Punctured Chase Combining HARQ for Next Generation Wi-Fi Systems

A Thesis

submitted by

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THESIS CERTIFICATE

This is to certify that the thesis titled **Punctured Chase Combining HARQ for Next Generation Wi-Fi Systems**, submitted by **Romil Vikram Sonigra**, to the Indian Institute of Technology Madras, for the award of the degree of **Bachelor and Master of Technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: Wi-Fi,IEEE 802.11, HARQ, Incremental Redundancy (IR), Punctured Chase Combining (PCC), ARQ, LDPC Codes, LDPC Puncturing, Chase Combining (CC)

Hybrid ARQ protocol is a retransmission scheme which uses diversity gain to improve performance. This comes at the cost of huge buffer requirements compared to the simple ARQ scheme and also increased complexity resulting from storing and combining soft LLRs. In this thesis, we focus on a specific HARQ protocol named Punctured Chase Combining (PCC) and compare it's performance with another HARQ protocol named Incremental Redundancy (IR) and also with the ARQ protocol keeping the Wi-Fi scenario in mind. We also discuss the LDPC coding scheme and puncturing scheme along with it's importance in limiting the performance of HARQ protocol.

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ABBREVIATIONS

AWGN	Analog White Gaussian Noise
ARQ	Automatic Repeat Request
BER	Bit Error Rate
BPSK	Binary phase shift Keying
CC	Chase Combining
CCA	Clear Channel Assessment
CQI	Channel Quality Index
FFT	Fast Fourier Transform
HARQ	Hybrid Automatic Repeat Request
IFFT	Inverse Fast Fourier Transform
i.i.d.	Independent and Identically Distributed
IR	Incremental Redundancy
ISI	Inter Symbol Interference
k-SR	k Step Recoverable
LLR	Log-Likelihood Ratio
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
OFDM	Orthogonal Frequency Division Multiplexing
PCC	Punctured Chase Combining
PER	Packet Error Rate
PSD	Power Spectral Density
PDP	Power Delay Profile
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature phase shift Keying
SISO	Single Input Single Output
Tx	Transmission

CHAPTER 1

INTRODUCTION & PROBLEM STATEMENT

Link adaptation and ARQ are areas of performance improvement in current Wi -Fi systems. The changes in noise levels results in a drastic reduction in the throughput. Currently, the improvements are obtained by adapting Modulation and Coding Scheme (MCS) based on the channel conditions through Channel Quality Information (CQI) feedback. Wi-Fi usage is increasing rapidly and hence the need for continuous improvements. Hybrid ARQ is a proven technology, which is being used in cellular (3G and 4G) and other unlicensed band wireless standards, that has the potential to give even better performance. One or two retransmissions using HARQ schemes have the potential to provide a gain of around 4-6 dB, as seen in LTE. The benefits of HARQ are,

- Improvement in the link performance due to combining several re-transmissions.
- Improved coverage in low SNR region and improved throughput in cell-edge scenarios.
- Extension of the existing set of MCSs, with adaptive HARQ, thus making link adaptation more robust and efficient leading to higher throughput.
- Reduction in the re-transmission latency when compared to conventional ARQ schemes.Reduction in the re-transmission latency when compared to conventional ARQ schemes.

We intend to leverage advanced HARQ, as used in LTE, in Wi-Fi as a part of the 802.11ax and future standards. In their celebrated work [1], Schalkwijk and Kailath showed that a simple linear feedback coding scheme achieves the capacity. The associated probability of error decays doubly exponentially. Similarly, Lau [2] has shown that for Rayleigh fading channels with feedback, the associated error probability error decays dramatically than without feedback when channel state is fed back to the transmitter and the associated MCS is chosen that is matched to the channel state.
In general, a single HARQ scheme may not be optimal for all channel conditions as the effectiveness of HARQ depends on the channel quality. Hence, our proposal was

to study methods of intelligently adapting the HARQ schemes through feedback about channel conditions.

1.1 Dense WLAN Scenario

A dense WLAN scenario has many people concentrated in small areas, resulting in a high density of Stations (STAs) and to offer satisfactory service for high data-rate applications, many Access Points (APs) have to be deployed. One of the relevant challenges in such dense scenarios is to mitigate noise and interference issues which increase the packet error rate which in turn reduce the overall throughput. This is because the energy levels in the channel will cross the Clear Channel Assessment (CCA) threshold more frequently causing the STAs to back-off. In such scenarios, HARQ has the potential to significantly improve the performance.

In a typical WLAN scenario, the signal quality will be worse at the edge of an AP's coverage area, which demands robust HARQ schemes like Incremental Redundancy, whereas in the interior of the coverage area, schemes like ARQ and Chase Combining might work out better because of lower complexity and hence less computational requirement.

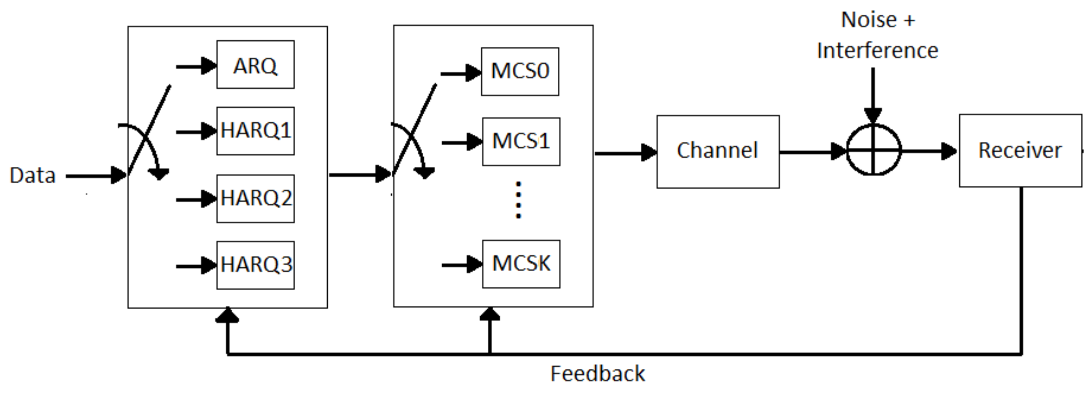


Figure 1.1: Block Diagram for HARQ Protocol

CHAPTER 2

RETRANSMISSION SCHEMES

Let us take a look at the different retransmission schemes available.

2.1 ARQ Protocol

In the ARQ Protocol, when a packet is not decoded successfully, the receiver throws away the packet and asks for a retransmission of the entire packet. Hence, it equivalent to repeating the entire codeword twice and sending it. Thus, any useful information present in the 1st packet which was not decoded successfully is lost. The advantage of this protocol is that there is no buffer requirement as the previous packet is simply discarded and also the complexity for implementing it is much lesser as compared to the HARQ protocols.

2.2 HARQ Protocol

2.2.1 Incremental Redundancy

In the IR HARQ protocol, initially the rate, r, codeword is punctured (only the parity bits are punctured) to obtain a higher rate, r_1 and this punctured codeword is transmitted in the 1^{st} transmission. If retransmission is requested, then a part of the redundancy or parity bits that were punctured earlier are transmitted. Now, these parity bits are combined with the earlier transmission to obtain a codeword with rate, r_2. Now if another retransmission is requested, then we send more of the remaining redundancy bits so as to meet rate, r_3 and so on. If all the redundancies are exhausted and yet another retransmission is requested, then we repeat the required number of bits (information and/or parity bits). This technique and it's results have been explained in the Dual Degree Project Thesis by Shishir G, [3]

2.2.2 Punctured Chase Combining

In PCC HARQ protocol, we send the entire codeword in the 1^{st} transmission. If retransmission is requested, then the repetition of some bits (information and/or parity bits) is transmitted. These repeated bits are combined with the earlier codeword so that we can benefit from diversity gain. Similarly, if further retranmissions are requested, then another set of bits is repeated till the entire codeword has been repeated following which, we start the entire repetition process again.

For e.g.: Say we have a rate $r = \frac{5}{6}$ mother-code. Let codeword size be 1944 bits (one of the standard sizes as we'll see later).

Tx No.	No. of bits transmitted	rate	total bits transmitted
1	1944	$\frac{5}{6}$	1944
2	216	$\frac{3}{4}$	2160
3	1080	$\frac{1}{2}$	3240
4	648	$\frac{5}{12}$	3888

CHAPTER 3

LDPC CODES STRUCTURE & PUNCTURING

3.1 LDPC Code Structure

$$\mathbf{H}_p = [\mathbf{H}_o | \mathbf{H}_d] = \left[\begin{array}{c|ccccc} \mathbf{P}^{b_1} & \mathbf{I} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{P}^{b_2} & \mathbf{I} & \dots & \mathbf{0} & \mathbf{0} \\ \vdots & \mathbf{0} & \mathbf{P}^{b_3} & \dots & \mathbf{0} & \mathbf{0} \\ \mathbf{P}^{p} & \vdots & \vdots & \dots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \dots & \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \dots & \mathbf{P}^{b_{m_b-1}} & \mathbf{I} \\ \mathbf{P}^{q} & \mathbf{0} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{P}^{b_{m_b}} \end{array}\right]$$

Figure 3.1: LDPC Dual Diagonal Parity Structure

The LDPC Code that we use has a Dual Diagonal Parity structure, [4] i.e. 2 diagonals of the matrix are non-zero while all others are zero with the exception of the block named P^p as seen in Fig. 3.1 This structure ensures that information is shared between adjacent nodes i.e. every block node provides information to its adjacent node after 1 iteration.

3.2 Puncturing Techniques

Puncturing is a technique used in Coding theory to go from a rate r_i code to a higher rate r_j code. It involves the exclusion of certain redundancy (parity) bits from the codeword which shrinks the codeword size while keeping the message bits (information bits) size the same leading to an increase in the code rate.

Since, in IR, we need to puncture the code to obtain a higher rate and in retransmissions, we send these excluded redundancies, hence puncturing is an important aspect of using IR HARQ. Also, at times, we can not use a certain desired rate directly as the mother code due to limited flexibilty in obtaining the said rate in an efficient way, hence we use lower rate code as the mother code and puncture to obtain the desired code. However, this puncturing comes with a cost in terms of performance as we'll see in this section.

3.2.1 Consecutive Puncturing

In the consecutive puncturing scheme, consecutive bits in the codeword are punctured to obtain the desired rate r_d from mother code rate r_m. This scheme, as expected, performs the worst since we a Dual Diagonal Parity Structure for the LDPC code which has information transfer between adjacent nodes.

3.2.2 Random Puncturing

In the random puncturing scheme, 'x' bits are randomly punctured to obtain r_d from r_m. The location of the punctured bits are known at both the transmitter and the receiver.

3.2.3 k-SR Puncturing

In the k-SR puncturing approach, [5], the blocks in the LDPC code are split into 1-SR nodes, 2-SR nodes and so on. SR stands for Step Recoverable.
1-SR node means that this node can recover it's data in 1 iteration. Similarly 2-SR requires 2 iterations and so on and so forth as can be seen in Fig. 3.2.

Fig. 3.2, Fig. 3.3 and Fig. 3.4 have been taken from [5]

There are two important things to note in the k-SR puncturing technique:

- A punctured node is said to be recovered when it receives a message from a check node.
- The higher the number of steps required for recovering the message, the less reliable the message is statistically.

As shown in Fig. 3.3, all the odd blocks are punctured first to obtain the 1-SR

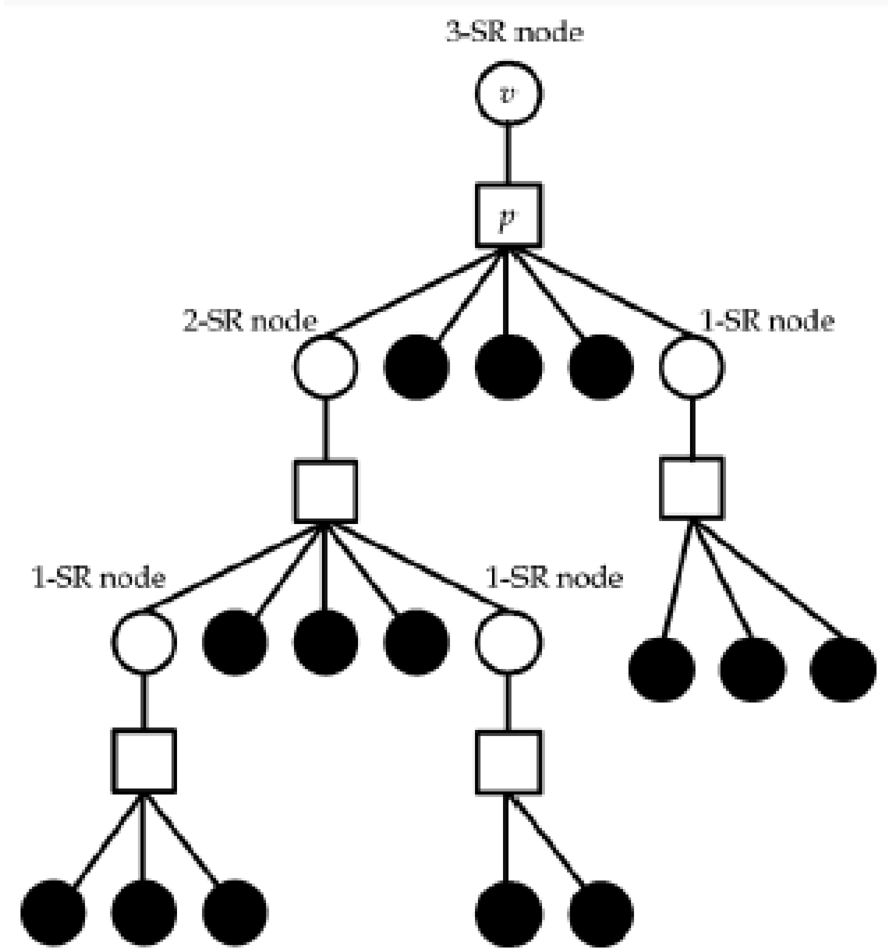


Figure 3.2: k-SR Puncturing mechanism

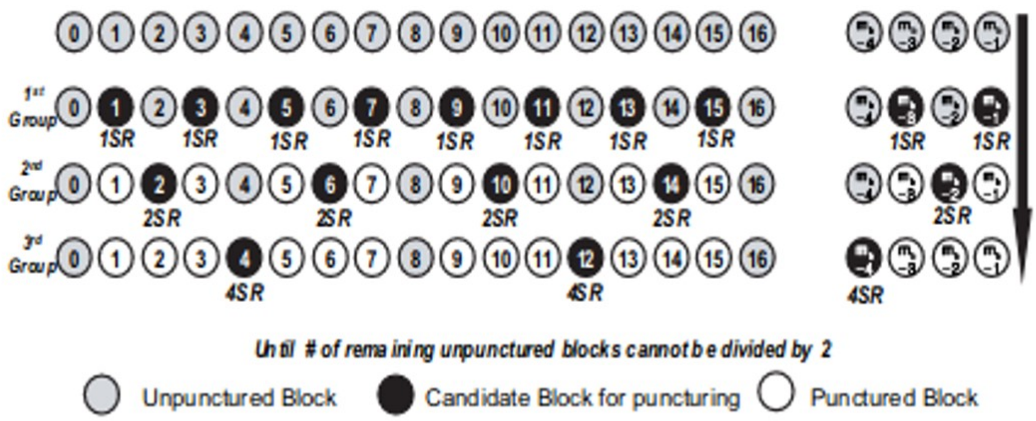


Figure 3.3: k-SR Puncturing structure

nodes. This is possible due to the Dual Diagonal Parity structure of the LDPC Code as discussed in Section 3.1. Next, we see that all the 4n+2 node locations are punctured to obtain the 2-SR nodes. This algorithm focuses on maximising the number of 1-SR nodes, followed by maximising the number of 2-SR nodes and so on, so that we have nodes with higher reliability after their messages are recovered.

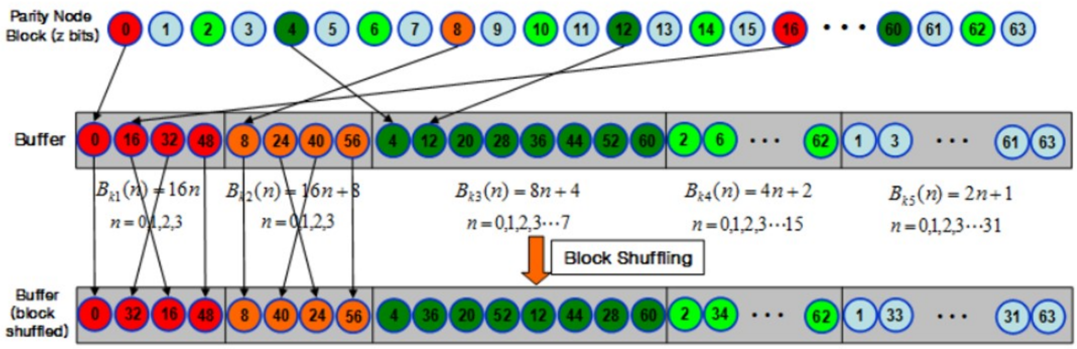


Figure 3.4: k-SR Retransmission order

Once we've obtained the locations of the nodes to be punctured, we must now decide the order in which these punctured nodes will be transmitted. To decide this, we look at the reliability aspect. Since greater the **k** in k-SR, the higher the number of iterations required to obtain the message and hence the lesser it's reliability. Therefore, we transmit higher SR nodes first.

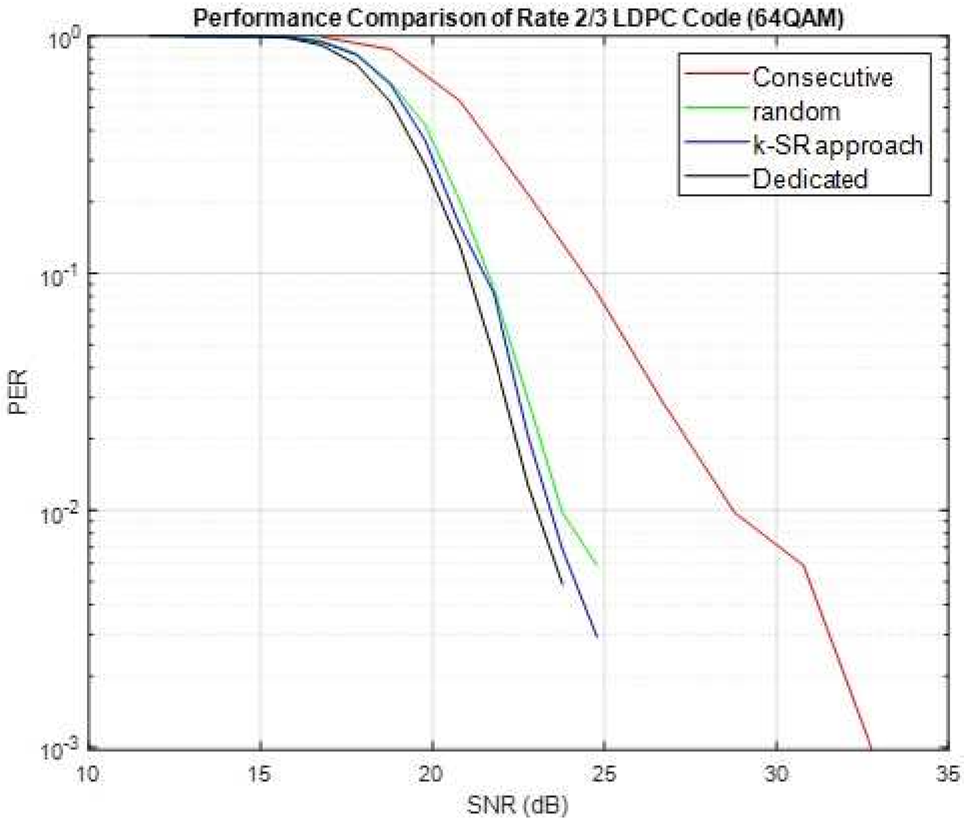
For e.g.: Let us look at Fig. 3.4. Here the nodes and their SR values are:

Node Colour	k-SR
Red	16-SR
Orange	8-SR
Dark Green	4-SR
Light Green	2-SR
Blue	1-SR

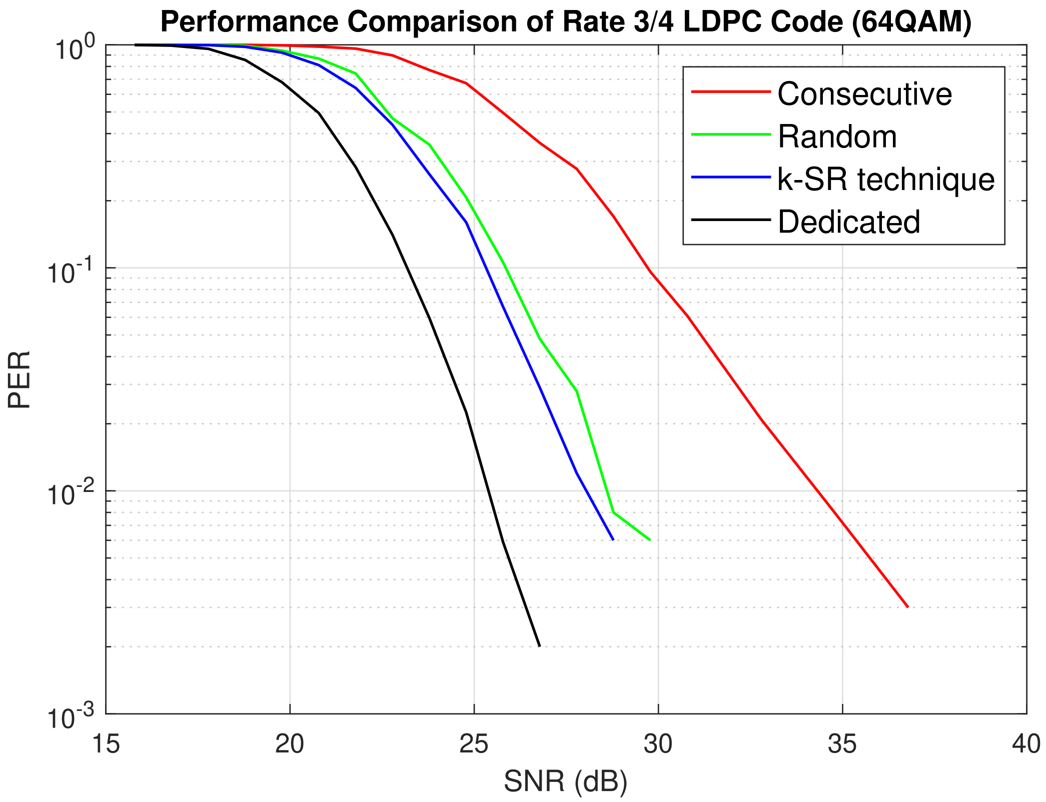
Thus, we transmit all the red nodes first followed by all the orange nodes, followed by all the dark green nodes, followed by light green nodes and finally the blue nodes.

3.2.4 Puncturing Impact on Coding Gain

The coding gain of punctured code is poorer compared to a dedicated code. Hence, the puncturing strategy must be chosed such that this gap in performance is minimized.



(a) Rate = $\frac{2}{3}$



(b) Rate = $\frac{3}{4}$

Figure 3.5: Comparison between Punctured Code and Mothercode at different rates

As can be seen from Fig. 3.5 the performance of the mother rate code is better than all the 3 puncturing schemes considered. The mother rate code is a rate = $\frac{1}{2}$ LDPC code for both the plots. Also, k-SR technique performs the best of the 3 puncturing methods. However, as the rate increases, the gap in the performance increases as is seen in Fig. 3.5 (b).

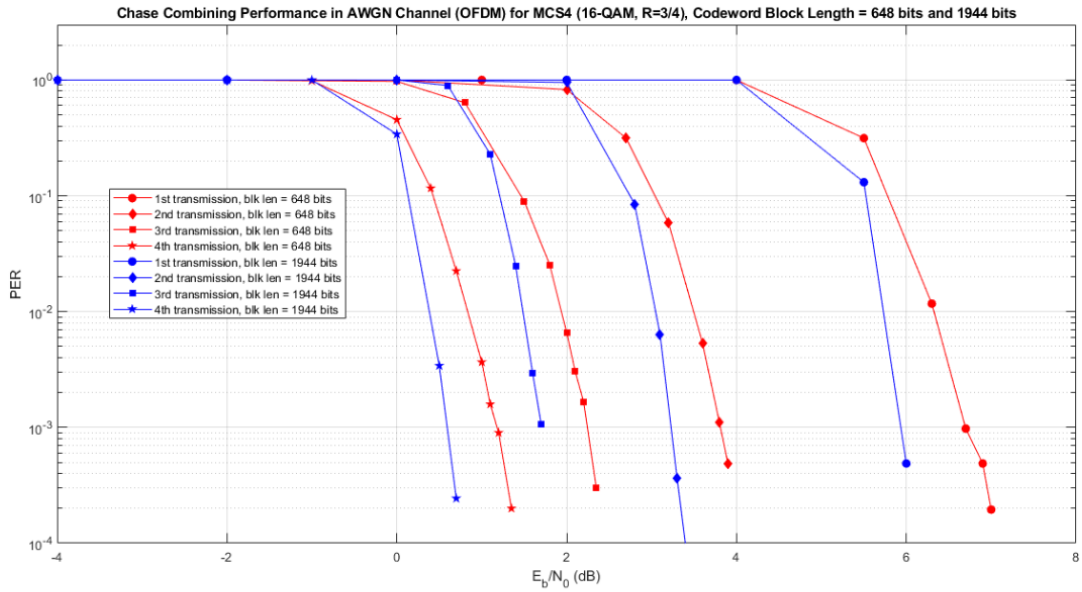
An important thing to note is that when we puncture a codeword, it's length decreases and as we see in the next section, codeword length has a huge impact on performance.

3.3 Codeword Length

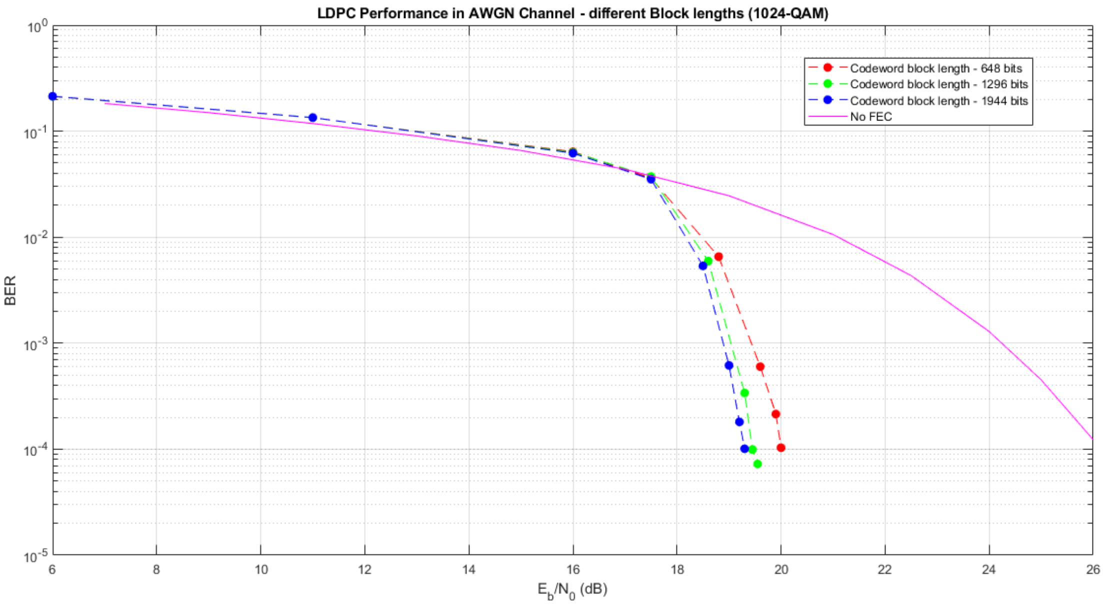
There are 3 standard sizes for LDPC codeword as mentioned in the 802.11ax standard. These are: 648 bits, 1296 bits and 1944 bits.

However, codeword size impacts the performance. Longer the codeword, the better it's performance. This can be seen from the following plots.

Fig. 3.6 shows us how the packet error rate falls for different codeword lengths of LDPC code. As mentioned earlier, larger the codeword length, better the performance and hence faster decay of the PER.



(a) Comparison between 648 bits and 1944 bits



(b) Comparison between 648 bits, 1296 bits and 1944 bits

Figure 3.6: Performance comparison between codeword size of 648 bits, 1296 bits and 1944 bits

CHAPTER 4

SIMULATION

In this chapter, we describe the setup for simulation.

We've been using the WLAN tgax channel Model-D from the WLAN package in MATLAB.

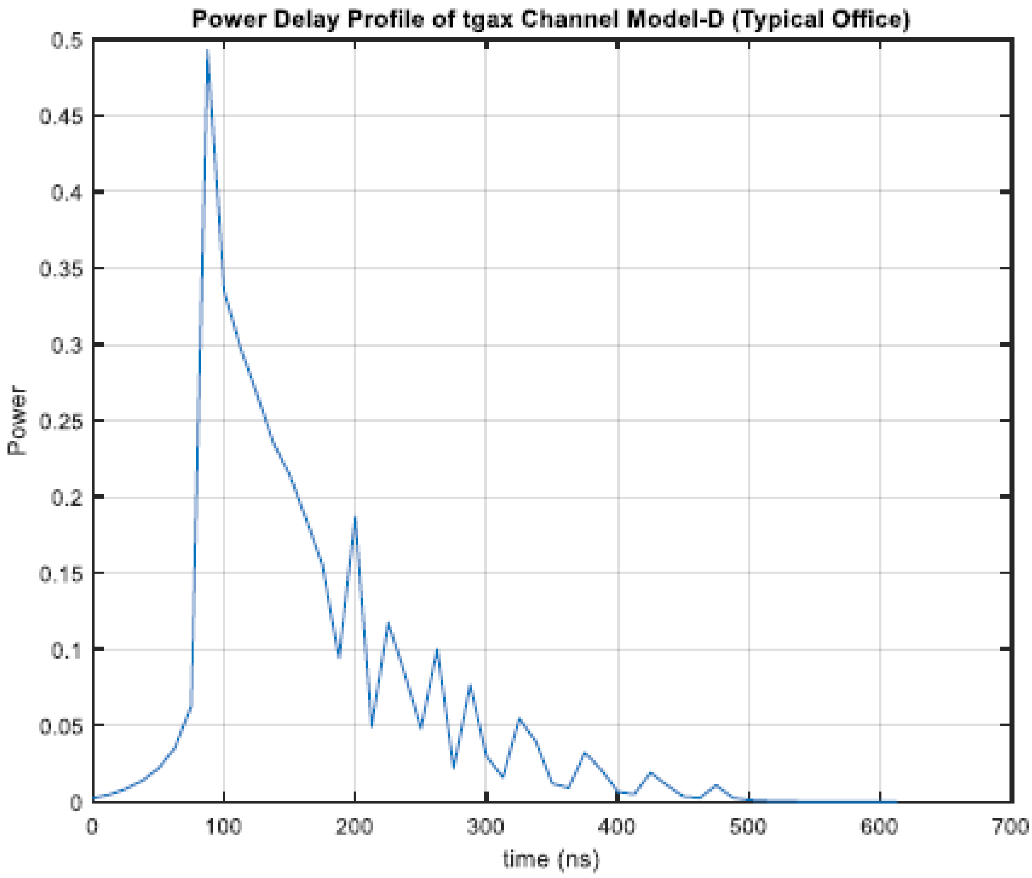


Figure 4.1: Power Delay Profile for Channel Model-D

The power delay profile for Model-D is shown in Fig. 4.1

The packet size considered for all simulations is initialized to 8000 bits. However as the simulation proceeds, to ensure that integer number of codewords fit in a packet, the packet size is changed to the nearest integer multiple of codeword length. In accordance with the standards, we've used the following mother rate codes: $\frac{1}{2}$, $\frac{2}{3}$, $\frac{3}{4}$ and $\frac{5}{6}$

Fig. 4.2 shows the Bell-shaped Spectrum model used for correlation with maximum doppler shift, $f_D = 5Hz$.

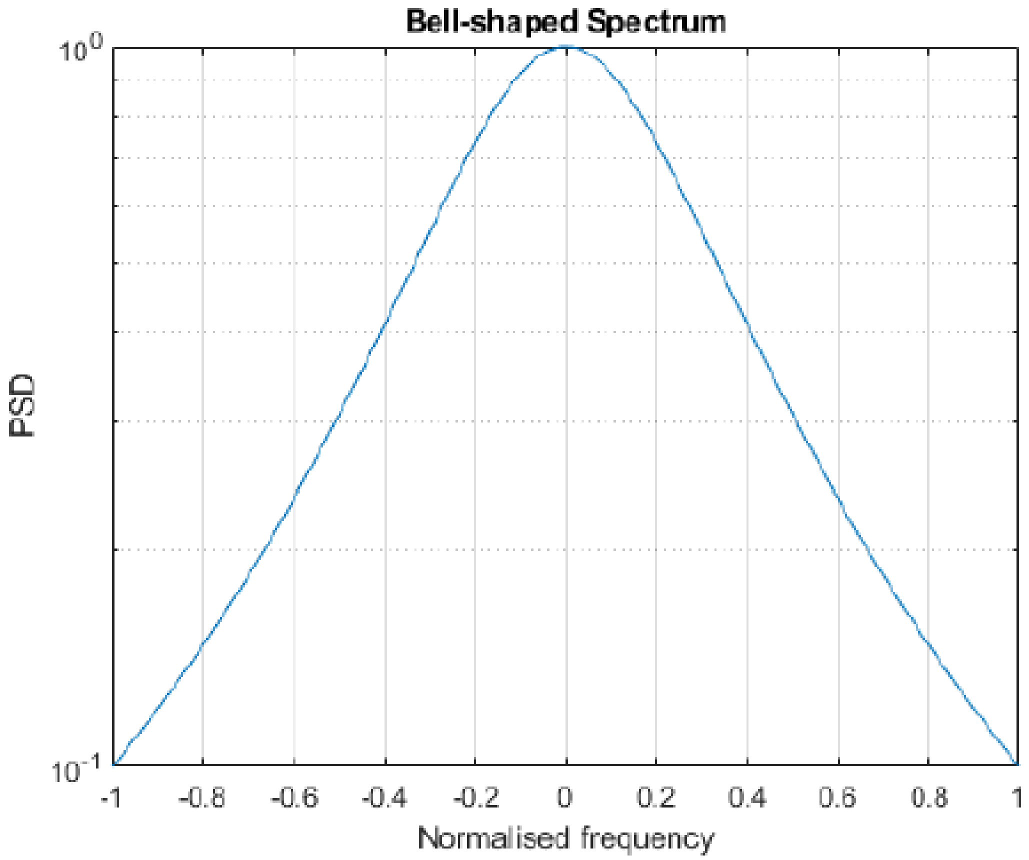


Figure 4.2: Bell-shaped Spectrum based correlation model

CHAPTER 5

PLOTS AND IMPORTANT RESULTS

5.1 Fixed Rate Scheme

In this section, all the plots obtained follow a fixed rate across all SNR strategy. The rates in each transmissions are:

Tx no.	Rate
1	$\frac{5}{6}$
2	$\frac{3}{4}$
3	$\frac{2}{3}$
4	$\frac{1}{2}$

Fig. 5.1 shows the spectral efficiency of different modulations across all 4 given rates i.e. $\{\frac{1}{2}, \frac{2}{3}, \frac{3}{4}, \frac{5}{6}\}$ and across the SNR range.

The curve labeled **Max Thruput** represents the maximum throughput across different rates and modulations at the given SNR value.

Fig. 5.2 shows the comparison between different transmission schemes. **1 Tx** represents a scheme with only 1 transmission, **2 Tx** represents a scheme with 1 transmission and 1 retransmission and **4 Tx** represents a scheme with 1 transmission and 3 retransmissions.

To obtain the curve for 2 Tx scheme, two mother-rate codes are chosen namely rate = $\frac{2}{3}$ and $\frac{5}{6}$. Now, using rate = $\frac{2}{3}$, the 1st transmission is at rate = $\frac{2}{3}$ and 2nd transmission (1st retransmission) is at rate = $\frac{1}{2}$. Similarly, using rate = $\frac{5}{6}$, the 1st transmission is at rate = $\frac{5}{6}$ and 2nd transmission (1st retransmission) is at rate = $\frac{3}{4}$. Now, to obtain the curve for 2 Tx, we choose the scheme with the best spectral efficiency among the 2 sets mentioned above at each SNR and across all modulations.

For 1 Tx strategy, the combination of rate and modulation which performs the best at a given SNR is chosen.

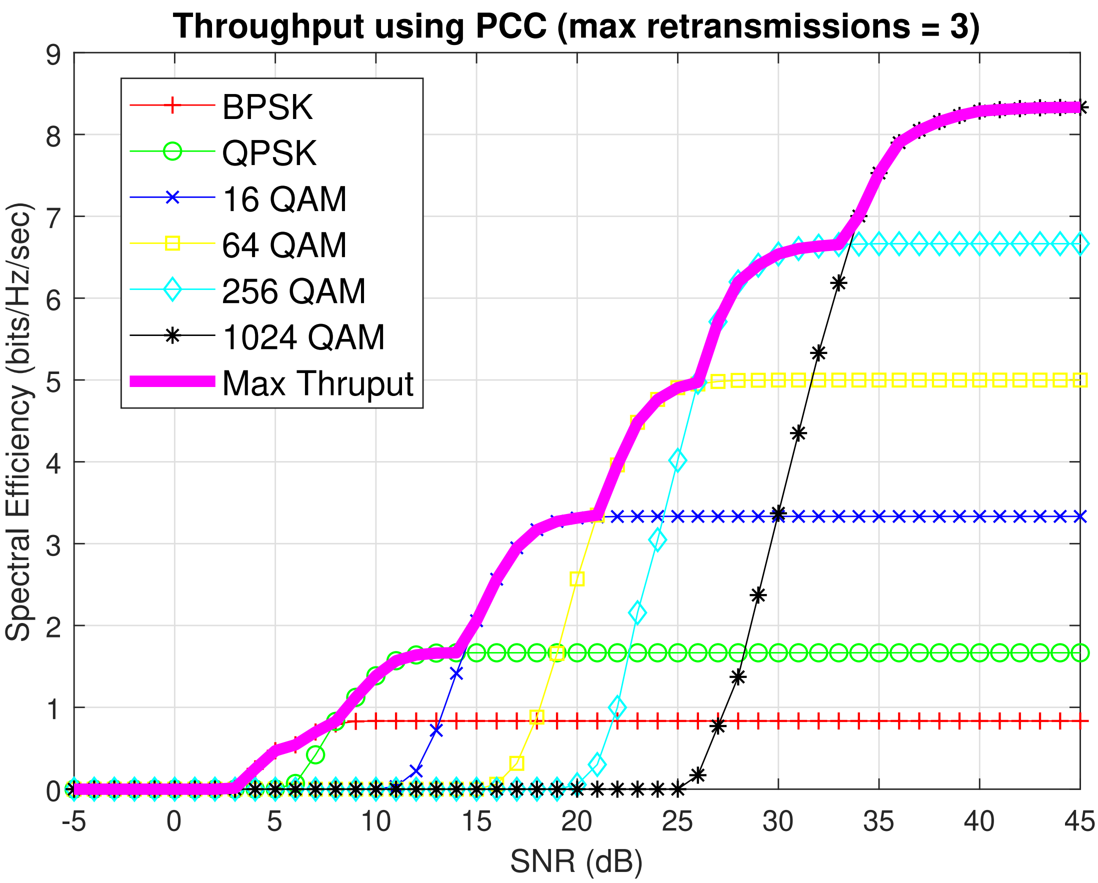


Figure 5.1: Throughput for different Modulations

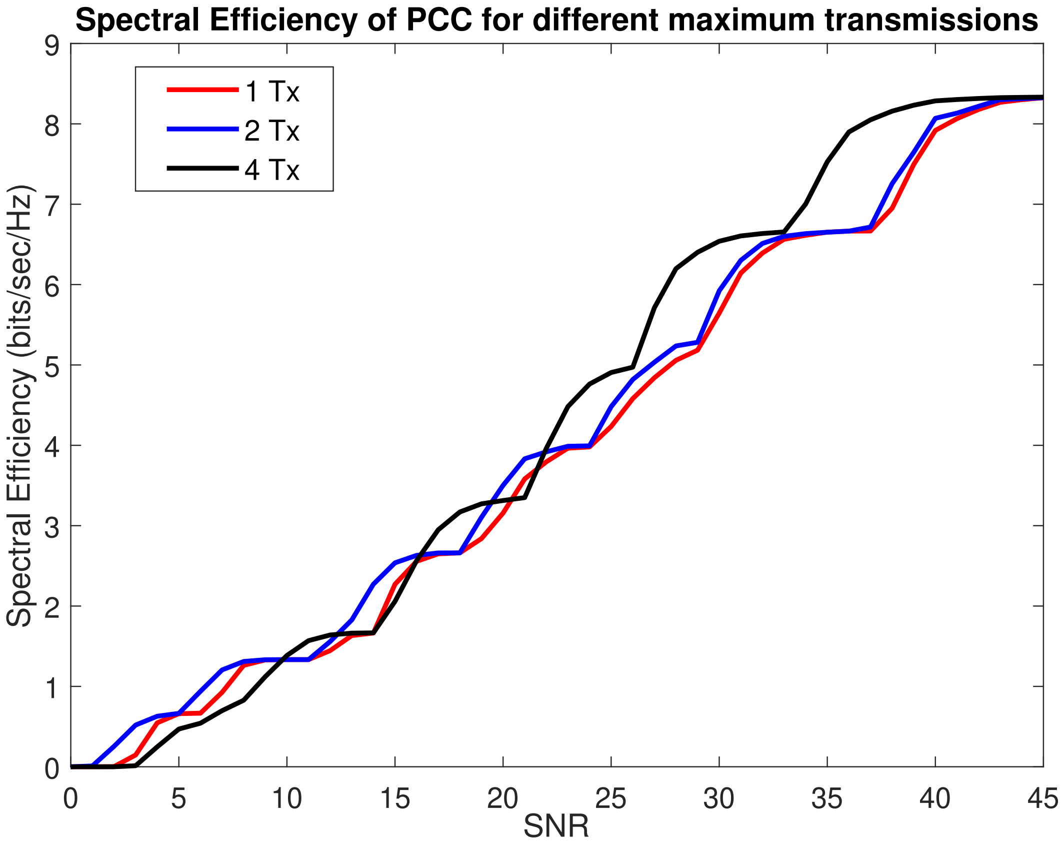
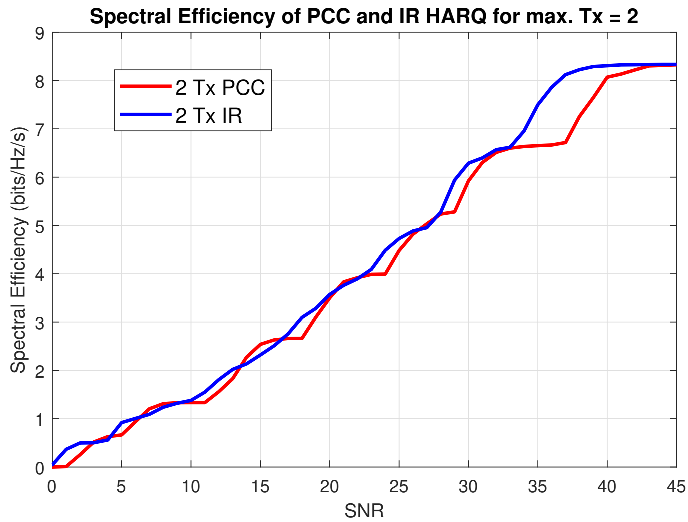


Figure 5.2: Comparison between different maximum transmission schemes using PCC

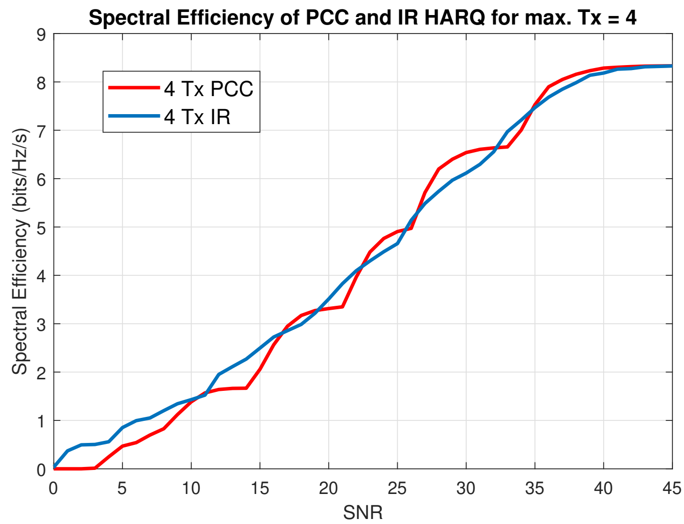
As expected, in the higher SNR regions, 4 Tx scheme is best since we go from the ambitious rate = $\frac{5}{6}$ to a robust rate = $\frac{1}{2}$ however the same doesn't happen for other 2 schemes.

However, as we move to the lower SNR region, 2 Tx scheme outperforms 4 Tx scheme because the mother-rate code with rate = $\frac{2}{3}$ outperforms rate = $\frac{5}{6}$. In PCC, to go from rate r_1 to a lower rate r_2, repetition of bits is transmitted. Thus, obtaining rate = $\frac{1}{2}$ from rate = $\frac{2}{3}$ is more robust than obtaining the same from rate = $\frac{5}{6}$.

Also, 1 Tx scheme never does better than 2 Tx scheme because the best performance that 1 Tx can obtain is when the entire packet is transmitted in the 1st transmission and this rate matches the 1st transmission rate of 2 Tx scheme. We would expect that in very low SNR regions i.e less than 5dB, 1 Tx scheme using mother-rate code of rate = $\frac{1}{2}$ should be better than 2 Tx scheme where mother-rate code is rate = $\frac{2}{3}$, however, BPSK the modulation scheme that dominates this SNR region is robust enough to ensure that the performance difference between the 2 schemes in the 1st transmission is negligible and any additional gain seen by 2 Tx scheme is due to it taking advantage of diversity gain using the 2 transmissions. The same does not apply to 4 Tx scheme because it's mother-code rate = $\frac{5}{6}$ is very far from rate = $\frac{1}{2}$ and hence the same robustness can not be achieved by simple repetition of bits to achieve lower rate code.



(a) Max. Tx = 2



(b) Max. Tx = 4

Figure 5.3: Comparison between PCC and IR across different transmission schemes

Fig. 5.3 (a) shows comparison between 2 Tx scheme for PCC and IR. In the high SNR region IR outperforms PCC because the 2^{nd} transmission of IR achieves mother-rate code performance and the 1^{st} transmission of IR has a performance close to the mother-rate code performance because the difference between the 2 rates is not large which in turn ensures that the performance loss due to puncturing is quite small.

The IR mother-rates are: rate = $\frac{1}{2}$ and $\frac{3}{4}$ and 1st transmission rates are: $\frac{2}{3}$ and $\frac{5}{6}$ respectively. Thus, rate = $\frac{2}{3}$ is obtained by puncturing rate = $\frac{1}{2}$ code and rate = $\frac{5}{6}$ is obtained by puncturing rate = $\frac{3}{4}$ code.

Fig. 5.3 (b) shows the comparison between PCC and IR for 4 Tx scheme. Here, in the higher SNR region, PCC performs slightly better than IR because of loss in the performance due to puncturing in IR. In this region, instead of using all 4 transmissions at a higher modulation, using a lower modulation and successfully transmitting the packet at a higher rate leads to a better performance.Thus, here, the 1st and the 2nd transmission dominate the spectral efficiency and since the 1st and 2nd transmission of IR have a huge performance loss due to puncturing hence PCC dominates.
In the lower SNR region, since the opposite of higher SNR region occurs and the 3rd and 4th transmission of IR are closer to the mother-rate code performance hence IR dominates PCC.

5.2 Breakpoints

In the earlier section, we saw the performance due to a scheme where the rates for each transmissions were fixed irrespective of the SNR. Now, in this section we talk about adapting the rates to the given average SNR using a breakpoints model.

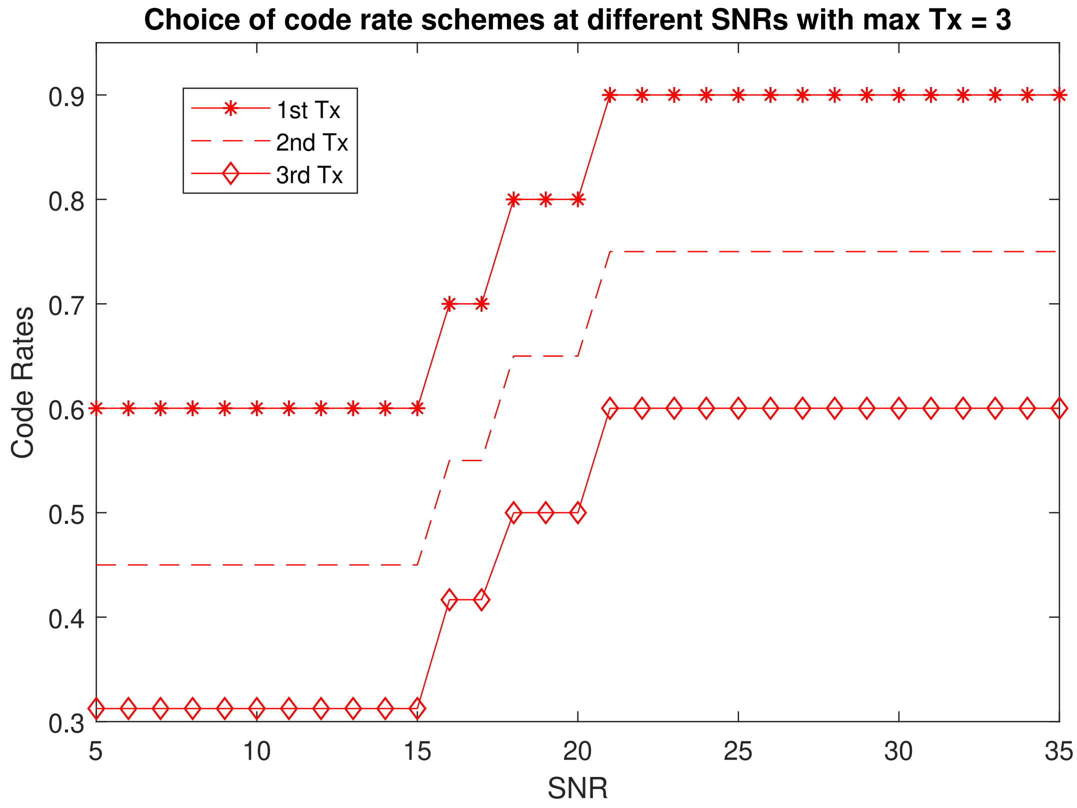
We've chosen 4 rate schemes: The following table is for 3 Tx scheme as shown in Fig. 5.4 (a)

Tx. no.	Scheme 1 Rate	Scheme 2 Rate	Scheme 3 Rate	Scheme 4 Rate
1	0.6	0.7	0.8	0.9
2	0.45	0.55	0.65	0.75
3	0.3	0.4	0.5	0.6

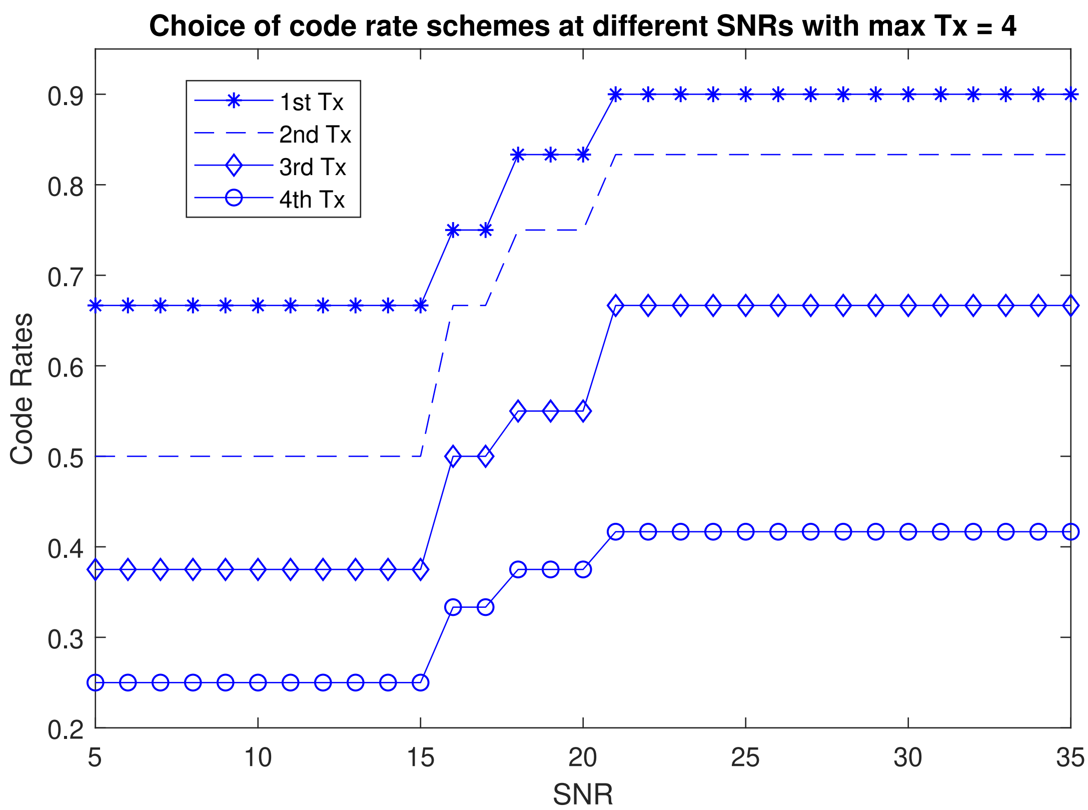
The following table is for 4 Tx scheme as shown in Fig. 5.4 (b)

Tx. no.	Scheme 1 Rate	Scheme 2 Rate	Scheme 3 Rate	Scheme 4 Rate
1	$\frac{2}{3}$	$\frac{3}{4}$	$\frac{5}{6}$	0.9
2	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{3}{4}$	$\frac{5}{6}$
3	$\frac{3}{8}$	$\frac{1}{2}$	0.55	$\frac{2}{3}$
4	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{3}{8}$	$\frac{5}{12}$

Both of the above tables show the breakpoints for 64 QAM modulation. Different modulations have different breakpoints.



(a) Max. Tx = 3



(b) Max. Tx = 4

Figure 5.4: Breakpoints for 64 QAM

The 4 Tx breakpoints are based on ARQ performance in the SNR range from -10dB to 50dB. The following table based on Fig. 5.4 (b) mentions the SNR range in which the different schemes dominate:

SNR Range (dB)	ARQ dominant rate	Dominating Scheme
upto 15dB	$\frac{1}{2}$	Scheme 1
16dB to 17dB	$\frac{2}{3}$	Scheme 2
18dB to 20dB	$\frac{3}{4}$	Scheme 3
21dB and above	$\frac{5}{6}$	Scheme 4

The above table is obtained from ARQ protocol performance in the same SNR range. The region where ARQ protocol with rate = $\frac{2}{3}$ performs best, there we choose scheme 2 as shown in the above table. Since both IR and PCC use 4 Tx whereas ARQ uses 2 Tx, the idea is that using ARQ protocol, we transmit at rates = {r, $\frac{r}{2}$ }, hence for HARQ, we choose the 1st transmission rate to be slightly more aggressive i.e. $r_{1st} > r$, the 2nd transmission rate to be the same as the 1st transmission of ARQ i.e. $r_{2nd} = r$, the 3rd transmission rate to be somewhere is between r and $\frac{r}{2}$ and the final transmission i.e. 4th transmission rate = $\frac{r}{2}$. This can be seen in breakpoints table for 4 Tx.
For 3 Tx case, since we can not sweep the same range of rates as done for 4 Tx case, hence we choose a less aggressive 1st transmission and a less robust 3rd transmission as compared to the 4 Tx case. The 2nd transmission rate is chosen as average of the 1st and the 3rd transmission rates.

5.3 Long Term SNR based PCC

Once the breakpoints were fixed, the spectral efficiency plots for obtained. However, no PER constraint was kept on them.
Now, PER is an important constraint in communications. We can use 1024 QAM modulation having PER = 0.5 and still get spectral efficiency = 5. However, with 50% PER, communication is not possible. Hence, we obtained the performance of PCC with and without a PER constraint.

Fig. 5.5 shows 4 Tx PCC with PER = 0.1% and Fig. 5.6 shows 4 Tx PCC with PER = 1%. As expected, the performance with PER constraint is worse than without PER constraint. Comparing the PER constraint plots we see that stricter the constraint, more

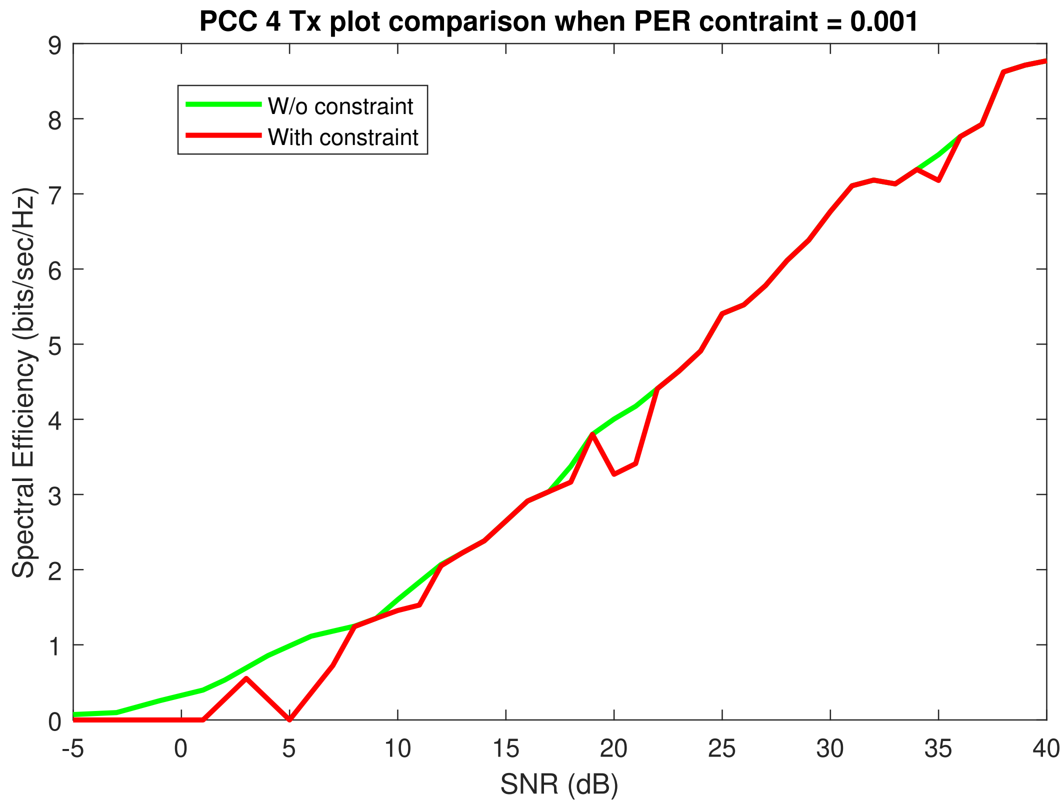


Figure 5.5: Comparison of throughput with and without PER constraint = 0.001

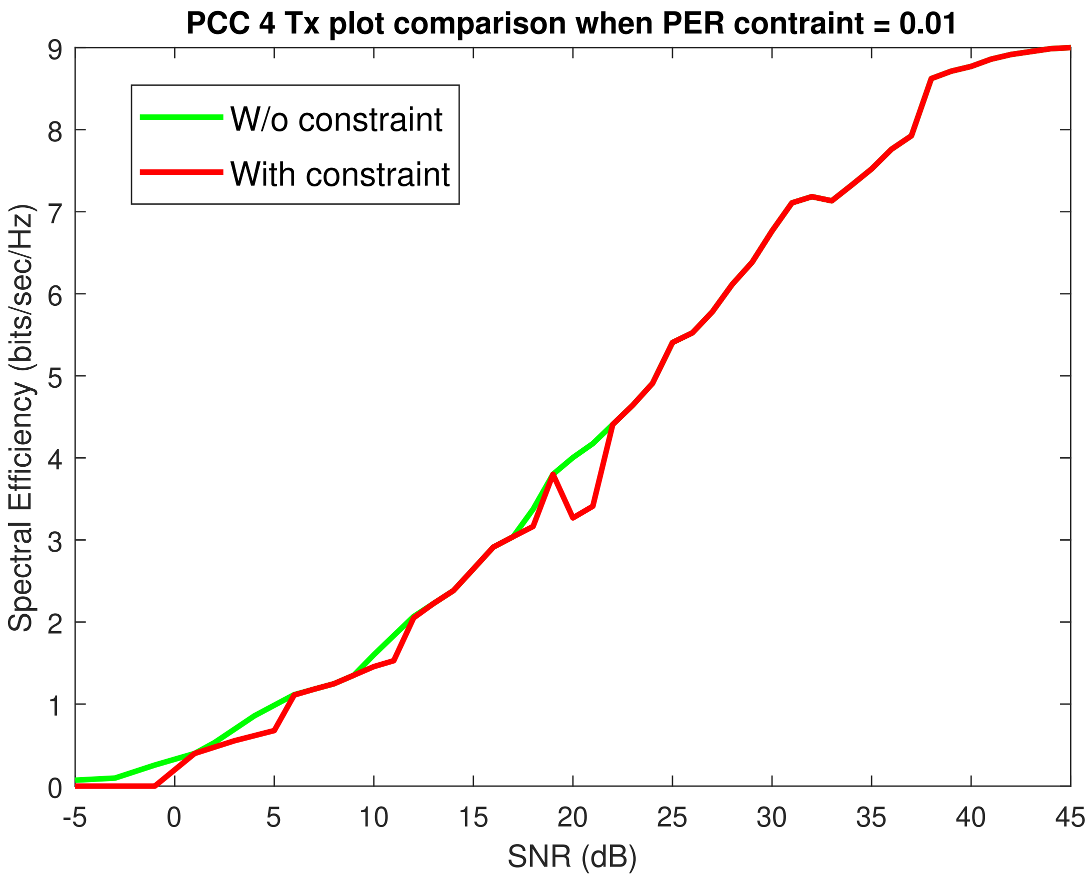


Figure 5.6: Comparison of throughput with and without PER constraint = 0.01

the deviation in performance of the with contraint curve as compared to the without constraint curve.

An important observation from these figures is that at high SNR, PER constraint is being met which could imply that our breakpoints could be pushed to lesser SNR values for those modulation schemes and in the low SNR region, the breakpoints chosen are way too aggressive and need to be shifted right i.e. to be shifted to higher SNR values.

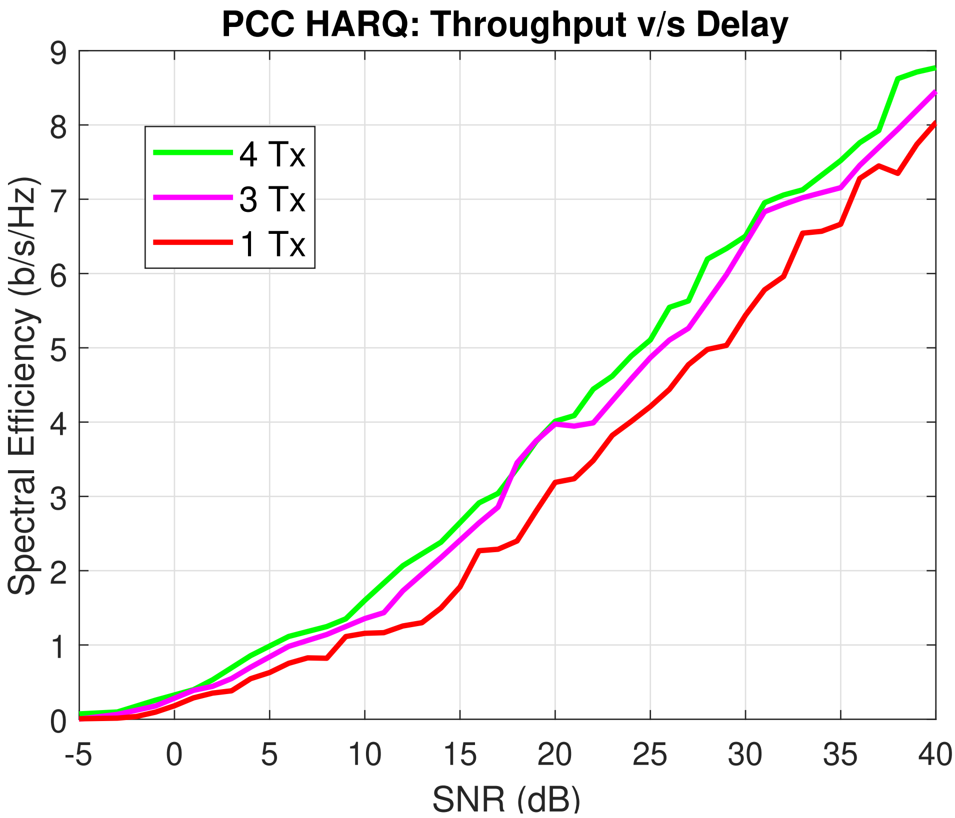


Figure 5.7: Comparison of throughput due to different transmissions in PCC

Fig. 5.7 shows the comparison in performance between 4 Tx, 3 Tx and 1 Tx schemes. As expected, 4 Tx and 3 Tx supersede 1 Tx in performance throughput the SNR range since the breakpoints now decide the mother-rate code. This ensures that the 1st transmission is close to the optimal ARQ protocol rate for the given SNR value. As discussed earlier, the 2nd transmission of 4 Tx scheme has the same rate as ARQ protocol's 1st transmission rate and therefore by extension is equal to the rate chosen for the 1 Tx scheme.

Here, while more transmissions allow for higher spectral efficiency, they also lead to a delay in overall transmission.

Fig. 5.8 shows the comparison between PCC and IR for 3 Tx scheme. Here as expected, in the lower SNR region i.e. approximately below 17dB, IR performs better

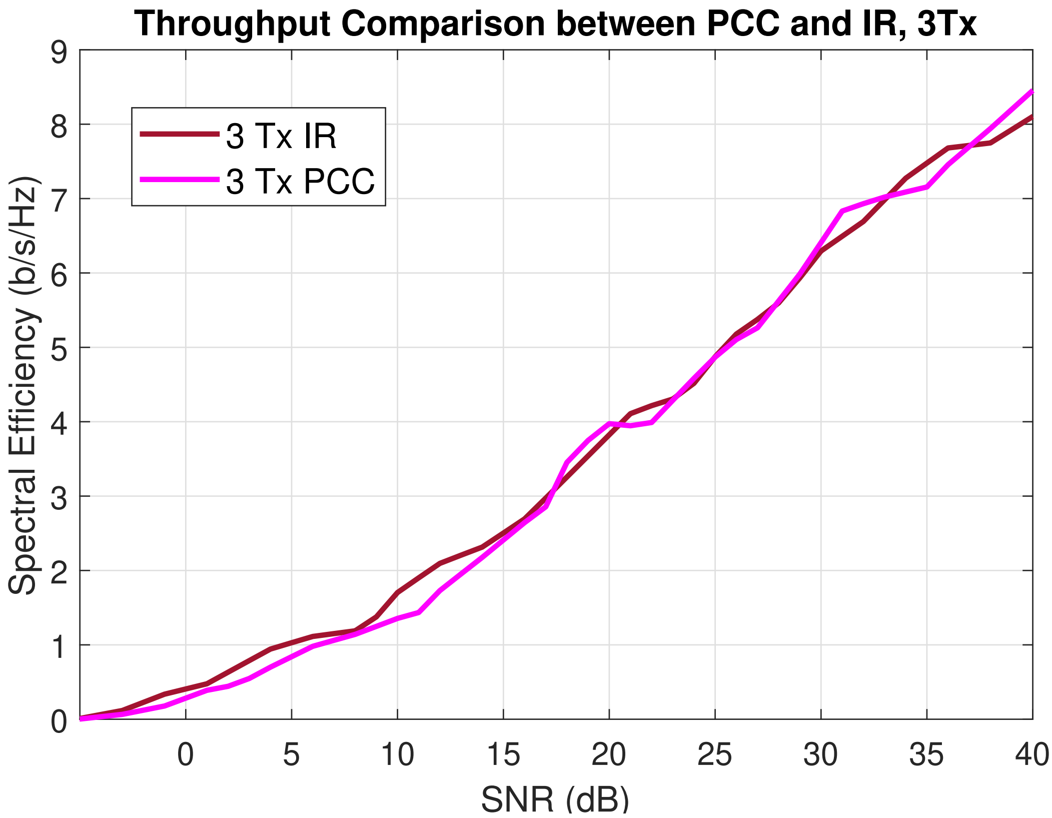


Figure 5.8: Comparison between IR and PCC for 3 Tx

than PCC. This occurs because at lower SNR and higher transmissions, IR has perfomance close to mother-rate code whereas PCC moves away from the performance of mother-rate code at the given rate.

For e.g.: Say that SNR = 10dB, then the scheme chosen would rate = $\{0.7, 0.55, 0.4\}$ for Tx no. = $\{1, 2, 3\}$ respectively. Now, we would choose a mothercode of rate = 0.5 for IR and rate = $\frac{2}{3}$ for PCC. Now, in the 2nd transmission, IR is closer to the mother-code rate performance because new redundancies have been transmitted making it more robust whereas PCC has used repetition and hence is less robust. Similarly for 3rd transmission, there will be some new redundancies transmitted along with some repeated bits for IR whereas for PCC, only repetition occurs thereby making it less robust than IR. Hence, IR performs better than PCC in low SNR region.

However, as SNR increases, the 1st and 2nd transmission start dominating thus, ther performance is similar for both. However, since PCC's 1st transmission is at mother-rate code i.e. the entire packet is transmitted with all the redundancies, hence it reaches saturation i.e. maximum spectral efficiency before IR.

Fig. 5.9 shows the comaprison in performance between ARQ protocol and HARQ protocol (both IR and PCC). As expected, both PCC and IR's performance supersedes

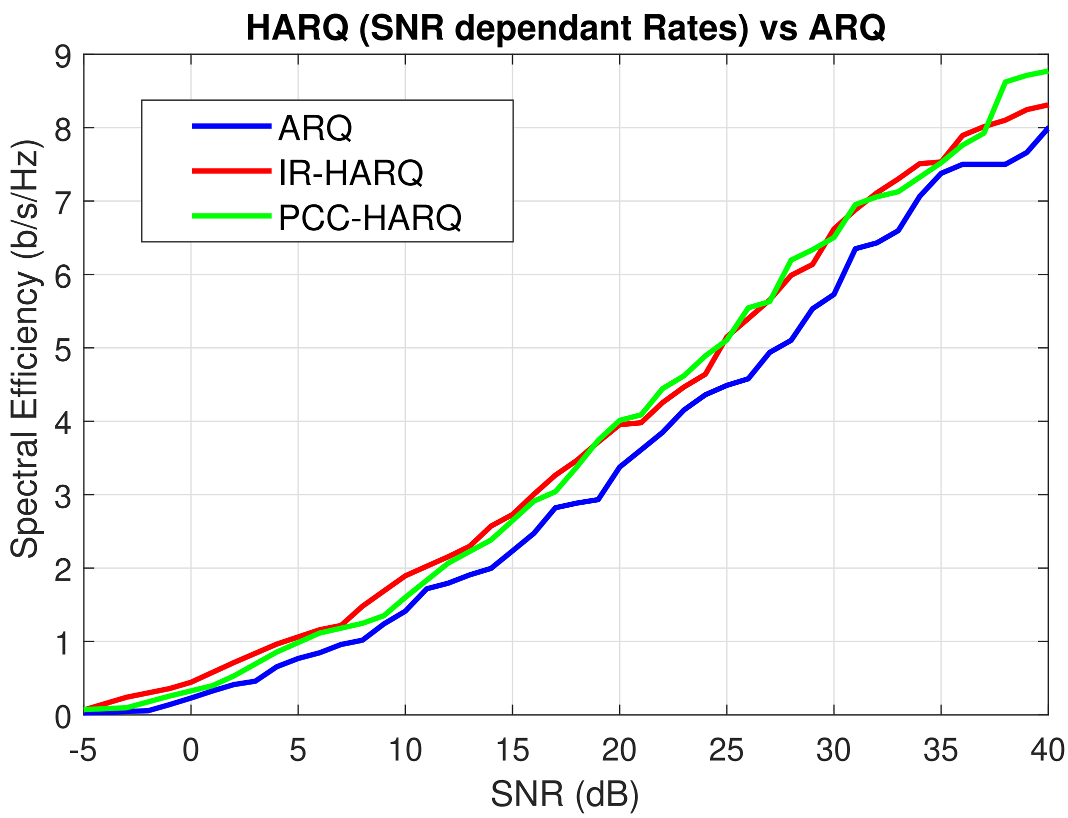


Figure 5.9: Comparison between ARQ, IR and PCC

ARQ's performance throughout the SNR range. However, the performance of both PCC and IR are very similar. There inferences drawn from earlier plots hold here as well and in the low SNR region IR performs better than PCC and in the high SNR region PCC is slightly better than IR. Here, since the last transmission rate for all 3 protocols are the same it allows for a fair performance comparison based on code rate however there is a delay cost associated with HARQ.

Comparison between	Avg. SNR difference (dB)
PCC v/s IR, max. 4 Tx	0.029 (IR gain)
PCC v/s IR, max. 3 Tx	0.2628 (PCC gain)
PCC (max. Tx=4) v/s ARQ	2.1354 (PCC gain)
PCC: max. Tx=4 v/s max. Tx=1	3.4314 (4 Tx gain)
PCC: max. Tx=3 v/s max. Tx=1	2.3758 (3 Tx gain)

However, as we can see from Fig. 5.9, upto about 20dB, IR dominates PCC whereas post 20dB PCC has a slightly better performance than IR HARQ. To quantify the same in terms of average SNR gain we look at the following table (max. Tx = 4, for all):

Comparison between	SNR Range (dB)	Avg. SNR difference (dB)
PCC v/s IR, max. Tx=4	-8dB to 19dB	0.8211 (IR gain)
PCC v/s IR, max. Tx=4	20dB to 45dB	0.8240 (PCC gain)
PCC v/s IR, max. Tx=4	-8dB to 19dB	0.8211 (IR gain)
PCC v/s ARQ	-8dB to 19dB	1.5858 (PCC gain)
PCC v/s ARQ	20dB to 43dB	2.6997 (PCC gain)
IR v/s ARQ	-8dB to 19dB	2.4055 (IR gain)
IR v/s ARQ	20dB to 43dB	2.5381 (IR gain)

This table suggests that perhaps using a fusion scheme between PCC and IR HARQ might show further improvement.

5.4 Short Term SNR estimation

Fig. 5.10 shows the AR model used for predicting the instantaneous SNR value based on M number of previous packets. M=2 gives a decent estimate and M=4 gives an almost accurate estimate of the true SNR.

Now, we know that the correlation between instantaneous SNR of consecutive transmissions is based on the bell-shaped spectrum model. The PSD of the bell-shaped spectrum is given by:

$$\mathcal{S}(f) = \frac{1}{1 + 9(\frac{f}{f_d})} \quad |f| \leq f_d$$

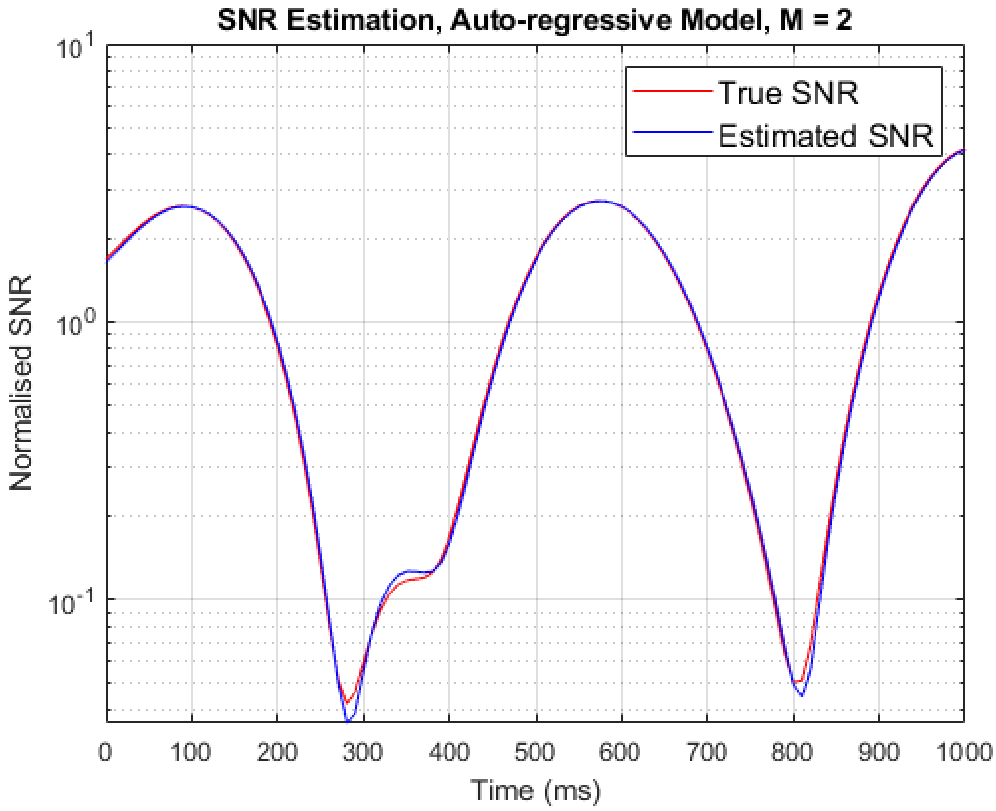
The autocorrelation function corresponding to $\mathcal{S}(f)$ is:

$$\mathcal{R}_h(\Delta t) = \frac{\pi f_d}{3} exp(-\frac{2\pi}{3} f_d \Delta t)$$

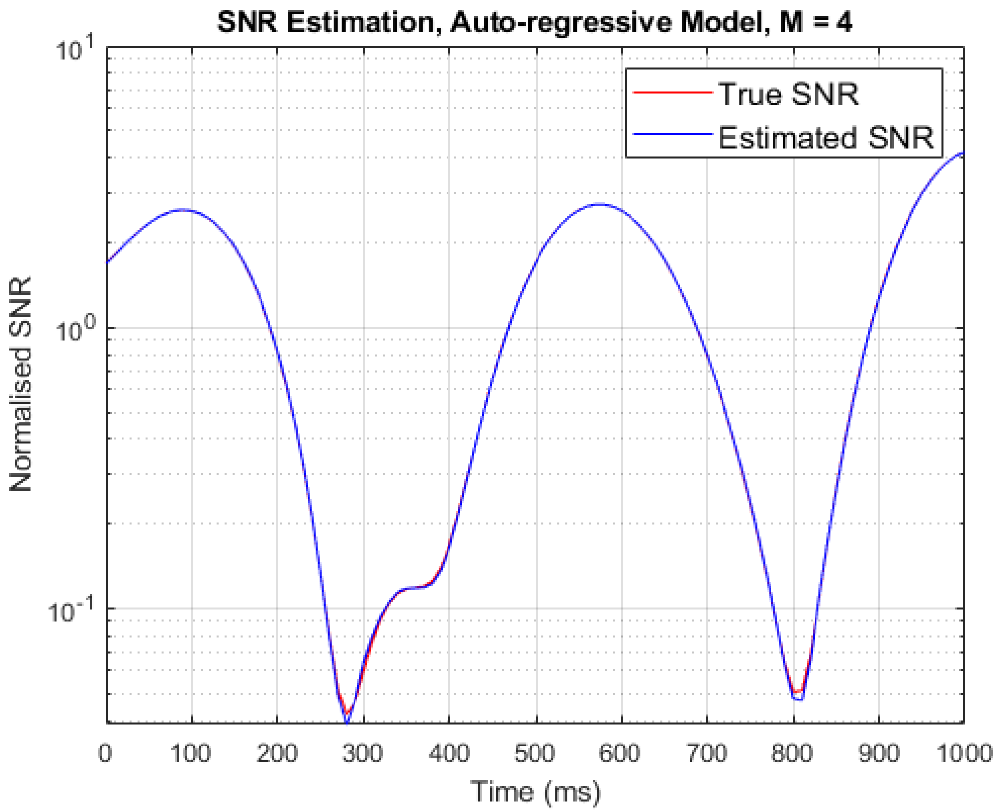
Thus, using an AR model of the form:

$$\mathcal{R}_t = \sum_{i=1}^{M} a_i R_{t-i} + noise$$

can be used to estimate the autocorrelation values between the SNR of consecutive transmissions and thereby used to predict the instantaneous SNR for the current transmission.



(a) M=2



(b) M=4

Figure 5.10: SNR estimation using AR model

5.5 Long Term SNR vs Short Term SNR

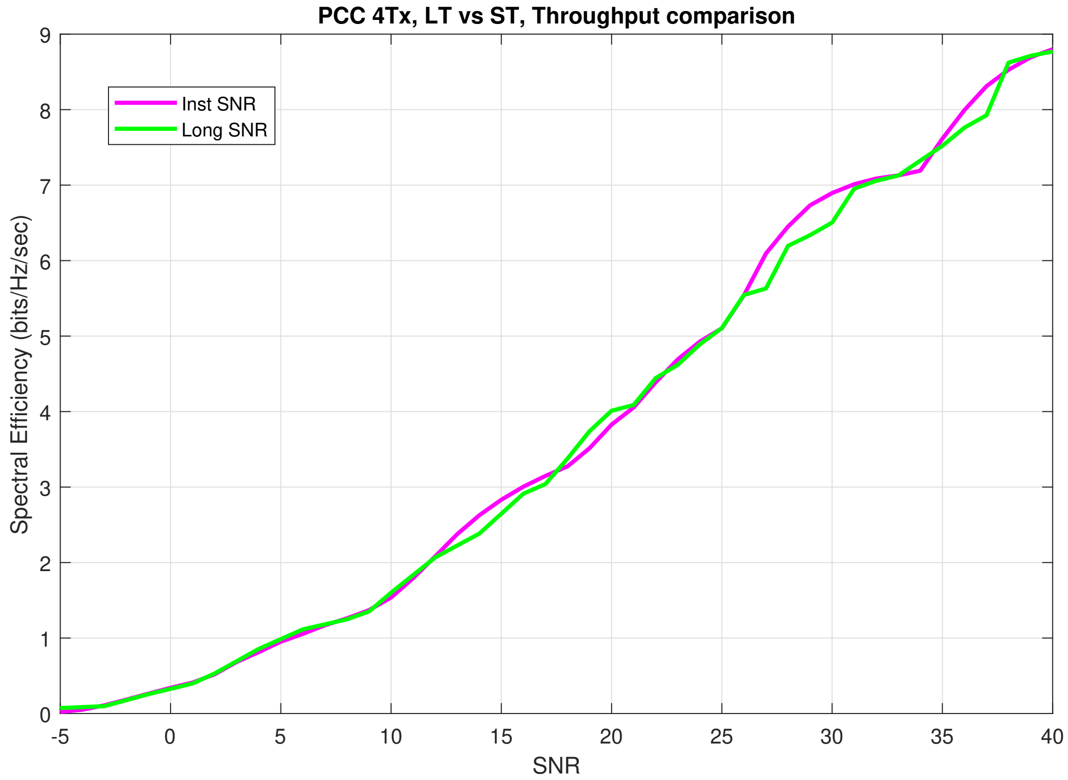


Figure 5.11: Comparison between Long Term SNR and Short Term SNR strategy using PCC for 4 Tx

Fig. 5.11 shows the comparison in performance between the Short Term SNR estimation startegy (instantaneous SNR estimation) and Long Term SNR i.e. Expected SNR. As is expected, the instantaneous SNR strategy performs better than using the Expected (Average) SNR strategy since we now have a more accurate estimate of SNR for the given transmission.

CHAPTER 6

LITERATURE SURVEY

In this chapter, we are going to discuss a survey on literature in HARQ protocol. We will start with the history of HARQ and it's predecessor ARQ protocol and then discuss current developments in the same.

ARQ protocol stands for Automatic Repeat Request protocol. It existence in the wireless literature goes back to the initial practical implementations of wireless systems. It is a predecessor for the HARQ protocol which stands for the Hybrid Automatic Repeat Request protocol. In their celebrated work [1], Schalkwijk and Kailath showed that a simple linear feedback coding scheme achieves the capacity. The associated probability of error decays doubly exponentially. Similarly, Lau [2] has shown that for Rayleigh fading channels with feedback, the associated error probability error decays dramatically than without feedback when channel state is fed back to the transmitter and the associated MCS is chosen that is matched to the channel state. HARQ was first seen in LTE and has been instrumental in bringing about the 4G revolution [6]. The different types of HARQ protocols have been explained and compared with each other and ARQ protocol by Sachin K. R. et al, [7] and Frenger et al, [8]. As mentioned in [9] by Beh, Doufexi and Armour, HARQ can be implemented for OFDMA with a stronger performance as compared to ARQ protocol. The performance of HARQ with OFDMA in downlink has been explored by Chowdhury Mizan Mahmood Taher and Dr. Muhieddin Amer in [10].

Moving to 802.11 WLAN, HARQ has been proven effective in simulations by Chatzimisios et al, [11]. As for the 802.11ax standard, Deng, Lin et al, [12] have given a performance analysis for HARQ and the road ahead to incorporate it in the standard with all specifications.

As seen in section 3.1, LDPC coding plays a huge role in HARQ performance. Richardson et al, [13] discuss an efficient encoding scheme for LDPC codes. Mostafa, [14] discuss a possible HARQ rate-compatible structure and Nguyen et al, [15] discuss short length LDPC codes. An important analysis by Changyan Di et al, [16] discusses the performance of finite length LDPC codes which gives us a better bound on LDPC code performance. The Dual Diagonal Parity structure of LDPC code and some LDPC puncturing schemes are discussed by Park et al in [4, 17]. The optimal puncturing strategy, novel k-SR node technique has been explained by Jeongseok Ha and S. W. McLaughlin, [5].

Additional results were obtained from Qualcomm India and the OFDM structure is as explained by U Madhow in his book [18].

CHAPTER 7

KEY RESULTS and SUMMARY

There are majorly 2 types of HARQ protocol, Incremental Redundancy and Punctured Chase Combining. IR involves transmitting punctured redundancies upon retransmission request and PCC involves transmitting repetition of data and redundancy bits during retransmission.

We've seen the Dual Diagonal Parity structure of LDPC code and the impact of puncturing on the performance of LDPC codes in section 3.2. We've also discussed the different puncturing schemes namely consecutive puncturing, random puncturing and k-SR puncturing method. Also, we've discussed the impact of codeword length on performance.

In chapter 5, in most of the comparison plots between PCC and IR, we've seen that in the low SNR region i.e. approximately below 20 dB, IR outperforms PCC however in the high SNR region PCC outperforms IR. This is because in the low SNR region, a more robust scheme is preferred and since in IR, new redundancies are transmitted in each iteration, hence it's performance is closer to the mother-rate code performance with a smaller rate making it more robust as compared to PCC which used repetitions and hence has a performance farther away from a mother-rate code for the rate at the given transmission. Also, in the high SNR region, the 1st and the 2nd transmission dominates where PCC has a performance closer to mother-rate code since we use mother-rate code with less redundancies (i.e. higher rate) in high SNR region. Thus, in high SNR region, the performance of 1st transmission of IR is significantly affected due to puncturing.

To reduce this impact, instead of using fixed rates, we vary the rates based on average SNR using the breakpoints model, Fig. 5.4. To further improve performance, we introduce AR modelling of instantaneous SNR so that we have a better prediction of the channel conditions for the packet to be transmitted.

CHAPTER 8

FUTURE WORK

- The problem we're trying to tackle is one where we consider how both interference as well as noise affect our signal and we use intelligent and adaptive HARQ protocol to achieve high throughput particularly in bad channel conditions. We plan on training a neural network which will provide the intelligence needed to decide on optimal MCS and retransmission protocol at different locations.

- So far, we've assumed perfect channel estimation however, in reality there is some SNR uncertainity which can be modeled using a gaussian function and results can be extended to this SNR Mismatch case.

- Also, we have simply assumed that the channel is known at the transmitter and receiver. However, pilot symbols are used for this estimation which leads to imperfect channel estimation which may also impact the performance and hence requires analysis.

- Due to the requirement of storing previous transmission packets, there is a buffer requirement at the receiver. Since we can not have an infinite size buffer, hence we must also take into account buffer constraints and accordingly quantize bits. This will also have an impact on LLR values due to quantization error and thus the impact of these constraints needs to be explored.

- So far, all the results have been restricted to SISO. Since, MIMO is a proven technique to exploit antenna gain, thus extending these results to MIMO is an important future task.

- As seen in section 3.2, puncturing method has a huge impact on performance and hence designing an optimal method is key to improving performance. Thus, exploring puncturing patterns further is an important continuation to the project.

- All the plots and results talk about throughput v/s SNR or PER v/s SNR or delay v/s SNR. However, there is no result for comparing Throughput v/s delay v/s SNR. This can be extended to the case of multiple STAs and multiple APs and deciding on optimal modulation and retransmission strategies in those conditions. This is one of the most important future aspects of the work which will perhaps lead to some pragmatic solution to the dense WLAN scenario problem.

REFERENCES

[1] J. Schalkwijk and T. Kailath. A coding scheme for additive noise channels with feedback–i: No bandwidth constraint. *IEEE Transactions on Information Theory*, 12(2):172–182, 1966.

[2] V. K. N. Lau. Channel capacity and error exponents of variable rate adaptive channel coding for rayleigh fading channels. *IEEE Transactions on Communications*, 47(9):1345–1356, 1999.

[3] Shishir G Bhat. Incremental redundancy hybrid automatic repeat request scheme in next generation wi-fi systems. *Master's Thesis towards Dual Degree Programme, IIT Madras*, 52:1–45, 06 2020.

[4] H. Y. Park, K. S. Kim, D. H. Kim, and K. C. Whang. Structured puncturing for rate-compatible b-ldpc codes with dual-diagonal parity structure. *IEEE Transactions on Wireless Communications*, 7(10):3692–3696, 2008.

[5] Jeongseok Ha and S. W. McLaughlin. Optimal puncturing distributions for rate-compatible low-density parity-check codes. In *IEEE International Symposium on Information Theory, 2003. Proceedings.*, pages 233–233, 2003.

[6] Erik Dahlman, Stefan Parkvall, and Johan Sköld. *4G: LTE/LTE-advanced for mobile broadband*. 03 2011.

[7] Sachin Kr, Nikhil Srinath Betgov, Apeksha Sk, C Nisarga, and Usha Ms. A review of hybrid arq in 4g lte. *International Journal of Advance Research and Innovative Ideas in Education*, 1:160–165, 2015.

[8] P. Frenger, S. Parkvall, and E. Dahlman. Performance comparison of harq with chase combining and incremental redundancy for hsdpa. In *IEEE 54th Vehicular Technology Conference. VTC Fall 2001. Proceedings (Cat. No.01CH37211)*, volume 3, pages 1829–1833 vol.3, 2001.

[9] K. C. Beh, A. Doufexi, and S. Armour. Performance evaluation of hybrid arq schemes of 3gpp lte ofdma system. In *2007 IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications*, pages 1–5, 2007.

[10] Chowdhury Mizan Mahmood Taher and Dr. Muhieddin Amer. Hybrid automatic repeat request in lte. 2013.

[11] Periklis Chatzimisios, Anthony Boucouvalas, and Vasileios Vitsas. Ieee 802.11 wireless lans: Performance analysis and protocol refinement. *EURASIP Journal on Wireless Communications and Networking*, 2, 03 2005.

[12] D. Deng, Y. Lin, X. Yang, J. Zhu, Y. Li, J. Luo, and K. Chen. Ieee 802.11ax: Highly efficient wlans for intelligent information infrastructure. *IEEE Communications Magazine*, 55(12):52–59, 2017.

[13] T. J. Richardson and R. L. Urbanke. Efficient encoding of low-density parity-check codes. *IEEE Transactions on Information Theory*, 47(2):638–656, 2001.

[14] Mostafa El-Khamy, Hou Jilei, and Naga Bhushan. H-arq rate-compatible structured ldpc codes. pages 1134 – 1138, 08 2006.

[15] Thuy Nguyen, Aria Nosratinia, and Dariush Divsalar. Rate-compatible short-length protograph ldpc codes. *IEEE Communications Letters*, 17, 02 2013.

[16] Changyan Di, D. Proietti, I. E. Telatar, T. J. Richardson, and R. L. Urbanke. Finite-length analysis of low-density parity-check codes on the binary erasure channel. *IEEE Transactions on Information Theory*, 48(6):1570–1579, 2002.

[17] H. Y. Park, J. W. Kang, K. S. Kim, and K. C. Whang. Efficient puncturing method for rate-compatible low-density parity-check codes. *IEEE Transactions on Wireless Communications*, 6(11):3914–3919, 2007.

[18] Upamanyu Madhow. *Fundamentals of Digital Communication*. Cambridge University Press, South Asia, 2017.