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RELIABLE AND COVERT SATELLITE COMMUNICATION - REVERSE LINK

A Project Report

Submitted by

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For the award of the degree

Of

MASTER OF TECHNOLOGY

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CERTIFICATE

This is to undertake that the Thesis titled **RELIABLE AND COVERT SATELLITE COMMUNICATION - REVERSE LINK**, submitted by **RAMAKRISHNA PEMMANABOINA**, to the Indian Institute of Technology Madras, for the award of **MASTER OF TECHNOLOGY**, is a bona fide record of the research work done by me under the supervision of Professor K.Giridhar. 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.

Place: Chennai 600 036
Date: 20th June 2021

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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 performance of the reverse link in presence of the residual CFO error and an algorithm to implement PRACH. A 36MHz transponder is shared between the forward link and the reverse link, each using about 17.875MHz in a FDD configuration. To achieve the covertness, the pre-processing SNR at the receiver is made very low, and nearly 15dB below thermal noise which makes it difficult to intercept. 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.

The residual CFO error introduces the Inter Carrier Interference and due to this the performance degrades. To overcome the effect of CFO error, DQPSK modulation scheme is employed.

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CHAPTER 1

INTRODUCTION

Satellite communication has become one of the most important resources of a country and plays an important role in security and economic development. With increased demand on wireless communication, advanced space technology is becoming a part of the daily life.

Satellite communication is essential for the security of the country and covertness of the communication is an important part to handle along with the reliability. The primary goal of the RCS (Reliable and Covert Satellite communication) project is to provide communication with reliability and low probability of detection and interception.

1.1 Objective of the work

The objective of the project work is to study the effect of residual CFO on the reverse link communication constructed by Nikita Tanwar, previous project member. Introduce PRACH into the existing RCS project.

1.2 Flow of Thesis

- In the first chapter, basic introduction of the RCS project will be discussed.
- In the second chapter, the waveform used for the reverse link will be discussed.
- In the third chapter, the CFO error and it's effects will be discussed.
- In the fourth chapter, the transmitter and receiver blocks of the RCS reverse link will be discussed.
- In the fifth chapter, the algorithm to implement PRACH will be discussed.

CHAPTER 2

Waveform - Reverse Link

2.1 SI - OFDMA

OFDMA is a multi-user version of OFDM scheme where multiple access is achieved by assigning subsets of orthogonal narrowband sub-carriers to individual users. Since the bandwidth is distributed among multiple users, this scheme allows multiple users to transmit at the same time. In OFDMA, inter symbol interference (ISI) can be avoided by the application of guard interval cyclic prefix. Also, OFDMA provides low computational complexity as it can be implemented using the Fast Fourier Transform (FFT). But high peak-to-average-power ratio (PAPR) is an issue in the OFDMA scheme which requires expensive linear power amplifiers.

Interleaved OFDMA (I-OFDMA) Frank *et al.* (2005) is a scheme which can handle the high PAPR issue along with low complexity for user separation. I-OFDMA can be derived from single carrier MA scheme, DS-CDMA perspective by replacing the conventional spreading sequence like Walsh-Hadamard by Frequency domain orthogonal signature sequences (FDOSS) or it can be derived from multi carrier MA scheme, OFDMA perspective by introducing interleaving subcarrier.

Since it can be regarded as both single carrier and multiple carrier based MA scheme, it benefits from the advantages of both schemes like, low PAPR value, low computational complexity for equalization and user separationFrank *et al.* (2007). So, to maintain low computational complexity along with low PAPR value, I-OFDMA has been chosen as the waveform for the reverse link.

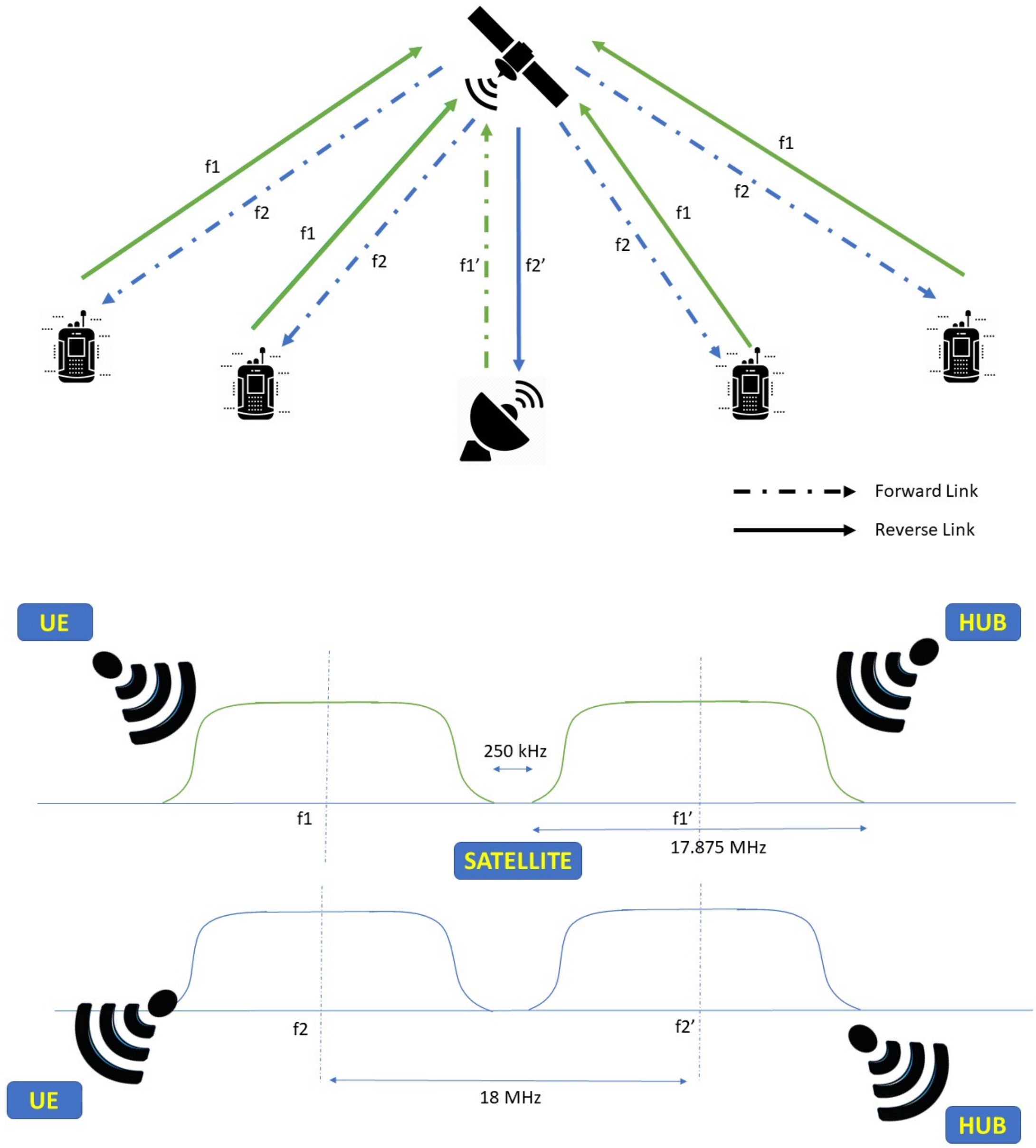


Fig. 2.1: Reliable covert satellite communication FDD layout

2.2 Specifications and Frame structure

In the network, a maximum of 32 UEs can be accommodated at any given time. The Hub and the UE operate at two different carrier frequencies separated by 18MHz using the duplexer setup. Figure 2.1 illustrates the FDD layout of the RCS. The channel bandwidth of each carrier is 17.875 MHz with 250 kHz guard band. The forward link constitutes the carrier frequencies $f1'$ and f2 for Hub and UE respectively and reverse link constitutes of $f2'$ and f1 fr Hub and UE respectively.

2.2.1 Specifications

Multiple access	SI - OFDMA
Transponder Signal bandwidth available	18MHz
Frame duration	1000 ms
Useful Symbol duration	131.072 μs
Chip duration(T_c)	64 ns or 0.064 μs
Cyclic prefix (T_{cp})	8192 ns or 8.192 μs
Roll-off factor(β)	0.144
Occupied bandwidth	17.875 MHz
Modulation	DQPSK
FEC	Matrix parity with CRC, rate 80/108
Bit rate	4 kbps per user
Max number of users supported	32
Spreading factor	64
Repetition factor	2
Frequency of operation	Ku-band (10 GHz to 14 GHz)

2.2.2 Frame structure

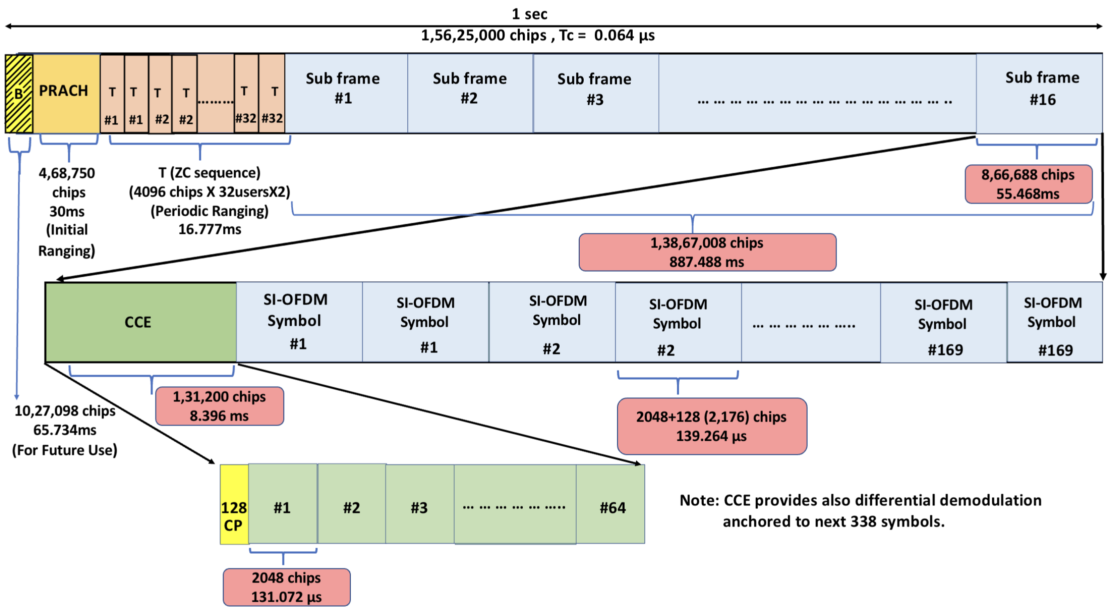


Fig. 2.2: Reverse link frame structure

Every UE will transmit 16 subframes (1,38,67,008 chips and 888 ms of duration) in the reverse link. Each subframe consists of 169 data symbols (2048 data and 128 CP chips). So, each UE will transmit 2704 data symbols in each transmission. The data symbols in the subframe were transmitted twice to attain a 3dB gain. Each subframe consists a CCE block (1,31,200 chips and 8.396 ms duration) which transmits a pilot sequence repeated 64 times to obtain 18dB gain. The frame also contains pool of spreading sequences used for spreading of the data.

CHAPTER 3

Carrier Frequency Offset

In the previous submission of the RCS reverse link project, residual carrier frequency offset (CFO) error has not been included. The orthogonality in OFDMA sustains because the transmitter and receiver operate with same frequency reference. If this condition fails, the perfect orthogonality of the subcarrier will be lost and this causes Inter Carrier Interference (ICI). So, frequency synchronization errors are to be studied in OFDMA systems. CFO is the type of frequency synchronization error that can lead to the ICI. To obtain better performance from OFDMA systems, CFO should be estimated and compensated.

The received signal will be shifted in frequency (δf) when CFO happens. The illustration can be seen in the figure 3.1. The sampling of the subcarriers will be done at

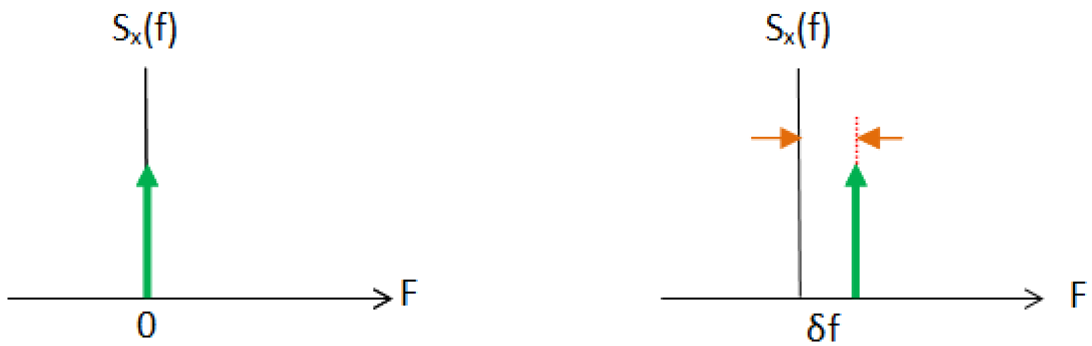


Fig. 3.1: Illustration of frequency offset

the peak of the waveform. So, due to the frequency offset the sampling will happen at offset point rather than at the peak which causes the reduction of the amplitude and results in ICI from adjacent subcarriers. The effect of CFO on sampling can be seen in the figure 3.2.

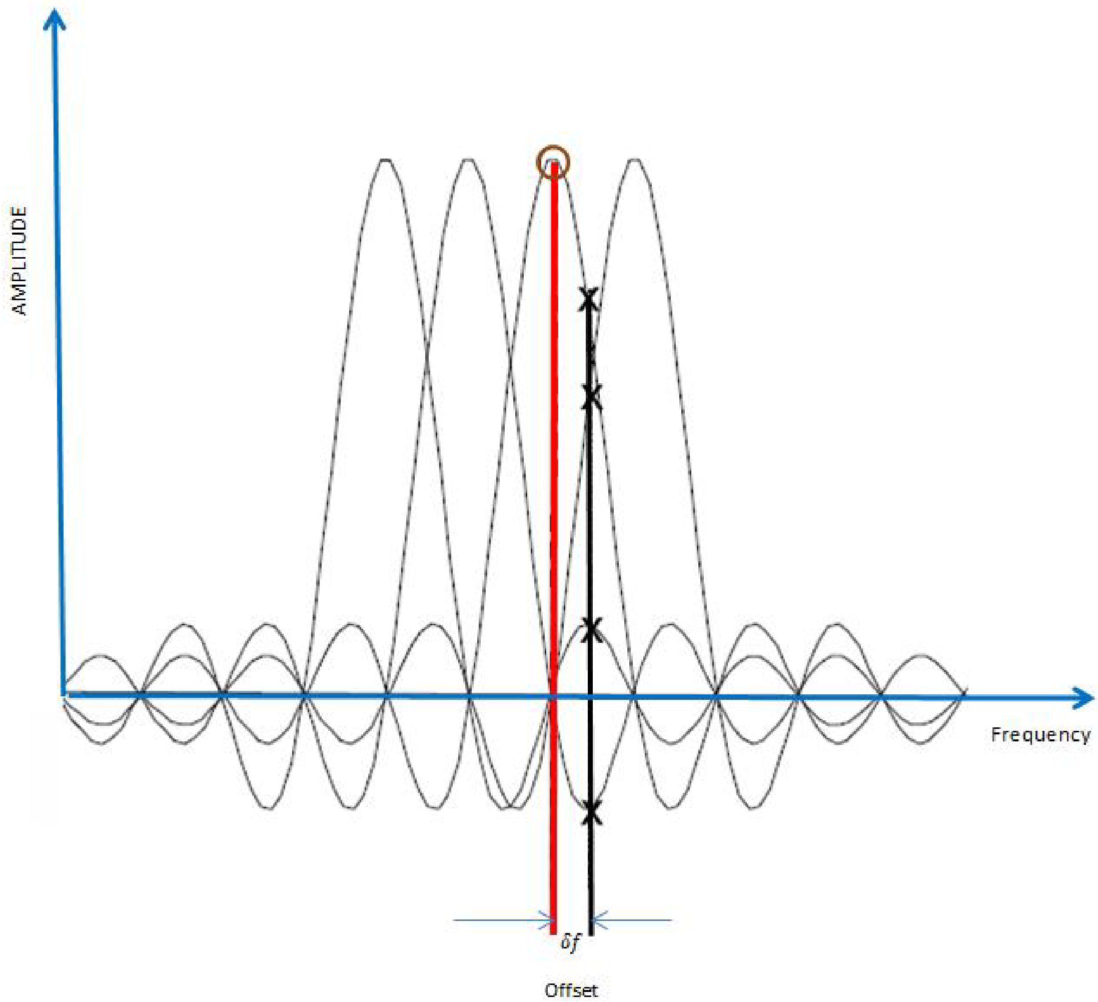


Fig. 3.2: Illustration of the effect of frequency offset on sampling

The reasons for the existence of CFO could be, frequency mismatch between transmitter and receiver due to drift in their respective oscillators, Doppler shift caused due to the relative motion between transmitter and receiver, the behaviour of radio waves transmitted.

The equation that defines the inclusion of CFO error in the project is,

$$y(k) = \sum_{m=1}^{N} x(k,m) * exp(j2\pi\delta f(m)kT_c)$$

Here, *y* is the signal received at the Hub and *y(k)* denotes the k^{th} chip of the received signal. The residual frequency error of m^{th} UE is denoted by $\delta f(m)$ and *x(k,m)* denotes the k^{th} bit of m^{th} UE's input. T_c denotes the chip duration.

To battle the residual CFO, the modulation scheme opted was Differential QPSK (DQPSK).

CHAPTER 4

Transmitter and Receiver blocks

4.1 Transmitter Block

In the transmitter of each UE, the data to be transmitted will go through a forward error correction block of 80/108 rate to obtain a coding gain of 2 to 3 dB. The transmission works on spread interleaved OFDMA. The modulation scheme opted is DQPSK, in which the information will be conveyed by the phase difference between the present symbol and the previous symbol. After the modulation, each symbol is spread using a spreading sequence of length 64 to provide the covertness. In this project Zadoff-chu sequence is preferred over Walsh code. The reason is, when Walsh code is used, the energy is concentrated at a single subcarrier and if deep fade happens at that subcarrier, all of the data would be lost. But in case of Zadoff-chu, it is spread over the 64 subcarriers. The Zadoff-chuChu (1972) sequence can be formed using the equation,

$$z_{seq} = exp(-j\pi un(n + c_f + 2q)/N_{zc})$$

where

N_{zc} is the length of the sequence (64 in our case),

$0 < u \leq N_{zc}$ and gcd(N_{zc}, u) = 1,

c_f = mod($N_{zc}, 2$),

q = 0 and n = [0, 1, $\cdots$,N$_{zc} - 1$].

One of the requirements of the RCS project is covertness. The spreading of the data symbol using the Zadoff-chu sequence helps in obtaining gain of 18.06 dB. The effect of Zadoff-chu sequence on PAPR has been submitted in the earlier submission on RCS reverse link. It has been stated that if different Zadoff-chu sequences were used for different UEs, the overall PAPR at the satellite end would increase drastically even though the individual PAPR is close to unity. Due to this reason a single sequence is being used by all the UEs for spreading. After spreading, the obtained sequence is repeated 32 times so that in the frequency domain representation an interleaving of 32 is achieved to accommodate 32 users. In order for the data of different UEs to be orthogonal to each other, no two UEs select the same subcarriers for their transmission. To achieve this, comb selection is done. This is done by multiplying the time domain representation of each UE by $exp(jkn)$ where k is the comb index selected of that particular UE. To maintain better value of PAPR, appropriate comb selection should be done such that all the UEs transmitting should be equidistant from each other. The transmitter at the UE should be compensate for the frequency offset estimated through the forward link. Since the channel we would be transmitting corrupts the signal, the receiver end should be able to estimate the channel and use it to retrieve the data. To achieve this, pilot symbols are used which are known at both receiver and transmitter ends. Since the

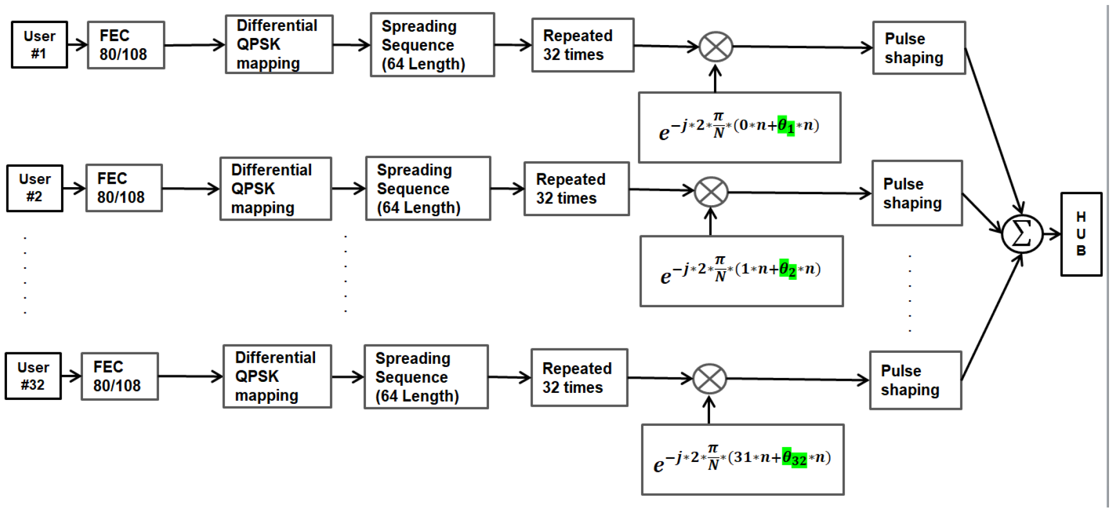


Fig. 4.1: Reverse link transmitter block

subcarriers are orthogonal to each other, this allows the receiver to assume the received signal to be the product of transmitted signal and the channel response. In the previous submission, it has been stated that depending upon the number of UEs in the network, the pilot symbols vary. A look up table has been formed for the selection of pilot symbols to maintain low PAPR value. Pulse shaped (Raised cosine window) SI-OFDMA is used as per the framing structure and converted to analog form, mapped onto the carrier and transmitted. To study the effect of the residual CFO error on the performance of the reverse link, each UE is expected to have some residual CFO error. In simulation level, CFO error is introduced into each UE data before adding the individual UE data signals.

4.2 Receiver block

In the receiver block, the first thing to focus on is timing synchronization. The UE before joining into the network, transmits the PRACH signal and this makes sure that the timing synchronization happens. Cross correlation on the received signal using the Zadoff-chu sequence helps in obtaining a IBI free FFT window. The channel estimation can be done using the pilot symbols transmitted by the UEs. Since the pilot symbol information of every UE is known at the receiver, this can be used to estimate the channel frequency response (CFR). The pilot symbols after spreading were repeated 64 times to boost SNR by 18.06 dB. So, these 64 copies are summed and averaged. The FFT of this signal gives the CFR of all the UEs. Using the comb location of the UEs,

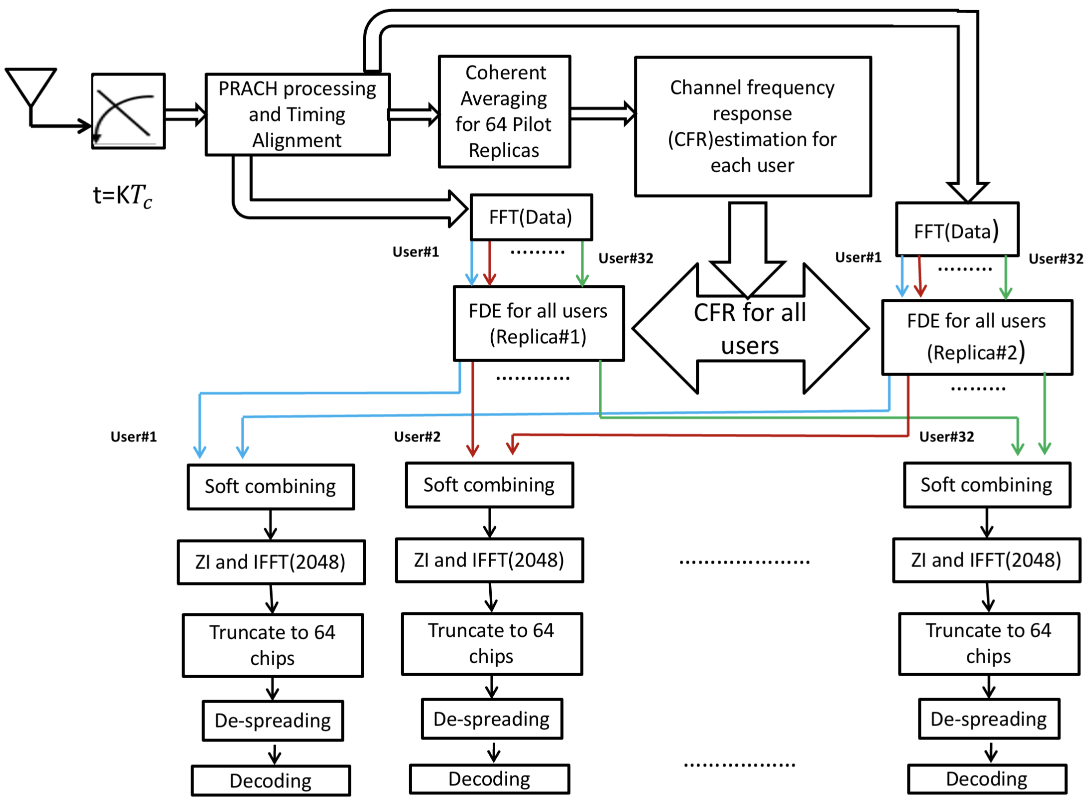


Fig. 4.2: Caption

the exact CFR of each UE is derived. The estimated CFR contains phase error due to the shift caused while estimating the IBI free window. The FFT of the IBI free window would give the frequency response of each UE interleaved by 32. The knowledge of comb location helps in separating the UE's responses. The equalization used is Zero forcing equalization (ZFE). Since the effect of noise is minimal, ZFE is a best option. After ZFE, the IFFT is done to retrieve time domain response of the data symbol spread. De-spread of the signal gives the data symbol. DQPSK demodulation helps in retrieving the coded bits. Decoding helps in retrieving the original data bits.

4.3 Simulation results

It is a known fact that performance of QPSK modulation scheme outweighs DQPSK under normal circumstances. The below plot is an simulated result of the same. When

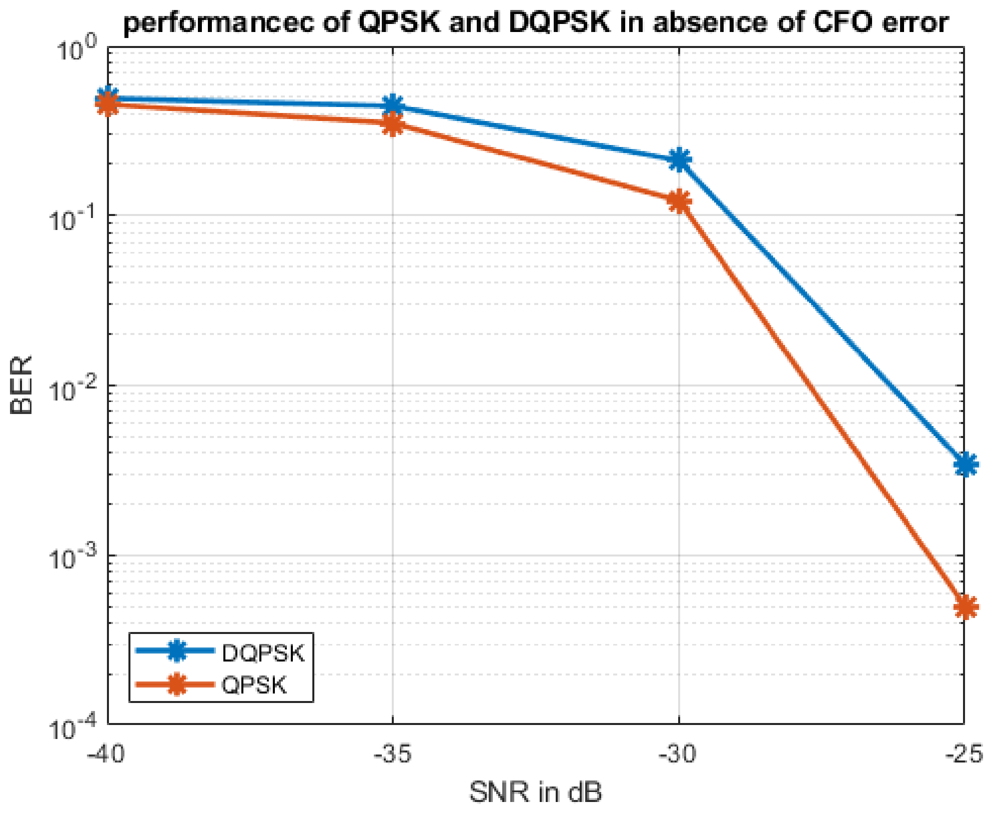


Fig. 4.3: Performance comparison between QPSK and DQPSK modulation schemes in absence of CFO error

the residual CFO error is imposed, the performance of QPSK degrades much because of the phase build-up happening due to CFO error. Even if the SNR is increased, the

BER doesn't improve for QPSK case. The performance of DQPSK also takes a hit but not as worse as QPSK does. This is because, the information is stored in the difference in phase and the phase imposed by CFO error deosn't effect much after the DQPSK demodulation happens. The results in figure 4.4 and figure 4.5 explain the changes due to CFO error.

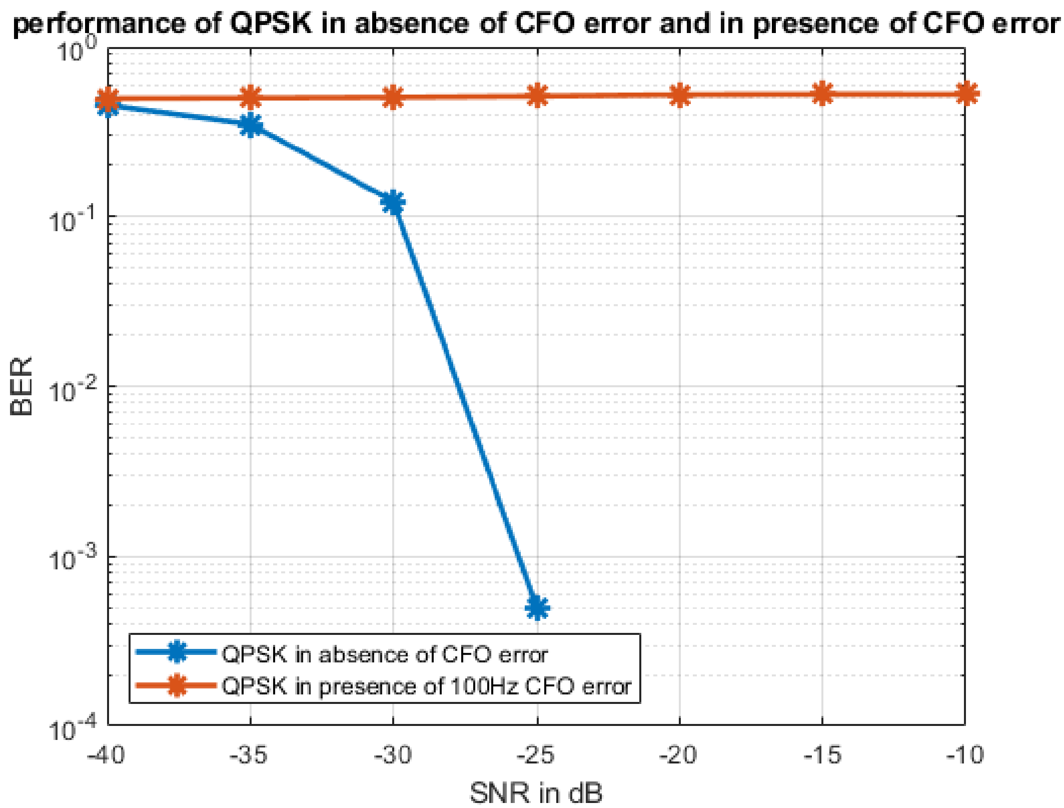


Fig. 4.4: Performance of QPSK modulation in presence of CFO error

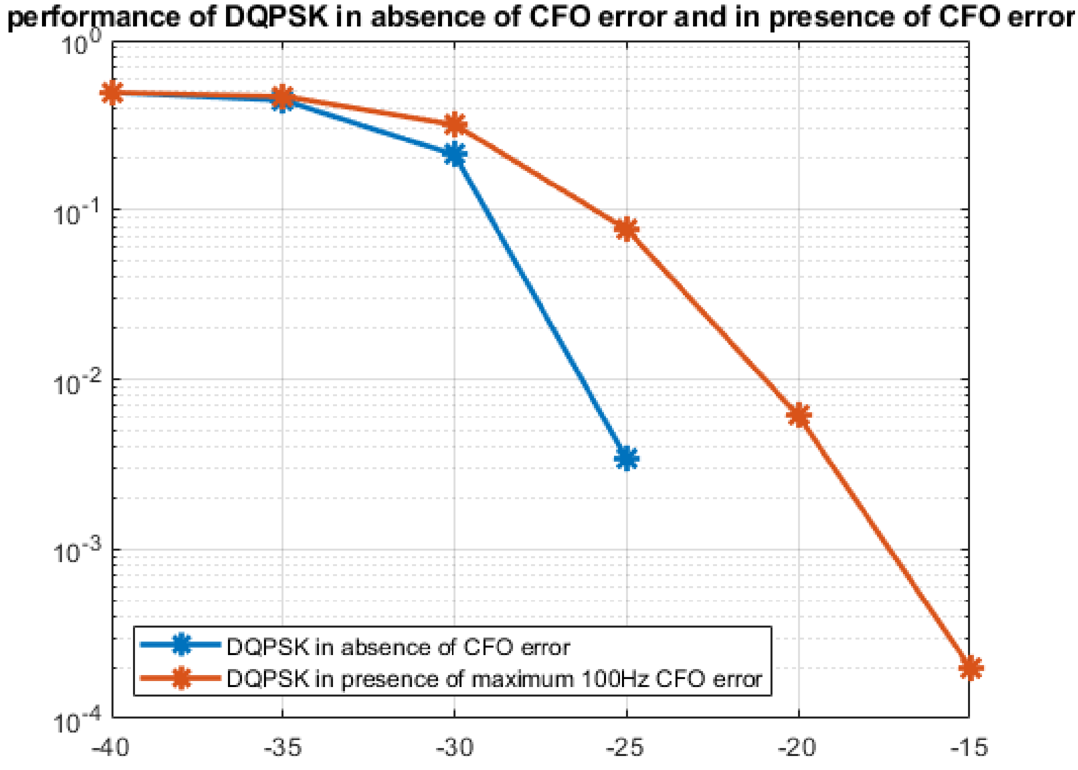


Fig. 4.5: Performance of DQPSK modulation in presence of CFO error

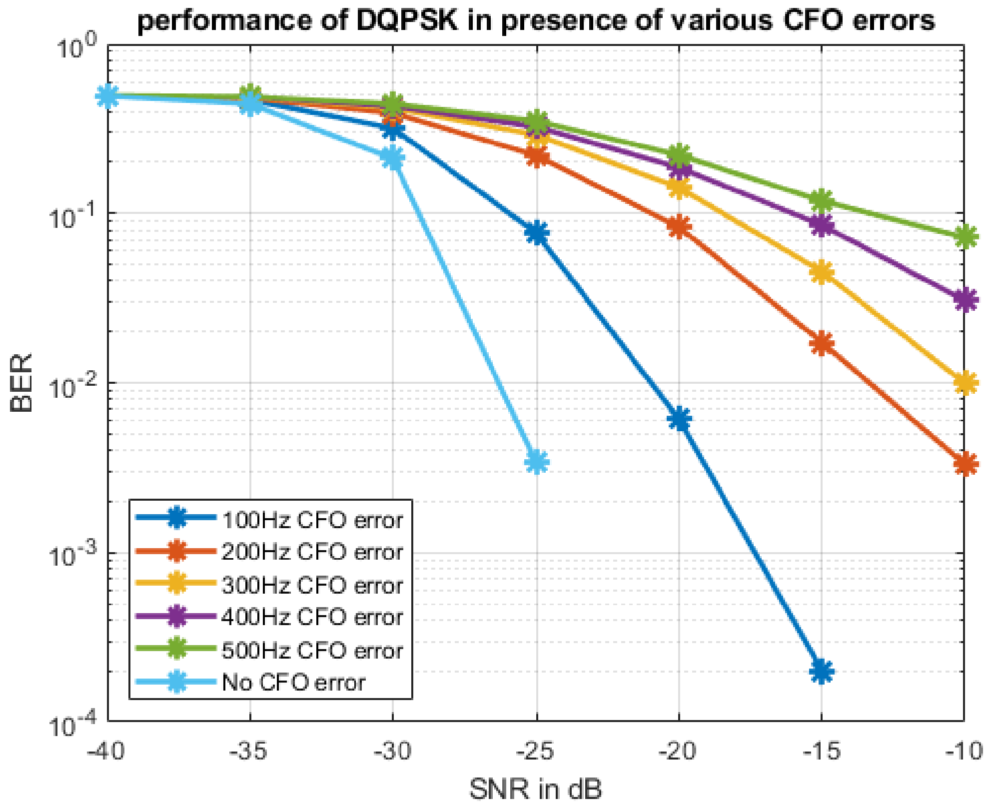


Fig. 4.6: Performance of DQPSK modulation in presence of various CFO error

The figure 4.6 shows the performance in presence of various CFO error values. As the CFO error value increases, it can be seen that the performance degrades. The system works better at 100Hz CFO error but as the value changes to 200Hz, the change in performance is clearly visible and as the value is increased, the performance continues to degrade.

The scatter plot of the DQPSK demodulated symbols explains the effect of various CFO values on the performance. The figure 4.7 illustrates the scatter plot of the demodulated data symbols when a CFO error of 100Hz is present.

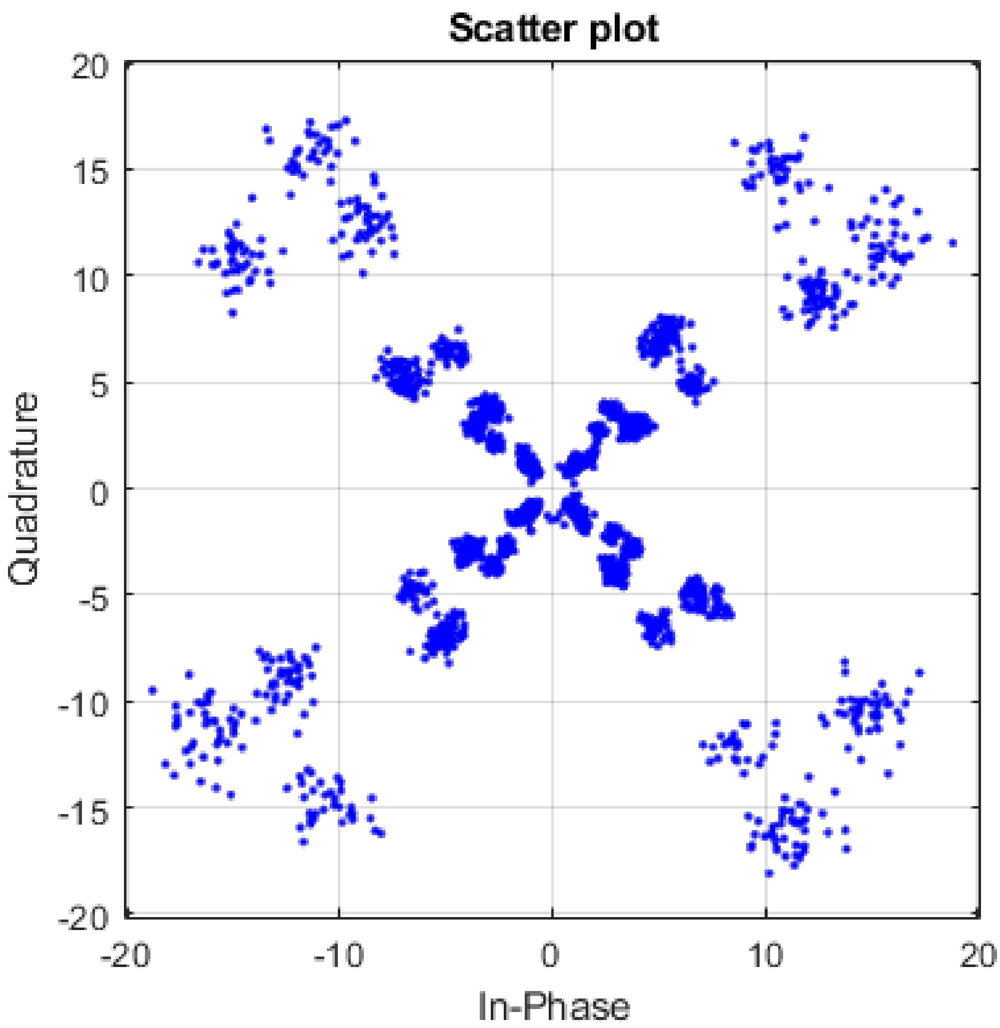


Fig. 4.7: Scatter plot of demodulated symbols under 100Hz CFO error

The figure 4.8 illustrate the scatter plot of the demodulated data symbols when there is no CFO error in the network. When the above mentioned two cases are compared,

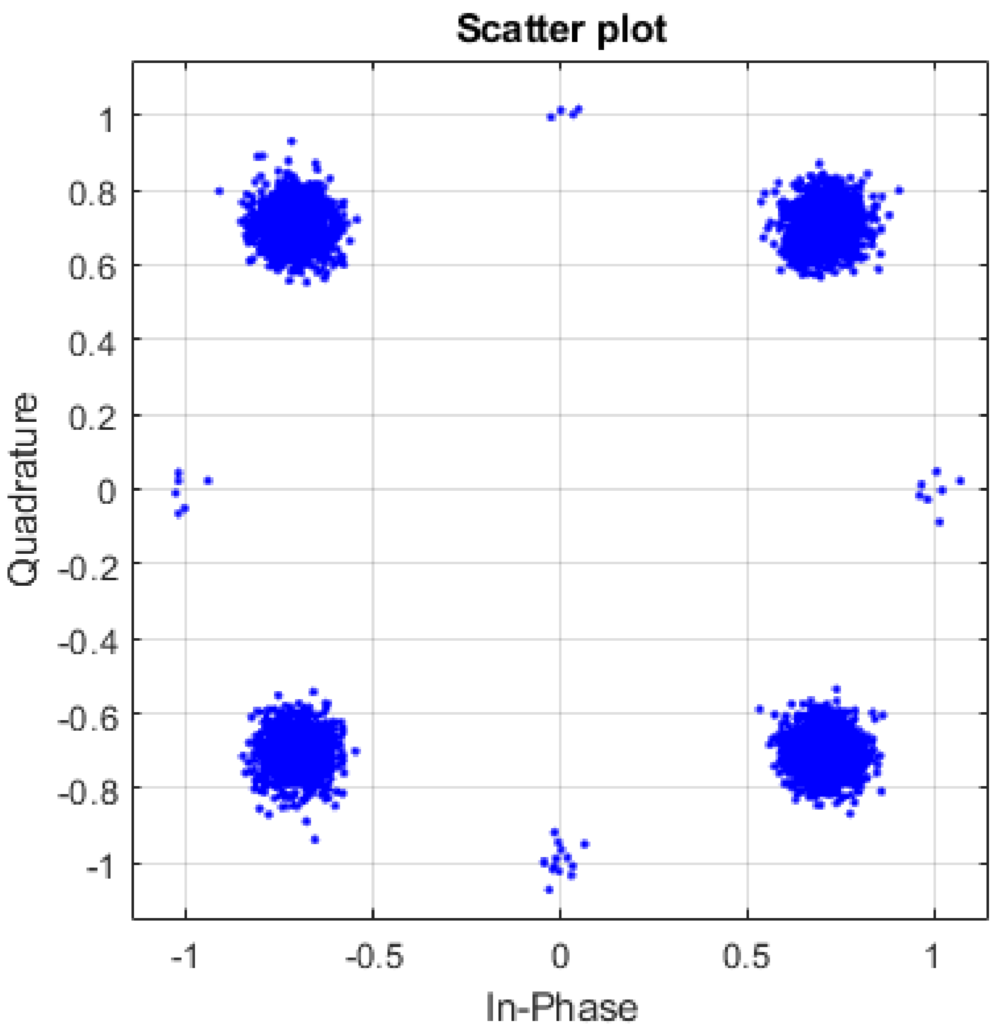
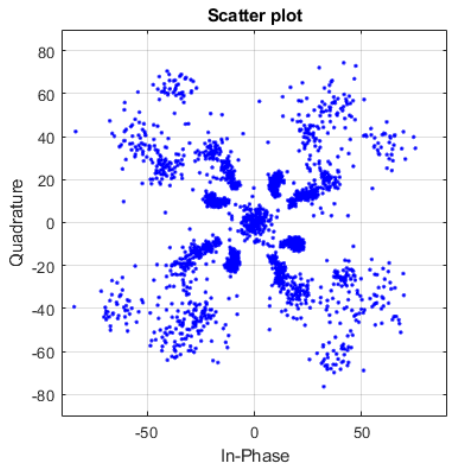
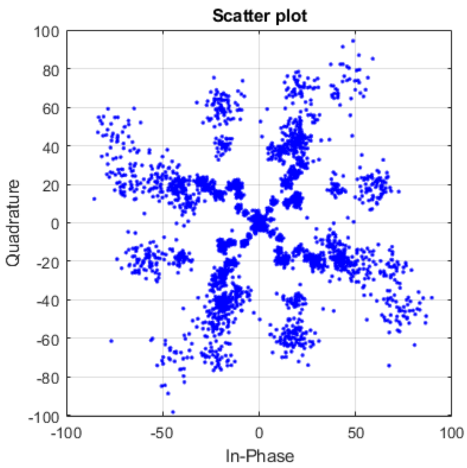


Fig. 4.8: Scatter plot of demodulated symbols under no CFO error

it is clearly visible that due to CFO error, ICI is happening. The above mentioned cases were taken under the same SNR value of -10 dB. As the value of CFO error gets increased, the dispersion of the demodulated data symbols increases. The figures 4.9 and 4.10 explains the same.

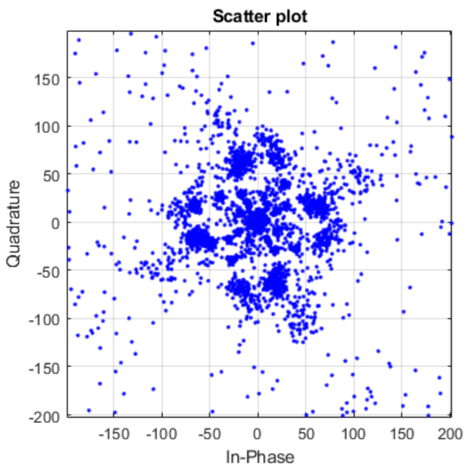


(a) CFO error: 200Hz

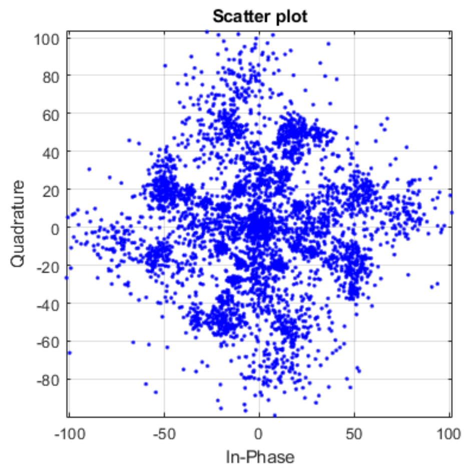


(b) scatter plots under various CFO errors

Fig. 4.9: CFO error: 300Hz



(a) CFO error: 400Hz



(b) CFO error: 500Hz

Fig. 4.10: scatter plots under various CFO errors

4.4 Summary

The effect of residual CFO error is minimal for 100Hz and it will be the typical value that could be encountered in our reverse link. If the effect of CFO error on CCE (common channel estimation) could be handled, the channel estimation would improve which in turn will increase the performance of the reverse link.

CHAPTER 5

PRACH

5.1 Introduction

Every new user will be in reception mode listening to Forward link data and through Control sub-frames in it one can decode the current network status (which includes Number of users present, current PRACH pool size and so on). Until user has some information to send, it will perform timing and CFO error estimation and track the boundary of every Forward link frame.

While UE tries to join the network, as mentioned in Reverse link frame structure, it transmits the PRACH (after compensating for forthcoming CFO error) advancing 472 msec (assuming GEO satellite is at an altitude of 35786 km) with reference to its received Forward link boundary once in every sec. This will ensure that UE's PRACH will be arrived anywhere in the 30 msec buffer spared for the differences in actual distance travelled by it. Hence, Hub will perform cross-correlation on the received data during this 30 msec buffer (repeated every sec) detecting all the PRACHs being transmitted.

5.2 PRACH pool algorithm

5.2.1 Signal structure

size : 4096 chips

sequence : Zadoff-chu (ZC) of length 4096

5.2.2 Pool details

Based on number of users already connected in the network, new user has to select a PRACH from the pool of sequences in random fashion as mentioned below. This helps us in decreasing the chance of multiple users selecting same sequence as PRACH. In fact, one can avoid this from happening if each user is allotted with a unique PRACH sequence. But this will shoot up the number of cross-correlators being run at hub side simultaneously which increases the complexity in multiple folds. Therefore, a PRACH pool (based on number of UEs present in the system) has been designed as a trade off between complexity and same PRACH being selecting.

Pool-A: when No. of UEs ≤ 16

Contains 8 different ZC sequences using seeds $1, 3, 5, 7, 11, 13, 15, 17$

Pool-B: when No. of UEs > 16 and ≤ 28

Contains 4 different ZC sequences using seeds $1, 3, 5, 7$

Pool-C: when No. of UEs > 28 and ≤ 32

Contains 2 different ZC sequences using seeds $1, 3$

5.3 PRACH transmission @UE side

A new UE, after successfully recovering the forward link's timing boundary and CFO error at its reception, Control sub-frame data will be decoded. Through this, network status can be obtained and based on the validity of the pool, a PRACH sequence will be chosen randomly. The chosen PRACH will be pre-compensated for forthcoming CFO error during reverse link transmission and transmitted at 472 msec advance the upcoming Forward link frame. This will ensure the timing synchronization at hub side (Coarsely, transmitting Forward link and received reverse link frame boundaries will be coincided).

5.4 PRACH processing @Hub side

On-going pool configuration decides how many correlators need to be run simultaneously at the hub side. Ideally, if a single peak or no peak has occurred at a certain correlator output decides the presence or absence of a unique user sending that corresponding PRACH sequence respectively. Later, hub will send the additional timing advancement unique to that user and expects its user-ID to be sent in data sub-frames. After Hub being able to decode the unique user-ID successfully, UE will be attached to the network and given access to send the desired information. There can be different kinds of scenarios possible where it is not straight forward to range each user independently sometimes.

5.4.1 Scenario - A: Multiple UEs having same/different time of flights (ToF) transmitting unique PRACH sequences

In this case, among all UEs sending PRACH, pseudo-orthogonality achieved through different sequences. Therefore, Hub will identify each of them uniquely and assign the resources.

5.4.2 Scenario - B: Multiple UEs having different ToFs transmitting same PRACH sequence

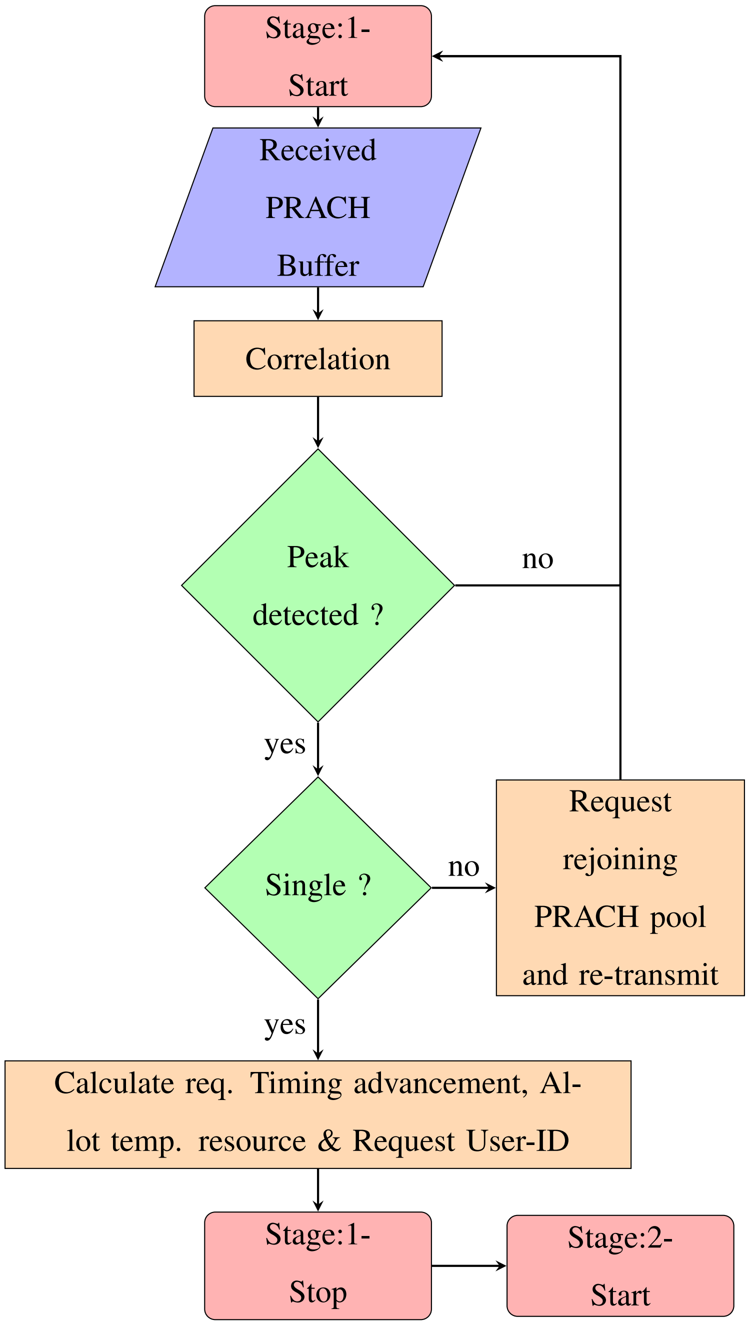
If this case occurs, at a single correlator output Hub will be seeing multiple peaks at different locations. Although this reveals the number of new users trying to join the network, Hub cannot notify the ranging information back to users. Therefore, it will ask for re-selecting PRACH for all multiple users who has selected same PRACH hoping they may select unique sequences next time.

5.4.3 Scenario - C: Multiple UEs having same ToFs transmitting same PRACH sequence

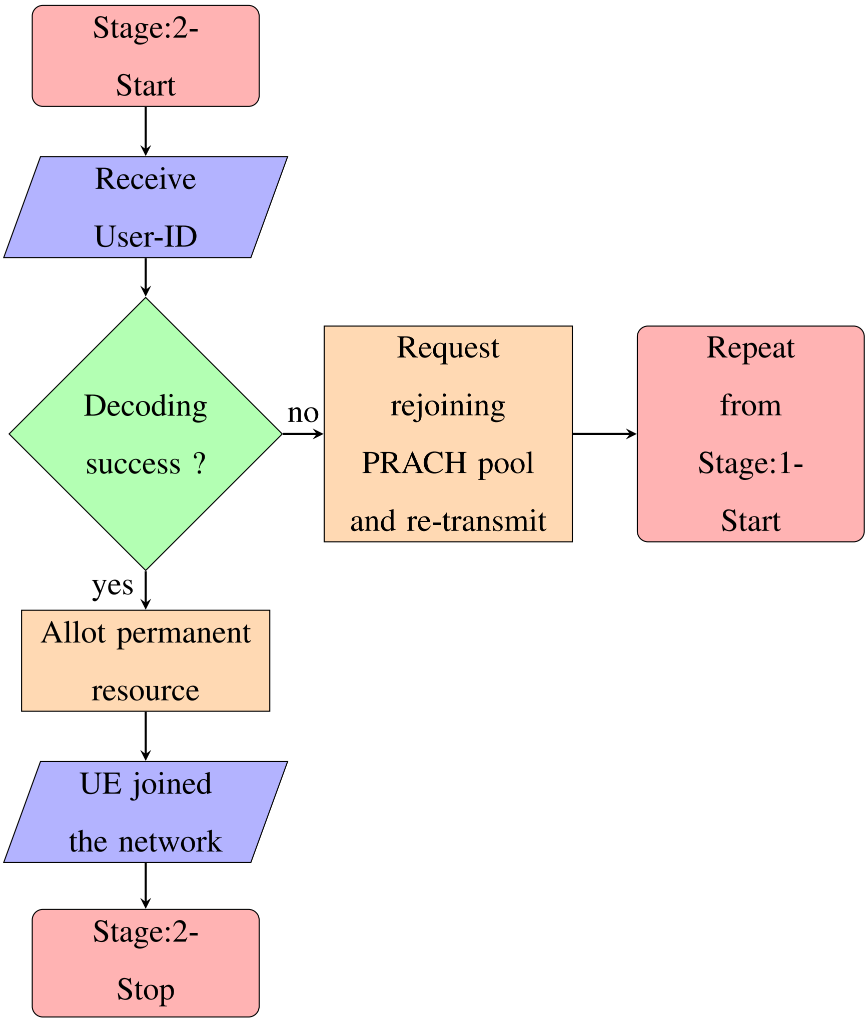
In this case, even multiple users has sent PRACH, due to their ToF being same (this does not necessarily mean they are co-located), a unique peak can occur at the correlator corresponding to that PRACH sequence. Hub can mistake this situation to be as a single user sending the detected PRACH sequence. As a part of handshaking protocol, Hub will inform the additional timing advancement need to be done for the user who has sent that PRACH sequence. Now, every user may advance with same amount and transmit their unique USER-IDs in the data sub-frames on the same resource (which is that frequency comb in reverse link). As every user data has interfered with each other, Hub will fail to decode the user-ID and it will not grant the permission for the user/users who has sent that particular PRACH and ask them to re-choose PRACH sequences from the available pool hoping those multiple users will select unique sequences next time.

5.5 PRACH processing flowchart

5.5.1 Stage:1



5.5.2 Stage:2



Stage:2-
Start
Receive
User-ID
Decoding
success ?
no
Request
rejoining
PRACH pool
and re-transmit
Repeat
from
Stage:1-
Start
yes
Allot permanent
resource
UE joined
the network
Stage:2-
Stop

5.6 Simulation results

5.6.1 Setup

In the simulation, four users are trying to gain resource allocation. The location of a UE is randomly selected in the region of operation *(a 1000 km circle)* and their corresponding ToF is calculated.

5.6.2 Simulation

In the first case, same PRACH sequence is used by every UE. The ToF of every UE is calculated and the delay is imposed onto the PRACH sequence of the UEs. The PRACH sequences of the four UEs obtained after the inclusion of delays is added and this signal is assumed to be received at the HUB with addition of WGN. A single correlator is present in this scenario and the received signal is given as input to the correlator and the output of the correlator would provide the information about the timing advancement required by the UEs as a whole and estimate the number of UEs trying to gain resources.

If the two or more UEs in spotlight are close enough such that the difference in their ToFs is negligible then the peaks corresponding to these UEs in the correlator output would occur at same location and the the detector would misjudge the number of UEs. This is considered as a failure. Even though it can detect the number of UEs and the timing advancement required, mapping of the timing advancement and the UE cannot be done.

In the second case, a unique PRACH sequence is allocated to each UE. Multiple correlators are present in this scenario. Here, each correlator provides information about the timing advancement of the UE using the corresponding PRACH sequence. Mapping between timing advancement and the UE is possible in this case. An iteration is considered to be a success only if the HUB can correctly detect the timing advancement required by every UE. This simulation is done for 1000 iterations and the average probability of success is calculated.

5.6.3 Result

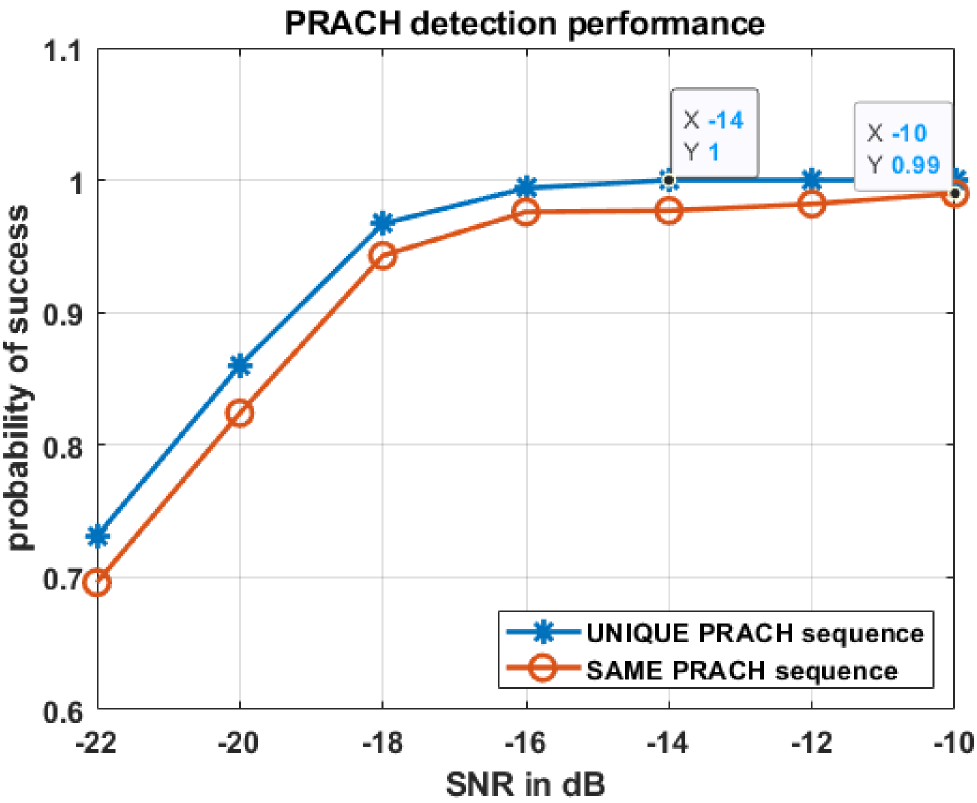


Fig. 5.1: Performance comparison of two algorithms mentioned

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