RELIABLE AND COVERT SATELLITE COMMUNICATION FORWARD LINK

Submitted by

NITIN CHAUHAN

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DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY MADRAS
CHENNAI-600036

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THESIS CERTIFICATE

This is to certify that the thesis entitled **"Reliable and covert satellite communication forward link "** submitted by **NITIN CHAUHAN** to the Indian Institute of Technology, Madras for the award of the degree of **Master of Technology** is a bona fide record of research work carried out by him under my 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.

K Giridhar
Professor
Department of Electrical Engineering
Indian Institute of Technology Madras
Chennai – 600 036.

Place: Chennai

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ABSTRACT

Reliable and Covert Satellite (RCS) Communication System is a fully indigenous custom air-interface for providing point to multipoint voice and text links. This system's primary goal is to provide: (i) reliable communications along with (ii) a low probability of detection and interception (LPD/LPI). Here, up to 32 user terminals (UTs) can be attached to a ground-station (Hub) via a geo-stationary satellite. The system can support users spread over vast geographical areas (say, over the entire peninsular region of India).

This thesis presents the design of the forward link, where the waveform of choice is a Block modulated Single carrier DS CDMA. A 36MHz transponder is shared between the forward link and the reverse link, each using about 17.875MHz in a FDD configuration. While a companion thesis (by Ms Nikita Tanwar EE18M051) describes the reverse link, this thesis concerns the forward link design and performance.

To provide covertness to the system, the pre-processing SNR observed at the intended receiver (and hence, in any eavesdropper) is very low, and nearly 15dB below the thermal noise floor. Direct sequence type spreading, narrow banding, information repetition, and novel block FEC are employed in tandem to give a total post-processing gain of nearly of 38.1dB. This ensures tremendous reliability and a healthy fade-margin (excess link margin) of more than 13.35 dB (fully loaded), which provides >99% uptime even in the presence of Rician fading.

The other major challenge of the project is to design the waveforms in such a way that PAPR is low not only at the UT output, but will be low at the satellite output end (after amplify and forward). Based on the number of users active in the system at any given point of time, a lookup table is designed to ensure low PAPR all the time for the pilot signals. System-level simulation for the forward link is performed to capture the reliable un-coded and coded error-rate performance.

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Chapter 1

Reliable Covert Satellite Communication

1.1. Introduction

Space technology is of immense economic and political value in the present-day scenario with countries with advanced space technology are able to offer new enhanced products and services for their citizens for e.g. the upcoming Starlink project of SpaceX and also establish dominance/advantage over other countries in the military realm.

Satellite Communication is essential in strategic applications and the requirement of reliable covert satellite communication is vital for our country in the present security scenario. RCS forward link is point to multi point communication via Satellite between the central Hub and user equipment present across the length and breadth of our country.

1.2. Objective of the work

The objective of the project work is to design a satellite air interface for a full duplex communication between a central hub and 32 in numbers users via a geostationary satellite (approx. 36500 km from earth) across a geographical area expanse over the whole country having following features: -

1. Low probability of interception and low probability of detection.
2. High Reliability.
3. Low Peak to Average Power Ratio, manageable within the constraints of the satellite specification.
4. User support data rate of 4kbps within the available 36 MHz bandwidth.

1.3. Scope of the thesis

The scope of the thesis is to design the Satellite communication forward link with specifications conforming to the requirements of the project and evaluate the performance of the same through link level simulations. The design would incorporate all the necessary processing blocks/subsystems for transmitter and receiver.

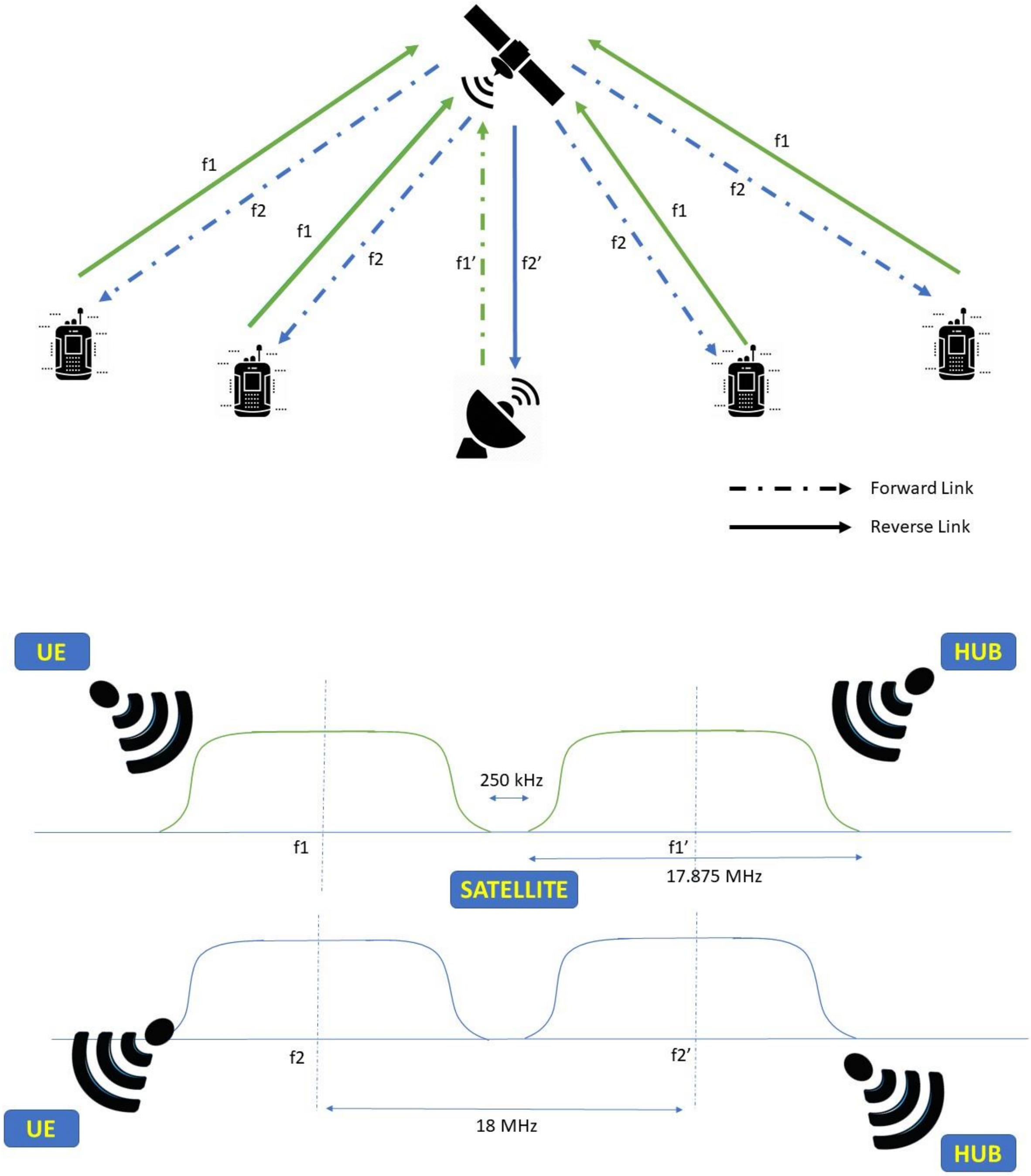

Figure 1.1 Reliable Covert Satellite Communication FDD layout

The FDD layout for RCS is as shown in figure 1. FDD setup will require the Hub and User Equipment to operate over two different carrier frequencies using a duplexer setup. f1 and f1' being carrier frequency separated by 18 MHz and f2 and f2' being another set of carrier frequencies separated by 18 MHz. The channel bandwidth for f1 and f1' will be 17.875 MHz each separated by a 250 kHz guard band; with same specification for f2 and f2'.

Forward link – The Hub will be transmitting over f1’ and the UE will be receiving over f2.

Reverse link – The UE will be transmitting over f1 and the Hub will be receiving over f2’.

Waveform choice - Block modulated Single carrier DS CDMA has been selected for forward link. Using the spread spectrum technique with 2048 length spreading code providing a 33.1 dB processing gain at the receiver, fulfills the requirement of LPI/LPD with SNR at the receiver being well below the noise floor. Single carrier was preferred over multi carrier due to better PAPR performance, with PAPR being important requirement of the system. Block modulated approach relaxes any requirement of critical timing synchronization and caters of any delay spread due to multipath in presence of large obstacles around the user.

Chapter 2

Forward Link –Transmitter

2.1. Introduction

RCS forward link transmitter will be located at the central hub where the data for the 32 users will be generated. The transmitter will consist of individual tx blocks for 32 users and common blocks of Digital to analogue converter followed by RF transmitter chain.

2.2. Transmitter block layout

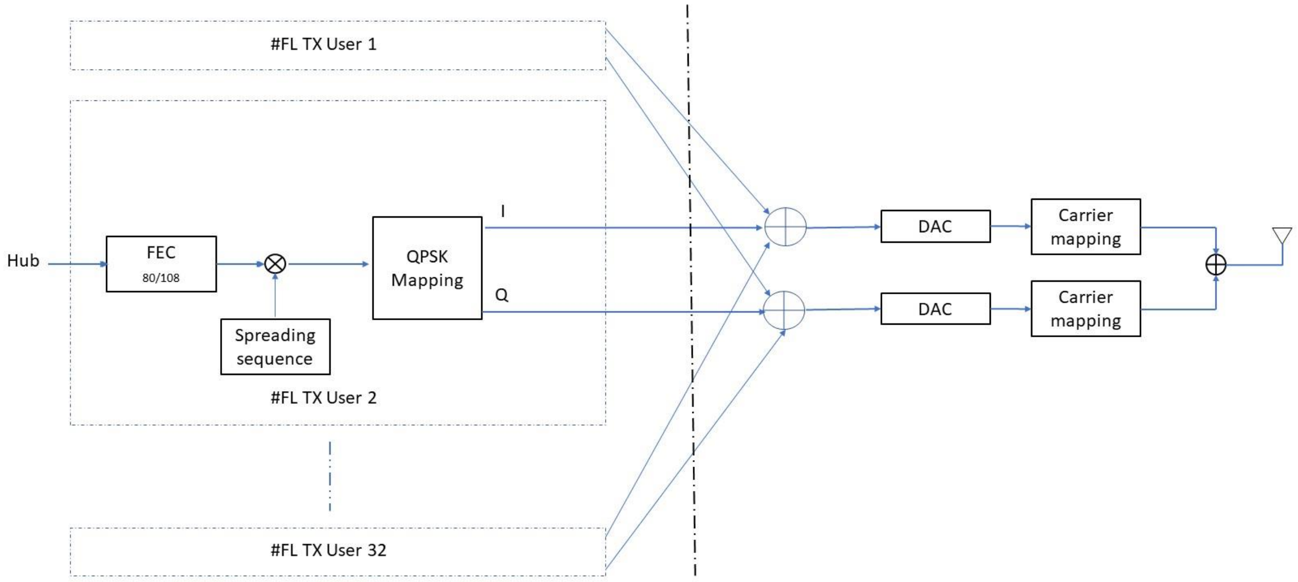

Figure 2.1 FL – Transmitter Block

Forward link FDD, uses single carrier DS CDMA with block modulation to achieve low probability of communication detection and interception. The Hub will generate the data for a specific UE, which will be encoded by the Forward error correction block (80/108 rate). The data stream will then be spread using orthogonal Walsh Hadamard code sequences by a factor of 2048 followed by mapping to QPSK symbols and separated into orthogonal I and Q stream. The spread sequence will then be block modulated as per the framing structure and pulse shaped (Raised cosine window), which will then be converted to analog form, mapped onto the carrier and transmitted. The Hub will have 32 in number #FL TX UE blocks as shown in figure.

The signals from each of these blocks will be added before digital to analogue converter (DAC). Summation, DAC and carrier mapping block will be common to all the UEs.

2.3 FEC scheme

Minimising the operational power requirement and latency of the data for the user is an important system requirement. This flexible FEC scheme method has CRC and two-dimensional parity check codes (Matrix Parity Check Code (MPCC)) for the error control. The approach involves, generation of syndrome table, encode and decode process. The implementation of encoding and decoding is done in digital (bit) level (low complexity). The method can detect and correct all one- and two-bit errors in a given code block. The scheme includes encoder and decoder using two level codes, first data bits encapsulated with CRC and after that matrix formed to compute 2-D parity codes. In decoder side, first the CRC verification carried and then parity check will be done. The FEC scheme implemented has 80/108 rate with 108 encoded bits transmitted for every 80 bit data.

D	D	D	D	D	D	D	D	P
D	D	D	D	D	D	D	D	P
D	D	D	D	D	D	D	D	P
D	D	D	D	D	D	D	D	P
D	D	D	D	D	D	D	D	P
D	D	D	D	D	D	D	D	P
D	D	D	D	D	D	D	D	P
D	D	D	D	D	D	D	D	P
D	D	D	D	D	D	D	D	P
D	D	D	D	D	D	D	D	P
CRC	CRC	CRC	CRC	CRC	CRC	CRC	CRC	P
P	P	P	P	P	P	P	P	P

10

12

8

12

Figure 2.2 Matrix parity and CRC check data matrix layout

The above figure represents the FEC scheme out with D referring to data bit, CRC as CRC bits and P referring to parity check. The BER performance of the FEC scheme in comparison to theoretical values is as shown :-

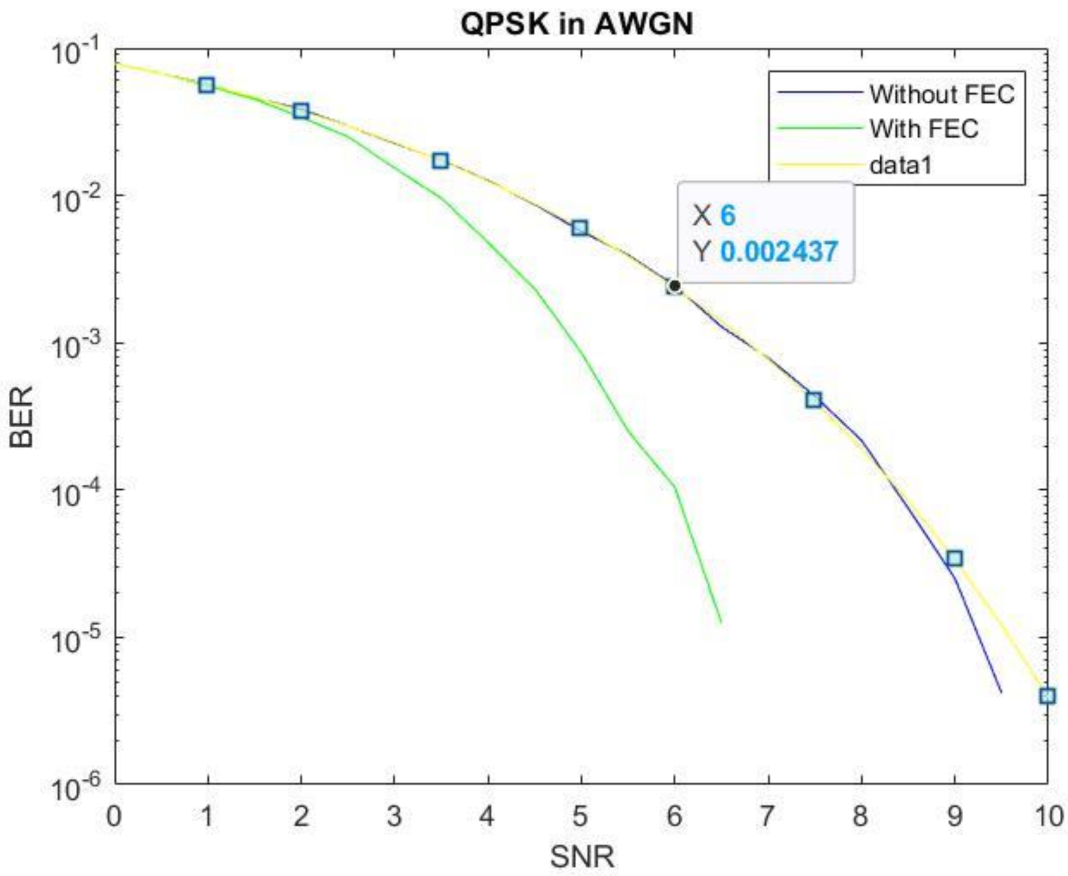

Figure 2.3 BER plot for FEC scheme

The performance over AWGN channel provided that the FEC scheme provides 2 dB gain @ 10^{-3} *uncoded ber* and 3 dB gain @ 10^{-5} *uncoded ber*.

Chapter 3

Forward Link Receiver and Frame Structure

3.1. Introduction

RCS forward link receiver is located at the user equipment. The receiver blocks and subsystems structure will be common for all the users.

3.2. Forward link receiver

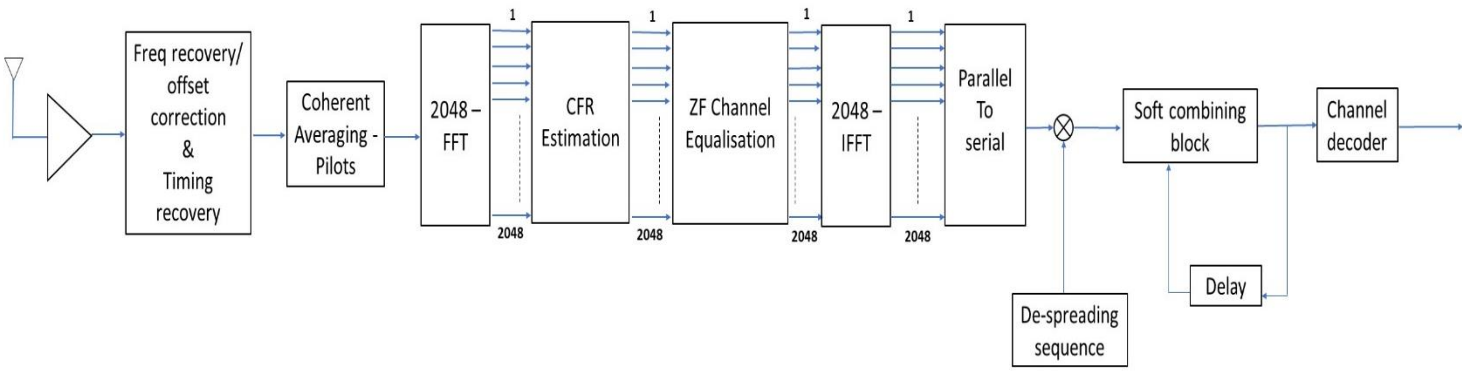

Figure 3.1 FDD Forward link- UE Receiver Block Diagram

(i) The UE receiver block will be as shown in the figure 3.1. For every frame, the received signal will be processed for determining the frequency offset and timing recovery using hypothesis testing from the preamble of the received framed implemented through correlated banks. Corresponding frequency offset correction will be applied along with timing boundary knowledge to the following received symbols.

(ii) For every subframe, received pilot symbols for channel estimation are coherently added to boost the SNR (12 dB) and then the channel frequency response will be estimated with knowledge of transmitted Zadoff Chou pilot symbols using frequency domain estimation.

$$\widehat{H} = Y * conj(F * (Zc))$$

$\widehat{H}$ – Channel estimate

Y – Received symbol

F – DFT matrix

Zc - Zadoff chou sequence

Accordingly, all received data symbols are equalized using the channel estimate from pilots through zero forcing followed by the de-spreading operation.

$$\hat{X} = (\hat{H}^T)\,(\hat{H}\hat{H}^T)^{-1} * Y$$

$\hat{X}$ – Estimate of transmitted symbol

The de-spreading sequence will be unique to every UE.

(iii) The de-spreaded symbol will be delayed by one super symbol duration and then soft combined with the subsequent symbol to obtain a coherent averaging gain of 3dB.

(iv) The soft combining will be followed by QPSK demodulation and error correction using Matrix Parity CRC correction.

3.3 Frame structure – Forward Link.

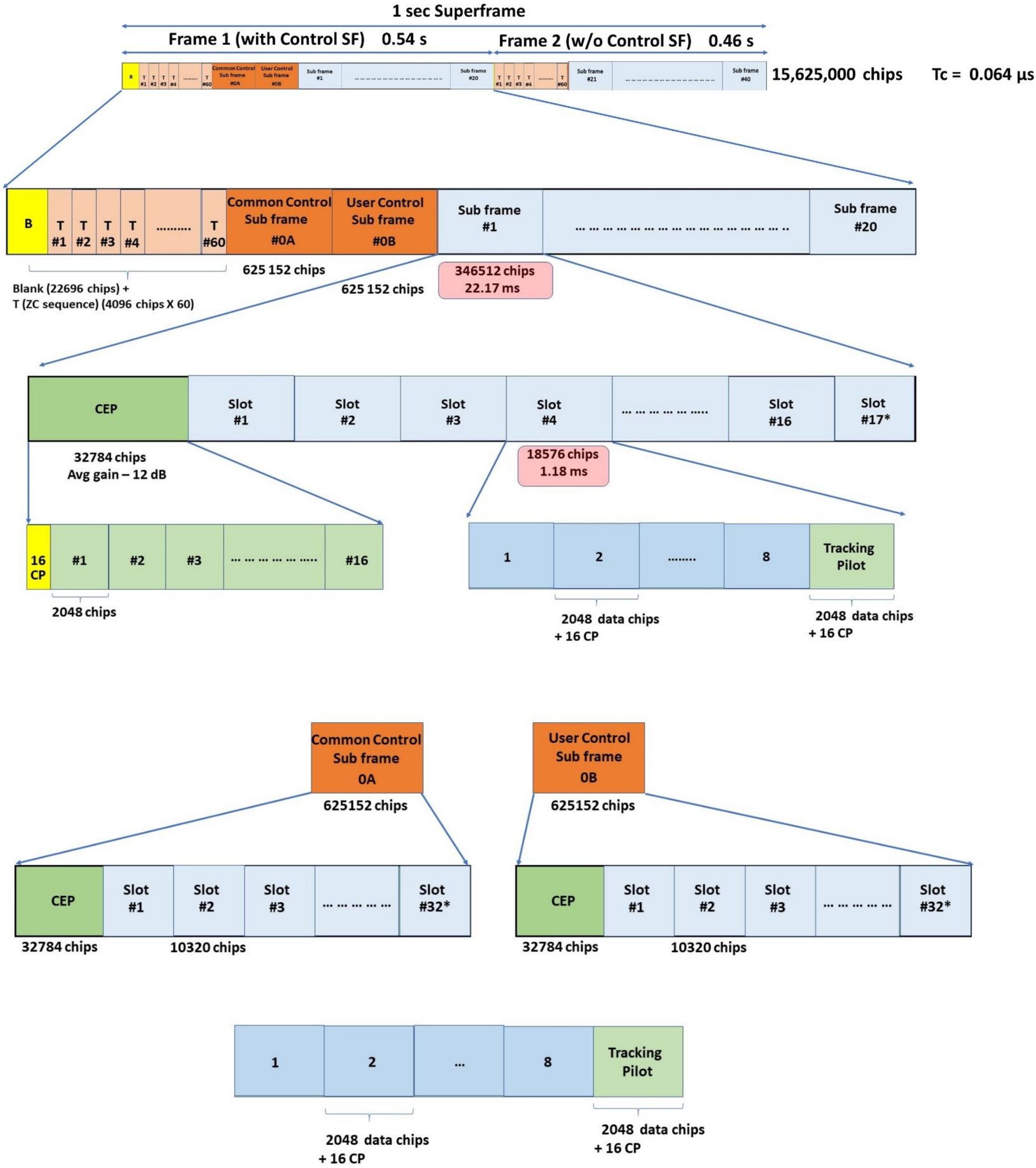

Figure 3.2 Frame Structure – FDD Forward link

Description of Frame Structure – FDD Forward link

(i) The frame structure design has been undertaken assuming a 10 GHz carrier with 2 ppm clock error will have frequency error range of ± 20 kHz.

(ii) The initial preamble structure will have 22696 chips as blank followed by 60 frames of tracking ZC sequence of 4096 chips each. The ZC sequence will be used for VCO frequency offset estimation and tracking. Presently the blanks chips provide flexibility with further enhancement and scope for improvement in design if required.

(iii) There are 02 control sub frames which will be used for control signalling over forward link. The first subframe 0A and 0B consist of 625152 chips each with 08 symbols per slot. Control subframe 0A will be used for common control signalling whereas control subframe 0B will be used for UE specific control signalling.

(iv) Each sub frame will consist of one Channel Estimation Pilot (CEP) and 17 data slots for the UEs. Each CEP will consist of 32784 chips.

(v) Each CEP consists of 2048 length Zadoff-Chu and repeated 16 times chips and a single 16 chip cyclic prefix. This repetition helps to add received sequence coherently to get 12 dB boost in SNR in addition to 15 dB boost in transmitted power for CEP. This is required as we are interested in CFR at chip-level.

(vi) Each slot for UE data consists of 08 blocks of data with 2048 chips + 16 chips for cyclic prefix. The 08 blocks will consist of 04 symbols with each symbol followed by a copy, to provide a coherent averaging gain in the link budget. The 08 blocks are followed by a tracking pilot which will be utilised for phase error tracking caused due to residual frequency offset over multiple subframes. 17^{th} slot of the sub frame is different from other slots (without the tracking pilot as it will be followed by a block of CEP).

CHAPTER 4

Simulation Results – Forward link

4.1 Link Level Simulation

Link level simulation was undertaken assuming no CFO error and perfect timing synchronisation. The simulation was undertaken in a progressive manner, simulating the various modules of the transmitter and receiver.

4.1.1 BER performance in single tap channel

Ser No	Simulation Parameter	Value
1.	No of users	01
2.	Spreading factor	Walsh code – 2048
3.	Spreading gain	33.1 dB
4.	Modulation	4 – QAM
5.	No of symbols	8000

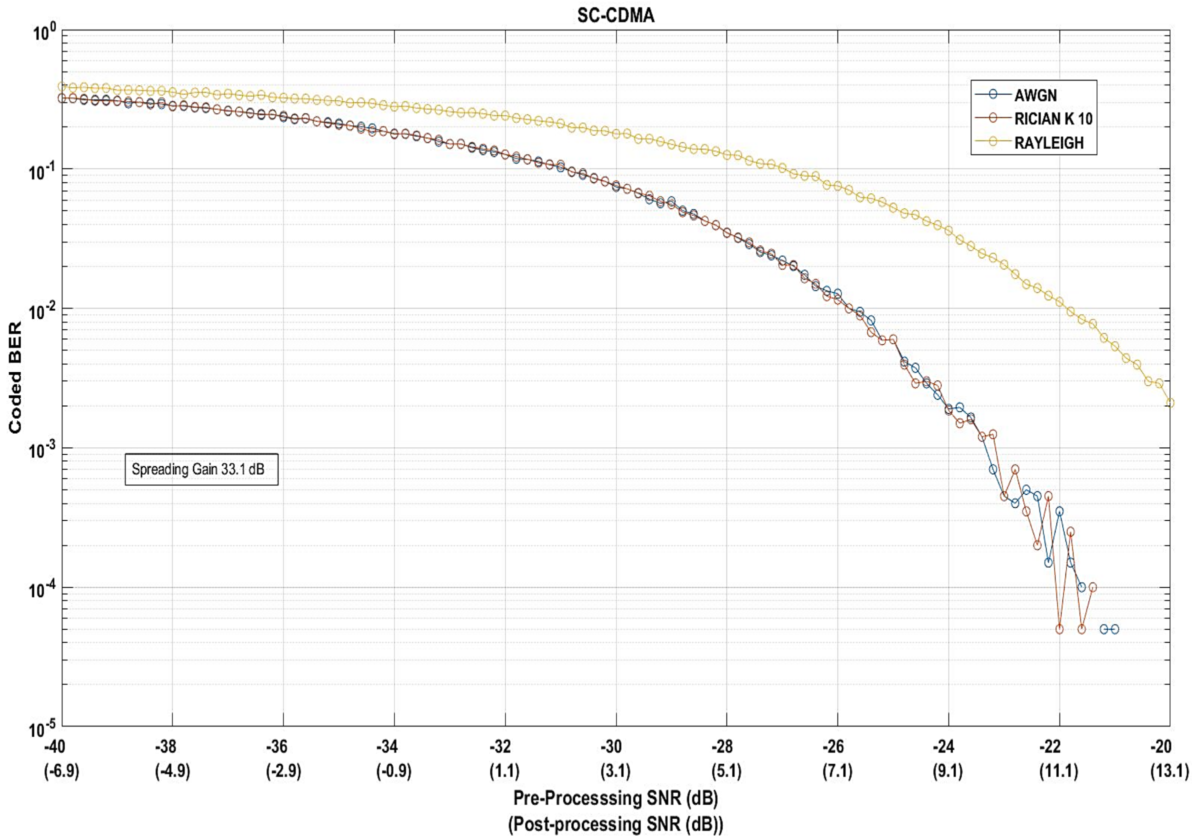

Figure 4.1 SC CDMA BER plot for various channels

The pre processing SNR represents the received signal SNR whereas the post processing SNR represents the SNR of the signal post de spreading and demodulating the signal. The post processing SNR on x axis allows for comparison of the plot obtained with QPSK AWGN BER theoretical plot. The results shows how the performance of the system is better in an AWGN and single tap Rician K factor-10 channel than a Rayleigh channel.

4.1.2 BER performance in single tap Rician channel with FEC

Ser No	Simulation Parameter	Value
1.	No of users	01
2.	Spreading factor	Walsh code – 2048
3.	Spreading gain	33.1 dB
4.	Modulation	4 – QAM
5.	FEC	80/108
6.	FEC gain	MPCC & CRC 2 dB gain @ 10^{-3} $uncoded\ ber$ 3 dB gain @ 10^{-5} $uncoded\ ber$
7.	No of symbols	8000

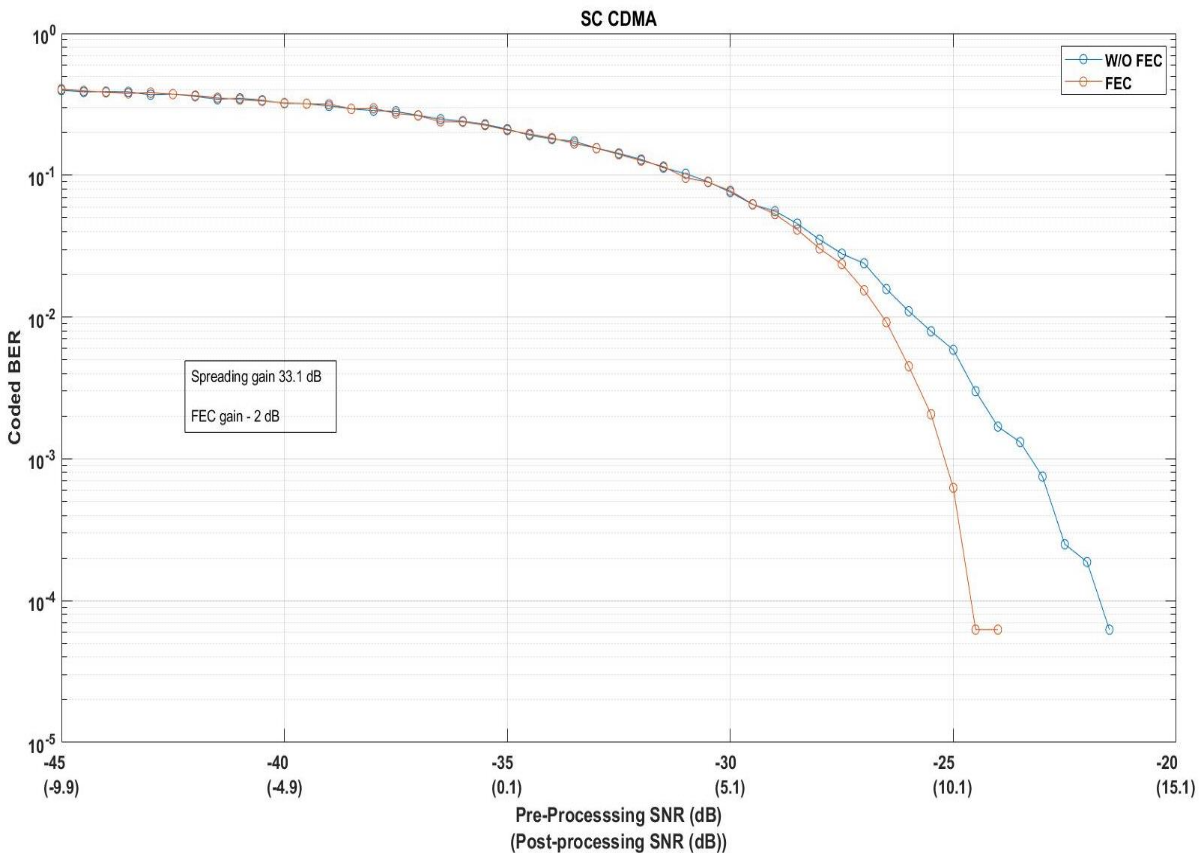

Figure 4.2 SC CDMA BER plot with FEC

The ber performance plot to check the implementation of FEC scheme showed that the observed gain was on expected lines of 2 dB at $10^{-3}\, uncoded\ ber$ and 3 dB at @ $10^{-5}\, uncoded\ ber$

4.1.3 BER performance in single tap Rician channel with FEC and symbol repetition

Ser No	Simulation Parameter	Value
1.	No of users	01
2.	Spreading factor	Walsh code – 2048
3.	Spreading gain	33.1 dB
4.	Modulation	4 – QAM
5.	FEC	80/108
6.	FEC gain	MPCC & CRC 2 dB gain @ $10^{-3}\, uncoded\ ber$ 3 dB gain @ $10^{-5}\, uncoded\ ber$
7.	Symbol Repetition Gain	3 dB
8.	No of symbols	8000

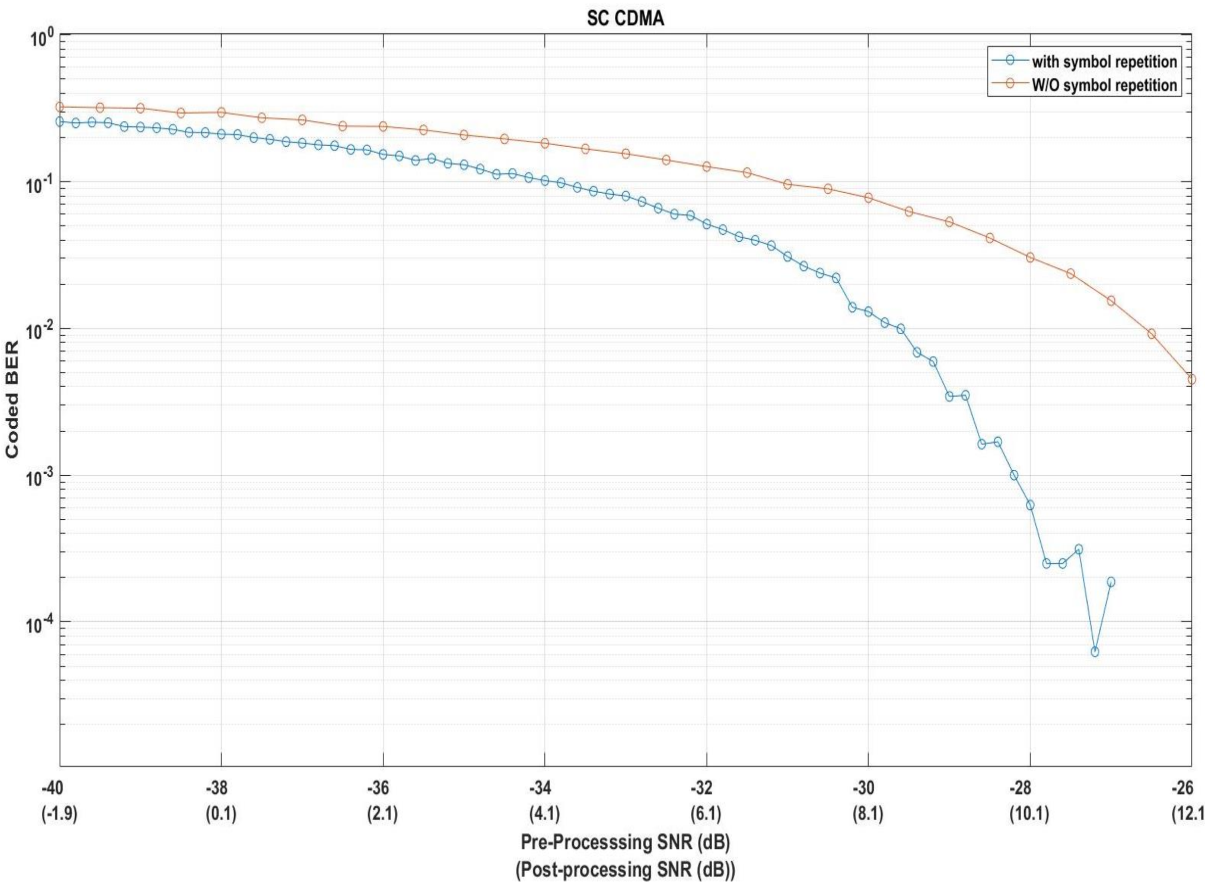

Figure 4.3 SC CDMA BER plot with FEC and symbol repetition

The BER performance showed 3dB gain with symbol repetition due to coherent averaging.

4.1.4 BER performance multi user SC CDMA

Ser No	Simulation Parameter	Value
1.	No of users	04
2.	Spreading factor	Walsh code – 2048
3.	Spreading gain	33.1 dB
4.	Modulation	4 – QAM
5.	FEC	80/108
6.	FEC gain	MPCC 2 dB gain @ 10^{-3} $uncoded\ ber$ 3 dB gain @ 10^{-5} $uncoded\ ber$
7.	Symbol Repetition Gain	3 dB
8.	No of symbols	2400 / users

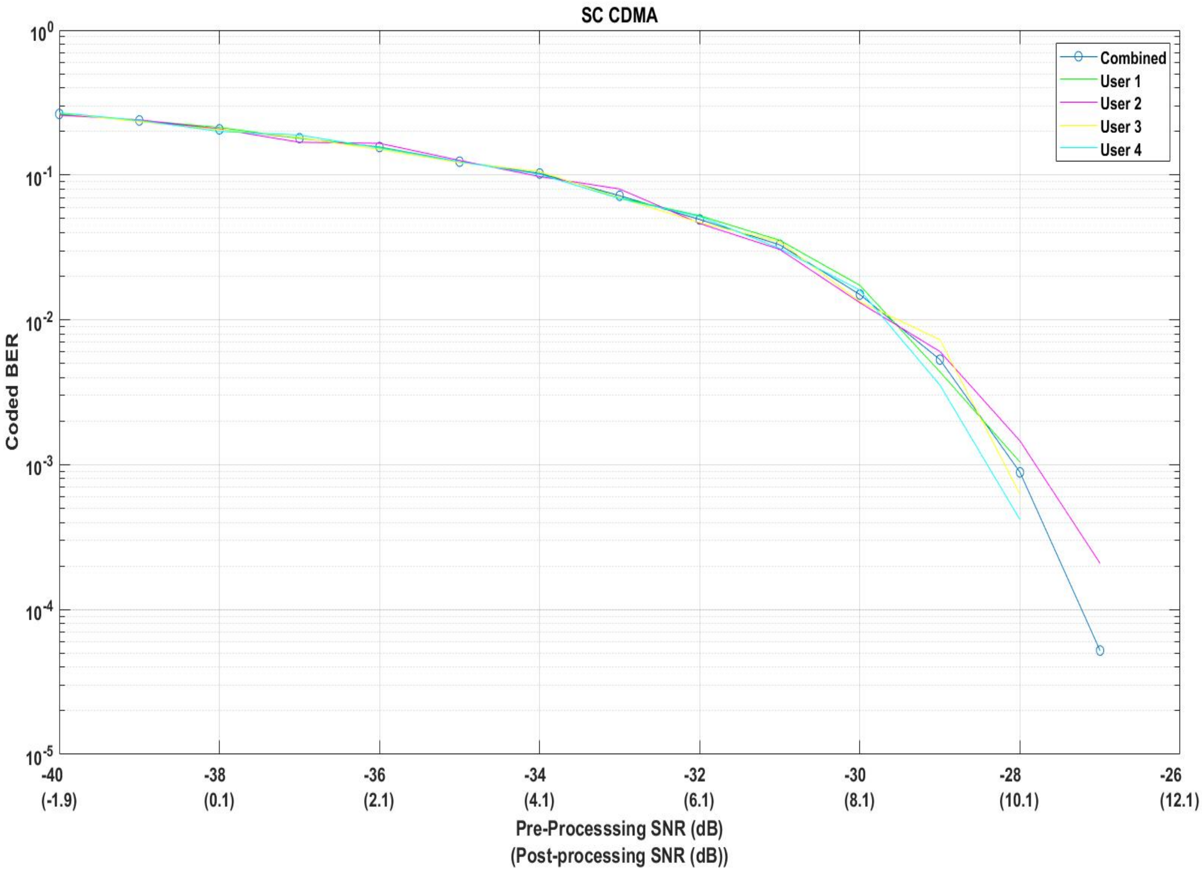

Figure 4.4 SC CDMA BER plot for four users

The BER performance for multi user scenario over forward link is approximately equal to the theoretical BER when the post processing BER (dB) is compared to QPSK AWGN BER performance.

4.3 PAPR analysis

Peak to Average Power Ratio is an important parameter in satellite communication as the combined signal transmitted for 32 users by the Hub will be amplified and retransmitted by the satellite. In event of high PAPR the signal can saturate the output PA at the satellite leading to corruption/clipping of the signal and loss of information. PAPR for forward link was analyzed and following are the significant findings.

4.3.1 PAPR Forward link – varying number of users

Ser No	Simulation Parameter	Value
1.	Over sampling factor	04
2.	Spreading factor	Walsh code – 2048
3.	Modulation	4 – QAM
4.	No of symbols	8
5.	No of iterations	1000

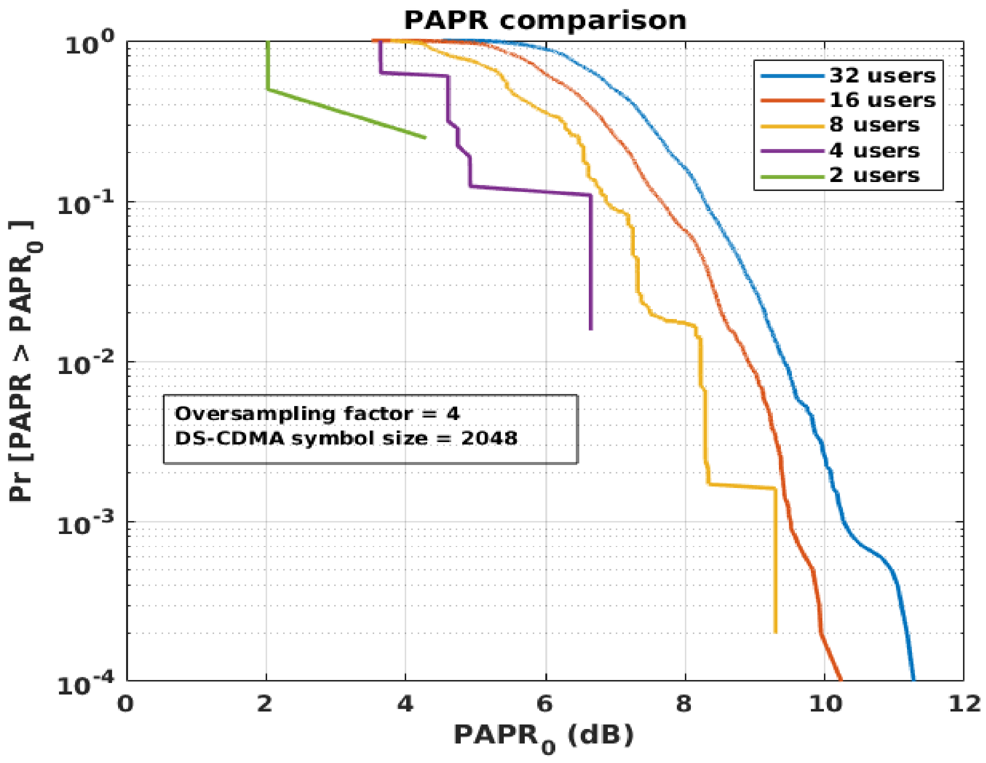

Figure 4.5 PAPR CCDF plot for forward link with varying number of users.

The PAPR plot observed in fig 4.5 clearly indicated that the PAPR increases with increase in the number of users in the system.

A significant observation during the aforementioned simulation was that the PAPR of the link is dependent on the Walsh code being used to spread the signal. In a single user scenario if walsh code 2 was assigned then the PAPR of the signal was found to be 8 dB compared to PAPR of 2 dB if Walsh code 5 is assigned. This observation brought out that the walsh code allocation is an important factor for PAPR especially for few users in the system scenario.

4.3.2 PAPR Forward link – Walsh code pattern

Ser No	Simulation Parameter	Value
1.	Over sampling factor	04
2.	Spreading factor	Walsh code – 2048
3.	Modulation	4 – QAM
4.	No of symbols	8
5.	No of iterations	1000
6.	No of users	32

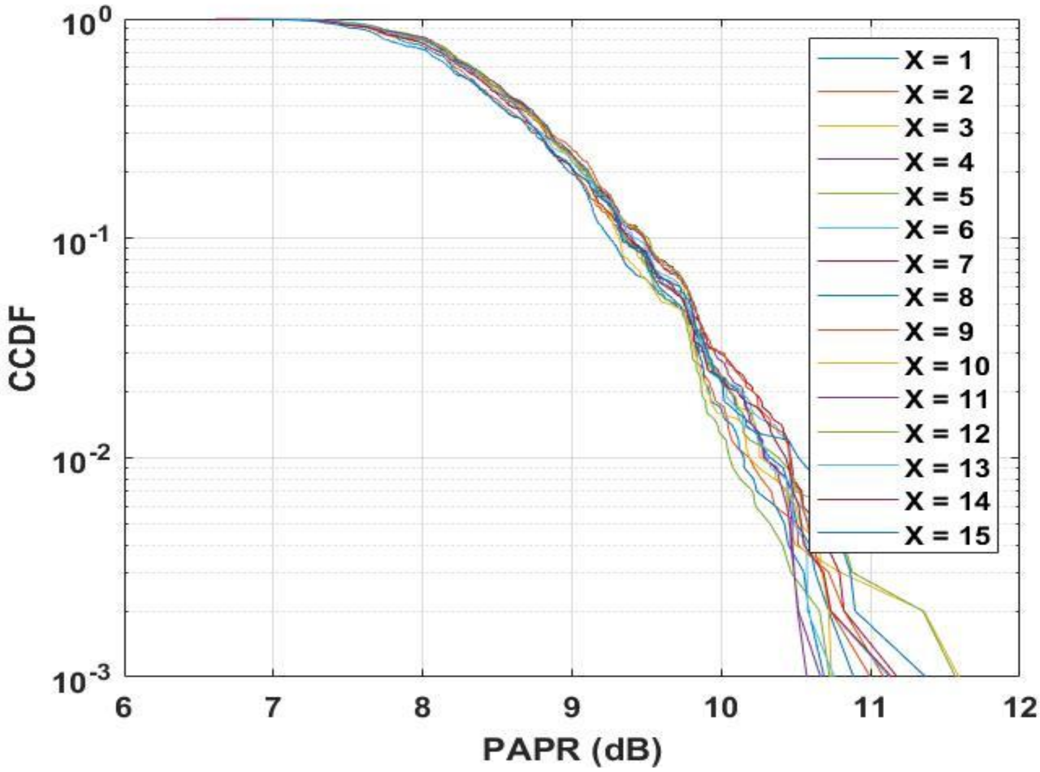

Figure 4.6 PAPR CCDF plot for forward link with varying walsh code patterns.

PAPR for fully loaded system was analyzed for various possible walsh code allocation patterns. There are 32 users and 2048 possible walsh codes in the system with 10^{70} possible combinations for allocation. The abovementioned plot has captured the PAPR for 15 such patternised allocation possibilities wherein X represents difference between successive walsh code numbers. For e.g. x = 1 represents 2,3,4,5,6 etc. x = 3 represents 2,5,8,11,14 etc and so on.

It can be observed that the walsh code allocation for almost all patterns are within 0.1-0.2 dB of each other and hence sequential allocation x=1 can be used for allocation of walsh code for large number of users (>6) present in the system. Walsh code allocation for users less than 08 can be done using a lookup table with specific Walsh code assigned in case of fewer (<6) users transmitting. Thus far it has been observed that for users less than (<6) 16x+1 walsh code allocation gives lower papr than sequential allocation.

4.4 Summary

All the results and observations presented in this chapter confirms that the design made for the project conforms to the requirement of RCS forward link. The BER plots indicate great reliability with healthy fade-margin (excess link margin) of more than 13.35 dB (fully loaded), which provides >99% uptime even in the presence of Rician fading. The walsh code allocation minimizes the PAPR of the transmitted signal for the Hub whereas the spreading factor of 2048 and the processing gain at the receiver result in operational SNR much below the noise floor (approx. 15 dB) fulfilling the requirement of LPI/LPD.

4.4.1 Recommendations for the future

The project can be enhanced for future applications with greater data rate support for users, using Turbo coder for greater reliability, soft decision decoding with LLR estimates for better channel estimation and equalization , in the event of lesser PAPR restriction MC CDMA or variants of OFDM with spreading can be evaluated as prospective waveform for covert satellite communication.

Chapter 5

Improved method for low ACI in OFDM

5.1 Introduction

5G is the latest iteration of cellular communications technology envisioned to provide and improve on existing standards on the parameters of coverage, data rate, latency, and reliability. It will increase the energy efficiency, spectrum efficiency, network efficiency providing faster & reliable access.

It is understood that OFDM due to its poor frequency localisation/out of band radiation and spectral shape, won't match the requirements of 5G multi carrier waveform. AW – OFDM was conceptualised and it's performance was analysed in comparison with other potential 5G multi carrier waveforms.

5.2. AW-OFDM

Asymmetric Windowed – Orthogonal Frequency Division Multiplexing (AW-OFDM) was conceptualised as a multi carrier waveform to improve on the various parameters of OOB radiations/frequency localisation, Peak to Average Power ratio, Bit error rate; with least complexity in design and lenient requirement of timing synchronization over the other Multi-carrier waveform candidates for 5G.

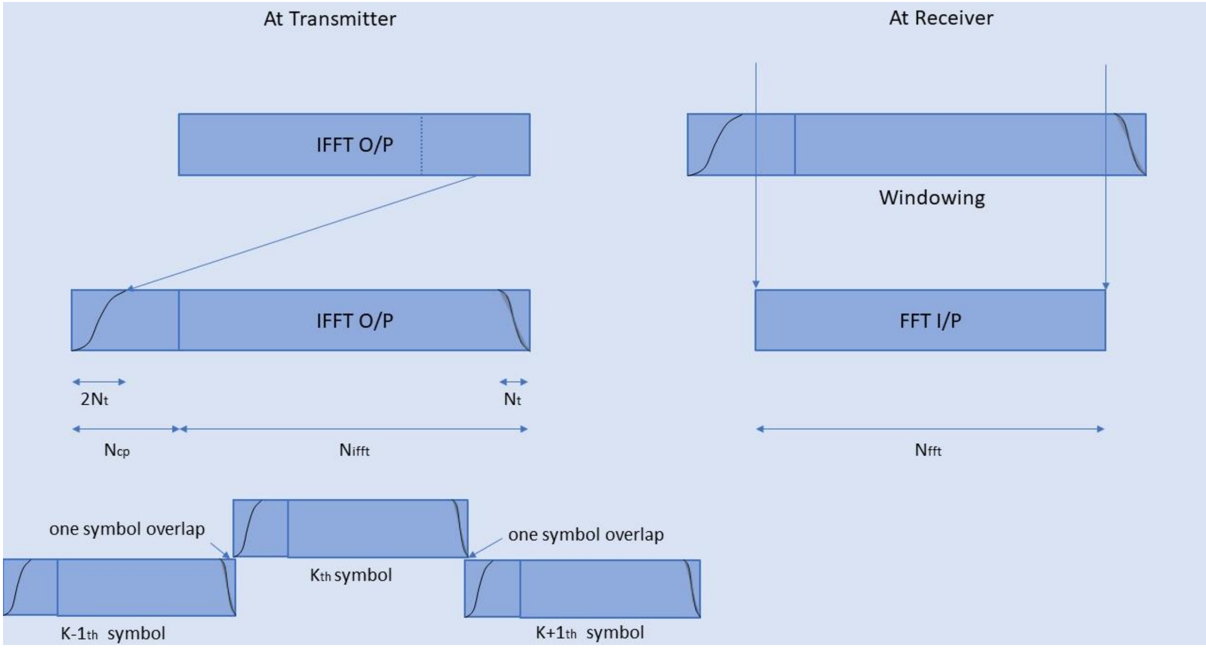

Figure 5.1 Asymmetric Windowing in AW-OFDM

Asymmetric windowing can be undertaken using either sigmoid or raised cosine function at the transmitter to reduce the Out of band transmission with 2Nt or 3Nt on the appended cyclic prefix and Nt on the overlapping side of the IFFT sequence.

At the receiver end, windowing followed by FFT and demodulation will be undertaken to retrieve the original transmitted bit sequence.

5.3 Features

The performance of AW-OFDM has been compared with OFDM and WOLA (proposed 5G waveform candidate) and the results are as follows:

(i) Spectral Efficiency – OOB transmission

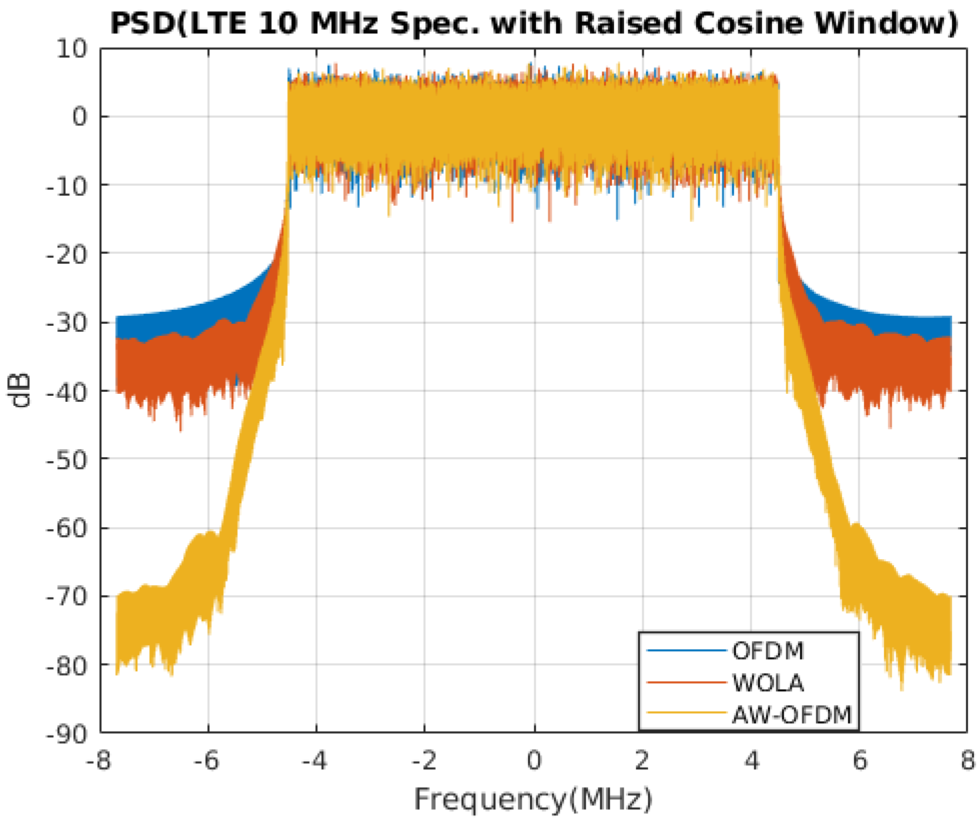

Figure 5.2 OOB transmission plot comparison

The OOB transmission comparison for OFDM, Weighted Overlap and Add (WOLA) and AW-OFDM is as shown in figure 5.2 It is observed that AW-OFDM has significantly lower OOB transmission than WOLA.

(ii) High Reliability – BER

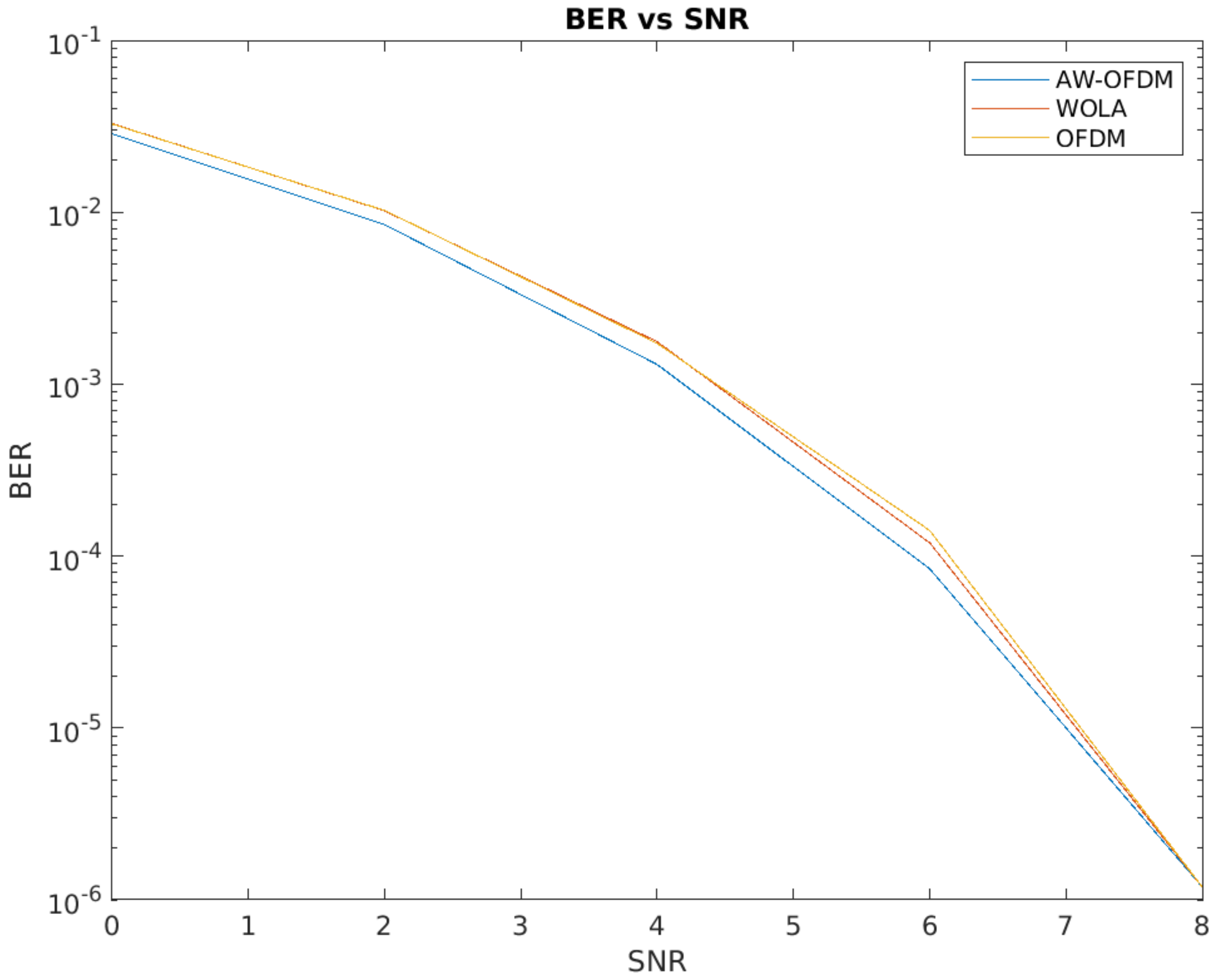

Figure 5.3 BER v SNR plot

The plot for BER vs SNR for AW-OFDM, WOLA and OFDM for a given transmit power is as shown in figure. It is observed that BER for AW-OFDM was comparatively lower than both OFDM and WOLA.

(iii) Peak to Average Power Ratio (PAPR)

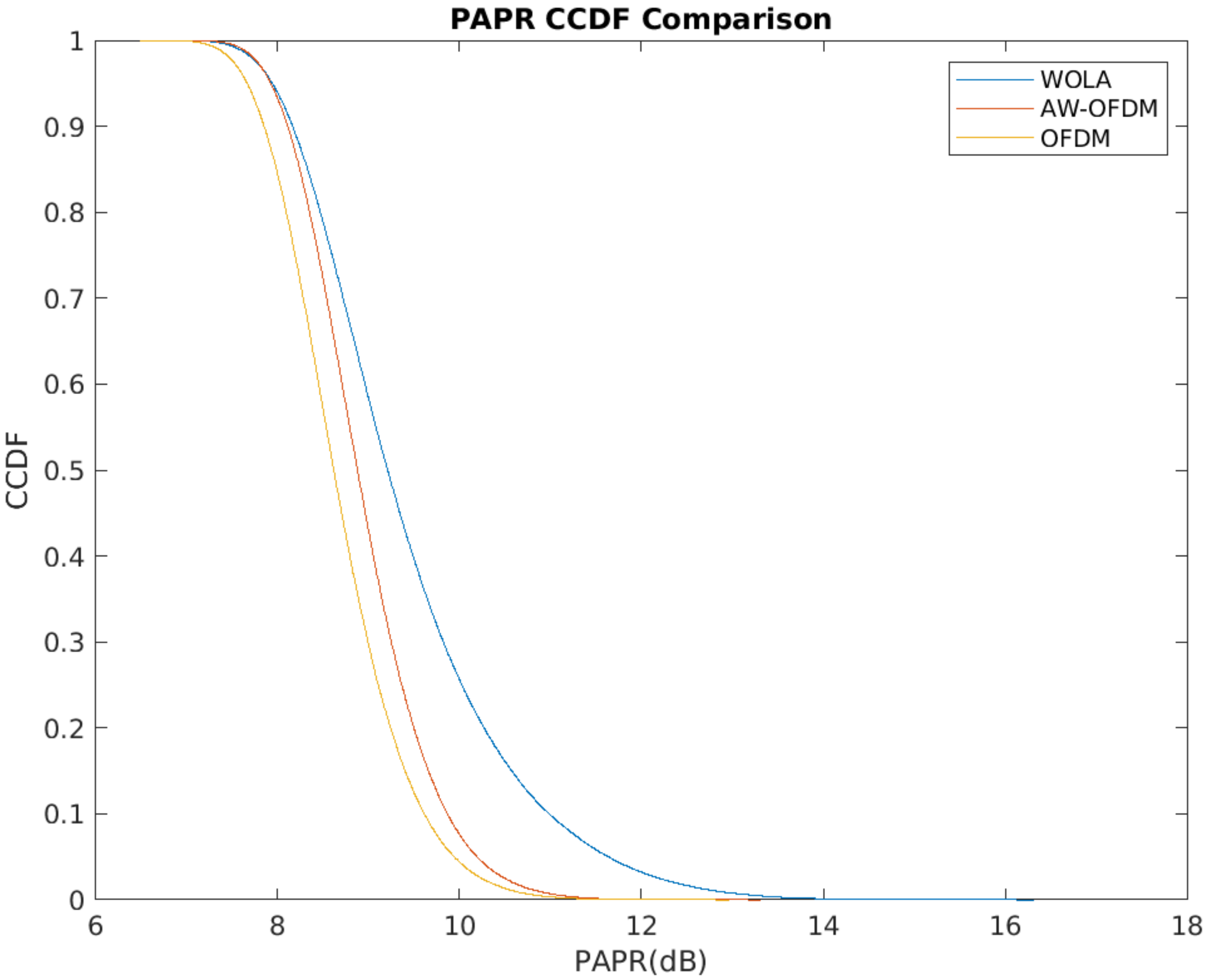

Figure 5.4 PAPR plot

PAPR performance comparison for AW-OFDM, OFDM and WOLA is as shown in figure 5.4 AW-OFDM has low PAPR as compared to WOLA and comparable with OFDM.

(iv) Windowing flexibility

WOLA has windowing flexibility of Ncp – DS(Delay spread) – 2*Nt (Tapered region). AW-OFDM has windowing flexibility of Ncp – DS – Nt , hence an additional flexibility of Nt.

Receiver processing in WOLA requires critical windowing for weight overlap and add, however AW-OFDM does not have any critical windowing requirement.

References

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