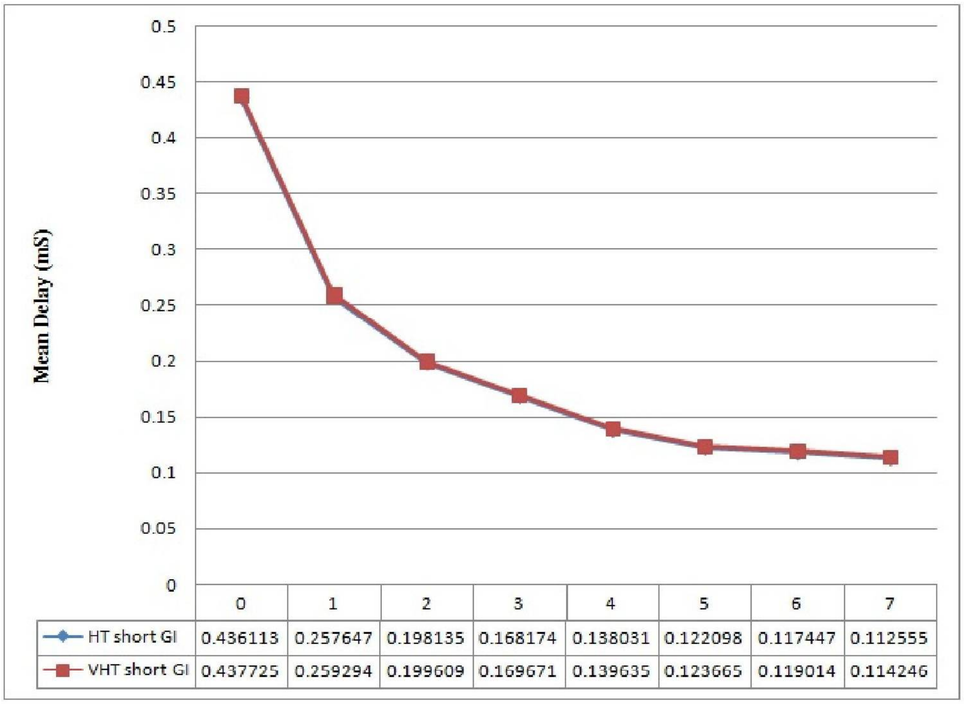
	0	1	2	3	4	5	6	7
HT SGI	0.487941	0.449984	0.328022	0.263953	0.202825	0.171429	0.160302	0.15229
VHT SGI	0.488003	0.451505	0.329593	0.265746	0.204366	0.172701	0.161745	0.153996

Fig 4.5 Mean Delay vs. MCS, SGI, 20 MHz Bandwidth



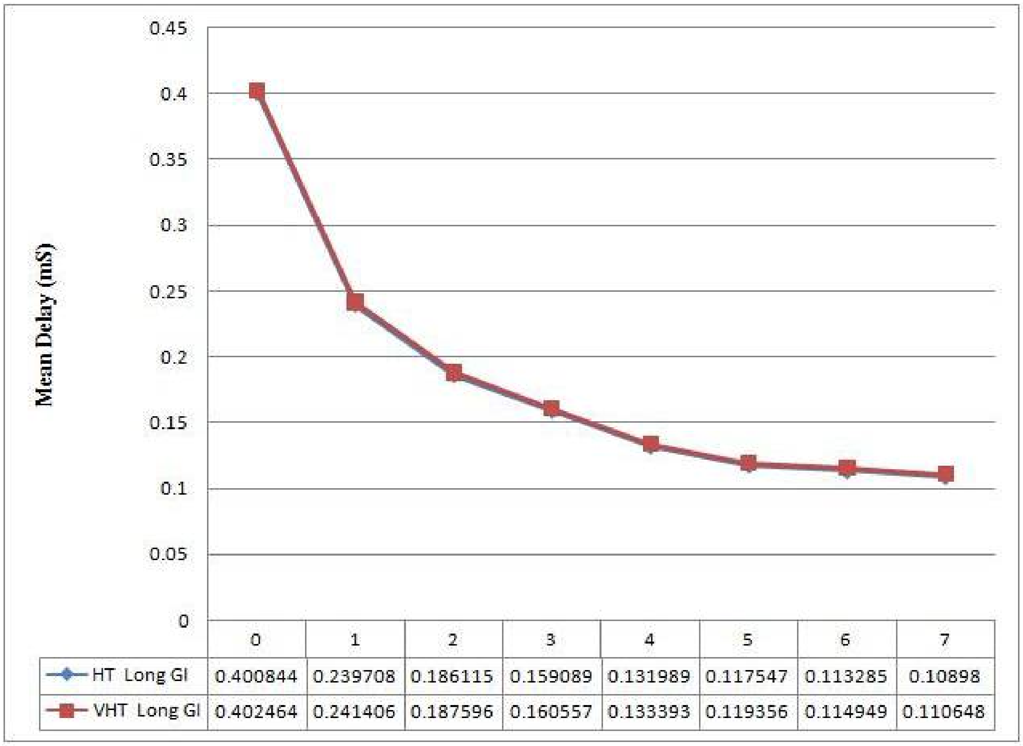
	0	1	2	3	4	5	6	7
HT Long GI	0.48799	0.413024	0.303218	0.245299	0.190292	0.162071	0.151798	0.144718
VHT Long GI	0.488019	0.414747	0.304865	0.246906	0.191531	0.163347	0.153337	0.146216

Fig 4.6 Mean Delay vs. MCS, long GI, 20 MHz Bandwidth



	0	1	2	3	4	5	6	7
HT short GI	0.436113	0.257647	0.198135	0.168174	0.138031	0.122098	0.117447	0.112555
VHT short GI	0.437725	0.259294	0.199609	0.169671	0.139635	0.123665	0.119014	0.114246

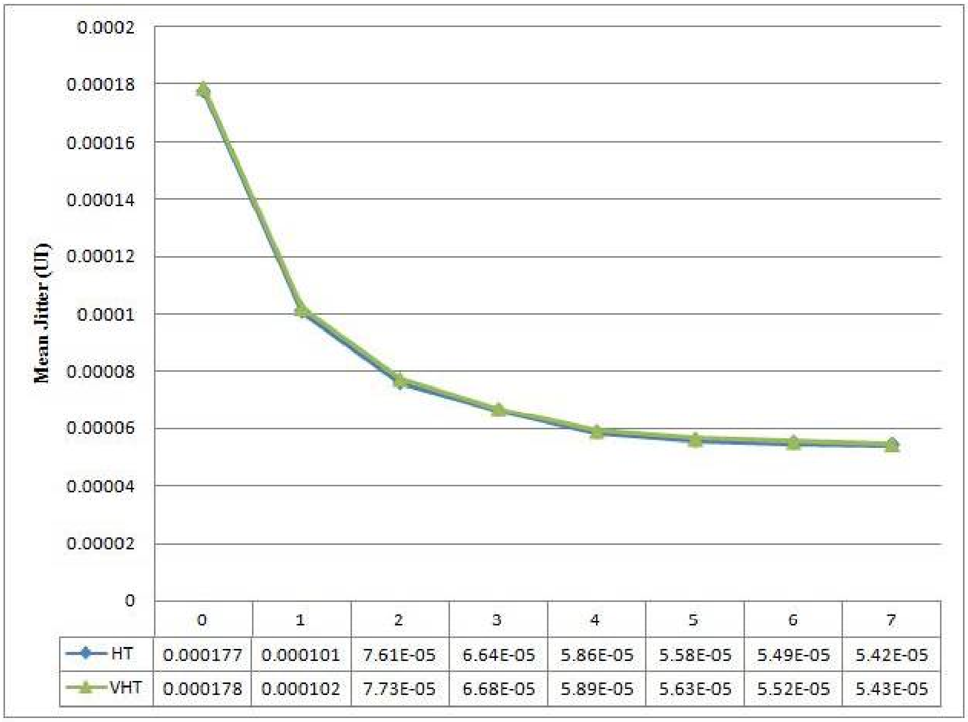
Fig 4.7 Mean Delay vs. MCS, SGI, 40 MHz Bandwidth



	0	1	2	3	4	5	6	7
HT Long GI	0.400844	0.239708	0.186115	0.159089	0.131989	0.117547	0.113285	0.10898
VHT Long GI	0.402464	0.241406	0.187596	0.160557	0.133393	0.119356	0.114949	0.110648

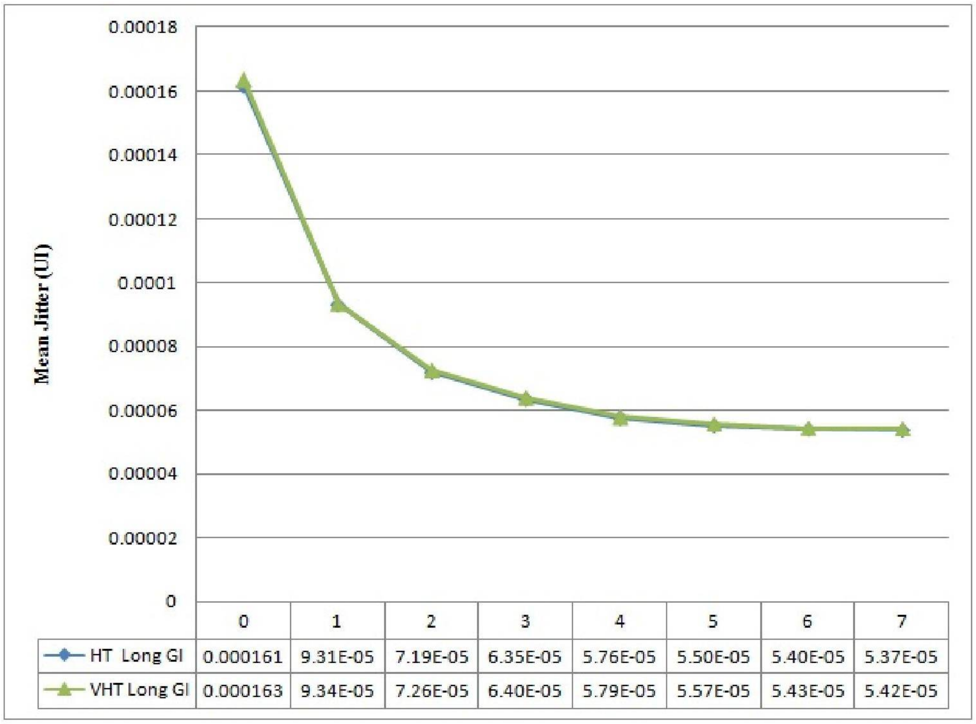
Fig 4.8 Mean Delay vs. MCS, long GI, 40 MHz Bandwidth

The next parameter analyzed is mean delay, with channel bonding concept when BW is 20 MHz and 40 MHz for both SGI and LGI. The results are plotted in figures-4.5 to 4.8



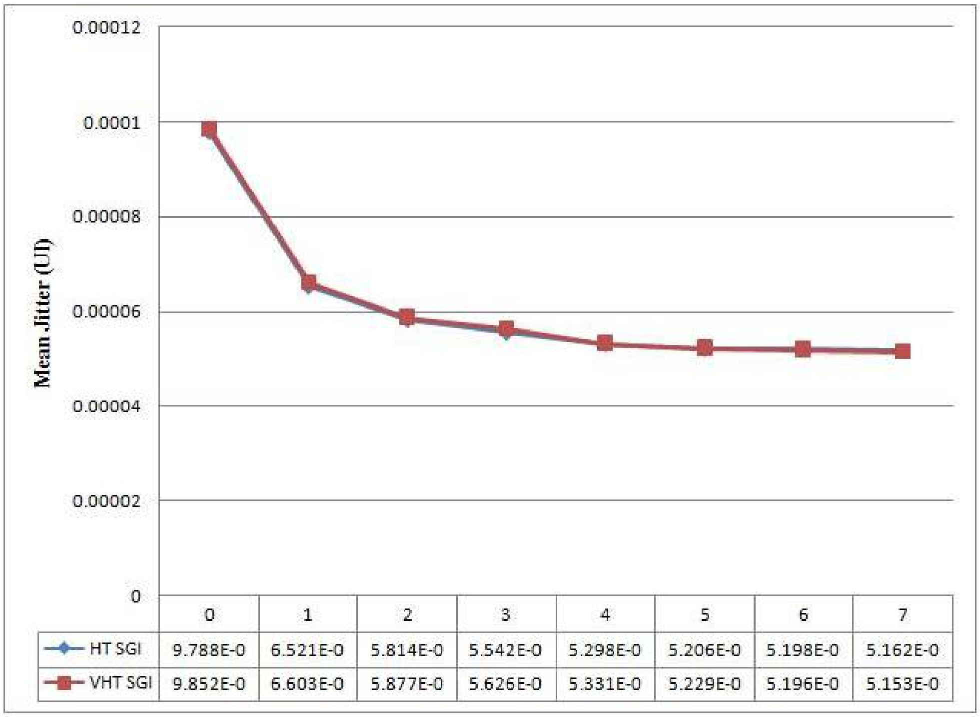
	0	1	2	3	4	5	6	7
◆ HT	0.000177	0.000101	7.61E-05	6.64E-05	5.86E-05	5.58E-05	5.49E-05	5.42E-05
▲ VHT	0.000178	0.000102	7.73E-05	6.68E-05	5.89E-05	5.63E-05	5.52E-05	5.43E-05

Fig 4.9 Mean Jitter vs. MCS, short GI, 20 MHz Bandwidth



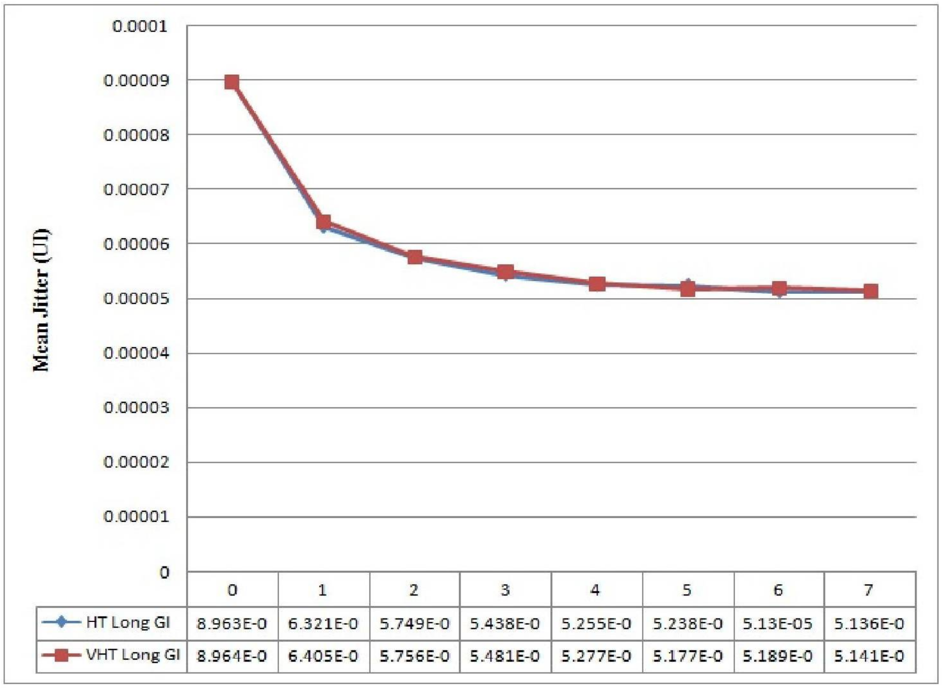
	0	1	2	3	4	5	6	7
◆ HT Long GI	0.000161	9.31E-05	7.19E-05	6.35E-05	5.76E-05	5.50E-05	5.40E-05	5.37E-05
▲ VHT Long GI	0.000163	9.34E-05	7.26E-05	6.40E-05	5.79E-05	5.57E-05	5.43E-05	5.42E-05

Fig 4.10 Mean Jitter vs. MCS, long GI, 20 MHz Bandwidth



	0	1	2	3	4	5	6	7
HT SGI	9.788E-0	6.521E-0	5.814E-0	5.542E-0	5.298E-0	5.206E-0	5.198E-0	5.162E-0
VHT SGI	9.852E-0	6.603E-0	5.877E-0	5.626E-0	5.331E-0	5.229E-0	5.196E-0	5.153E-0

Fig 4.11 Mean Jitter vs. MCS for short GI with 40 MHz Bandwidth



	0	1	2	3	4	5	6	7
HT Long GI	8.963E-0	6.321E-0	5.749E-0	5.438E-0	5.255E-0	5.238E-0	5.13E-05	5.136E-0
VHT Long GI	8.964E-0	6.405E-0	5.756E-0	5.481E-0	5.277E-0	5.177E-0	5.189E-0	5.141E-0

Fig 4.12 Mean Jitter vs. MCS for long GI with 40 MHz Bandwidth

In figures-4.9 to 4.12 mean jitter is studied, with channel bonding concept when bandwidth is 20 MHz and 40 MHz for both short and long GI.

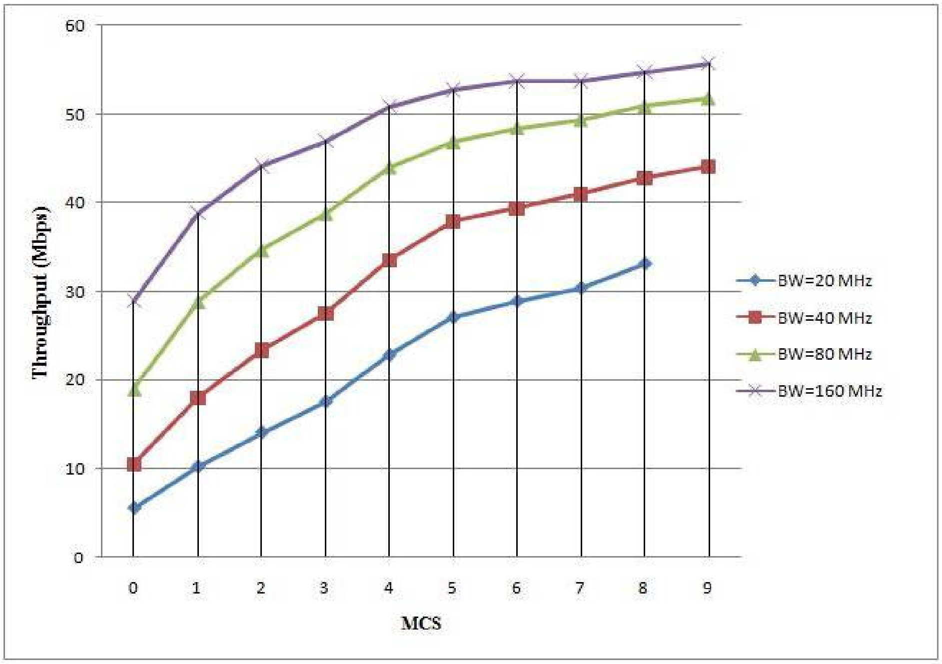


Fig 4.13 Throughput vs. MCS for SGI with 20, 40, 80, 160 MHz Bandwidth

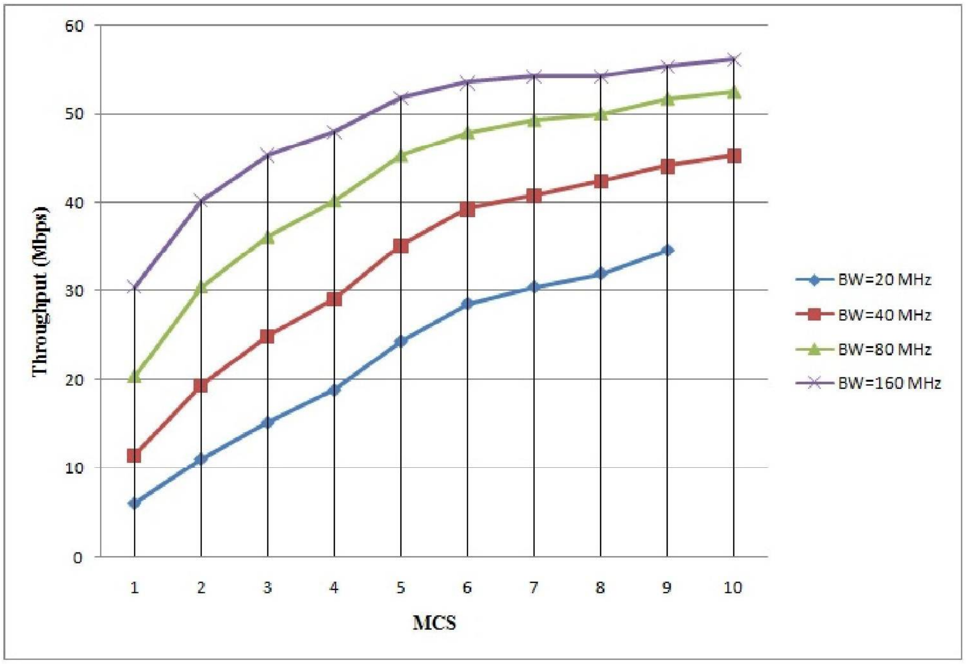


Fig 4.14 Throughput vs. MCS for long GI with 20, 40, 80, 160 MHz Bandwidth

The effect of channel bonding on throughput is simulated in figures-4.13 and 4.14 for SGI and LGI. The above simulation is done when STAs are separated by 1m.

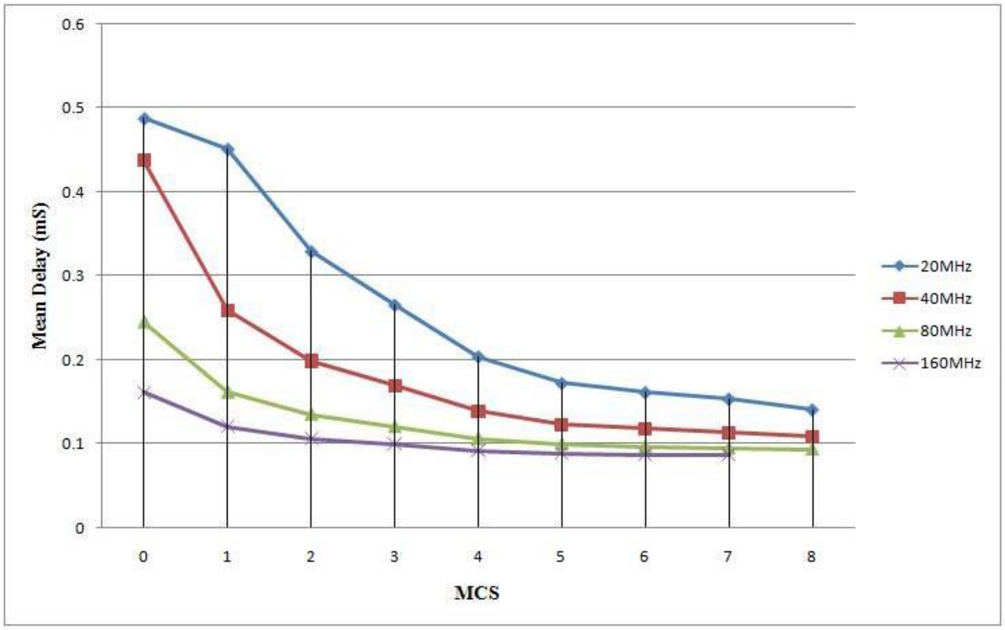


Fig 4.15 Mean delay vs. MCS for SGI with 20, 40, 80, 160 MHz Bandwidth

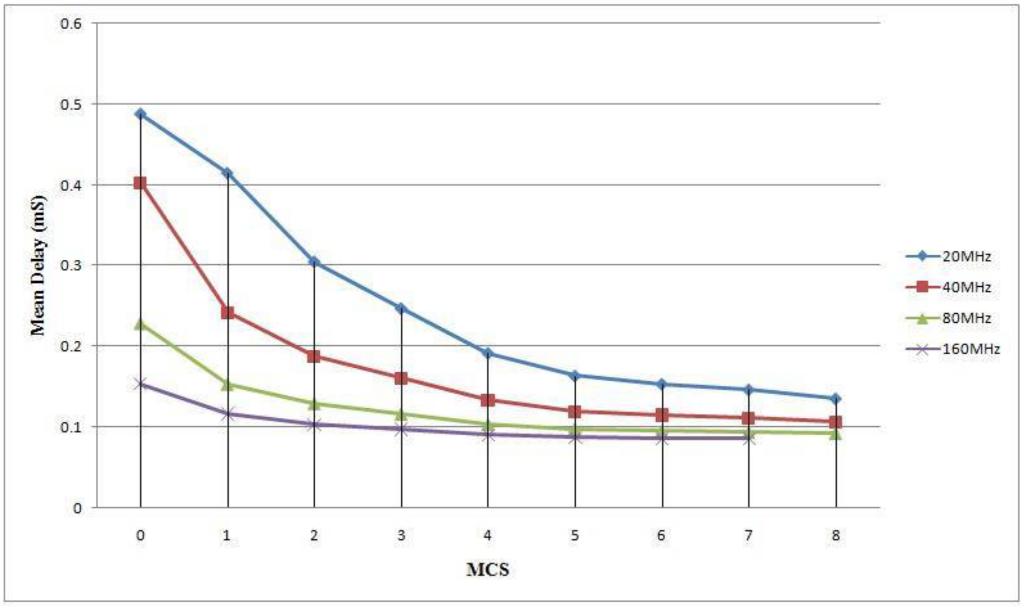


Fig 4.16 Mean delay vs. MCS for LGI with 20, 40, 80, 160 MHz Bandwidth

Similarly, the variation of mean delay with MCS at different bandwidths for SGI and LGI is in figures-4.15 and 4.16. The above simulation is done when the stations are separated by 10m.

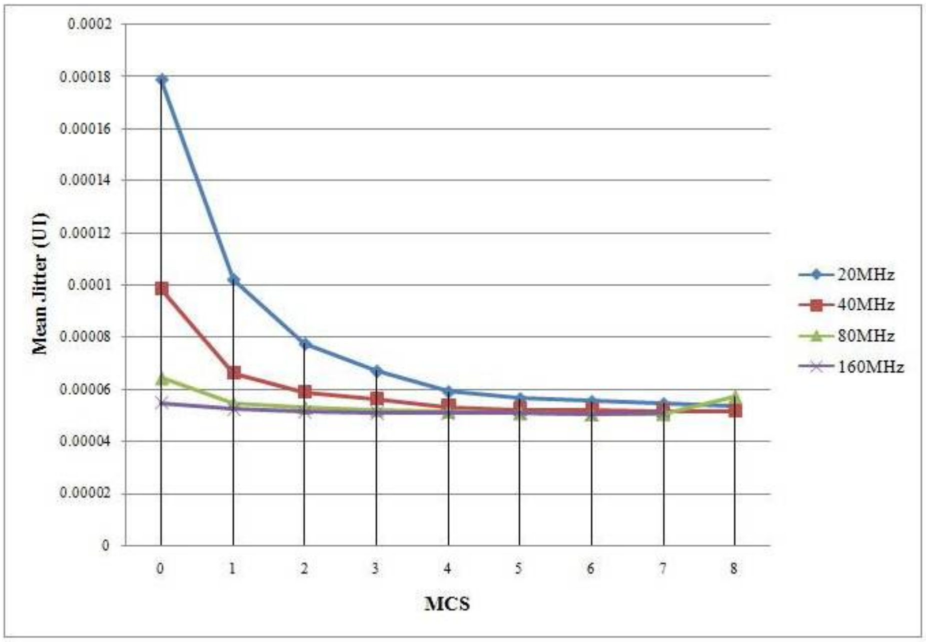


Fig 4.17 Mean jitter vs. MCS for SGI with 20, 40, 80, 160 MHz Bandwidth

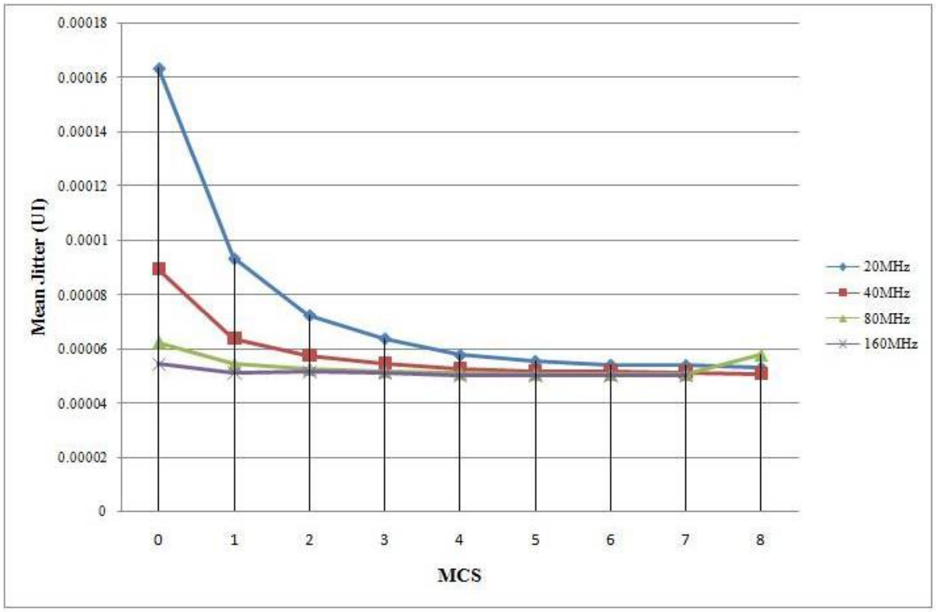


Fig 4.18 Mean jitter vs. MCS for long GI with 20, 40, 80, 160 MHz Bandwidth

Similar to mean delay, mean jitter also varies with varying bandwidth. This is seen in figures-4.17 and 4.18 for short and long GI. The above simulation is done when the stations are separated by 10m.

4.2.3.2 Discussion

From the values of throughput in figures-4.1 and 4.2 it is observed that higher MCS values give a better throughput irrespective of GI value. Long GI exhibits better throughput compared to short GI at all MCS values in both 11n and 11ac protocols.

In figure-5.1 VHT is 23 Mbps for MCS-4 but only 22.35 Mbps in HT. This trend is observed for the other MCS values too and also for long GI in figure-5.2. The improvement in throughput in 802.11ac protocol is proportionately more at higher MCS values. Hence, 802.11ac is exhibiting better throughput compared to 802.11n even at 20 MHz bandwidth.

The inferences derived in the above paragraphs for the throughput results of the 2 protocols at 20 MHz bandwidth is also observed for 40 MHz in figures-4.3 and 4.4.

In figures-4.13 and 4.14 throughput shows an almost linear improvement for 20, 40, 80 and 160 MHz from MCS-0 to MCS-5, after which the slope is slightly reduced. Improvement in throughput with bandwidth is also established unconditionally at both long and short GIs.

Mean delay is showing a constant improvement with higher MCS values at both 20 MHz and 40 MHz bandwidths and for both the protocols studied.

At MCS-2 mean delay in the 802.11n protocol is 0.328 for short GI (Figure 4.5) and 0.303 (Figure 4.6) for long GI. Similarly the values are 0.329 and 0.304 respectively for 802.11ac protocol with 20 MHz bandwidth. Hence mean delay is less for long GI as compared to short GI.

As seen in figures 4.9 and 4.10, at MCS-6 mean jitter in the 802.11n protocol is 5.49e-5 UI for short GI and 5.40e-5 UI for long GI. Similarly the values are

5.52e-5 UI and 5.43e-5 UI respectively for 802.11ac protocol with 20 MHz bandwidth. Hence mean jitter is also less for long GI as compared to short GI as in the case for mean delay. The behavioral response of mean jitter at 20 MHz bandwidth (figures-4.9 and 4.10) follows a similar trend as mean delay.

For any MCS, 802.11ac is not displaying improvement over 802.11n at 20 and 40 MHz bandwidth for both mean delay and mean jitter.

But we observe reduced delay in 802.11ac at higher bandwidths.

In 802.11ac, both delay and jitter performance shows improvement with bandwidth; the improvement is more marked at lower MCS values

4.2.4 Conclusion

As expected, 11ac and 11n do not differ much in terms of performance as far as 20 MHz and 40 MHz bandwidths are concerned. This is the case with all parameters (throughput, delay and jitter). However, from the results above it is seen that marginal improvement is present at higher values of MCS and at 40 MHz. 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.

4.3 Evaluation of Rate Adaptation Techniques

4.3.1 Introduction

The ns3.25 version of ns3 [1] used supports adaptive rate control algorithms like Ideal, and MinstrelHt RA managers for 802.11n and 11ac protocols in addition to ConstantRateWifiManager included in ns3.24 version of ns3.Therefore, the performance of 802.11ac and 802.11n WLANs is examined with reference to the Minstrel and IdealRA algorithms.

Ideal Rate Adaptation: Ideal RA is a Closed-Loop approach in which every STA tracks the SNR of each received packet and transmits this SNR to the original sender using an out-of-band mechanism. Each transmitter tracks the SNR transmitted last by a receiver and utilizes it to select the transmission mode based on a set of SNR limits constructed from the aimed BER and SNR/BER curves that are specific to the transmission mode. The Ideal RA mechanism chooses the best mode based on SNR of the packet transmitted earlier.

Consider that node-A transmits a unicast packet to node-B. On receiving the packet successfully node-B measures and notes the received packet's SNR into a tag and adds it to an ACK sent back to node-A. Hence, node-A is aware of the SNR of the packet transmitted to node-B using the out-of-band technique (hence, called 'Ideal'). A set of SNR thresholds is tabulated from the BER desired and from the SNR vs. BER plots. Node-A utilizes this data to choose a transmission mode with the knowledge of the receive SNR at node-B.

Minstrel Rate Adaptation: As discussed in [69] the RA techniques are classified as Acknowledgement (ACK) packet based, SNR based, and BER based, and are built on the metric used to predict channel conditions.

Minstrel RA algorithm, an ACK packet based algorithm supports multiple rate retries. It uses four critical design concepts: (i) Retry chain mechanism (ii) Statistics of transmission (iii) Normal transmission and (iv) Sampling transmission that are discussed below.

(i) Retry chain mechanism: It comprises four rate-count pairs, (r0, c0) to (r3, c3). One packet is initially sent at rate r0 for c0 tries. If unsuccessful the (r1, c1) combination is attempted. This is continued until the packet is successfully sent or discarded after (c0 + c1 + c2 + c3) failed attempts. The values c0 to c3 are chosen to complete the retry chain in 26ms. On successful transmit at any point, the rest of retry chain is ignored. Also, as the retry time for all data rates is almost equal, more retries are achieved at a higher data rate and vice versa.

(ii) Statistics of Transmission: The Minstrel algorithm maintains an account of the packet transmission statistics at each rate based on an Exponentially Weighted Moving Average (EWMA) which are used to re-evaluate the retry chain per 100 mS. The steps involved to re-evaluate are: measure the probability of transmissions which met with success for each data rate, calculate EWMA probability of successful transmission ratio and calculate the throughput for each data rate.

(iii) Normal Transmission: r0 and r1 rate values are selected as the rate that obtains the largest and second largest EWMA throughput respectively while r2 is the rate with the largest EWMA success ratio and r3 is the least data rate. This method targets to provide good throughput in the wireless environment.

(iv) Sampling Transmission: The rates chosen in the retry chain are r0 to r3. During sampling transmission, rates other than r0 to r3 are chosen to enable the algorithm to modify the rates in the retry chain if the old rates r0 to r3 do not give the optimum throughput. The modification of r0 to r3 is done as below.

For each sample packet, Minstrel randomly selects a rate not present in the retry chain. Now r0 to r3 are chosen based on:

r0: the higher sample rate or the rate with the highest ewma throughput

r1: the lower sample rate

r2: rate yielding highest ewma success ratio

r3: lowest available rate

This sampling mechanism means that Minstrel is more likely to sample higher rates, because higher rates are tried before the rate with the current highest throughput. Thus Minstrel is able to effectively increase its sending rates as the channel quality increases, which was an area of weakness in previous algorithm such as SampleRate. Rate algorithms for 802.11 have used the measured received Signal Strength Indication (RSSI) to choose the rate to use but do not consider the effect of multipath. In the minstrel rate algorithm, the rate that works well is used and other rates are ignored, but, all rates are tried periodically.

Results of this analysis are published in International Journal of Computing and Applications - Serials Publications as "Evaluation of the Effect of Rate Adaptation Techniques on IEEE 802.11ac and 802.11n" and presented in the 'First

International Conference on Smart Technologies in Computer and Communication, (SmartTech-2017), March, 2017.'

4.3.2 Performance Test

The ns3-3.25 version of ns-3 released in March 2016 is used for the analysis in this chapter, has a Wi-Fi module with enhanced support for broader channel widths (up to 160 MHz) and multiple SS (up to 4).

In the scenario, an adhoc WLAN is used. Operation of the WiFi Manager (Ideal or Minstrel) is tested as the SNR is varied. The output of the test case is the data rate for every HT/VHT bit rate value, which depends on the number of SS (1, 2, 3 or 4), the channel width (20 or 40 MHz for 802.11n and 20, 40, 80 or 160 MHz for 802.11ac) and the guard interval (long or short). Configuration parameters are listed below:

Ideal

- RTS threshold = 999999
- Power between steps = 1 dBm
- Time on each step = 0.5 seconds
- Packet Size = 1024 bytes
- Broadcast or unicast; default is unicast
- nss = 1,2,3,4
- Short Guard Interval = true or false
- Channel Width = 20, 40, 80,160 MHz (as appropriate)
- Standard = 802.11n-5GHz, 802.11n-2.4GHz, 802.11ac
- Minimum SNR = 5 db
- Maximum SNR = 35 dB

Minstrel

- RTS Threshold = 65535
- BE_MaxAmpduSize = 65535
- Step Size = 1 dBm

- Step Time = 1 seconds
- Packet Size = 1024 bytes
- Short Guard Interval = true or false
- Channel Width = 20, 40, 80,160 MHz (as appropriate)
- Standard = 802.11n-5GHz, 802.11n-2.4GHz, 802.11ac
- Minimum SNR = 5 db
- Maximum SNR = 35 dB.

4.3.3 Results and Discussion

4.3.3.1 Rate adaptation in 802.11ac and 802.11n

The adapted transmit data rate in 802.11ac and 802.11n protocols with change in SNR at receiver, for various SS – 1,2,3,4 when the CBW is 20 MHz and 40 MHz is plotted in figures-4.19a and 4.19b respectively. The type of RA used is “Ideal WiFi”.

As expected, 11n and 11ac do not differ in performance in the common bandwidths of 20 MHz and 40 MHz.

When Ideal Wi-Fi rate control is implemented in the 802.11ac WLAN protocol the transmit data rate adapted with variation in SNR for CBW 80 MHz and 160 MHz is as shown in fig-4.19c to 4.19d.

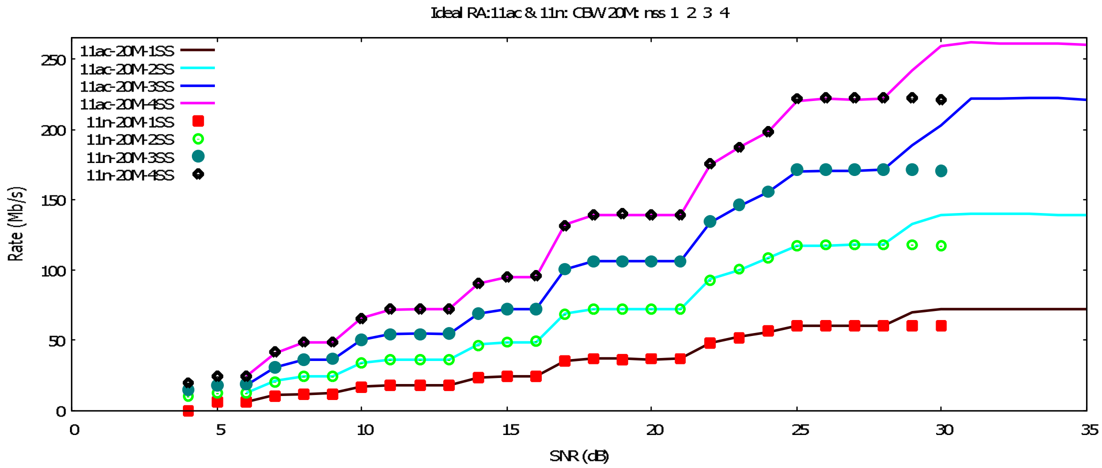


Fig 4.19a 802.11n & 11ac response to Ideal WiFi for 1,2,3,4 SS, 20 MHz CBW

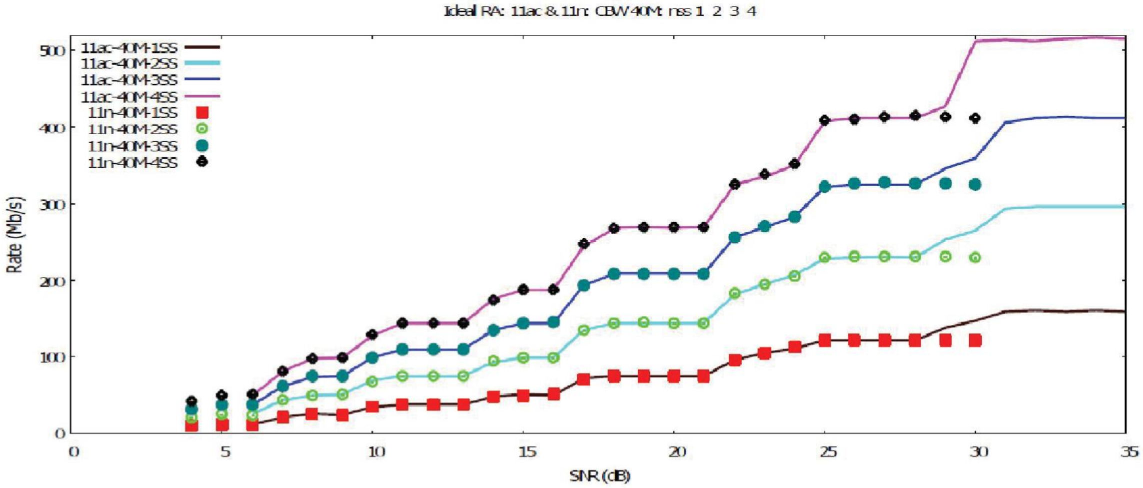


Fig 4.19b 802.11n & 11ac response to Ideal WiFi for 1,2,3,4 SS, 40 MHz CBW

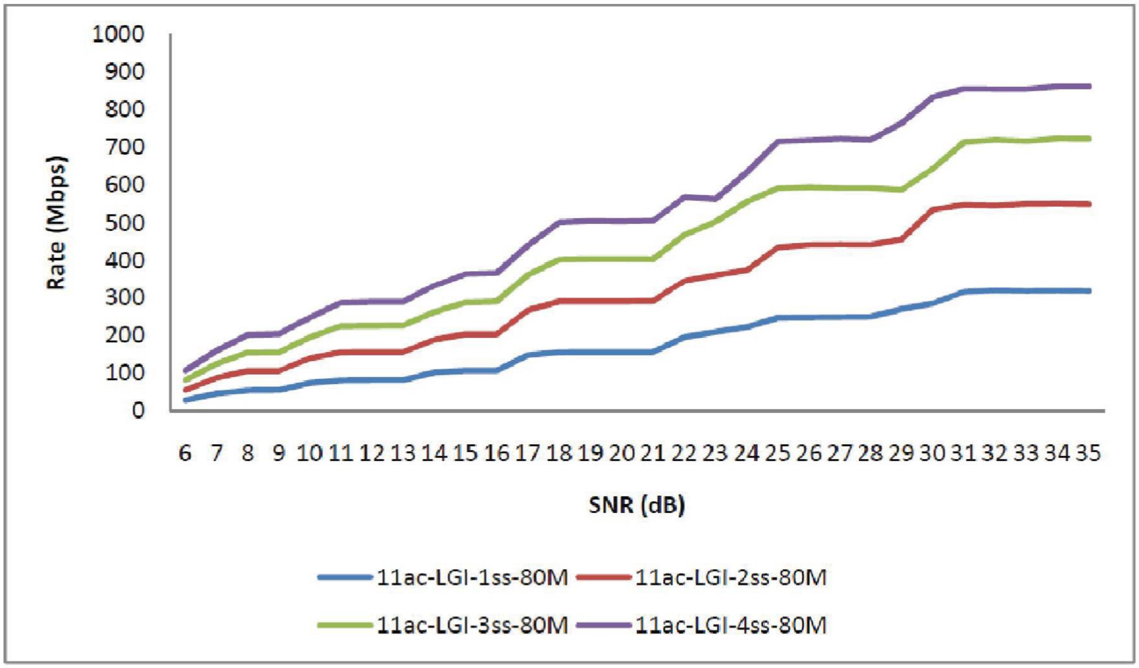


Fig 4.19c 802.11ac response to Ideal WiFi for 1,2,3,4 SS, 80 MHz CBW

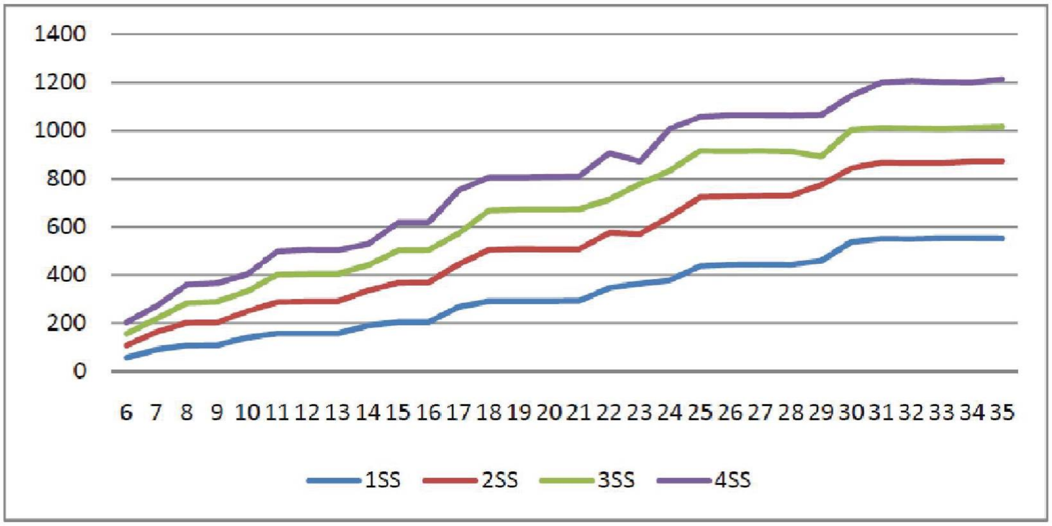


Fig 4.19d 802.11ac response to Ideal Wi-FI for 1,2,3,4 SS, 160 MHz CBW

A steady increase in transmit throughput is observed with increasing SNR, with increasing number of SS and also with increasing CBW.

It may be noted here that the theoretical data rates for different configurations in 802.11ac are as in Table-4.2. For all other values of bandwidth and SS (not explicitly mentioned in Table-4.2) the throughput may be calculated as follows with reference to the throughput at 20 MHz: 2.1 times for 40 MHz, 4.5 times for 80 MHz, 9 times for 160MHz. For every additional SS, the throughput increases correspondingly with throughput with 1SS as reference.

With Ideal Wi-FI RA, maximum throughput achieved also follows the pattern of theoretical data rates for different configurations, but the absolute values are scaled down.

Thus, the "idealized" RA algorithm results are consistent showing steady improvement of throughput. But, due to the constraint of adapting to SNR variations, the actual benefits of using higher BWs and SSs are not realized as expected with the theoretical values. Ideal RA introduces extra control overhead with SNR tags in ACK and the unicast data packets which increase with more SS.

Similar simulations with "Minstrel" RA are shown in figure-4.20a and 4.20b. These simulations are done with Short Guard Index (SGI).

Table 4.2 Minimum and Maximum Data Rates

MCS	20MHz, 1SS,LGI	20MHz, 1SS,SGI	160MHz, 8SS,LGI	160MHz, 8SS,SGI
0	6.5	7.2	468.0	520.0
1	13.0	14.4	939.0	1040.0
2	19.5	21.7	1404.0	1560.0
3	26.0	28.9	1872.0	2080.0
4	39.0	43.3	2808.0	3120.0
5	52.0	57.8	3744.0	4160.0
6	58.5	65.0	4212.0	4680.0
7	65.0	72.2	4680.0	5200.0
8	78.0	86.7	5616.0	6240.0
9	86.7	96.3	6240.0	6933.3

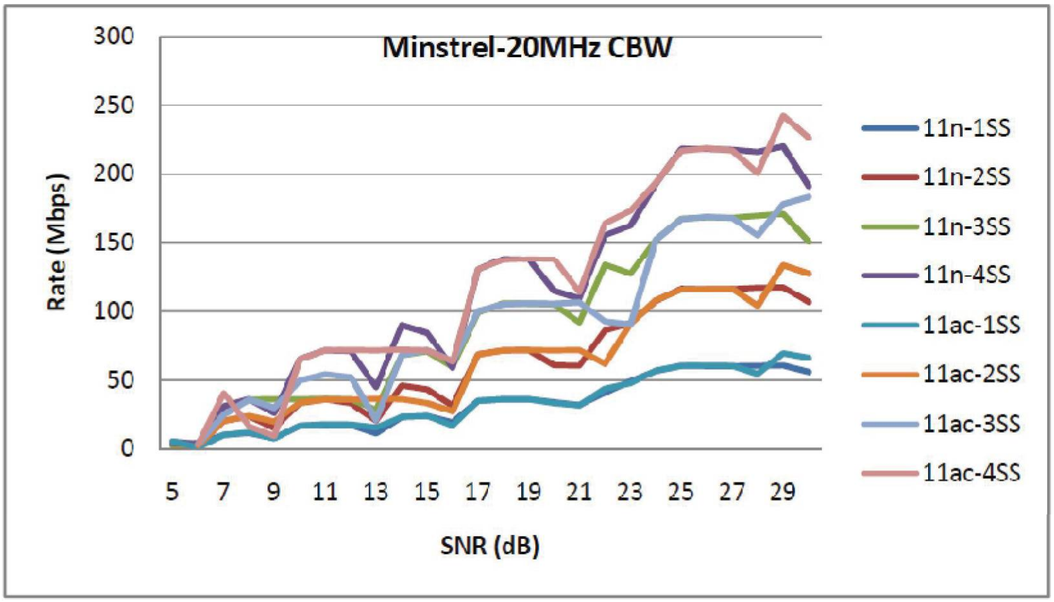


Fig 4.20a: 802.11ac & 802.11n Response to 'Minstrel' for 1,2,3,4 SS, 20 MHz CBW

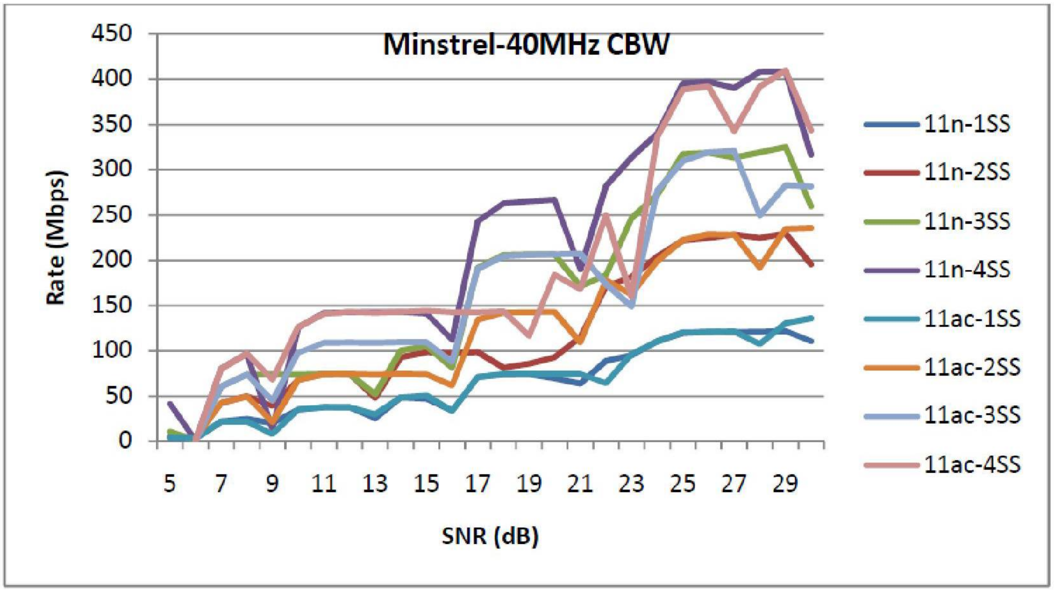


Fig 4.20b: 802.11ac & 802.11n Response to 'Minstrel' for 1,2,3,4 SS; 40 MHz CBW

Observations: At 20 MHz, behavior of 11n and 11ac is similar with all combinations of SS. same is the case with 40 MHz for 1 SS and 2 SS. However, for 3 SS, 11n shows improved throughput between 12 and 22 dB SNR over 11ac whereas for 4SS, 11ac is better than 11n for the same SNR range.

With 80 and 160 MHz CBWs (Figs-4.20c and 4.20d) the throughput parameters are not as expected – i.e. throughput is not improving with better SNR values. Maximum throughput is the same with CBW 80 and 160 MHz i.e. about 400 Mbps. With SNR values greater than 15 dB, the throughput is the same independent of the number of SS. This irregular behavior is not seen with single SS.

With Ideal RA, both 11ac and 11n perform consistently. With Minstrel, both 11ac and 11n behave similarly at 20 MHz CBW, but for 11ac, there is inconsistency at all other BWs and number of SSs.

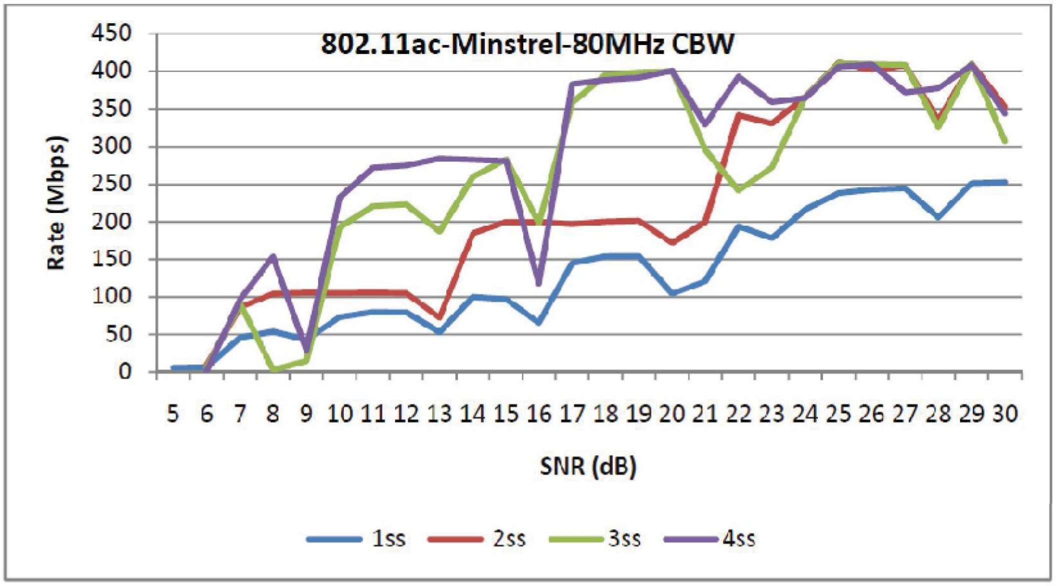


Fig 4.20c: 802.11ac Protocol Response to Minstrel; CBW=80 MHz

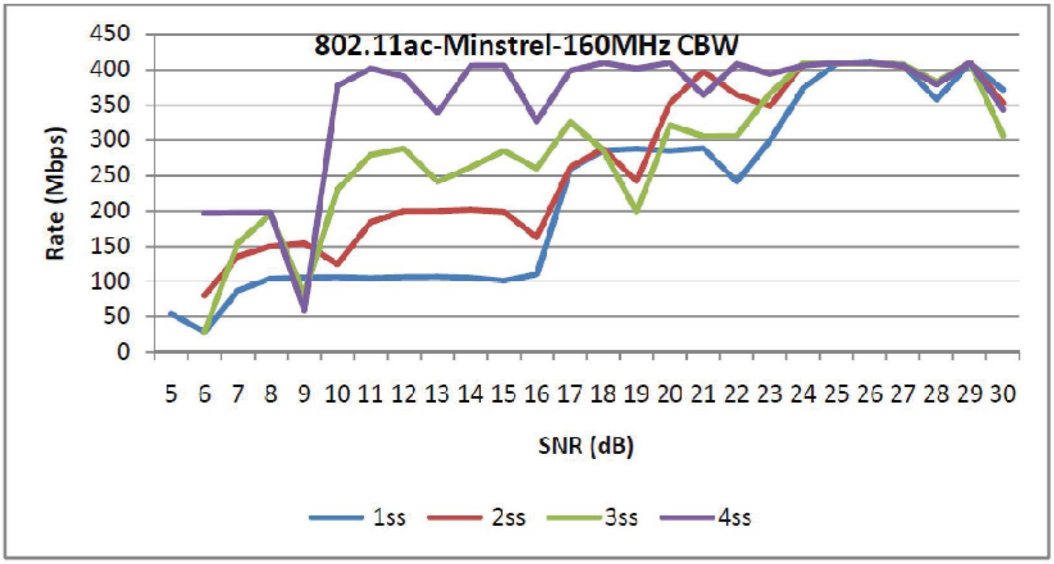


Fig 4.20d: 802.11ac Protocol Response to Minstrel; CBW=160 MHz

4.3.3.2 Effect of Guard Index (GI) with Ideal and Minstrel Rate adaptation in 802.11ac and 802.11n

With "Ideal" RA, figure-6.3 shows the observed transmit data rate in 802.11ac with change in SNR, for various SS – 1,2,3,4 when the CBW is 80MHz. The data is simulated for both cases when SGI is true and false to study the effect of GI on the data rates in the presence of Ideal RA.

From figure-4.21 it is observed that the length of the GI does not impact the response of 802.11ac protocols with Ideal Wi-Fi RA. The results are similar for other CBWs also. With Ideal rate control, the response of 802.11n is same as 802.11ac and hence it can be inferred that the guard interval parameter does not impact the throughput of the 802.11n system with Ideal Wi-Fi RA.

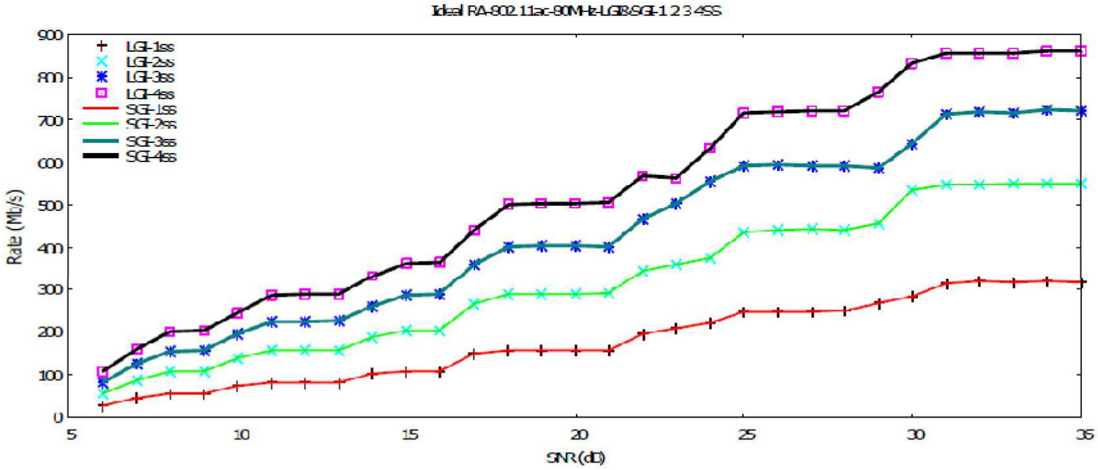


Fig 4.21: 802.11ac Response to 'Ideal' RA for 1,2,3,4 SS; 80 MHz CBW under the influence of GI

When "Minstrel" RA is implemented, figures-4.22a to 4.22d show the observed transmit data rate with change in SNR, in 802.11ac when the CBW is 20, 40, 80 and 160 MHz respectively. Similar study is done for 802.11n in figure-4.23a and figure-4.23b when CBW is 20 and 40 MHz respectively. The response of the system is simulated for the cases when SGI is true and false.

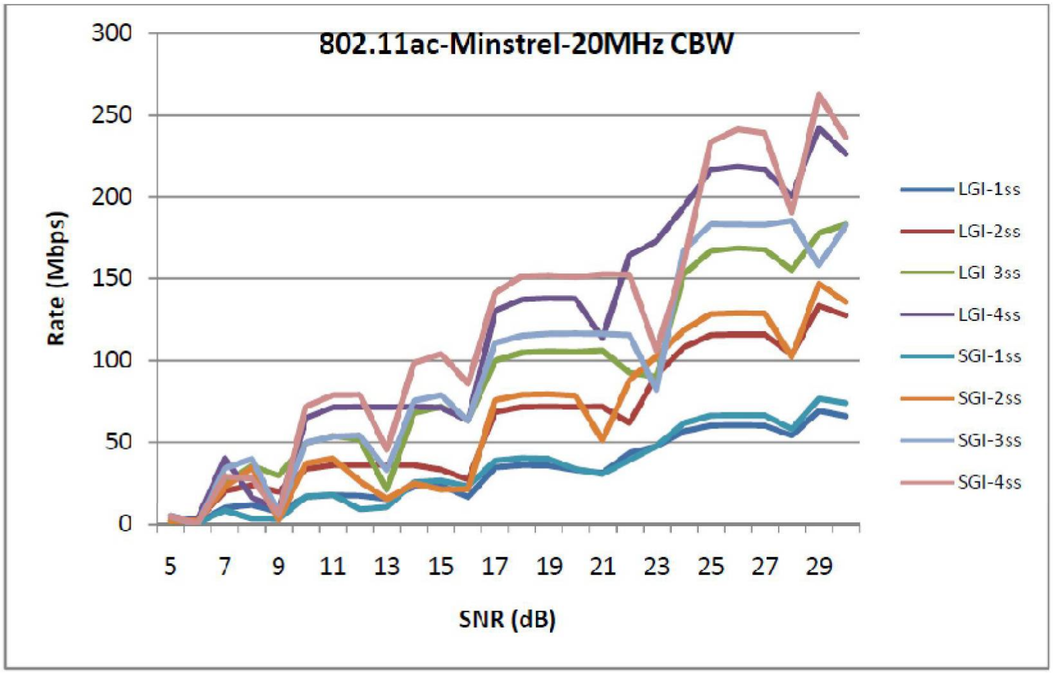


Fig 4.22a 802.11ac Response to Minstrel for 1,2,3,4 SS; CBW 20 MHz under the influence of GI

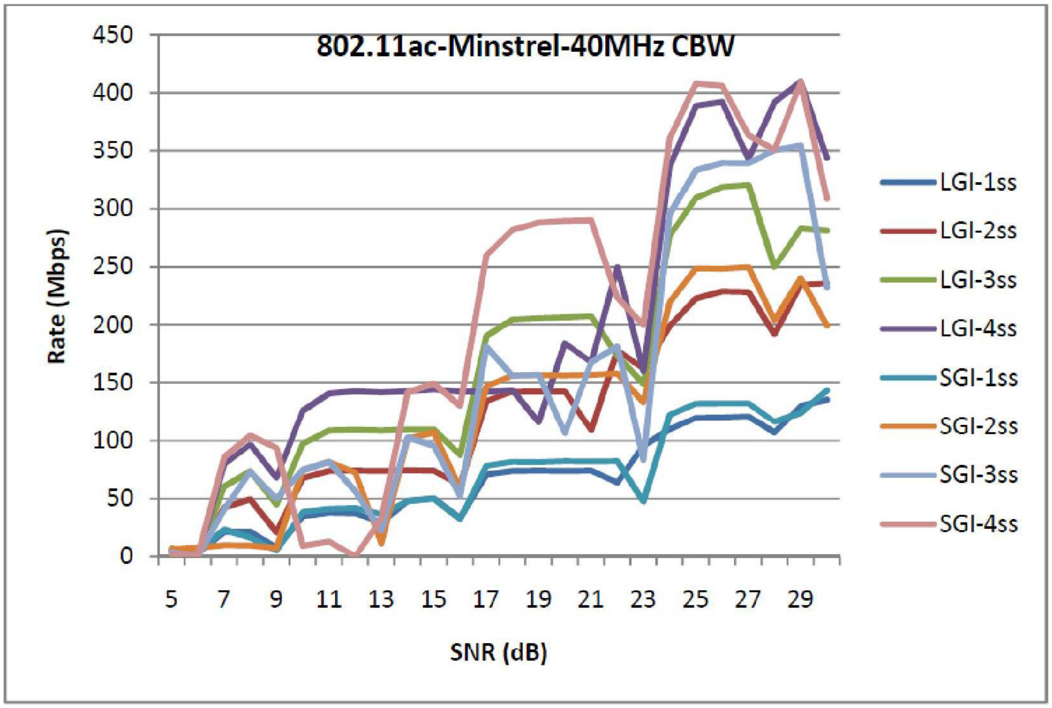


Fig 4.22b 802.11ac Response to Minstrel for 1,2,3,4 SS; CBW 40 MHz under the influence of GI

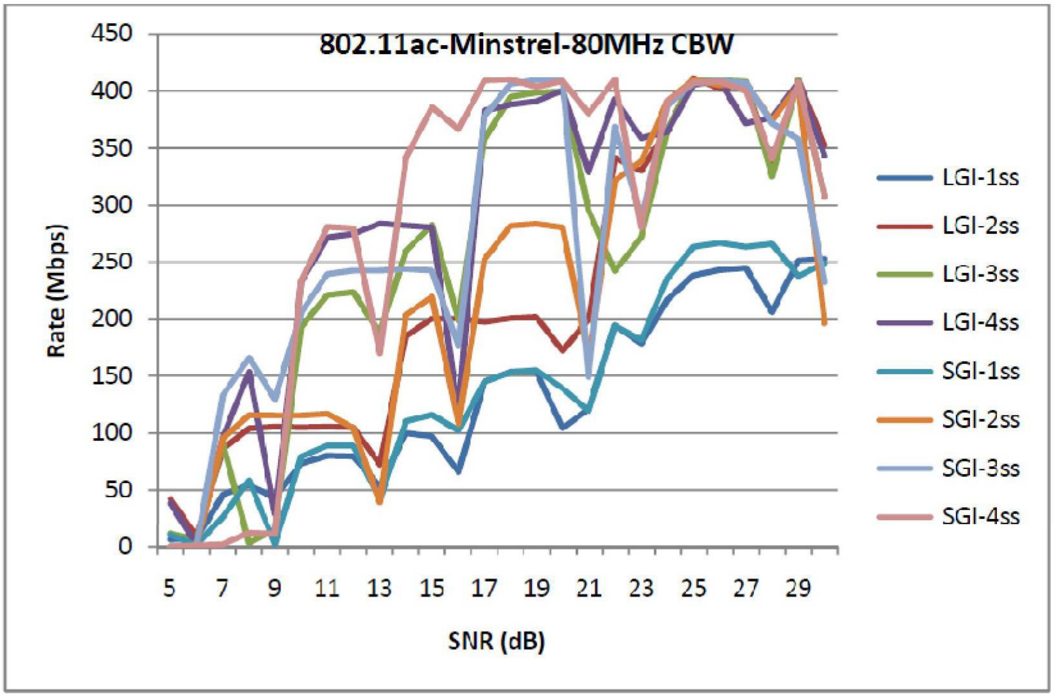


Fig 4.22c 802.11ac Response to Minstrel for 1,2,3,4 SS; CBW 80 MHz under the influence of GI

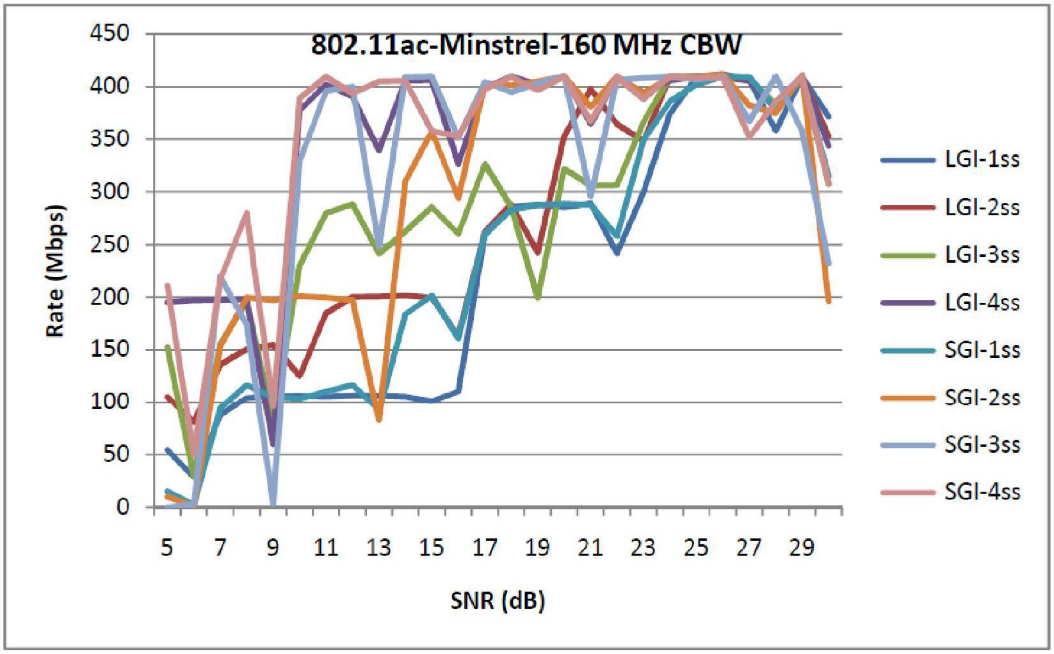


Fig 4.22d 802.11ac Response to Minstrel for 1,2,3,4 SS; CBW 160 MHz under the influence of GI

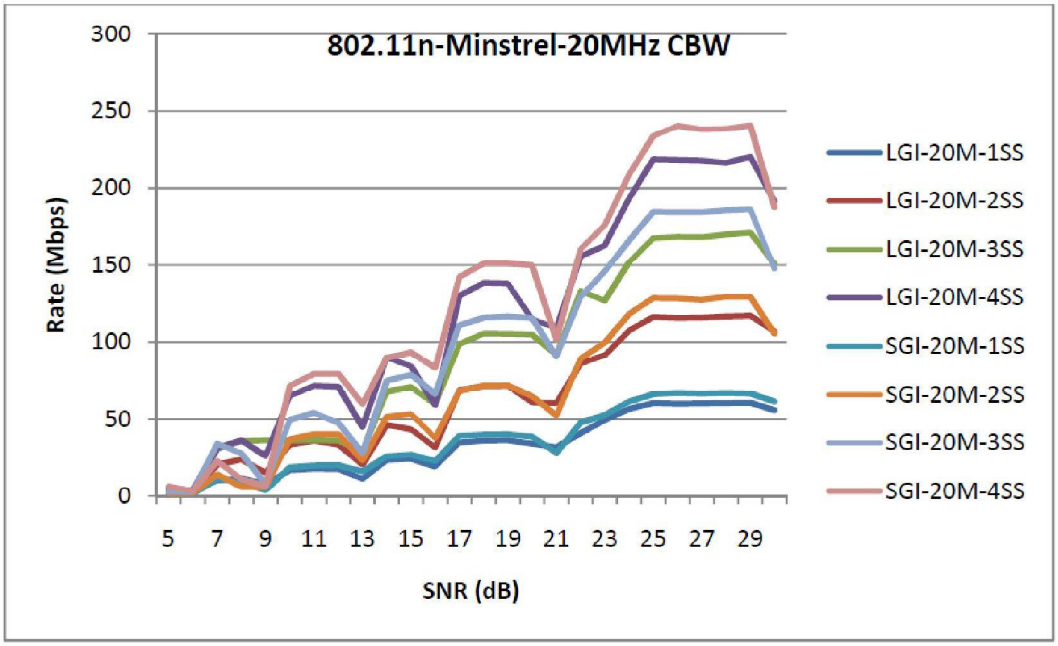


Fig 4.23a: 802.11n Response to Minstrel for 1,2,3,4 SS; CBW 20 MHz under the influence of GI

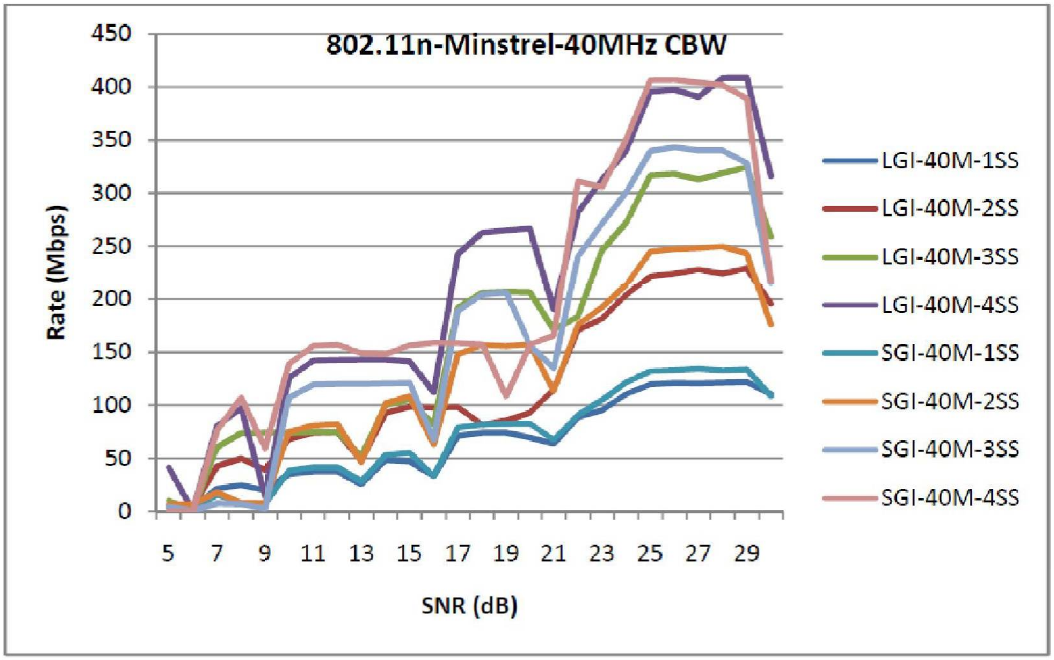


Fig 4.23b: 802.11n Response to Minstrel for 1,2,3,4 SS; CBW 40 MHz under the influence of GI

Unlike Ideal Wi-Fi RA, the Minstrel algorithm results in dissimilar data rates for different values of guard interval. The response (Figures-4.22a and 4.23a) in both protocols when the CBW is 20 MHz follows a similar pattern for SGI and Long GI (LGI) for all values of SS, with a marginally better data rates for Short GI (SGI) and for 40 MHz CBW for 802.11n. This trend is repeated for 1SS only when the CBW is 40, 80 and 160 MHz in 802.11ac protocol (Figures-4.22b to 4.22d). In the other cases, the transmit data rate observed does not follow a regular pattern with reference to the SNR received.

Thus, we conclude that in Ideal RA, there is no impact of GI on both 11ac and 11n. However, with Minstrel, the results do not follow a defined pattern for GI variation.

4.3.3.3 Comparison of Ideal and Minstrel in 802.11ac

The response of 802.11ac protocol to Ideal and Minstrel rate controls is compared at different bandwidths (20, 40, 80 and 160 MHz) in figures-4.24a to 4.24d. This simulation is done for 1, 2, 3 and 4 SS.

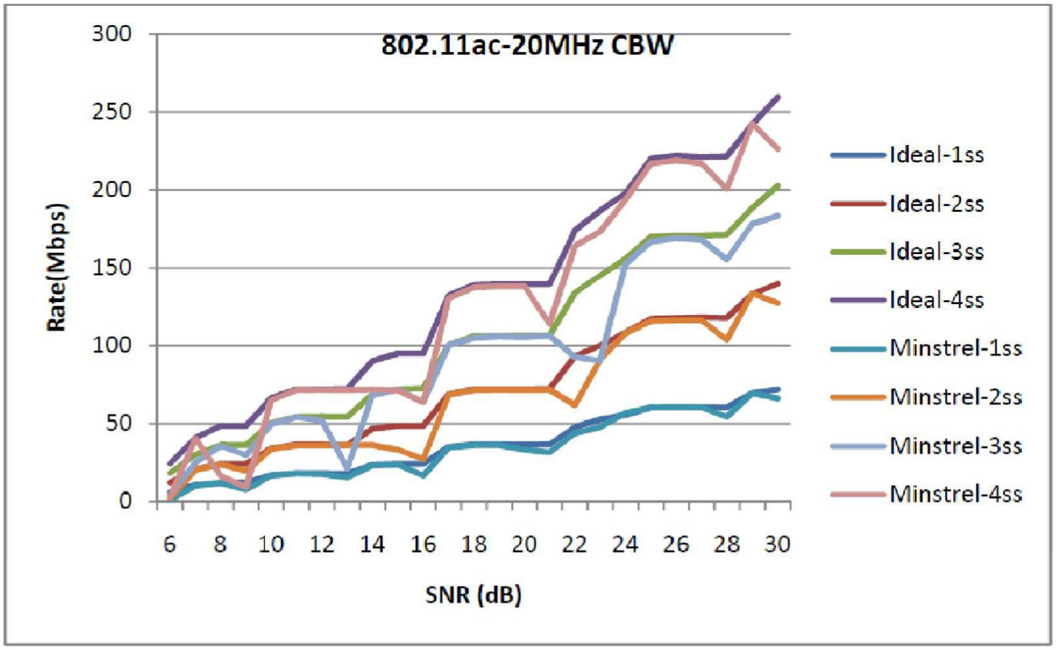


Fig 4.24a: 802.11ac Response to Ideal & Minstrel for 1,2,3,4 SS; CBW 20 MHz

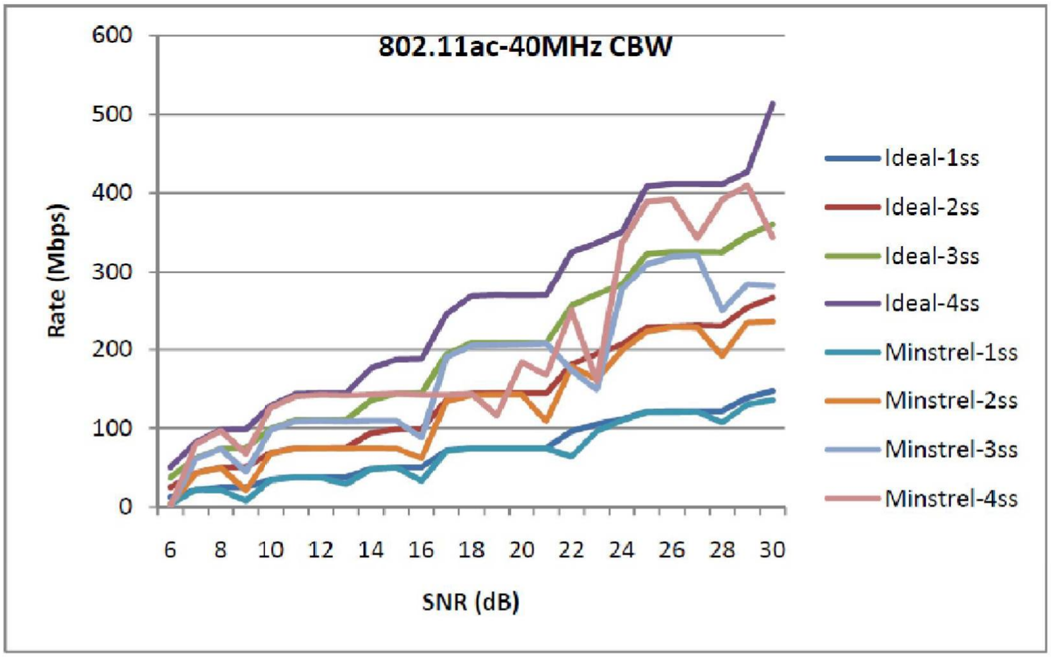


Fig 4.24b: 802.11ac Response to Ideal & Minstrel for 1,2,3,4 SS; CBW 40 MHz

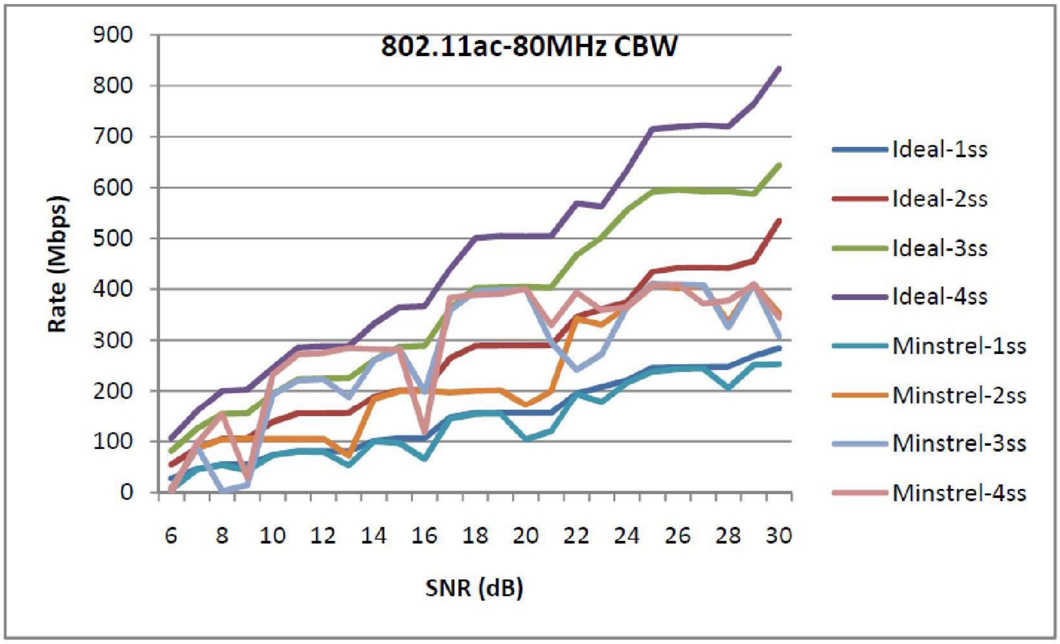


Fig 4.24c: 802.11ac Response to Ideal & Minstrel for 1,2,3,4 SS; CBW 80 MHz

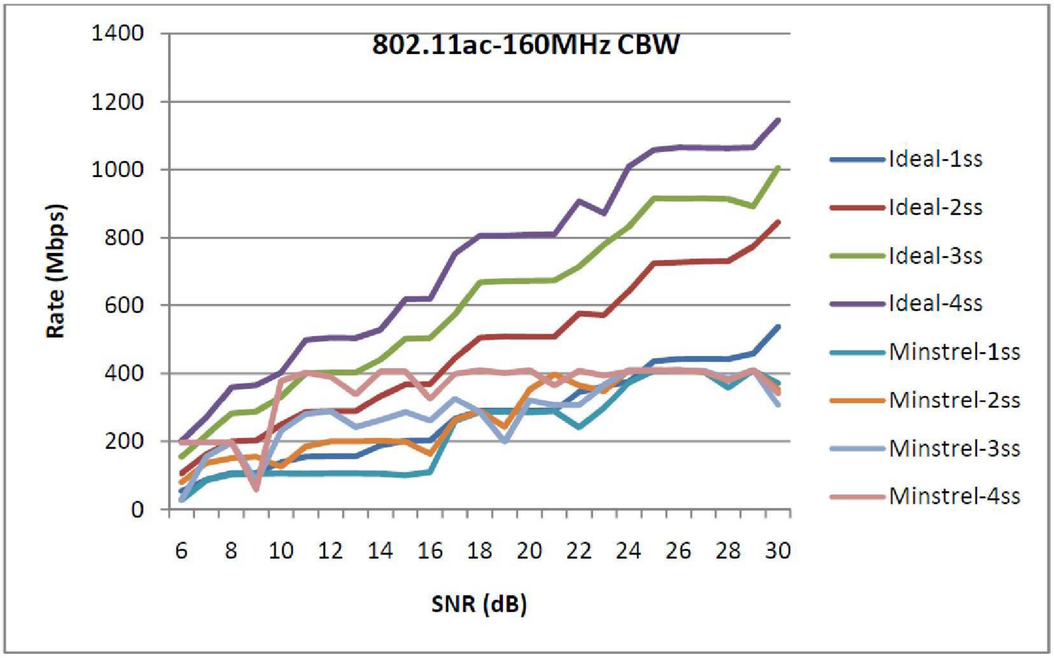


Fig 4.24d: 802.11ac Response to Ideal & Minstrel for 1,2,3,4 SS; CBW 160 MHz

If the data rates due to the 2 RA algorithms are compared, it is seen that the results are comparable with 20 and 40 MHz CBW. At 80 and 160 MHz CBWs performance of Minstrel is not up to the mark.

To conclude, for 11ac, both Ideal and Minstrel are suitable at 20MHz and 40 MHz, but Minstrel is not recommended for newer high CBWs.

4.3.3.4 Performance Evaluation of Ideal and Minstrel in 802.11ac - selected and achieved data rates

Based on the SNR values the algorithm selects the data rates for transmission based on the CBWs and the number of SS. Figures-4.25a to 4.25d compares the achieved data rates with the selected data rates for different bandwidths 20, 40, 80 and 160 MHz respectively when the Ideal RA algorithm is adopted. Simulation is done for 1, 2, 3 and 4 SS.

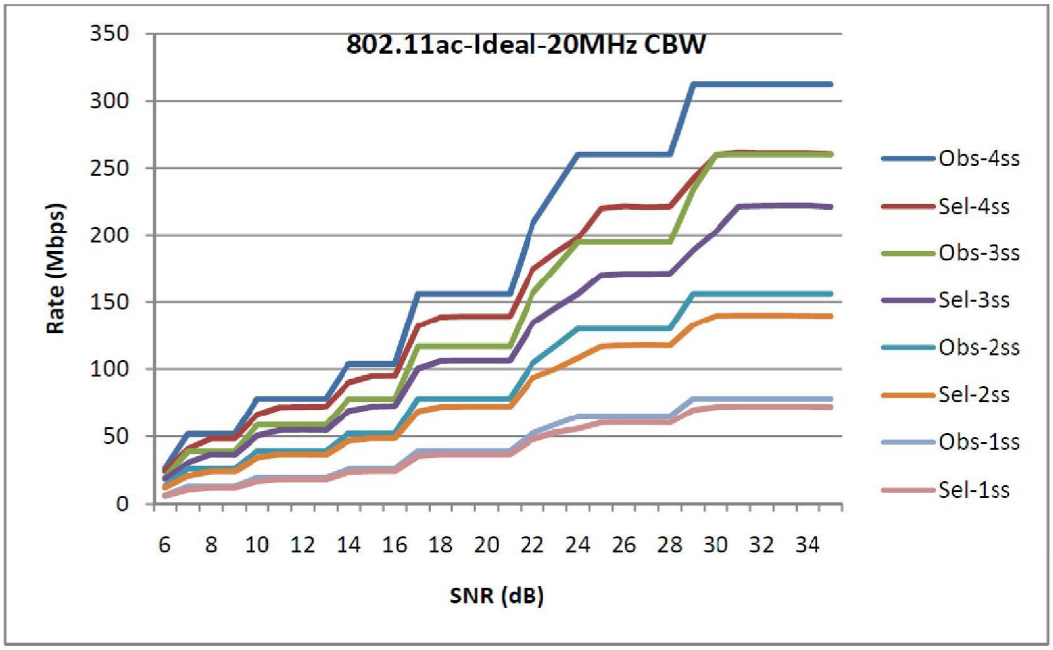


Fig 4.25a: Observed & selected rates-802.11ac-'Ideal'-1,2,3,4 SS; CBW 20MHz

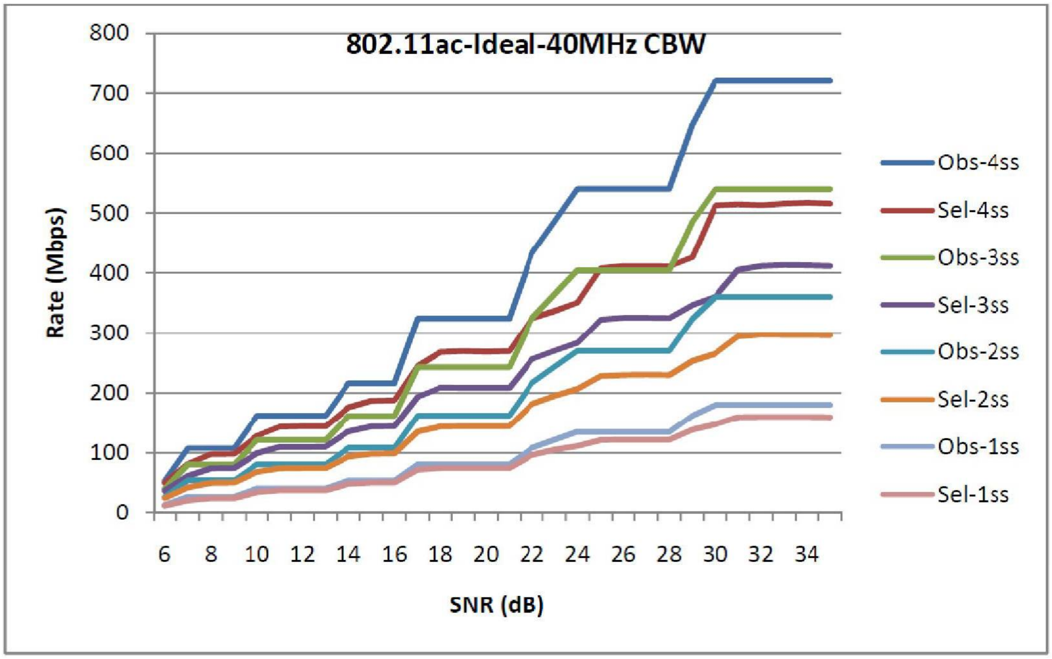


Fig 4.25b: Observed & selected rates-802.11ac-'Ideal'-1,2,3,4 SS; CBW 40MHz

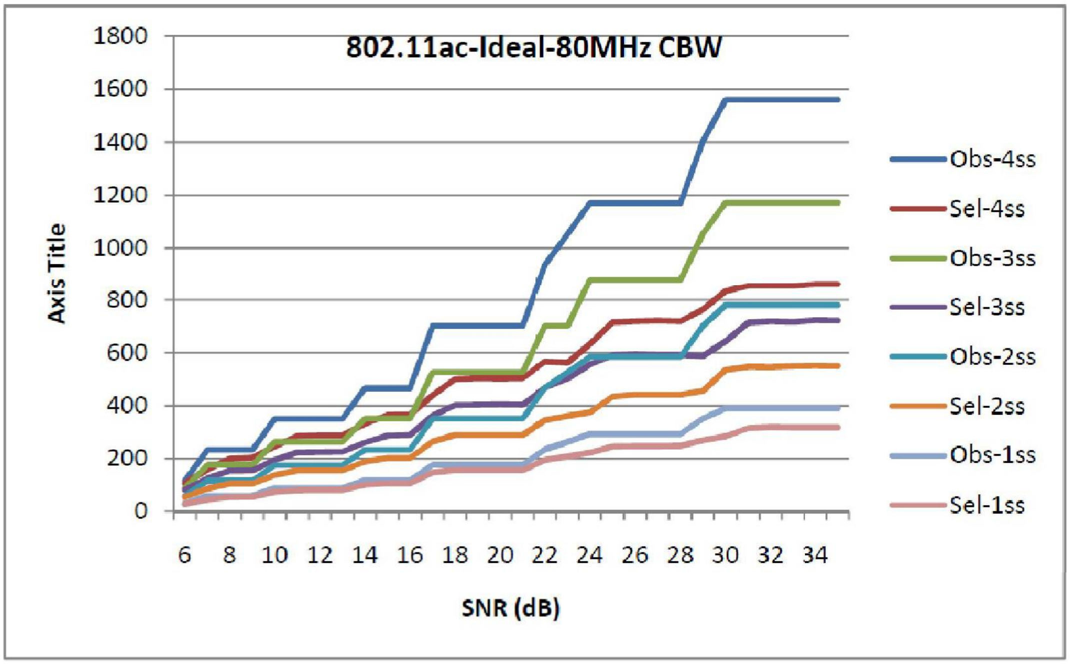


Fig 4.25c: Observed & selected rates-802.11ac-'Ideal'-1,2,3,4 SS; CBW 80 MHz

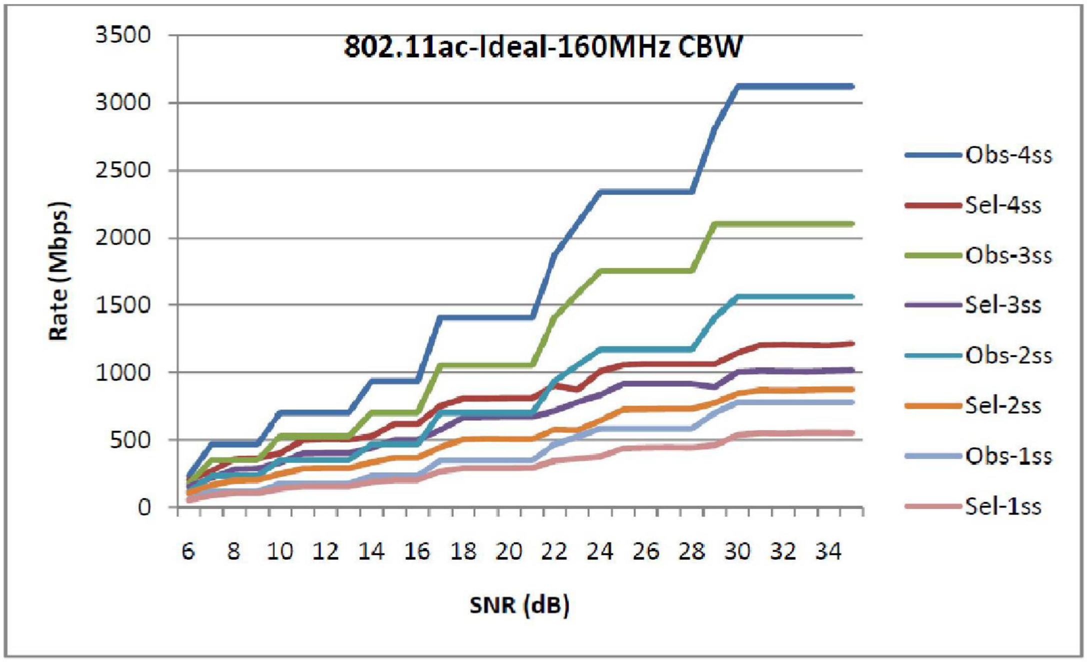


Fig 4.25d: Observed & selected rates-802.11ac-'Ideal'-1,2,3,4 SS; CBW 160 MHz

A similar comparison is done between the selected and observed data rates with Minstrel RA algorithm in figures-4.26a to 4.26d.

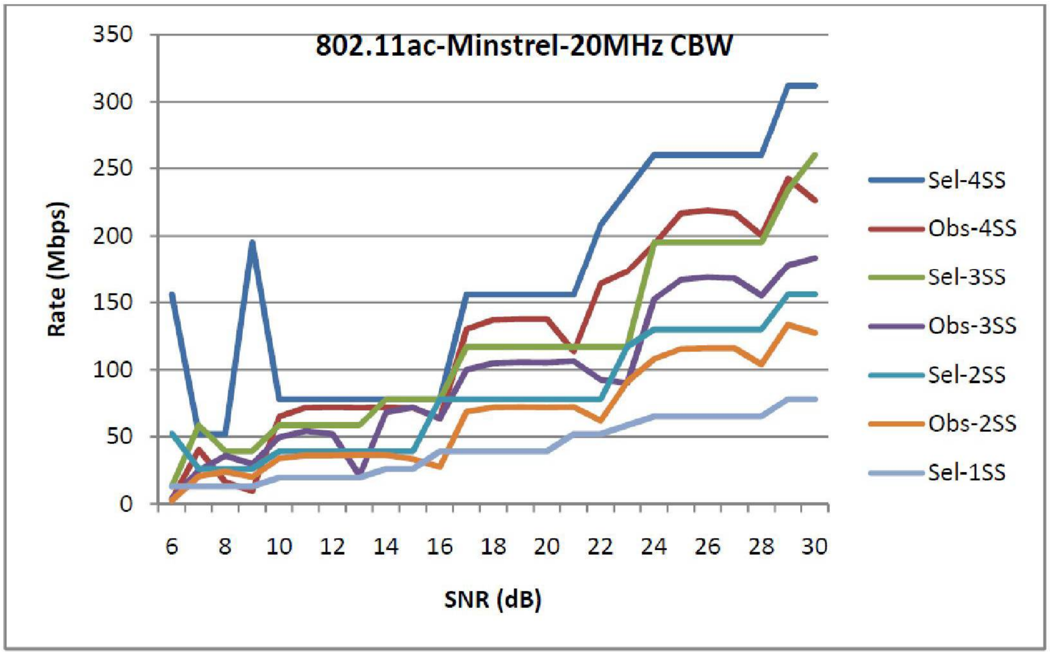


Fig 4.26a: Observed & selected rates-802.11ac-Minstrel-1,2,3,4 SS;CBW 20MHz

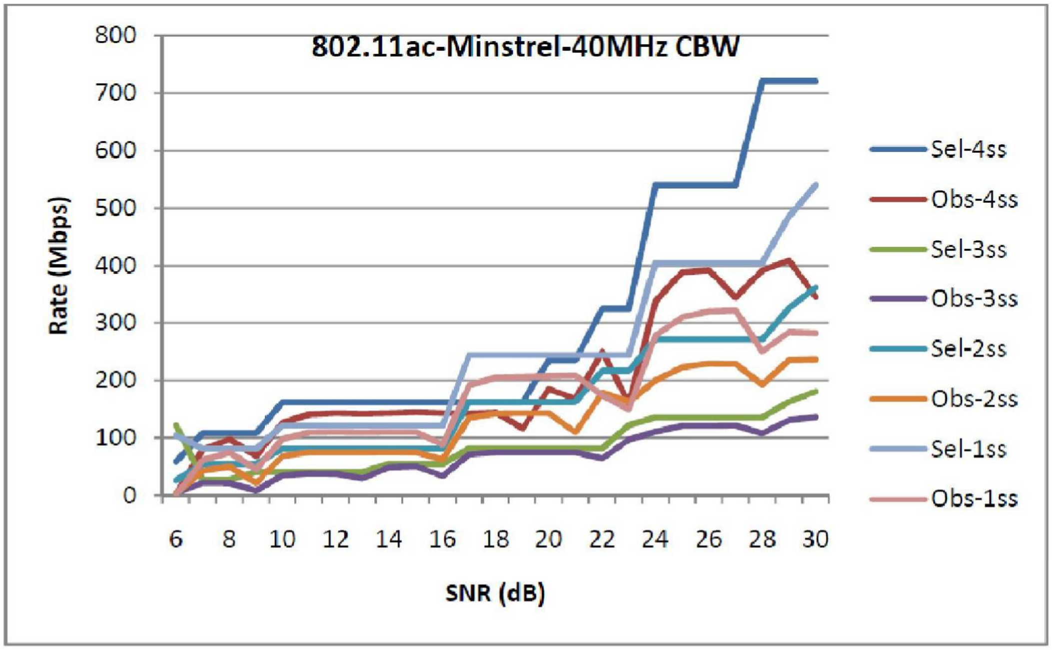


Fig 4.26b: Observed & selected rates-802.11ac-Minstrel-1,2,3,4 SS;CBW 40MHz

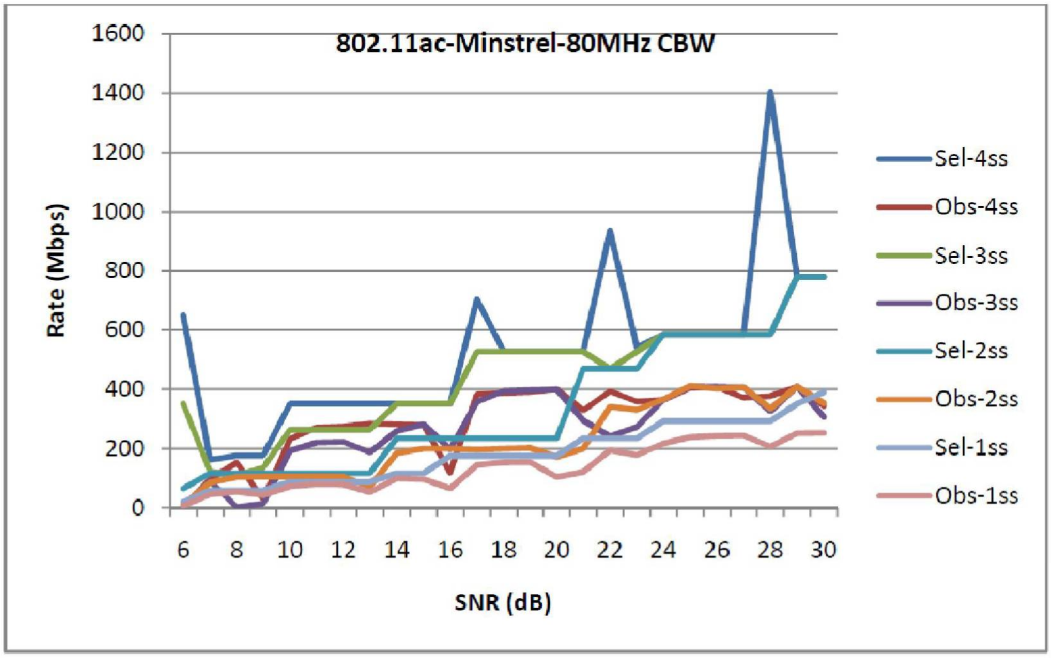


Fig 4.26c: Observed & selected rates-802.11ac-Minstrel-1,2,3,4 SS;CBW 80MHz

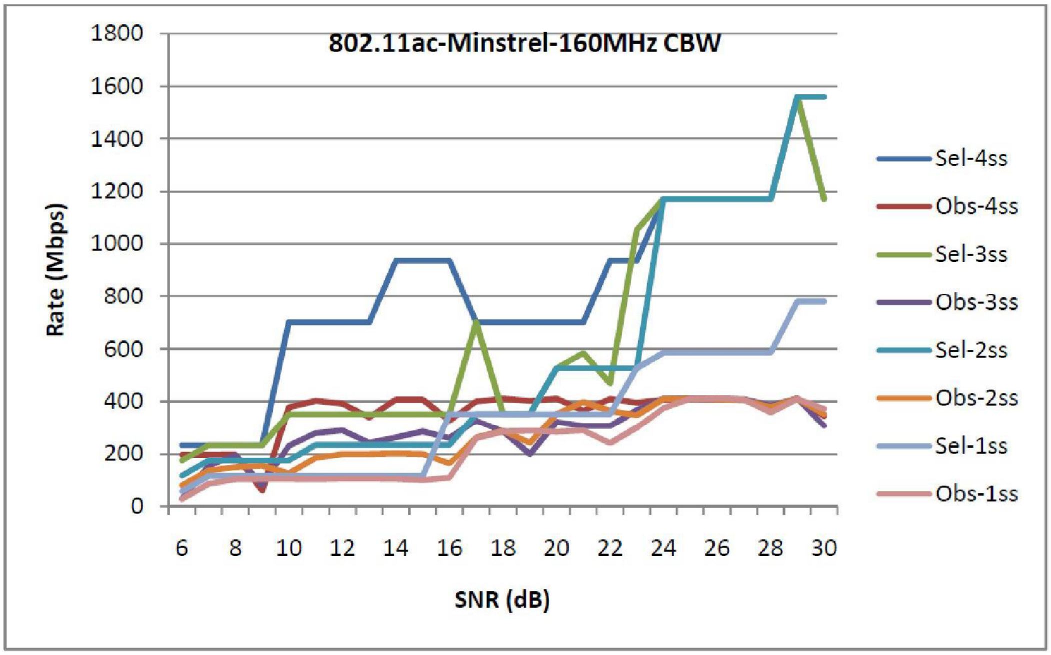


Fig 4.26d: Observed & selected rates-802.11ac-Minstrel-1,2,3,4 SS;CBW 160MHz

With Ideal Rate control mechanism, when the CBW is 20 and 40 MHz (Figs-4.25a and 4.25b), the observed rates are closely matching with the selected rates for a single SS. Increasing deviation from the selected rate is observed in 2, 3 and 4 SS respectively.

For 80 and 160 MHz CBW (Figs-4.25c and 4.25d), RA is working well for lower SNR values, up to 20 dB for single SS and up to only 9 dB for 2 SS. For 3 and 4 SS, the adapted rate is very different from the selected data rate.

When the CBW is 20 and 40 MHz and 1 or 2 SS are utilized for transmission with Minstrel RA, for SNR values less than 21 dB the observed rates (Figs-4.26a and 4.26b) are able to meet the expectation of the algorithm. With 3 and 4 SS this is met only up to about 17 dB SNR. The Minstrel RA deviates (by about 15%) from the selected rate for moderate SNR values (up to 22 dB). In the case of 40 MHz bandwidth the achieved rates are very low compared to the selected ones at high SNRs (> 22dB).

Similarly, for CBWs 80 and 160 MHz and 1 or 2 SS, observed rates are similar to the rates selected by the Minstrel algorithm, but only for SNR values less than 15 dB (Figs-4.26c and 4.26d). With 3 and 4 SS the deviation from selected rates is higher even at lower SNRs and intermediate high selected rates for 4 SS.

The difference between the selected and observed data rates in the presence of RA algorithm is plotted as standard deviation in the figure-4.27, for various bandwidths and different SS for both Ideal and Minstrel algorithms.

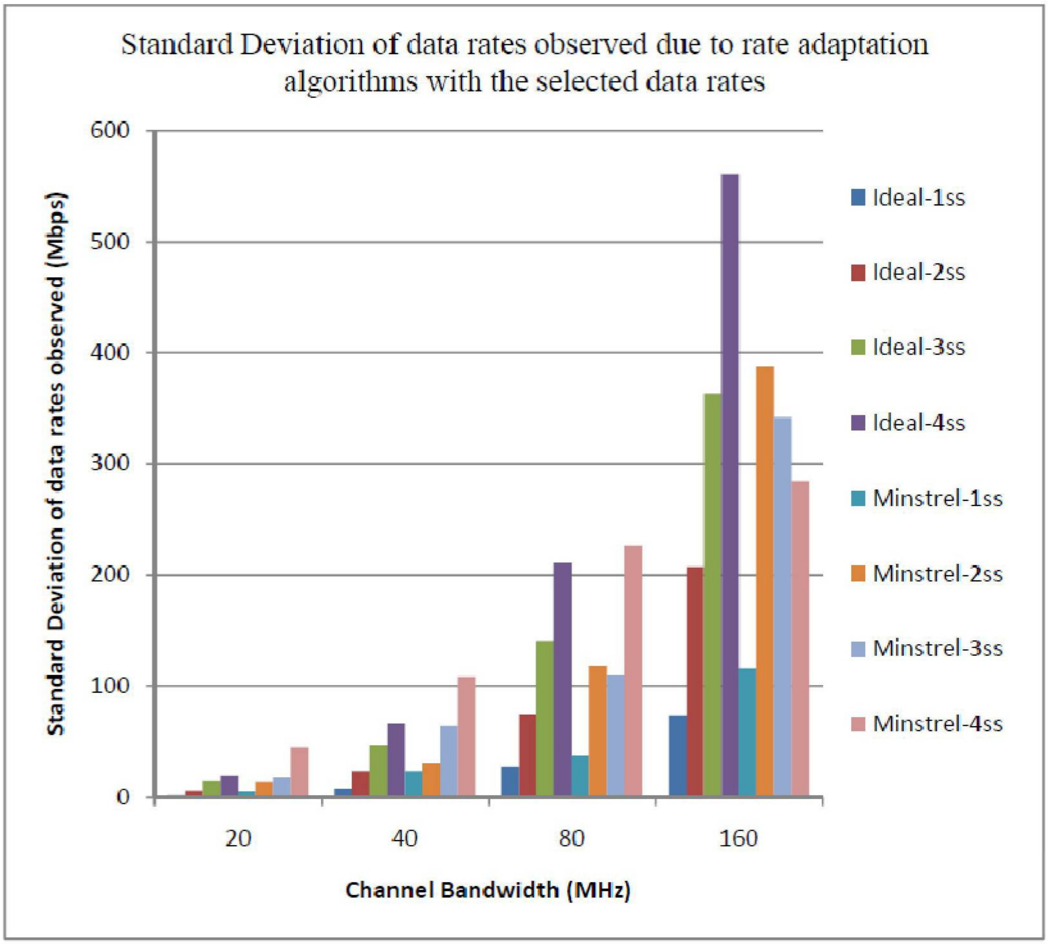


Fig 4.27: Observed & selected rates as standard deviation for 802.11ac Ideal and Minstrel RA

Deviation of the data rates observed due to RA from the data rates selected by the RA algorithm is gradually increasing with number of SS and with CBW for both algorithms. The behavior of the Minstrel algorithm is marginally better than the Ideal one only in the case of 3 SS in 80 and 160 MHz CBWs and also when using 4 SS to transmit data with 160 MHz CBW. In all other conditions there is scope to improve the (r,c) combination in Minstrel RA algorithm.

4.3.4 Conclusion

A comparison is done to study the effect of Ideal Wi-Fi and Minstrel RA algorithms in 802.11n and 802.11ac. CBWs 80 and 160 MHz in 802.11ac are not considered for 802.11n as it does not support them. With Ideal RA, both 11ac and

11n perform consistently. With Minstrel, both 11ac and 11n behave similarly at 20 MHz CBW, but for 11ac, there is inconsistency at all other BWs and number of SSs. In Ideal RA, there is no impact of GI on both 11ac and 11n. However, with Minstrel, the results do not follow a defined pattern for GI variation. For 11ac, both Ideal and Minstrel are suitable at 20MHz and 40 MHz, but Minstrel is not recommended for 80 and 160 MHz CBWs.

Minstrel is better than Ideal RA when the signal strength is raised from low to high due to Minstrel's property to choose high rates. Ideal RA introduces extra control overhead with SNR tags in ACK and the unicast data packets which increase with more SS. This results in throughput being lesser than the theoretical values.

The version of ns3 (ns-3.25) used in this chapter, does not support simulations using transmit beam forming and MU-MIMO. Also, only ``ConstantRateWifiManager``, Ideal and Minstrel RA Managers are supported for 802.11n or 802.11ac. Future Releases of NS3 is expected to be enhanced with other RA algorithms. It is proposed to analyse in further detail other performance aspects of 11ac, using upcoming ns3 releases.

4.4 Evaluation of Transmit Beam Forming

4.4.1 Introduction

A transmitter (beamformer) with multiple antennas transmits multiple copies of the data which undergo different amplitude and phase variations due to the multipath effect in the channel. If all the signals arrive in phase at the receiver (beamformee) they can be combined constructively at the receiver, thus improving SNR. For this to happen, the transmitter compensates the phase effects of the channel at the transmit antenna end so that all signals arrive in phase at the transmitter end.

Beamforming can be theoretically implemented in the dual directional link, but is practically realized in the AP-to-client direction due to the availability of memory, DC power, computational power and NTx antennas in the AP.

TBF concepts are explained in detail in section 2.2.4.

A study of the existing TBF techniques is carried out and detailed as a paper titled **"Study of Performance of Transmit Beamforming and MU-MIMO Mechanisms in IEEE 802.11ac WLANs"** and presented in International Conference on Inventive Communication and Computational Technologies (ICICCT 2017).It will be published in IEEE Explore, 978-1-5090-5297-4/17/©2017 IEEE

4.4.2 Test set-up

MATLAB R2016a version [45] has incorporated a WLAN System Toolbox with provision to design, configure the physical layer in IEEE 802.11ac WLAN standard and to simulate, analyze and test the performance of WLAN communications systems.

4.4.2.1 Transmission with Spatial Expansion

As a single user beamformee is only optional in 802.11ac standard, a transmitter with multiple antennas uses a feature called 'Spatial Expansion' to communicate with a receiver that is not a beamformee. Using this feature, many STSs are transmitted on even more transmit antennas to a receiver which is incapable of performing as beamformee.

As depicted in figure 4.28, custom spatial mapping scheme is selected which generates a custom spatial mapping matrix that contains details to map a subcarrier for a space-time stream (STS) to all transmit antennas leading to a matrix size $N_{st}\times N_{sts}\times N_t$, where N_{st}, N_{sts} and N_t are the number of occupied subcarriers, STSs and transmit antennas respectively. Some STSs may be replicated to match the number preferred to be transmitted. At the receiver, demodulation is performed to get back the data symbols and BER is measured.

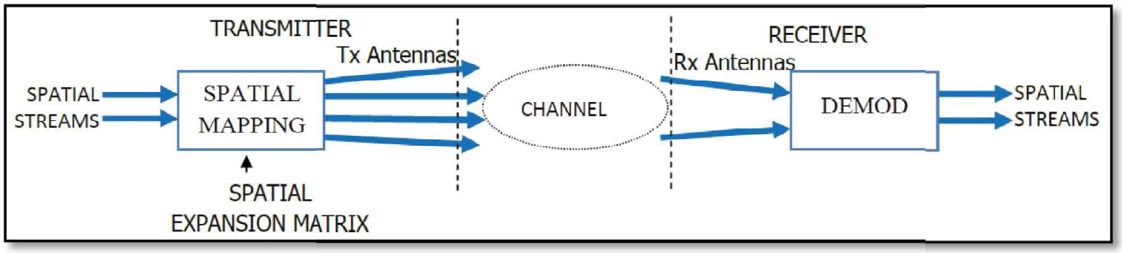


Fig 4.28 Transmission with Spatial Expansion

The transmit diversity gain is further enhanced more by spatial expansion in channels with flat fading than by directly mapping STSs to transmit antennas.

To demonstrate the advantages of TBF specifically, the data packet is transmitted using TBF without changing the channel conditions.

4.4.2.2 Transmission with Beamforming

When the receiver can function as a beamformee, the achieved SNR is higher as compared to that achieved with spatial expansion. A NDP is sent through the channel using 'direct' spatial mapping and is made use of in creating the beamforming steering matrix. The number of STSs selected for transmission matches the number of antennas used for transmission thus enabling the VHT-LTF to be utilized to sound channels between the transmit-receive antenna pairs. The beamforming matrix is used to form a transmit beam in the channel.

The same channel is utilized for transmitting sounding information and data. Also, as the feedback information from the beamformee is not compressed, beamforming can be treated as perfect.

In the figure 4.29, the NDP is first transmitted to sound the channel and create the steering matrix.

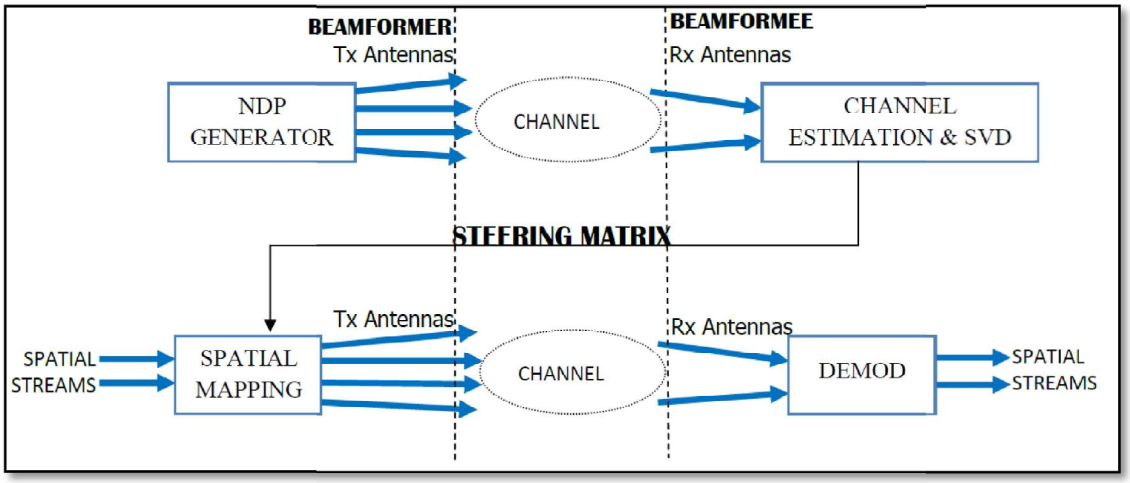


Fig 4.29 Transmission with Beam Forming

The steering matrix is then used to transmit, receive and demodulate the data packet.

4.4.3 Results and discussion

Results of this analysis are presented in **"Evaluation of the Contribution of Transmit Beam Forming to the Performance of IEEE 802.11ac WLANs"** and accepted for 1st International Conference On Smart Systems, Innovations And Computing" (SSIC-2017).

4.4.3.1 Constellation Diagram

The sample constellation diagrams are simulated for a single STS single receive antenna , 2- 3- and 4-transmit antennas with CBW 160 MHz and 40 MHz and MCS values 1, 9.

Figures 4.30a to 4.30e depict the constellation for MCS 9 and figures 4.31a to 4.31f for MCS 1.

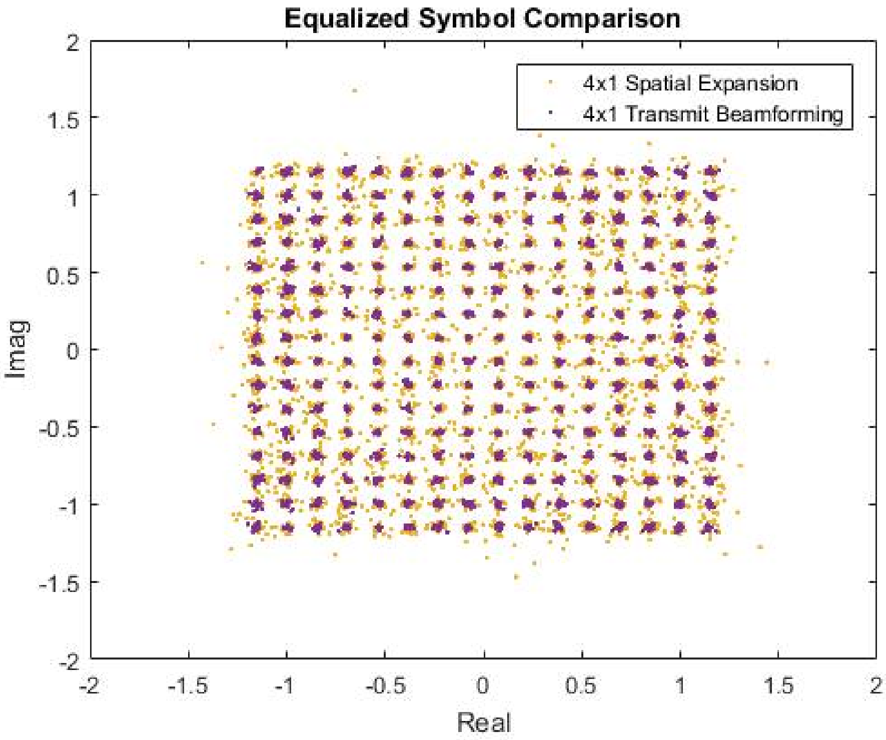


Fig 4.30a Constellation Diagram - CBW=160 MHz, MCS=9, 4×1 MIMO

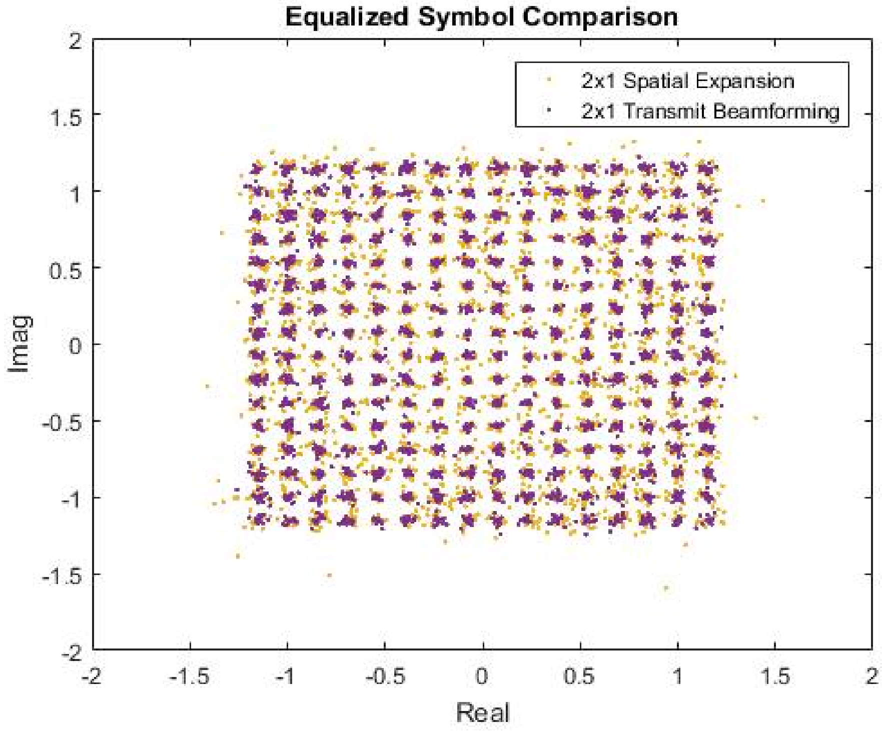


Fig 4.30b Constellation Diagram - CBW=160 MHz, MCS=9, 2×1 MIMO

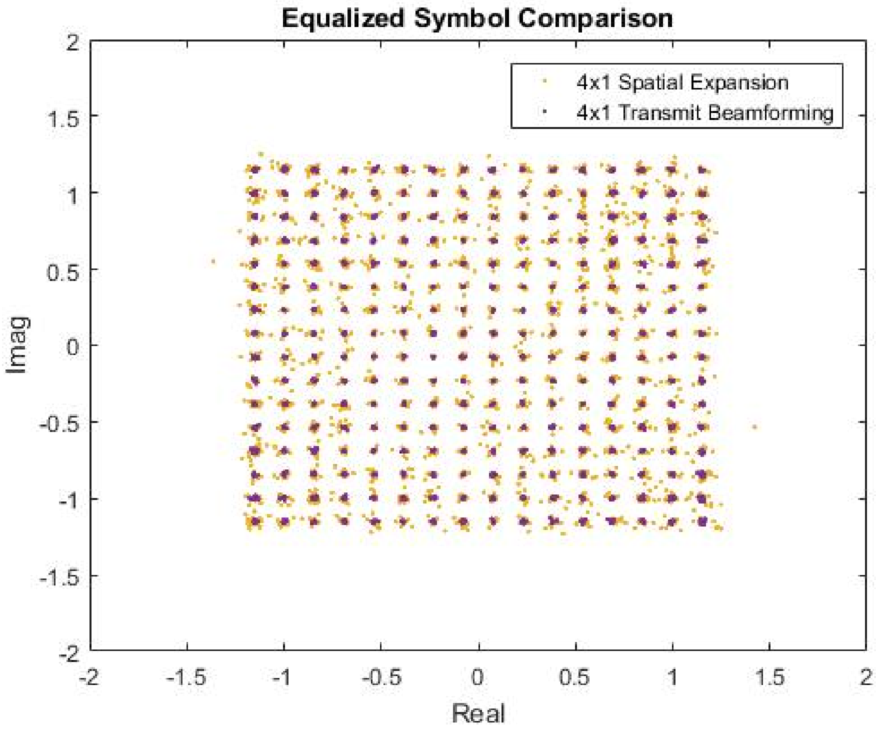


Fig 4.30c Constellation Diagram - CBW=40 MHz, MCS=9, 4×1 MIMO

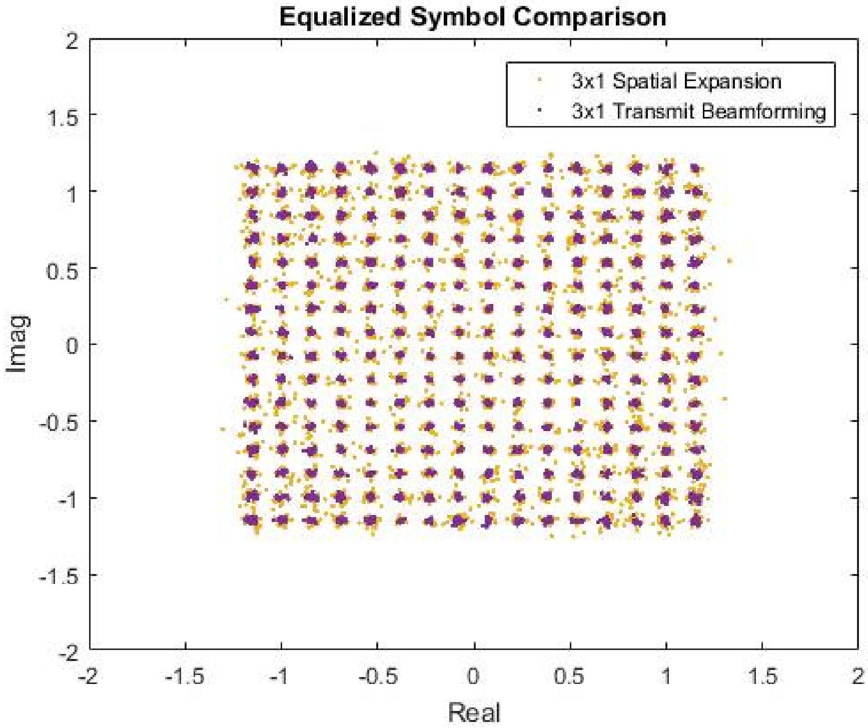


Fig 4.30d Constellation Diagram - CBW=40 MHz, MCS=9, 3×1 MIMO

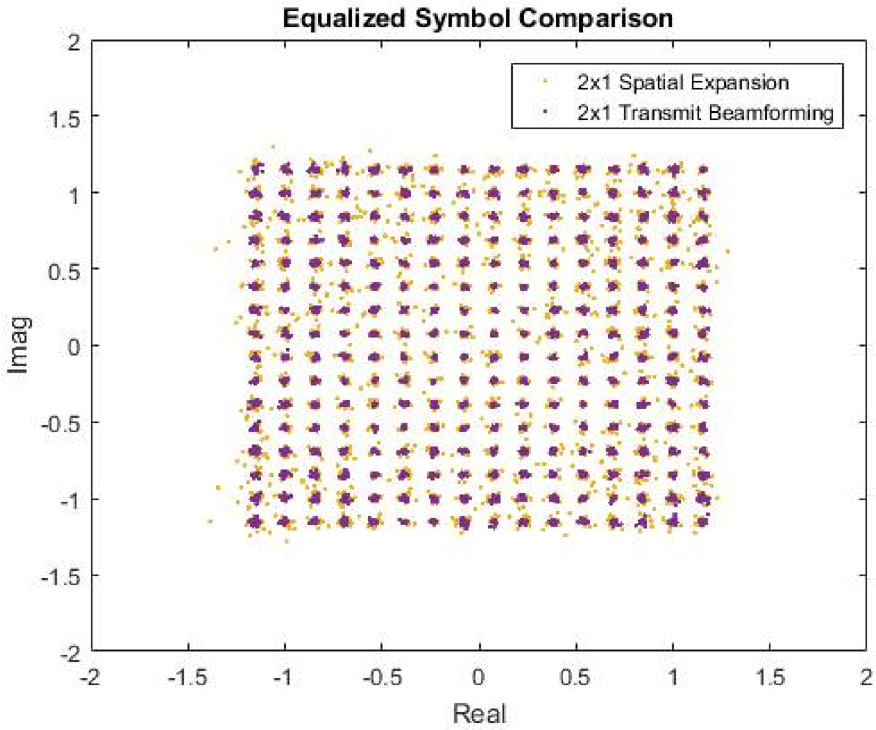


Fig 4.30e Constellation Diagram - CBW=40 MHz, MCS=9, 2×1 MIMO

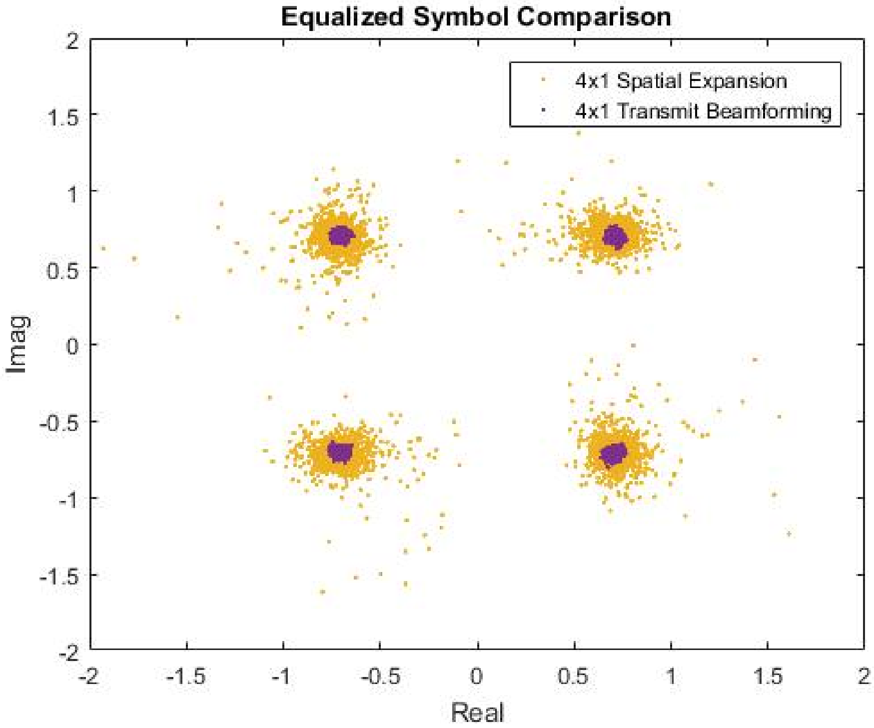


Fig 4.31a Constellation Diagram - CBW=160 MHz, MCS=1, 4×1 MIMO

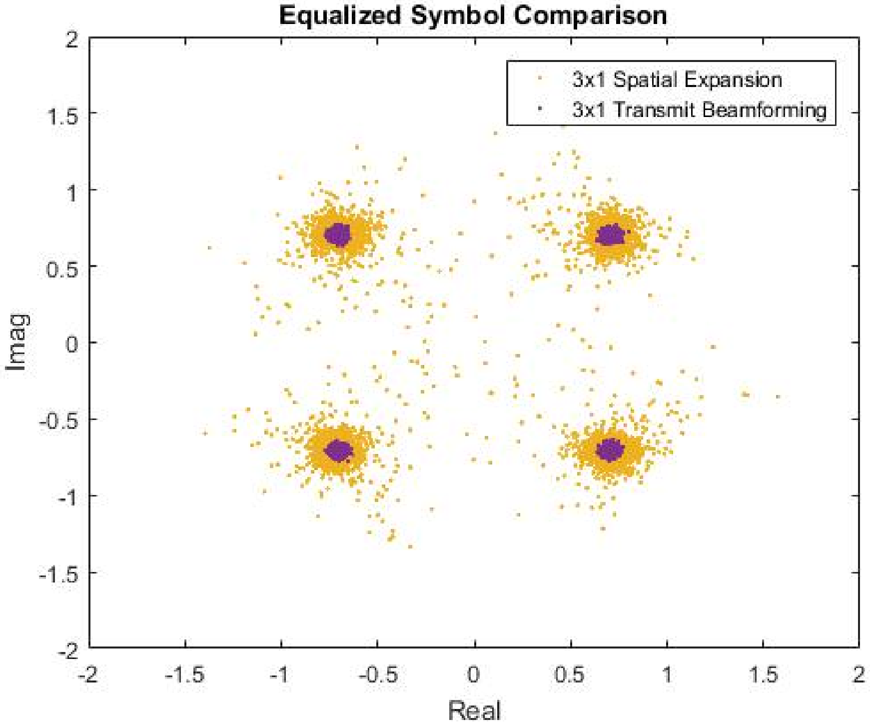


Fig 4.31b Constellation Diagram - CBW=160 MHz, MCS=1, 3×1 MIMO

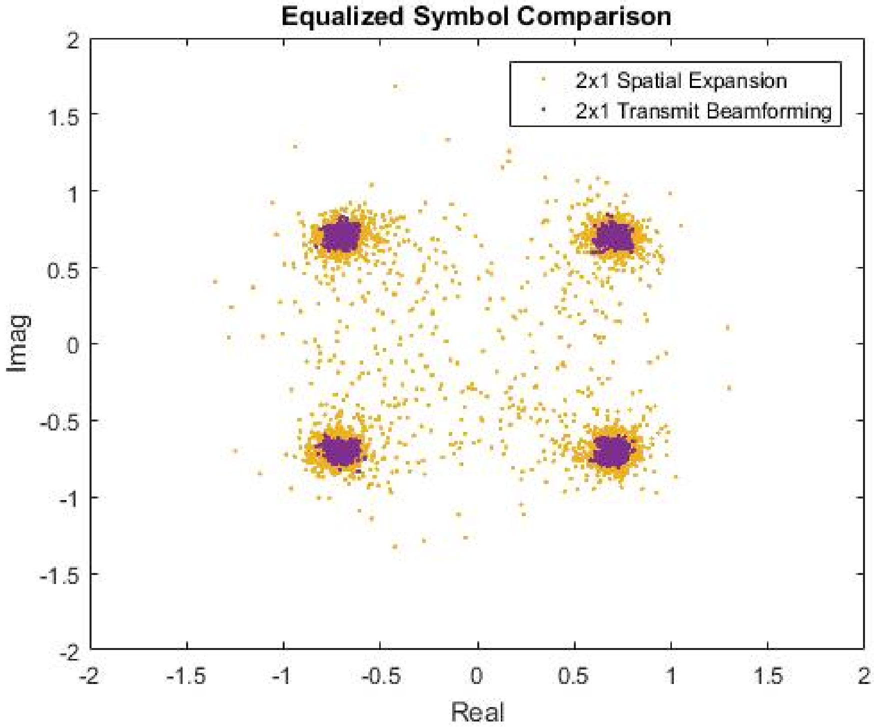


Fig 4.31c Constellation Diagram - CBW=160 MHz, MCS=1, 2×1 MIMO

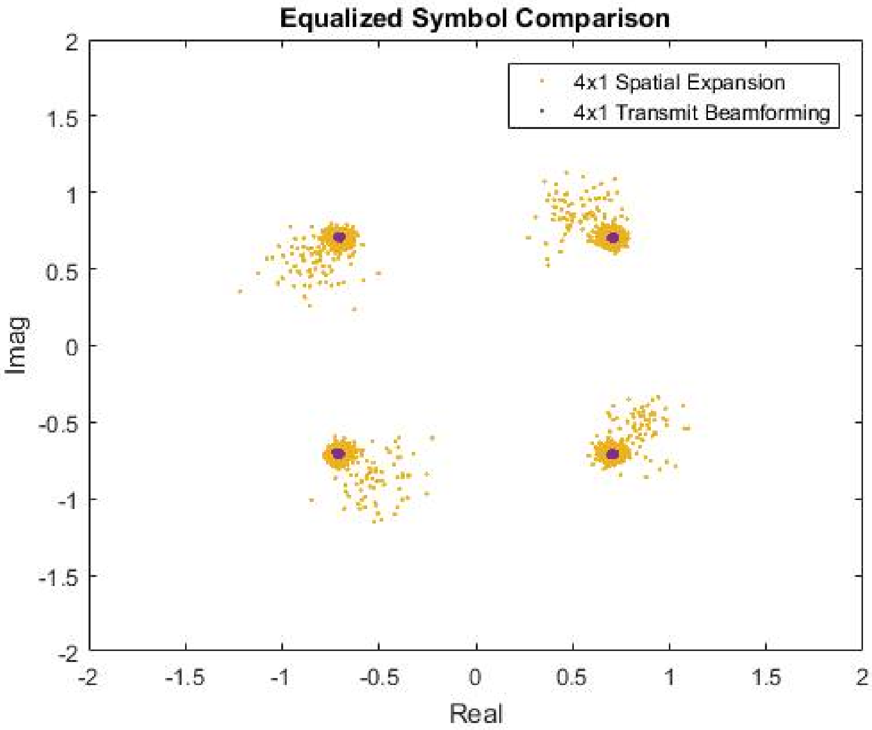


Fig 4.31d Constellation Diagram - CBW=40 MHz, MCS=1, 4×1 MIMO

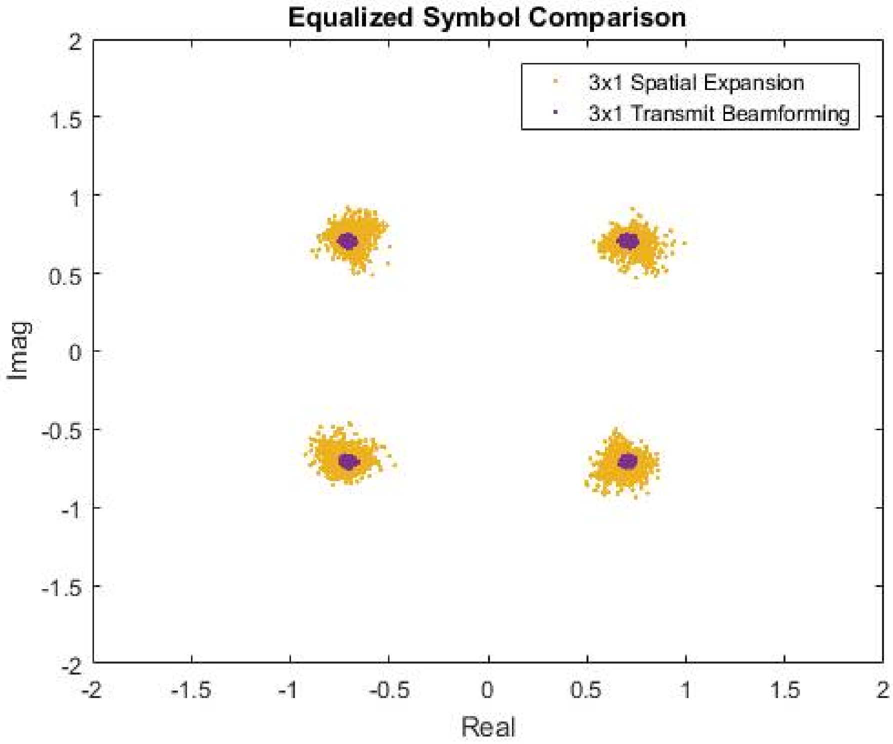


Fig 4.31e Constellation Diagram - CBW=40 MHz, MCS=1, 3×1 MIMO

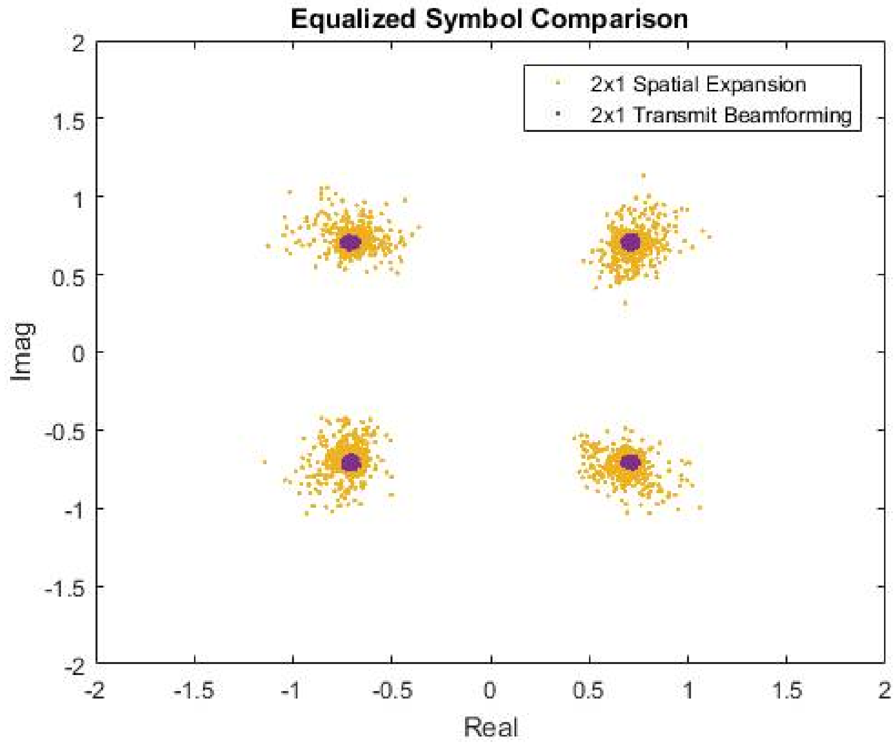


Fig 4.31f Constellation Diagram - CBW=40 MHz, MCS=1, 2×1 MIMO

Comparing TBF scenarios independently, in cases where highest throughput is achieved at the expense of poor constellation for e.g., CBW=160 MHz and MCS=9, TBF improves performance significantly. This is visible with 4 transmit antenna TBF case which is much better than the 2 transmit antenna TBF scenario. Similar results are noticed in lower throughput cases (MCS=1, CBW=40 MHz) with 2, 3 and 4 antennas also.

4.4.3.2 Error Vector Magnitude

The error vector magnitude (EVM) is a tool to measure the performance of digital communication systems. Some of the imperfections in the system like high phase noise, low image rejection ratio and high carrier leakage cause the otherwise perfect constellation points to diverge from the perfect locations and degrade the EVM.

The I-Q points are used to estimate EVM of an ideal transmitted signal and hence the quality of the demodulated signal. Figures 4.32a, 4.32b, 4.32c show the EVM (max) values for CBW=40 and 160 MHz, MCS=1 to 9 and for MIMO configurations 2×1, 3×1 and 4×1 respectively.

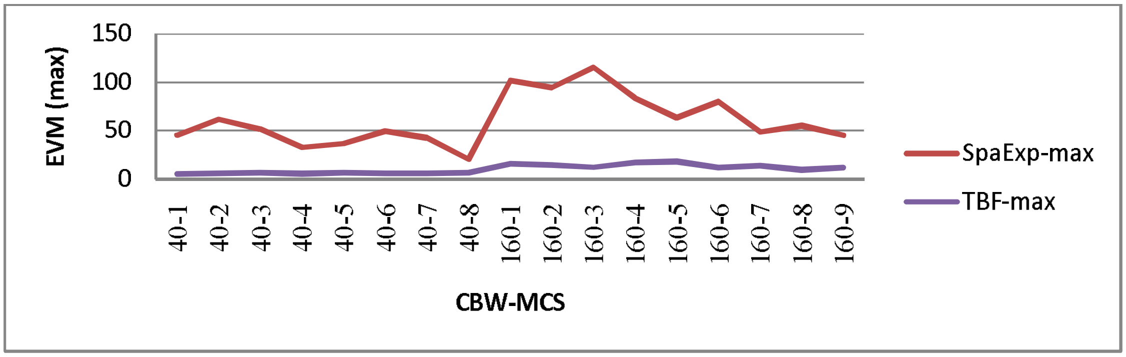


Fig 4.32a   EVM (max) for CBW=40 & 160 MHz, MCS=1 to 9, 2×1 MIMO

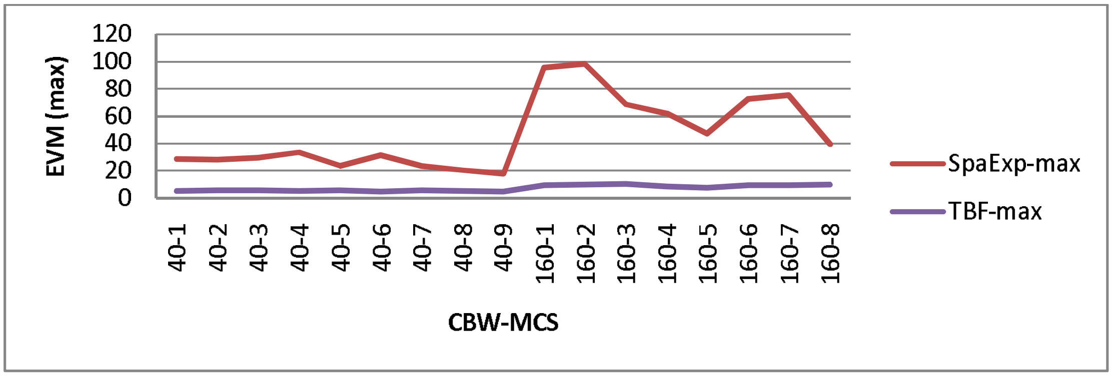


Fig 4.32b   EVM (max) for CBW=40 & 160 MHz, MCS=1 to 9, 3×1 MIMO

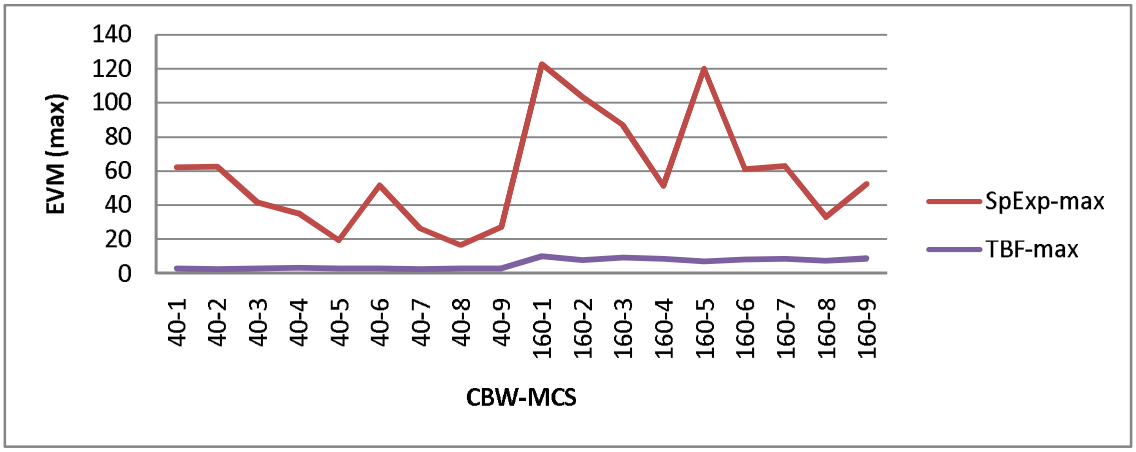
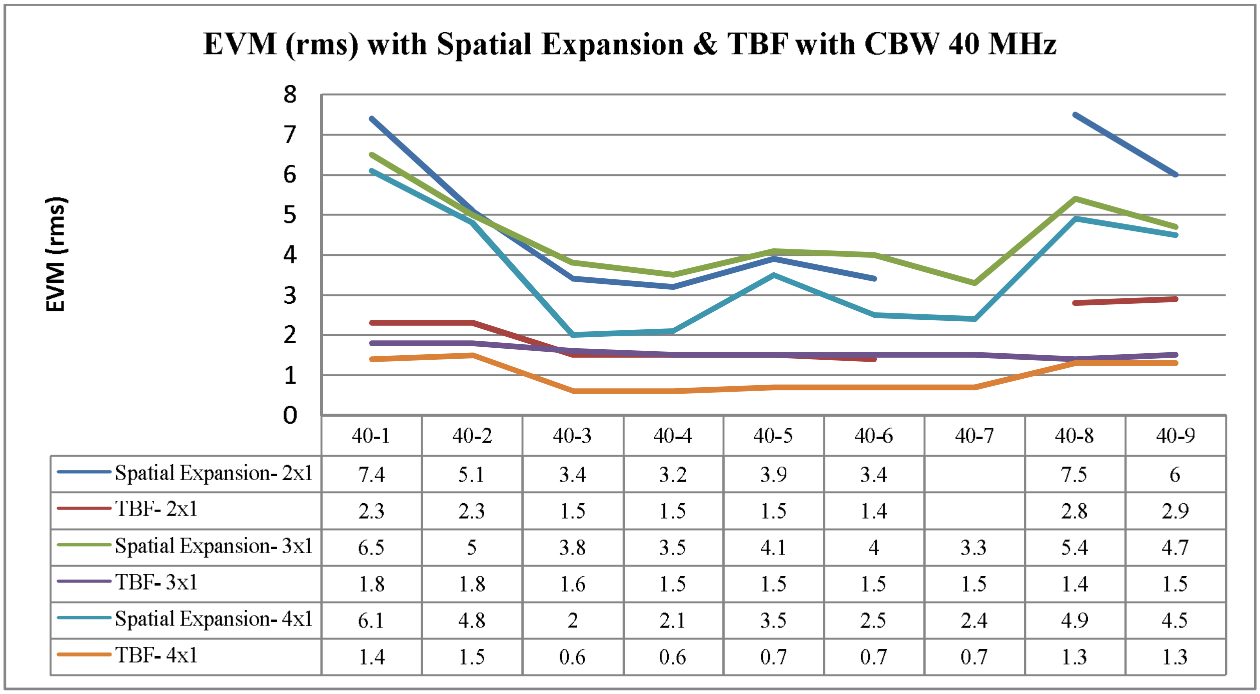


Fig 4.32c   EVM (max) for CBW=40 & 160 MHz, MCS=1 to 9, 4×1 MIMO

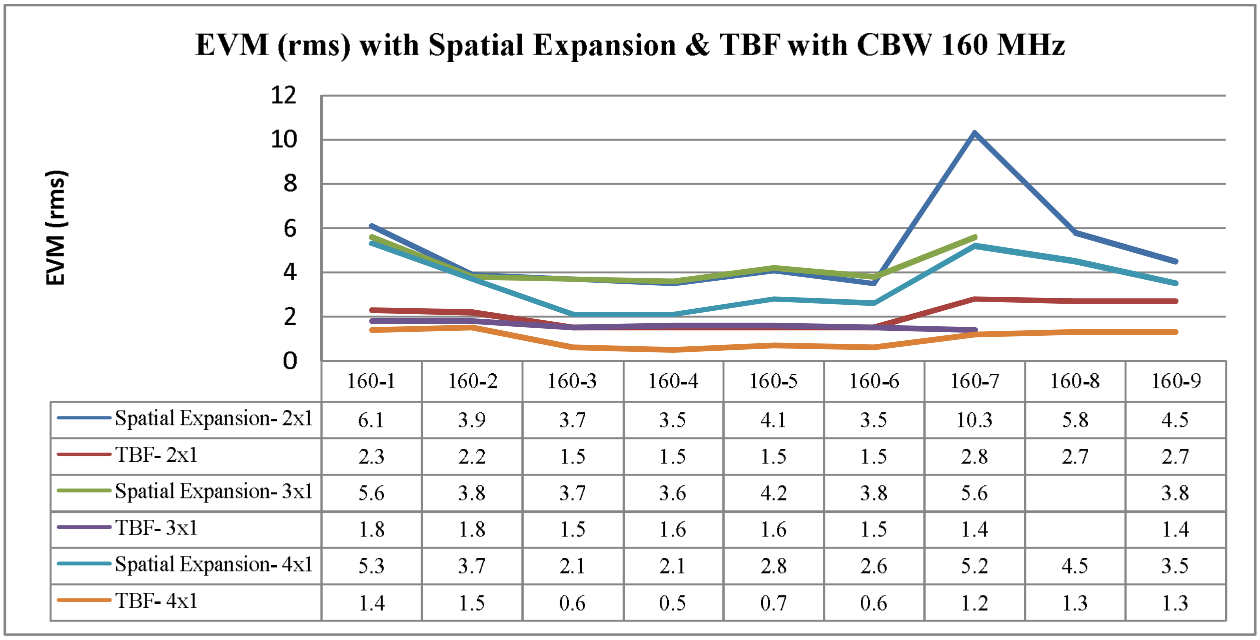
From figures 4.32a to 4.32c the following observations are deduced.

- 40 MHz CBW exhibits lesser EVM as compared to 160 MHz CBW.
- Dispersion of the EVM values reduces greatly after TBF irrespective of the number of transmit antennas, modulation scheme or CBW.
- After TBF 4×1 MIMO configuration displays a lower EVM (max) values compared to 2×1 MIMO configuration. For example, the EVM (max) values are 15.7, 9.5 and 11.9 for MCS1, MCS8 and MCS9 respectively for the 2×1 MIMO configuration, whereas they are reduced to 10, 7.6 and 8.8 for the 4×1 MIMO configuration.



	40-1	40-2	40-3	40-4	40-5	40-6	40-7	40-8	40-9
Spatial Expansion- 2x1	7.4	5.1	3.4	3.2	3.9	3.4		7.5	6
TBF- 2x1	2.3	2.3	1.5	1.5	1.5	1.4		2.8	2.9
Spatial Expansion- 3x1	6.5	5	3.8	3.5	4.1	4	3.3	5.4	4.7
TBF- 3x1	1.8	1.8	1.6	1.5	1.5	1.5	1.5	1.4	1.5
Spatial Expansion- 4x1	6.1	4.8	2	2.1	3.5	2.5	2.4	4.9	4.5
TBF- 4x1	1.4	1.5	0.6	0.6	0.7	0.7	0.7	1.3	1.3

Fig 4.33a EVM (rms) for CBW=40 MHz, MCS=1 to 9, 2×1, 3×1 & 4×1 MIMO configuration with Spatial Expansion and TBF



	160-1	160-2	160-3	160-4	160-5	160-6	160-7	160-8	160-9
Spatial Expansion- 2x1	6.1	3.9	3.7	3.5	4.1	3.5	10.3	5.8	4.5
TBF- 2x1	2.3	2.2	1.5	1.5	1.5	1.5	2.8	2.7	2.7
Spatial Expansion- 3x1	5.6	3.8	3.7	3.6	4.2	3.8	5.6		3.8
TBF- 3x1	1.8	1.8	1.5	1.6	1.6	1.5	1.4		1.4
Spatial Expansion- 4x1	5.3	3.7	2.1	2.1	2.8	2.6	5.2	4.5	3.5
TBF- 4x1	1.4	1.5	0.6	0.5	0.7	0.6	1.2	1.3	1.3

Fig 4.33b EVM (rms) for CBW=160 MHz, MCS=1 to 9, 2×1, 3×1 & 4×1 MIMO configuration with Spatial Expansion and TBF

After TBF, EVM (rms) values are also lower for higher transmit antenna MIMO configurations and also as compared to the numbers obtained with spatial expansion alone for CBW 40 MHz and 160 MHz.

4.4.3.3 Received power and space time streams

A 4×4 MIMO configuration with 4 spatial streams is used to study the power received in each stream after TBF. The distribution of power in STS-1, 2, 3, 4 for 40 MHz CBW is plotted in figure 4.34a.

The simulation is done for all MCS values between 1 and 9. The Mean received channel power per STS with TBF in watts for a particular STS is independent of MCS or the number of space-streams.

After TBF, power is maximum in the STS1 and reduces rapidly in STS-2, 3 and 4.

It may also be noted that the power received per STS say in STS-1, does not vary whether the number of STSs is 1, 2, 3 or 4. Same observation holds for STS-2, 3 and 4 also.

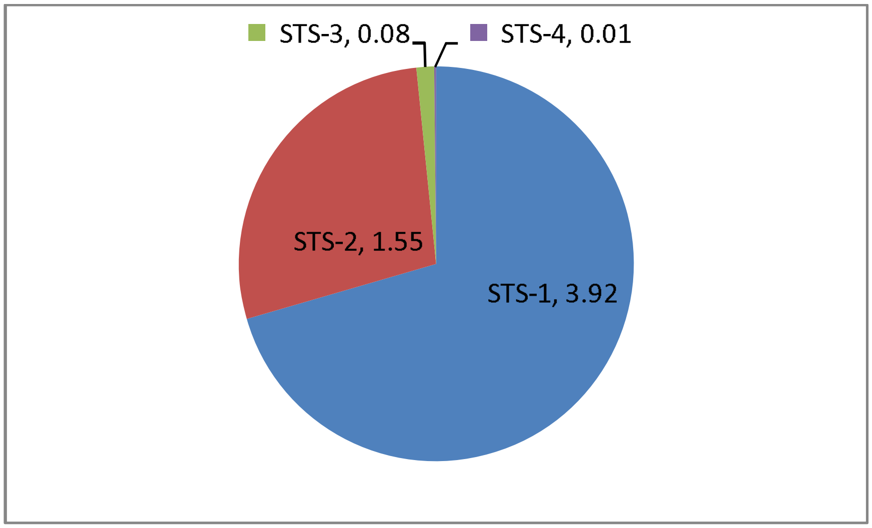


Fig 4.34a Mean received channel power (Watts) per STS with TBF for CBW 40 MHz

After TBF, power is maximum in STS1 and reduces rapidly in STS-2, 3 and 4.

The distribution of power in STS-1, 2, 3, 4 for 160 MHz CBW is as plotted in figure 4.34b.

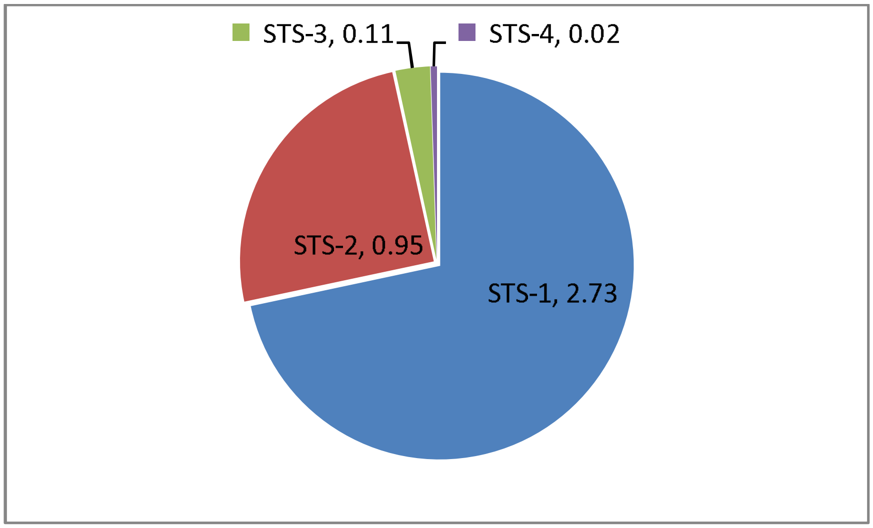


Fig 4.34b Mean received channel power in Watts per STS with TBF for CBW 160 MHz

As in the case of 40 MHz CBW, with 160 MHz CBW, also, the power received per STS say in STS-1, does not vary whether the number of STSs is 1,2,3 or 4 and similar observation holds for STS-2, 3 and 4.

With a single STS, and different MIMO configurations power received is plotted for various MCS values when CBW is 20, 40, 80 1nd 160 MHz in figures 4.35a to 4.35d.

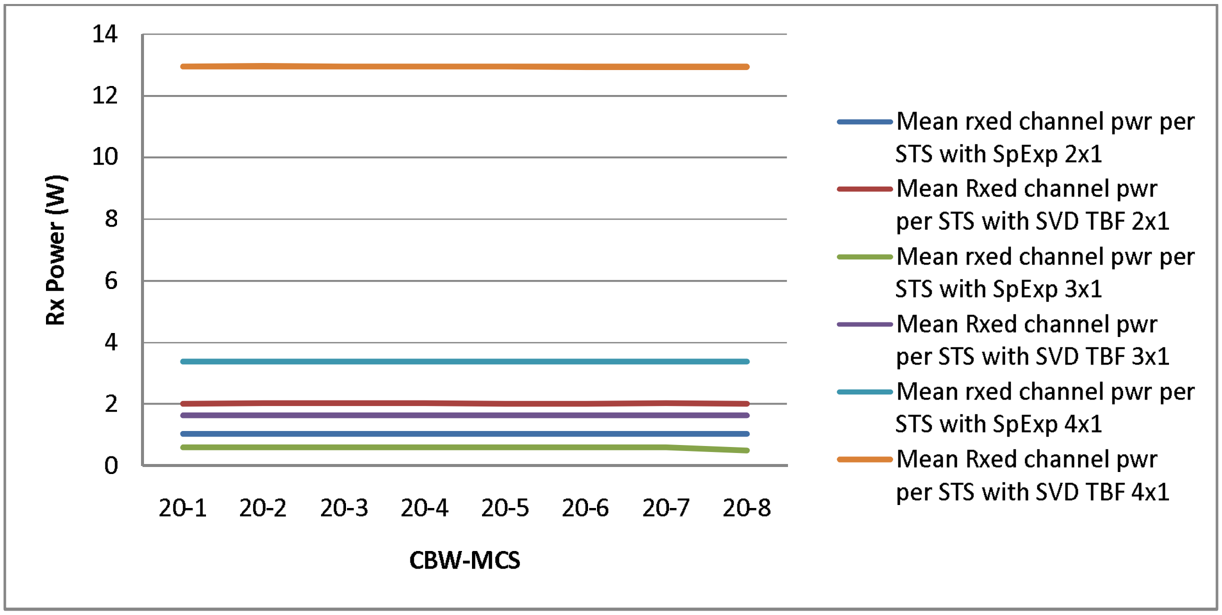


Fig 4.35a Mean received channel power in Watts with TBF for CBW 20 MHz

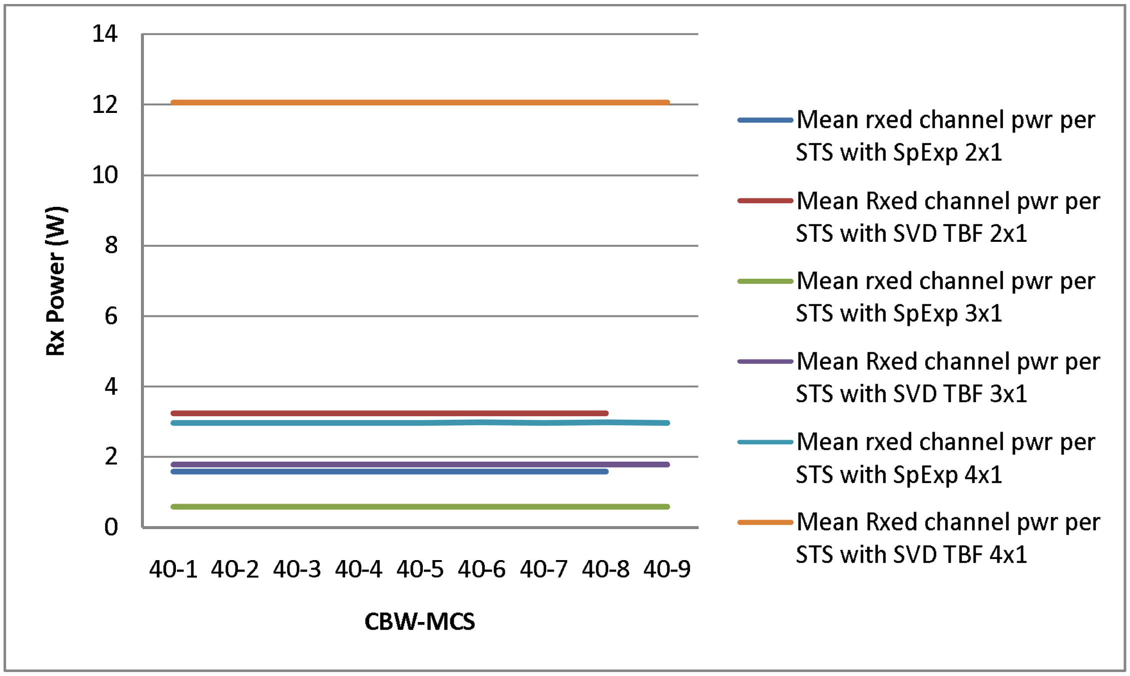


Fig 4.35b Mean received channel power in Watts with TBF for CBW 40 MHz

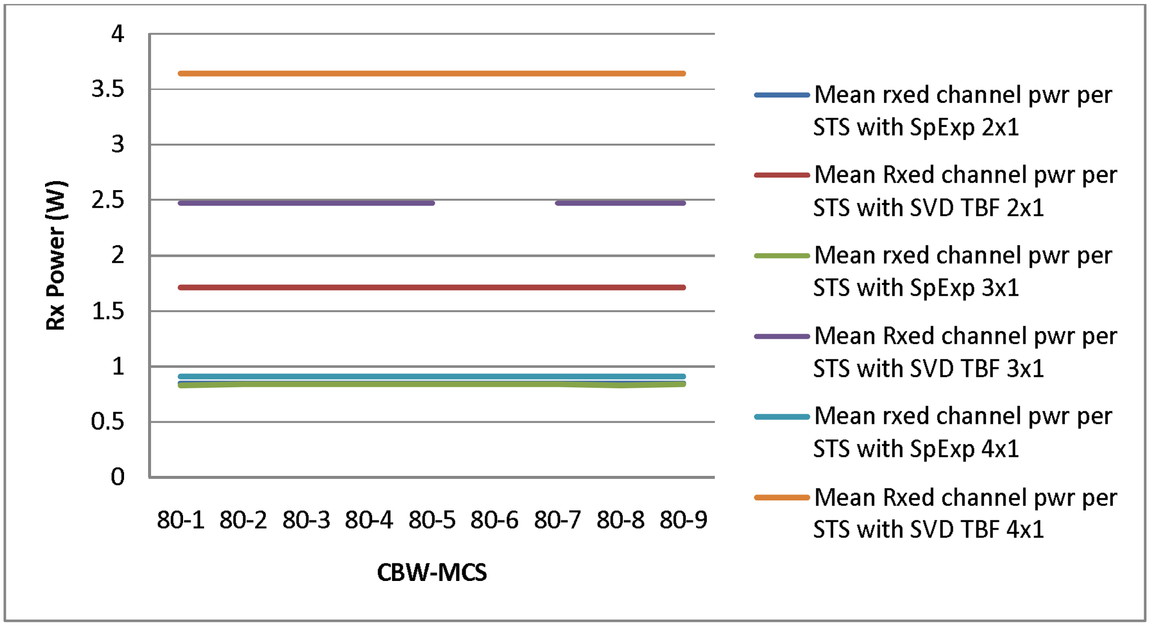


Fig 4.35c   Mean received channel power in Watts with TBF for CBW 80 MHz

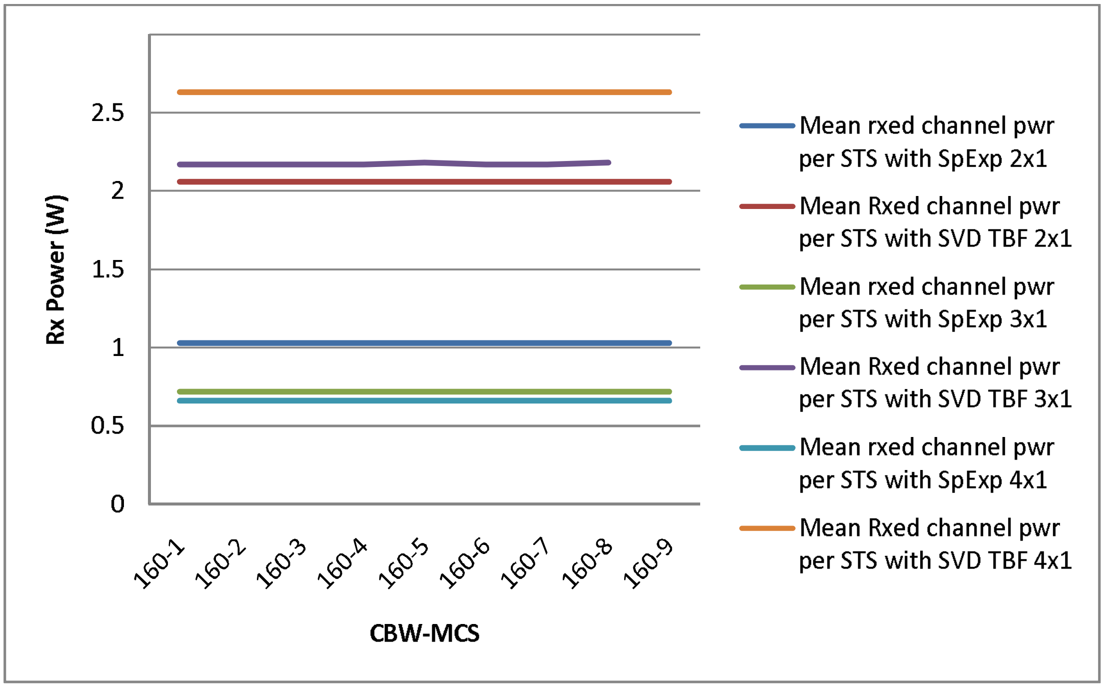


Fig 4.35d   Mean received channel power in Watts with TBF for CBW 160 MHz

Mean received channel power is always maximum for the 4×1 MIMO configuration.

4.4.4 Example Scenarios where Beamforming can be applied

4.4.4.1 Example-1

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

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, theoretically can 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.

4.4.4.2 Example-2

An example to depict the performance of TBF in interiors is discussed. 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 to support the maximum data rate. Hence the effect of TBF on the performance of WLANs is not well exhibited in short ranges. And at long ranges TBF gain is unable to support increase in data rates.

4.4.5 Conclusion

On studying the various scenarios in which TBF is used, it can be deduced that TBF is contributing to performance improvement. Even in cases where highest throughput is achieved at the expense of poor constellation, effect of TBF is observed and specifically more in the 4 transmit antenna case than the 2 transmit antenna TBF scenario. The response of TBF is similar in cases of lower throughput with 2, 3 and 4 transmit antennas.

TBF also aids in reducing the magnitude of EVM. With reference to CBW, 40 MHz has reduced EVM as compared to 160 MHz CBW. Also 4×1 MIMO configuration displays a lower EVM (max) values compared to lower transmit antenna MIMO configuration. The same is seen for the rms value of EVM too.

On simulating the received power, the first STS always has the maximum share of power irrespective of number of STS, CBW or MCS. The same parameter is maximum for the 4×1 MIMO configuration as compared to other configurations.

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.

MATLAB has been used for simulations.

4.5 Evaluation of MU MIMO performance

4.5.1 Introduction

With 802.11n, all data transmission from the AP was only to one client at any particular point of time. When servicing clients operating at variety of data rates, 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 distributed (maximum of four streams) between the clients. Multiple clients can be serviced simultaneously; hence congestion delay is not an issue. The presence of MU-MIMO feature is more obvious when multiple clients are present in sports stadiums or auditoriums, in hot spots and in other large enterprises.

Consider the scenario when multiple devices like internet browser, gamer and video streaming are connected to a router and are accessing internet bandwidth. The router makes decisions in millisecond interval and prioritizes the client devices. Even the millisecond difference will introduce latency and affect the internet speed in a single-user scenario.

MU-MIMO can stream data from router to multiple devices with different transmit antennas, simultaneously, and thus not choking the bandwidth. Hence the router does not have to prioritize the devices connecting to the internet.

The underlying concepts regarding MU_MIMO are discussed in Section 2.2.5.

A study of the existing MU MIMO techniques is carried out and detailed as a paper titled **"Study of Performance of Transmit Beamforming and MU-MIMO Mechanisms in IEEE 802.11ac WLANs"** and presented in International Conference on Inventive Communication and Computational Technologies (ICICCT 2017).It will be published in IEEE Explore, 978-1-5090-5297-4/17/©2017 IEEE

4.5.2 Simulation, results and discussion

Here, four scenarios are discussed to show how MU MIMO finds application in real time situations. The fourth one is analyzed mathematically while MATLAB results are shown for the other three.

The results of the simulation and analysis are presented in the paper titled **"Study on MU-MIMO feature in 802.11ac using MATLAB"**, and is approved for publication in International Journal of Engineering and Technology (IJET)

Table 4.3 is used to calculate the aggregate data rates achieved in different scenarios.

Table 4.3 Data Rates and Speeds Achievable by MU-MIMO

	20 MHz data rate (Mbps) (1SS, SGI)	SS multiplication factor	CBW multiplication factor	Max 40 MHz rate (Mbps) (8SS, SGI)	Max 80 MHz rate (Mbps) (8SS, SGI)	Max 160 MHz rate (Mbps) (8SS, SGI)
MCS0	7.2	×2 :2 streams ×3 :3 streams ×4 :4 streams ×5 :5 streams ×6 :6 streams ×7 :7 streams ×8 :8 streams	×1 for 20MHz ×2.1 for 40MHz ×4.5 for 80MHz ×9 for 160MHz	120	260	520
MCS1	14.4			240	520	1040
MCS2	21.7			360	780	1560
MCS3	28.9			480	1040	2080
MCS4	43.3			720	1560	3120
MCS5	57.8			960	2080	4160
MCS6	65.0			1080	2340	4680
MCS7	72.2			1200	2600	5200
MCS8	86.7			1440	3120	6240
MCS9	96.3			1600	3466.7	6933.3

4.5.2.1 Scenario-1

This case study (figure-4.36) is with a 4-Antenna AP communicating with four 1-antenna stations which are for example hand-held antennas. The PHY link rate in this configuration is 867 Mbps to each STA leading to an aggregate speed of (4×867) Mbps = 3.39 Gbps.

MCS9 corresponds 256 QAM and 5/6 rate coding. With reference to the table-4.3 "Data rates and speeds", with a single spatial stream, the data rate achieved is 866.7 Mbps when the channel bandwidth is 160 MHz and short GI is used.

In this configuration as there are 4 users, the aggregate speed achieved is (4×866.7) Mbps = 3.39 Gbps.

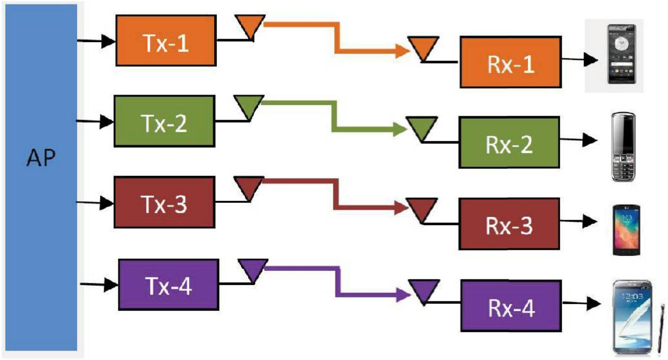


Fig 4.36 MU-MIMO Scenario-1

Configuration

- **Channel Bandwidth:** 160 MHz
- **Number of Users:** 4
- **User Positions:** [0 1 2 3]
- **Number of Transmit Antennas**: 4
- **Number of Space Time Streams for user 1, 2, 3 and 4:** 1, 1, 1, 1
- **MCS values for user 1, 2, 3 and 4:** 9, 9, 9 and 9
- **Type of Channel Coding:** BCC or Binary Convolution Coding
- **APEP Length or number of bytes assigned to user 1, 2, 3 and 4**: 2000, 1400, 1800, 2000

MATLAB results

- PSDU lengths (which is a function of both the APEP length and the MCS value) for the four users = 2336 2336 2336 2336
- Different fields in the PLCP header (LSTF, LLTF, LSIG, VHTSIGA, VHTSTF, VHTLTF and VHTSIGB) are extracted in the four user devices independently and parameters such as bandwidth, group ID, APEP length and MCS values retrieved using these fields. Based on this, the VHTData for each user is received.
- The packet length is extracted from the VHT-SIG-B information bits. For MU operation with 160 MHz, Packet length for the 4 users = 2000 1400 1800 2000

- The extracted APEP length matches the value set in the transmit end.
- The MCS values are extracted from the VHT-SIG-B information bits (bits 20 to 23)
- MCS for each user u1,u2,u3,u4 = 9, 9,9,9
- It is seen that four users are able to receive their individual APEP packet lengths at the set MCS values after demodulation at receiver. Hence, MU MIMO functionality is operational.

4.5.2.2 Scenario-2

This second case study (figure 4.37) taken is an 8-antenna AP, 160 MHz (MU-MIMO) transmitting to one 4-antenna STA, for example a Digital TV or set top box, one 2-antenna STA like a laptop and two one-antenna STAs which are for example hand-held antennas.

MCS9 corresponds 256 QAM and 5/6 rate coding. In this case we have 4 users with 4, 2, 1 and 1 spatial stream each. The corresponding data rate with reference to table-4.3, achieved is 3.4, 1.7, 0.867, 0.867 Gbps respectively.

The PHY link rate in this configuration is 3.4 Gbps to 4-antenna digital TV, 1.7 Gbps to the 2-antenna STA (laptop) and 867 Mbps to each 1-antenna STA leading to an aggregate speed of $3.4+1.7+(2\times0.867)$ Gbps = 6.8 Gbps.

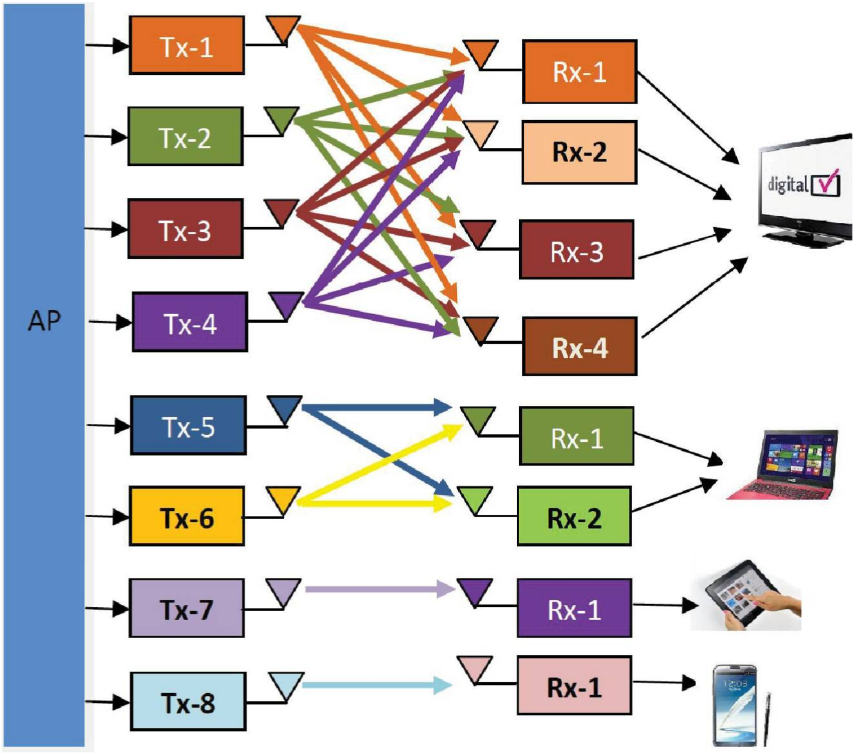


Fig 4.37 MU-MIMO Scenario-2

Configuration

- Channel Bandwidth: 160 MHz
- Number of Users: 4
- User Positions: [0 1 2 3]
- Number of Transmit Antennas: 8
- Number of Space Time Streams for user 1, 2, 3 and 4: 4, 2, 1, 1
- MCS values for user 1, 2, 3 and 4: 9, 9, 9 and 9
- Type of Channel Coding: BCC or Binary Convolution Coding
- APEP Length or number of bytes assigned to user 1, 2, 3 and 4: 2000, 1400, 1800, 2000

MATLAB results

- PSDU lengths (which is a function of both the APEP length and the MCS value) for the four users = 9353 4675 2336 2336
- Packet length for the 4 users = 2000 ,1400, 1800, 2000

- MCS for each user u1,u2,u3,u4 = 9, 9,9,9

4.5.2.3 Scenario 3

This third scenario (figure 4.38) again has an 8-antenna AP, 160 MHz (MU-MIMO) at the receive end there are four 2-antenna STAs like Digital TV, tablet, laptop and PC.

MCS9 corresponds 256 QAM and 5/6 rate coding. In this case we have 4 users with 2 spatial streams each. The corresponding data rate with reference to table-4.3, achieved is 1.69 Gbps each respectively.

The PHY link rate in this configuration is 1.69 Gbps to the each 2-antenna STA resulting in an aggregate speed of (2×1.69) Gbps = 6.77 Gbps like in scenario-2.

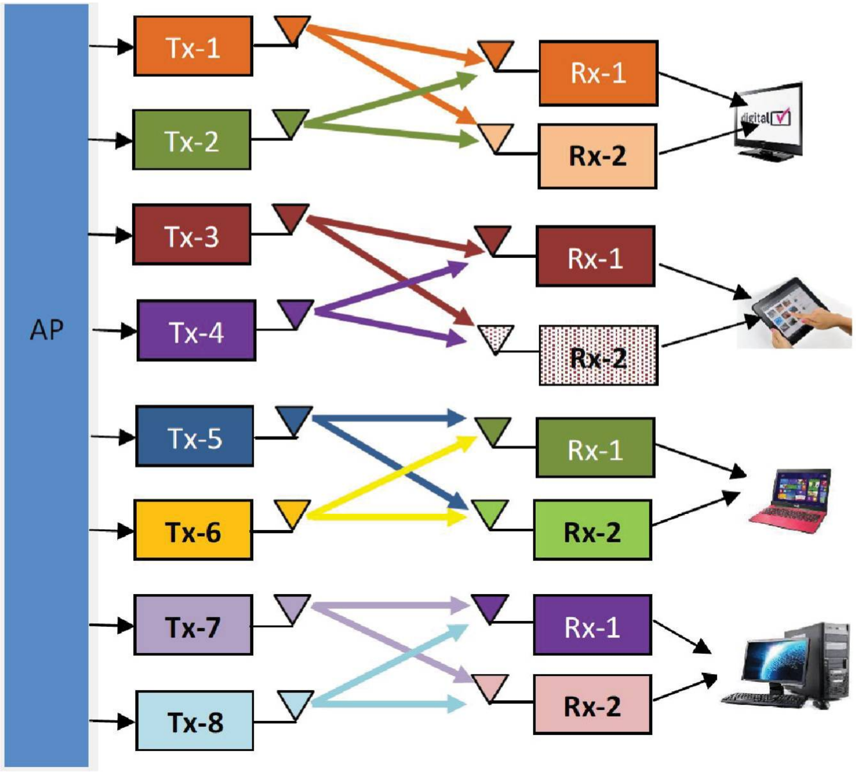


Fig 4.38 MU-MIMO Scenario-3

Configuration

- Channel Bandwidth: 160 MHz
- Number of Users: 4
- User Positions: [0 1 2 3]
- Number of Transmit Antennas: 8
- Number of Space Time Streams for user 1, 2, 3 and 4: 2, 2, 2, 2
- MCS values for user 1, 2, 3 and 4: 9, 9, 9 and 9
- Type of Channel Coding: BCC or Binary Convolution Coding
- APEP Length or number of bytes assigned to user 1, 2, 3 and 4: 2000, 1400, 1800, 2000

MATLAB results

- PSDU lengths (which is a function of both the APEP length and the MCS value) for the four users = 2335 2335 2335 2335
- Packet length for the 4 users = 2000 ,1400, 1800, 2000
- MCS for each user u1,u2,u3,u4 = 9, 9,9,9

4.5.3 Conclusion

It is seen that MU MIMO helps in distributing data to 4 users simultaneously using the space streams obtained through smart antennas. This is a major improvement over the limitation imposed by the MAC algorithm used in WLANs where stations can only gain access one following the other. Hence, latency and also throughput can be increased for multimedia applications.