INTERFERENCE MITIGATION IN WAIC SYSTEMS

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

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August 2019

Major Subject: Electrical Engineering

ABSTRACT

Advancements in the field of wireless communications in the last few decades have made it an indispensable part of how human made entities, and by extension, humans interact with each other. The inherent lack of the need for significant physical infrastructure brings with it great advantages in terms of mobility, operational and maintenance costs, and overall reliability and flexibility. The characteristics of wireless techniques make for an attractive proposition for enabling operational communications in aircrafts. However, wireless networks bring with them their own set of challenges in terms of range, dependability or susceptibility to interference and security.

The main objective of this thesis is to evaluate different wireless communications techniques for their feasibility to be employed as Wireless Avionics Intra-Communications (WAIC) systems. The major hindrance in ensuring reliable communications in this regard comes from the operation of the existing Radio Altimeter systems in the allotted frequency band of 4.2 - 4.4 GHz. WAIC systems based on wireless techniques such as Code Division Multiple Access (CDMA) and Orthogonal Frequency Division Multiplexing (OFDM) have been simulated in MATLAB for the analysis. The performance of the WAIC systems in the presence of interference from Altimeter signals and Additive White Gaussian Noise (AWGN) has been evaluated and studied.

DEDICATION

To my parents

ACKNOWLEDGEMENTS

I would like to express my sincerest gratitude to my graduate advisor Dr. Scott Miller, for his motivation, patience and immense knowledge. I want to especially thank him for being available whenever I required his help and guidance. I feel extremely fortunate to have had the opportunity to work with him.

I would like to thank Dr. Krishna Narayanan, Dr. Jiang Hu and Dr. Duncan Walker for serving on my Master's thesis committee.

I would also like to thank the Department of Electrical and Computer Engineering at Texas A&M University for providing many necessary and useful tools and resources that helped me in pursuing my research interests.

I would like to also express my gratitude to my friends who were there for me on days, both bad and good.

I'm also grateful for my family's immense support, love and motivation.

CONTRIBUTORS AND FUNDING SOURCES

Contributors:

This work was supported by the thesis committee comprising of Dr. Scott Miller, Dr. Krishna Narayanan and Dr. Jiang Hu of the Department of Electrical and Computer Engineering and Dr. Duncan Walker of the Department of Computer Science and Engineering.

Funding Sources:

My graduate study was partly supported by a merit scholarship from the Department of Electrical and Computer Engineering at Texas A&M University.

NOMENCLATURE

AVSI	Aerospace Vehicle Systems Institute
WAIC	Wireless-Avionics Intra-Communications
ITU-R	International Telecommunications Union – Radiocommunications
ARNS	Aeronautical Radio Navigation Service
FMCW	Frequency Modulated Continuous Wave
DS-CDMA	Direct Sequence - Code Division Multiple Access
BPSK	Binary Phase Shift Keying
MAI	Multiple Access Interference
BER	Bit Error Rate
RA	Radio Altimeter
AWGN	Additive White Gaussian Noise
SNR	Signal to Noise Ratio
SIR	Signal to Interference Ratio
OFDM	Orthogonal Frequency Division Multiplexing
LTE-A	Long Term Evolution – Advanced
IFFT	Inverse Fast Fourier Transform
IDFT	Inverse Discrete Fourier Transform
FFT	Fast Fourier Transform
DFT	Discrete Fourier Transform

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CHAPTER 1
INTRODUCTION AND LITERATURE REVIEW

The underlying basis for all of human inventions has been common. They were conceived out of the need for enhancing one or more of humans' natural abilities. One of the most influential inventions in all of human existence probably was the airplane. It revolutionized the way we bridged distances by bettering the efficiency of human locomotion by large orders of magnitude. A chain of events spawning from the demonstration of the first powered engine manned flight by the Wright brothers in December 1903 led to the creation of the commercial aviation industry with some remarkable inventions in the field of aviation technology.

A successful flight is dependent on the interplay of proper functioning between highly complex systems. This interplay is largely dependent on the proper functioning of the avionics systems. Avionics is a term coined with the help of a combination of the words 'aviation' and 'electronics'. They are the electronic systems installed in aircrafts that help facilitate communications, navigation and control and management of a myriad systems that perform individual functions such as collision avoidance, cabin pressure monitoring, engine monitoring, smoke detection, landing gear monitoring, to name a few.

All aircrafts today have avionics systems containing only wired connections. These complex systems of wires (Fig. 1) are critical to the functioning of the modern aircraft.

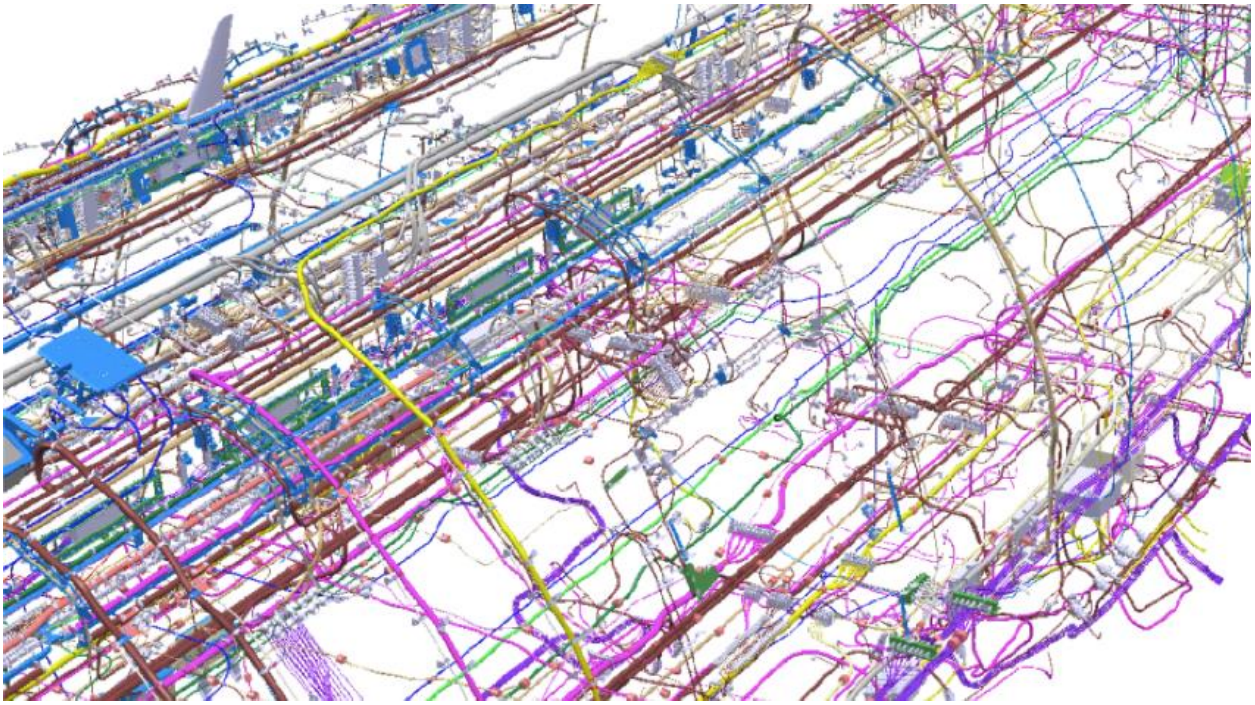

Figure 1: Wiring in a typical fuselage slice

If all the wires on a widebody passenger jet are removed and strung end-to-end, one could connect slightly more than 300 miles. That's the distance from London to Amsterdam! A modern jet has about 100,000 wires, weighing nearly 7400 kilograms or about 3 percent of the aircraft's weight. Many of these wires supply electricity to components, many others transmit operational data, including avionics, flight-control commands and sensor data on the performance of components like pneumatic and hydraulic systems [1]. According to estimates, potentially 30% of the wires could be replaced with the help of wireless techniques.

The motivation behind the aviation industry's interests in wireless alternatives stems from the following reasons [2]:

- Reduction in weight from electrical wiring and associated harnessing, leading to greater fuel efficiency.
- Reduction in installation complexity, leading to a faster assembly line.

- Reliable monitoring of parameters belonging to moving or rotating parts.
- Improved reliability of aircraft systems through means of dissimilar redundancy, eliminating common mode failures.

The Wireless Avionics Intra-Communications (WAIC) system was thus proposed. Research in this space is being conducted by Aerospace Vehicle Systems Institute (AVSI) in collaboration with International Civil Aviation Organization (ICAO) and International Telecommunications Union (ITU).

1.1 Wireless Avionics Intra-Communications (WAIC) System:

The WAIC is the system that facilitates radiocommunications between the avionics systems in the aircraft. The motivation behind the development of WAIC lies in the fact that the efficiency, as well as the reliability of the avionics stand to gain immensely. WAIC systems will provide communications links between two or more points located in short distances within a single aircraft. They are not expected to be used for infotainment purposes, for example consumer devices brought onboard the airplane. The avionics connected would not be restricted to the interiors of the aircraft. For example, for landing gear monitoring, functions such as brake condition monitoring, oleo pressure monitoring, tire pressure indicating will all provide real-time safety related system status information from outside the craft to the cockpit [2]. Links won't however be established between multiple aircrafts, terrestrial systems or satellites [3]. The WAIC system would essentially be used for facilitating aircraft safety related applications [4]. They are expected to be developed keeping in mind their deployment on regional, business, wide-body and two-deck aircraft, and also helicopters. The pervasiveness of the use case would warrant different requirements on the WAIC systems [5].

WAIC systems would eventually make air travel safer and more efficient. The potential benefits are hence underscored.

1.1.1 Advantages of WAIC System:

Wiring not only involves significant manufacturing costs, but also results in immense maintenance efforts, and consequent costs. It also adversely impacts the time needed for designing a new aircraft. The design complexity partly results from the need for redundant wiring. Since wires are physical entities, they are susceptible to wear and tear, and essentially come with an expiry date. Now, a lack of redundancy may cause system paralysis if the physical channel breaks between two communicating entities. Hence, for every wired link, two or three redundant links are established to serve as backup in case of failure of the primary channel. As wireless systems are less likely to be harmed by physical wear and tear, it's less probable that they would warrant the need for redundancy as much as their wired counterparts. Wireless links can also be designed to serve as redundancy components for some wired links. This will ensure *redundancy through dissimilar means*. The complexity is also enhanced because of harnesses associated with organizing the wires, which won't be required in a wireless setup. Additionally, the components associated with wired communications could be different for different aircraft types, so standardization becomes all the more difficult. A wireless sensors-based infrastructure can ensure uniformity in development and use. WAIC systems will also ensure more efficient fuel consumption. Employment of WAIC systems should effectively aid in reducing the cost of air travel in the future.

1.1.2 WAIC System Classification [6]:

In order to better understand the performance requirements of the WAIC systems, it's useful to classify the systems according to two characteristics: data rate and location of use case. This enables a lucid understanding of the holistic system requirements.

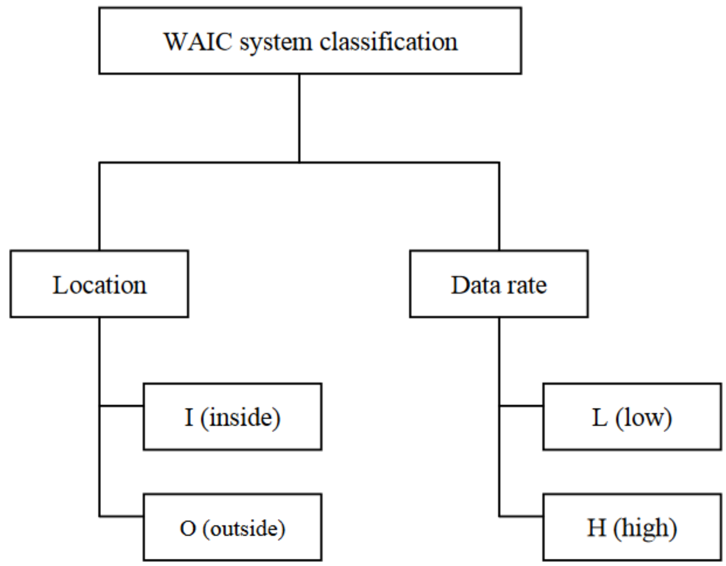

Figure 2: WAIC System Classification

Figure reprinted from [6].

The systems can be classified as high data rate (H) and low data rate (L) in terms of data rate requirements. Low data rate applications will have data rates less than 10 kbps whereas high data rate applications will have data rates greater than 10 kbps. Location based classification yields two categories as well. Applications located inside the fuselage will be classified as inside (I) applications. The ones located outside will be classified as outside (O) applications. Based on the above mentioned classifications, WAIC applications will be further classified as AB, where parameter A represents data rate (H, L) and parameter B represents location (O, I).

1.1.2.1 Classification LI

The following attributes define LI classification:

- Data rate: low (<10 kbps)
- Installed inside metallic enclosures

It is estimated that around 3500 LI transceiver nodes will be installed and they will be active during all phases of flight. Depending on the network topology and the location of installation, the expected communications range may vary from a few centimeters to some tens of meters. Majorly, propagation will not be line of sight as most LI nodes will be mounted in hidden locations.

Table 1 below lists the anticipated applications of the LI class.

Application	Type of benefit	Net peak data rate per data-link/ (kbit/s)	Node quantity	Activity period	New or existing application
Cabin pressure	Wire reduction	0.8	11	Ground, takeoff, cruise, landing	Existing
Engine sensors	Wire reduction, maintenance enhancement	0.8	140	Ground, takeoff, cruise, landing	Existing
Smoke sensors (unoccupied areas)	Wire reduction, maintenance enhancement, safety enhancements	0.1	30	Ground, takeoff, cruise, landing, taxi	Existing
Smoke sensors (occupied areas)	Wire reduction, flexibility enhancement safety enhancements	0.1	130	Ground, takeoff, cruise, landing	Existing
Fuel tank/line sensors	Wire reduction, safety enhancements, flexibility enhancements, maintenance enhancement	0.2	80	Ground, takeoff, cruise, landing, taxi	Existing
Proximity sensors, passenger and cargo doors, panels	Wire reduction, safety enhancements, operational enhancements	0.2	60	Ground, takeoff, cruise, landing, taxi	Existing
Sensors for valves and other mechanical moving parts	Wire reduction, operational enhancements	0.2	100	Ground, takeoff, cruise, landing, taxi	Existing
ECS sensors	Wire reduction, operational enhancements	0.5	250	Ground, takeoff, cruise, landing	Existing
EMI detection sensors	Safety enhancements	1.0	30	Ground	New
Emergency lighting control	Wire reduction, flexibility enhancement	0.5	130	Ground, takeoff, cruise, landing	Existing
General lighting control	Wire reduction, flexibility enhancement	0.5	1 000	Ground, takeoff, cruise, landing	Existing
Cabin removables inventory	Operational improvement	0.1	1 000	Ground	New
Cabin control	Wire reduction, flexibility enhancement	0.5	500	Ground, takeoff, cruise, landing	Existing

Table 1: LI Class Applications

Reprinted from [6].

1.1.2.2 Classification LO

The following attributes define LO classification:

- Data rate: low (< 10 kbps)
- Installed outside aircraft structure

For a large airplane, it is estimated that around 900 LO transceiver nodes will be installed and they will be active during all phases of flight.

Application	Type of benefit	Net peak data rate per data-link/ (kbit/s)	Node quantity	Activity period	New or existing application
Ice detection	Operational and safety enhancement	0.5	20	Ground, takeoff, cruise, landing	Existing and new
Landing gear (proximity) sensors	Wire reduction, flexibility enhancement	0.2	30	Ground, takeoff, cruise, landing	Existing
Landing gear sensors, tyre pressure, tyre and brake temperature and hard landing detection	Wire reduction, flexibility and operational enhancement	1.0	100	Ground, takeoff, landing	Existing
Landing gear sensors, wheel speed for anti-skid control and position feedback for steering	Wire reduction, flexibility and operational enhancement	5.5	40	Ground, takeoff, landing	Existing
Flight control system sensors, position feedback and control parameters	Wire reduction, flexibility enhancement	8.0	60	Ground, takeoff, cruise, landing	Existing
Additional proximity sensors, aircraft doors	Wiring reduction, flexibility enhancement	0.2	50	Ground, takeoff, cruise, landing	Existing
Engine sensors	Engine performance, wire reduction, flexibility enhancement	0.8	140	Ground, takeoff, cruise, landing	Existing and new
Cargo compartment data	Wire reduction, operational enhancements	0.5	25	Ground, takeoff, cruise, landing, taxi	Existing
Structural sensors	Wire reduction, flexibility enhancement, safety enhancements	0.5	260	Ground, takeoff, cruise, landing, taxi	New
Temp./humidity and corrosion detection	Wire reduction, safety enhancements, operational enhancements	1.0	260	Ground, takeoff, cruise, landing, taxi	Existing and new

Table 2: LO Class Applications

Reprinted from [6].

1.1.2.3 Classification HI

The following attributes define HI classification:

- Data rate: high (> 10 kbps)
- Installed inside aircraft structure

100 such transceiver nodes are expected to be in an aircraft. They will be active for the entire duration of flight.

Application	Type of benefit	Net peak data rate per data-link (kbit/s)	Node quantity	Activity period	New or existing application
Air data sensors	Wire reduction, maintenance enhancement	100	8	Ground, takeoff, cruise, landing	Existing
FADEC aircraft interface	Wire reduction, maintenance enhancement	12.5	10	Ground, takeoff, cruise, landing, taxi	Existing
Engine prognostic sensors	Wire reduction, operational enhancements	4 800 peak 80 average per sensor	30	Ground, takeoff, cruise, landing, taxi	New
Flight deck and cabin crew voice	Wire reduction, untethered operation, operational enhancements	64 raw 16 CVSD 2.4 MELP	10	Ground, takeoff, cruise, landing, taxi	Existing and new
Flight deck crew fixed imagery	Wire reduction, flexibility enhancement safety enhancements	2 000 File sizes to > 1 Mbyte 2.5 s update each	50	Ground, takeoff, cruise, landing, taxi	New
Cabin crew fixed imagery	Wire reduction, flexibility enhancement safety enhancements	1 000 File sizes to > 1 Mbyte 5 s update each	20 (included in above)	Ground, cruise, taxi	New
Flight deck crew motion video	Safety enhancements	64 or 256	50 (same as above)	Ground, takeoff, cruise, landing, taxi	Existing and new
Cabin crew motion video	Safety enhancements	64 or 256	20 (same as above)	Ground, takeoff, cruise, landing, taxi	Existing and new
Flight deck crew digital data (EFO…)	Wire reduction, flexibility enhancement	< 1 000 (1 250 kb, > 10 s transfer time)	10	Ground, takeoff, cruise, landing, taxi	New
Cabin crew digital data	Wire reduction, flexibility enhancement	< 100 (125 kb, > 10 s transfer time)	5 (included in above)	Ground, cruise, taxi	New

Table 3: HI Class Applications

Table 3 in previous page is reprinted from [6].

1.1.2.4 Classification HO

The following attributes define HI classification:

- Data rate: high (> 10 kbps)
- Installed outside aircraft structure

300 such transceiver nodes are expected to be in an aircraft. They will be active for the entire duration of flight.

Application	Type of benefit	Net peak data rate per data-link/ (kbit/s)	Node quantity	Activity period	New or existing application
Avionics communications bus	Wire reduction, flexibility enhancement, safety enhancements	100	30	Ground, takeoff, cruise, landing, taxi	Existing
Audio communications system	Wire reduction, flexibility enhancement, safety enhancements	20	10	Ground	Existing
Structural sensors	Wire reduction, flexibility enhancement, safety enhancements	45	250	Ground, takeoff, cruise, landing, taxi	New
External imaging sensors (cameras, etc.)	Wire reduction, flexibility enhancement, safety enhancements	1 000	5	Ground; rotorcraft operations/hover in confined areas	Existing
Active vibration control	Wire reduction, operational enhancements	50	25	Helicopter cruise	Existing

Table 4: HO Class Applications

Reprinted from [6].

1.1.3 Spectrum Allocation for WAIC

Facilitating any kind of communications requires a transmitter, receiver and a medium/channel. In the case of wireless communications, a specific radio frequency or a range of frequencies determine the channel. The popular Industrial, Scientific and Medical radio frequency bands such as 2.4 GHz and 5 GHz didn't seem viable as that would entail an acute interference problem in WAIC communications. The security of WAIC related communications is also of utmost importance, and unlicensed bands such as the ones mentioned above could leave significant room for a breach, which could have disastrous effects. The [7] [8] [9] ITU-R hence decided in 2015 in the World Radio Communications Conference that WAIC devices must communicate on the 4.2 GHz – 4.4 GHz frequency band. Previously, the band was allocated to the Aeronautical Radio Navigation Service (ARNS), for exclusively operating radio altimeters [10]. Now, the challenge in ensuring reliable WAIC communications would be to employ wireless techniques for WAIC operation such that the effect of interference from altimeter signals is minimized. In this regard, work was done in examining CDMA and OFDM based WAIC systems.

1.2 Radio Altimeter

The ITU defines radio altimeters as radio navigation equipment present on board an aircraft, that are used to determine the height of the aircraft above the earth's surface or another surface [11]. In order to understand, and hence mitigate the interference that the altimeter will exert towards WAIC communications, it was important to study the nature of the altimeter signal.

1.2.1 Linear Frequency Modulated (Chirp) Signal

The Radio Altimeter transmitter is a Frequency Modulated Continuous Wave (FMCW) generator that produces a linear frequency modulated signal, characterized by Fig. 3. These are also known as Linear Chirp signals. Fig. 4 shows an up-chirp signal which means that the frequency of the chirp signal increases with time. A down-chirp signal is one in which the frequency of the chirp signal decreases with time. This work considers only an up-chirp signal for studying the interference caused by the Radio Altimeter on the WAIC Systems.

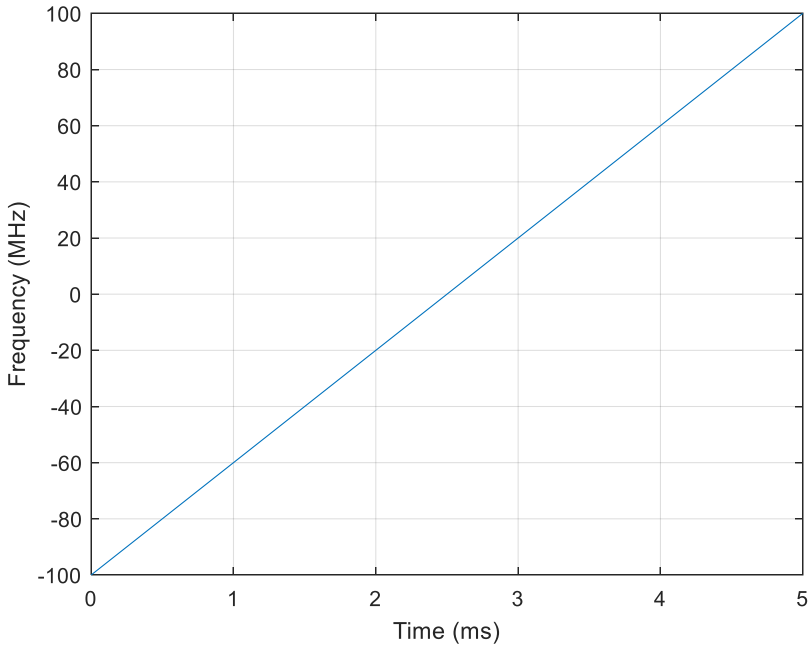

Figure 3: FMCW Signal Characteristics

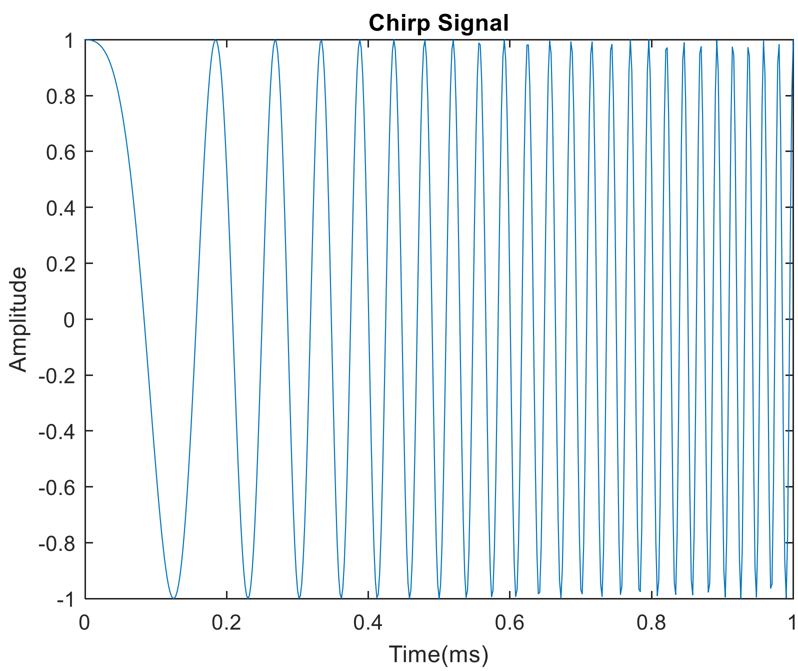

Figure 4: Up-chirp Signal Waveform

Let *r(t)* be a complex signal with phase $\theta(t)$. *r(t)* may be represented as below.

$$r(t) = e^{j\theta} \tag{1}$$

As *r(t)* is intended to be a linear frequency chirp signal, its frequency must be made to vary linearly with time. Hence, the instantaneous frequency can be specified as below.

$$f(t) = \frac{1}{2\pi}\frac{d\theta}{dt} \tag{2}$$

f(t) in the case of a linear up-chirp signal can be formulated as,

$$f(t) = kt + f_0 \tag{3}$$

where k is the sweep rate,

$$k = \frac{df}{dt} = \frac{f_1 - f_0}{T} \tag{4}$$

f_0 is the frequency at t = 0, and f_1 is the frequency at t = T. T is the sweep period, considered in this work as 5 ms.

Now, from equation 2, the instantaneous phase θ can be written as,

$$\theta(t) = \theta_0 + 2\pi \int_0^t f(\tau)\, d\tau \tag{5}$$

$$= \theta_0 + 2\pi \int_0^t (f_0 + k\tau)\, d\tau \tag{6}$$

$$= \theta_0 + 2\pi \left(f_0 t + \frac{k}{2} t^2\right) \tag{7}$$

As the altimeter signal is expected to sweep over a 200 MHz band in the range 4.2 – 4.4 GHz, over a sweeping period of 5 ms, f_0 has been considered as -100 MHz and f_1 as 100 MHz. This is because for ease of implementation in hardware, bandpass signal is considered to be processed at baseband.

In equation 7, θ_0 has been considered to be 0. Consequently equation 1 now becomes,

$$r(t) = Ae^{j2\pi\left(f_0 t + \frac{f_1 - f_0}{T} t^2\right)} \tag{8}$$

where A is the amplitude of the altimeter signal.

CHAPTER 2
DIRECT SEQUENCE
CODE DIVISION MULTIPLE ACCESS

Code Division Multiple Access (CDMA) is a popular technique used in the wireless domain for facilitating communications between users. It is a useful multiplexing method where users are allowed to transmit at the same time, using the entire available frequency range. This technique is different from Frequency Division Multiple Access (FDMA), where users communicate using allotted frequency bands, and Time Division Multiple Access (TDMA), where users communicate using different allotted time slots. In CDMA, multiplexing of users is done using distinct codes. This method is also known as spread-spectrum communications. Direct Sequence CDMA is a very widely used CDMA technique, courtesy its many useful properties [12-15]. Fundamentally, it involves the use of a distinct code for multiplying a user's data symbols before transmission, and using the same code for detecting/estimating the data at the receiver. At transmission, the multiplication results in spreading the signal into a wideband channel. It causes the transmitted signal to occupy a larger bandwidth and hence will be less correlated with narrowband interference[16].

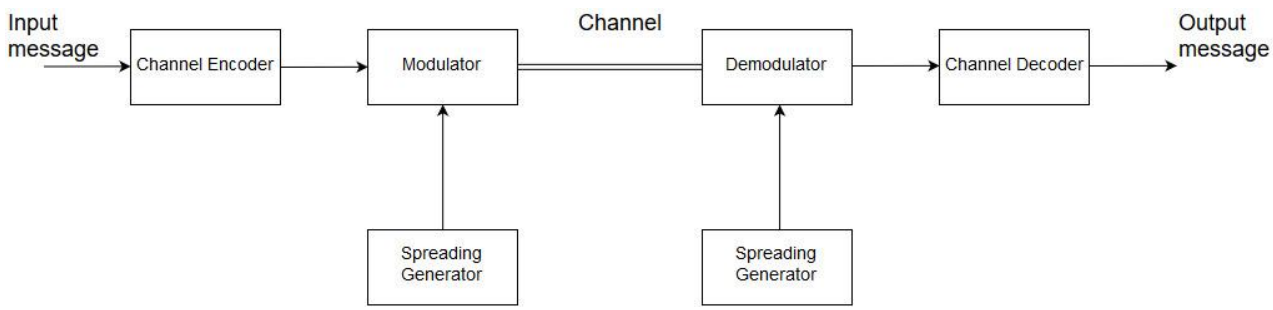

Figure 5: Spread Spectrum Technique

2.1 Modulation

In DS-CDMA, the code used for modulating the data signal is known as a spreading/signature sequence. The modulation process involves multiplying the message signal with the spreading sequence. The spreading sequence is a signal with a lower signal duration than the message signal. This means that the spreading sequence also has a wider bandwidth associated with it compared to the data signal intended to be communicated. The modulation operation hence results in a scrambled/spread signal, leading to a bandwidth close to the bandwidth of the spreading sequence. The duration of a pulse of the sequence is called the chip duration. The scrambled pulses after the modulation operation are called chips. The number of chips each data pulse gets spread into is called the spreading factor. The chip duration determines the bandwidth of the resulting DS-CDMA signal. The smaller the chip duration, the higher the bandwidth, and the greater the resistance to interference [17]. A smaller chip duration also means that each data bit is spread into larger number of chips, which means a larger spreading factor. Consequently, a larger spreading factor leads to larger protection from interference.

Let $A_k(t)$ be the WAIC user signal amplitude and $b_k(t)$ be the Binary Phase Shift Keying (BPSK) modulated signal for WAIC user k. $b_k = \pm 1$ depending on the data intended to be transmitted. Let $c_k(t)$ be the spreading code used in the modulation process. The transmitted signal for WAIC user k along with noise seen on the channel is therefore,

$$s_k(t) = \sum_{k=1}^{K} A_k(t) c_k(t) b_k(t) + n(t) \tag{9}$$

$n(t)$ is the Additive White Gaussian Noise (AWGN) seen on the channel. For simplicity of use, $A_k(t)$ has been assumed to be 1 for all users.

2.2 Demodulation

This section explains two demodulation techniques evaluated viz. the correlator and the decorrelator based demodulation methods.

2.2.1 Correlator Based Demodulation

The receiver is expected to know the signature sequence used during modulation at the transmission side. The original data is reconstructed by multiplying the received wideband signal with the same signature sequence. This process is called de-spreading. Mathematically the process is the correlation of the received signal with the known signature sequence key.

Effectively, the data symbols are correlated with the spreading sequence twice, once at the transmitter and another time at the receiver. However, the interference experienced at the channel only gets correlated at the receiver. Consequently, the interference and the transmitted signal have different bandwidths. Some signal processing at the receiver can thus separate out the message signal.

From equation 9, the received signal at the detector is given as,

$$s_k(t) = \sum_{k=1}^{K} A_k(t)c_k(t)b_k(t) + n(t)$$

$$= \sum_{k=1}^{K} c_k(t)b_k(t) + n(t) \qquad (10)$$

with the assumption about the WAIC user signal amplitudes noted earlier.

In the presence of the altimeter signal the received signal at the detector effectively becomes,

$$s_k(t) = \sum_{k=1}^{K} A_k(t)c_k(t)b_k(t) + n(t) + r(t) \qquad (11)$$

with $r(t)$ being the altimeter signal derived as equation 8 earlier. Before moving on to the match filtering process, the spreading sequence correlation parameter $\rho_{j,k}$ is defined below,

$$\rho_{j,k} = \frac{1}{T_b}\int_{T_b} c_j(t)c_k(t)\,dt \qquad (12)$$

T_b is the bit duration. In the case where $j = k$, the auto-correlation $\rho_{k,k} = 1$ and where $j \neq k$, the cross-correlation, $\rho_{j,k}$ value must lie between -1 and 1. It is this correlation parameter that effectively determines the success of the detection process. Now, the match filtering process will be as follows,

$$y_k = \frac{1}{T_b}\int_{T_b} s(t)c_k(t)\,dt \qquad (13)$$

$$= b_k + \sum_{j=1}^{K} \rho_{j,k} b_j + \frac{1}{T_b} \int_{T_b} n(t) c_k(t)\, dt + \frac{1}{T_b} \int_{T_b} r(t) c_k(t)\, dt \tag{14}$$

where $j \neq k$

The 2nd term in equation 14 is the Multiple Access Interference (MAI), the 3rd term is the noise term and 4th term is the impact of the Radio Altimeter signal interference. The MAI is reduced if the cross-correlation between the spreading codes used is closer to 0, in other words, if the codes used are nearly orthogonal to each other.

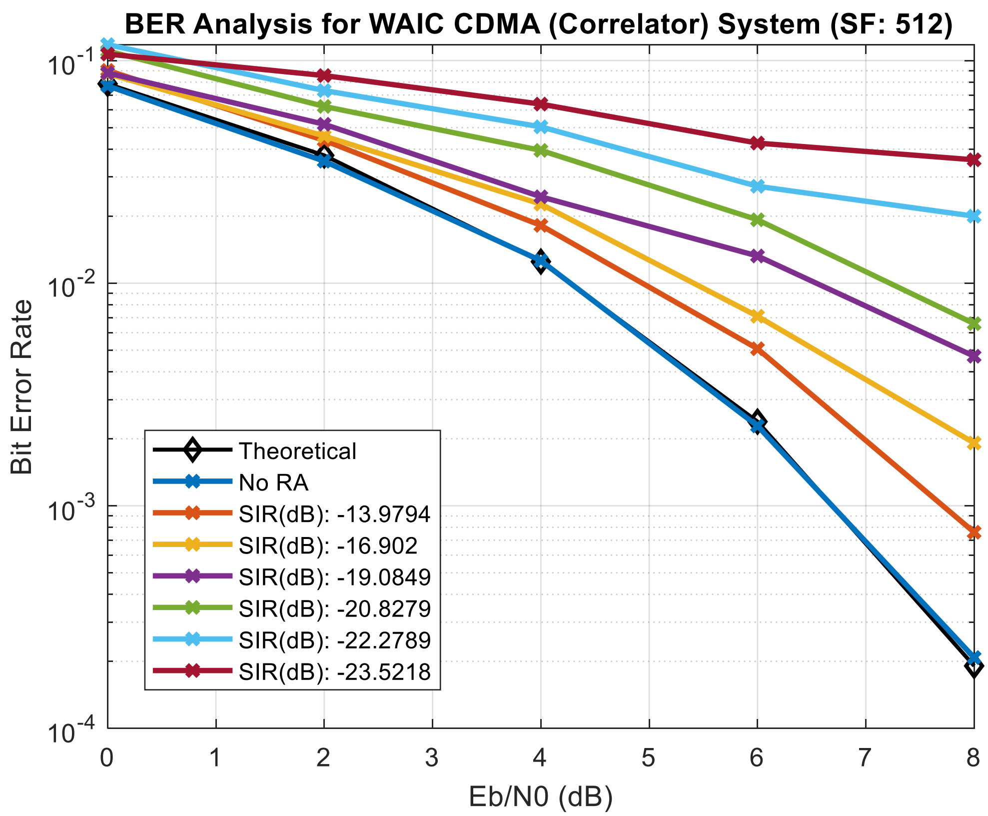

Figure 6: BER Performance Correlator based Demodulation

Fig. 6 shows the Bit Error Rate (BER) performance for a WAIC CDMA based system with correlator based demodulation. The test was set up to communicate an artificially generated WAIC signal of a particular symbol length. Then BPSK modulation is done. The signal is modulated using the signature code for the device and altimeter signals of varying strengths (as shown in figure) are added to the signal in the channel. AWGN of given Eb/N0 (x axis in plot) is also added.

The signature code is used again in the demodulation process and eventually positive symbols are detected as 1s whereas negative symbols were detected as 0s after the BPSK demodulation stage. The BER computation is done by transmitting 10000 WAIC data bits, with every transmission being monitored for the number of bits in error. When total number of errored bits become more than 200, the total number of transmissions needed to get to that point are used to determine the BER. It is seen that when there's no altimeter signal, the curve matches the theoretical BER for the given Eb/N0 values. SIR is the signal to interference ratio. It gives the ratio of the WAIC signal power to the power of the altimeter signal. It is expressed in dB in all plots. A spreading factor of 512 was used. The BER performance is seen to drop with an increase in altimeter interference level, which is expected.

2.2.2 Decorrelator Based Demodulation

Another approach that can be used at the receiver is based on the decorrelation demodulator. This technique is dependent on the estimation of the Radio Altimeter signals, that would be the major factor behind the interference that the WAIC communications would suffer from. The component of the known spread sequence that is completely orthogonal to the estimated altimeter signal is used for demodulation at the receiver. The orthogonal component is extracted using the Gram Schmidt orthonormalization process [22]. Let the estimated altimeter signal be,

$$r_e(t) = Ae^{j2\Pi\left(\frac{f_1-f_0}{T}(t-n)^2+f_0(t-n)\right)} \tag{15}$$

where n is the estimated shift in the altimeter signal propagation at the WAIC receiver. Now at the kth WAIC user, $r_e(t)$ is fed into the Gram Schmidt orthonormalization engine along with the signature code $c_k(t)$ used in the transmitter for modulation. The output of the engine gives the component of the code that is orthonormal to the estimated altimeter signal $r_e(t)$. Let the orthonormal component of the signature code for user k be $\sigma_k(t)$. This means the important correlation parameter now will be,

$$g_{j,k} = \frac{1}{T_b}\int_{T_b} c_j(t)\sigma_k(t)\,dt \tag{16}$$

where $0 < g_{j,k} < 1$ for all j, k.

Now, the decorrelation process will be as follows.

$$z_k = \frac{1}{T_b}\int_{T_b} s(t)\sigma_k(t)\,dt \tag{17}$$

$$= \sum_{j=1}^{K} g_{j,k} b_j + \frac{1}{T_b}\int_{T_b} n(t)\sigma_k(t)\,dt + \frac{1}{T_b}\int_{T_b} r(t)\sigma_k(t)\,dt \tag{18}$$

How good or bad the reception is in this case is determined by the error in estimation of the altimeter signal at the WAIC receiver. In one extreme case of no estimation error, the 3rd term of equation 18 will result in 0, as $r(t)$ and $\sigma_k(t)$ would be orthogonal to each other. In the case where there is an estimation error, $r(t)$ and $\sigma_k(t)$ would not be completely orthogonal to each other and reception would ultimately suffer. However, even in the most optimistic case where there is no estimation error of the interference-causing signal (altimeter in this case), the correlation between the component of the known signature sequence with itself would also decide the bit error rate. Naturally, the more accurate the estimate, the better the resistance to the altimeter caused interference.

Now, in the context of WAIC communication in the presence of radio altimeter signal, both reception techniques have been studied.

2.2.2.1 Radio Altimeter Estimation

This section explains a simple process of estimating the altimeter signal. The WAIC receiver performs a cross correlation operation between the received signal (which is composed of the altimeter signal, the WAIC signal intended for the receiver and noise), and the locally generated altimeter signal. Obviously, the altimeter signal component goes through some time delay compared to the known altimeter signal. The cross-correlation process results in a peak at the time delay which the altimeter signal undergoes, compared to the known altimeter signal. In the work, data was observed for 1us at the receiver, before passing to the estimator function.

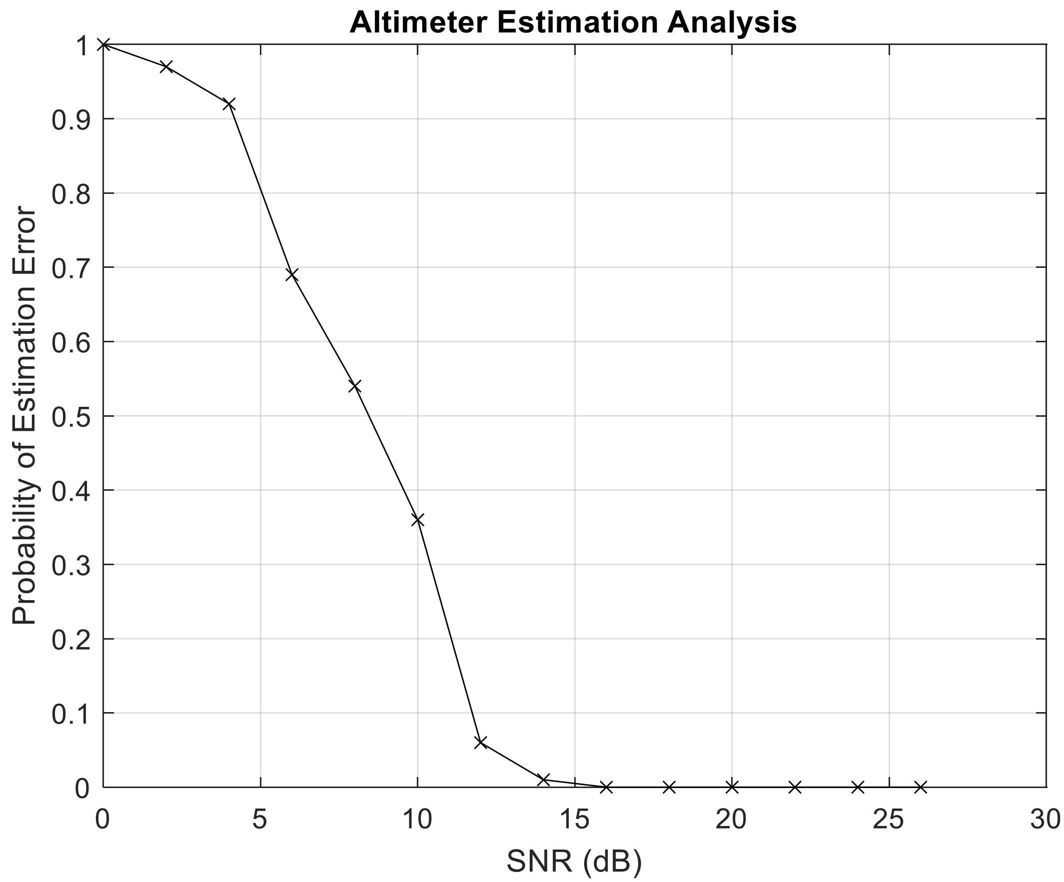

Figure 7: Probability of Estimation Error Analysis

For the experiment in Fig. 7, 1000 iterations were run for each SNR (dB) input parameter (AWGN). The signal power part of the SNR is computed taking 1us worth of the actual time shifted altimeter signal that is attempted to be estimated. If an error in altimeter estimation was observed to be less than 100 kHz, success was declared, else failure was called. Probability of estimation error is the number of fails over the 1000 iterations. It can be stated from the observations of the experiment that reliable estimation of the altimeter signal is only possible in an environment with SNR greater than 12 dB. Since the decorrelator based demodulation is dependent on reliable estimation of the altimeter signal, the system would not work well in environments with high AWGN.

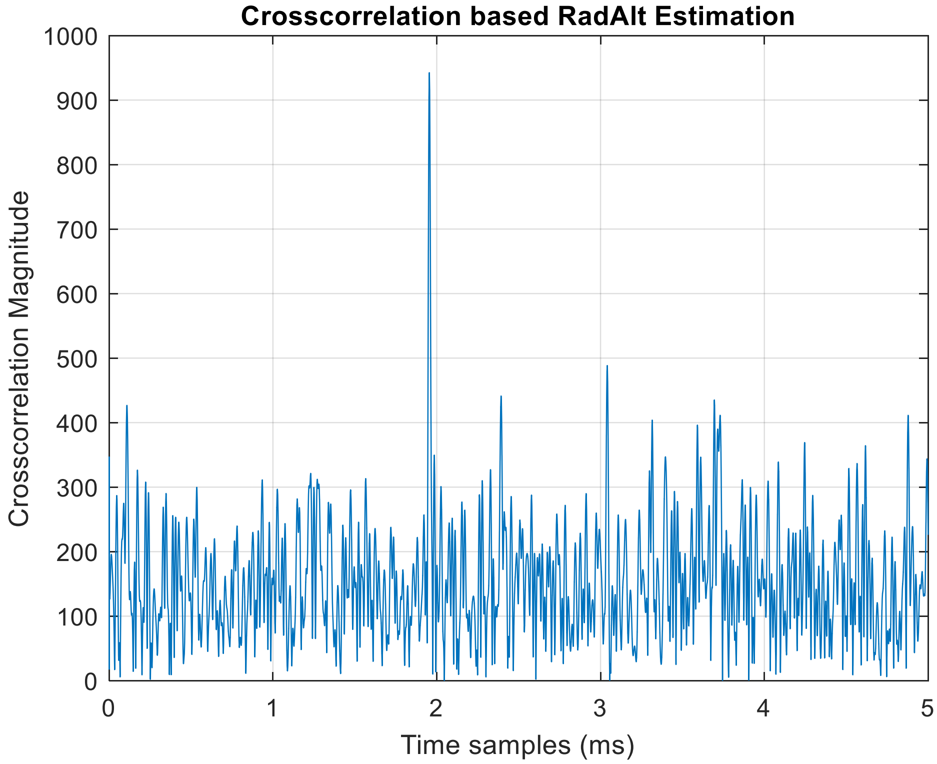

Figure 8: Radio Altimeter Estimation with SNR 15 dB

Fig. 8 shows the results of an experiment in which the altimeter signal was artificially shifted by 2000000 time samples and fed into the estimation engine. As can be seen, a peak around 2 ms is observed, denoting the estimated time delay. SNR due to AWGN is 15 dB. It can be seen that estimating the peak with an SNR of 15 dB will show reliable performance.

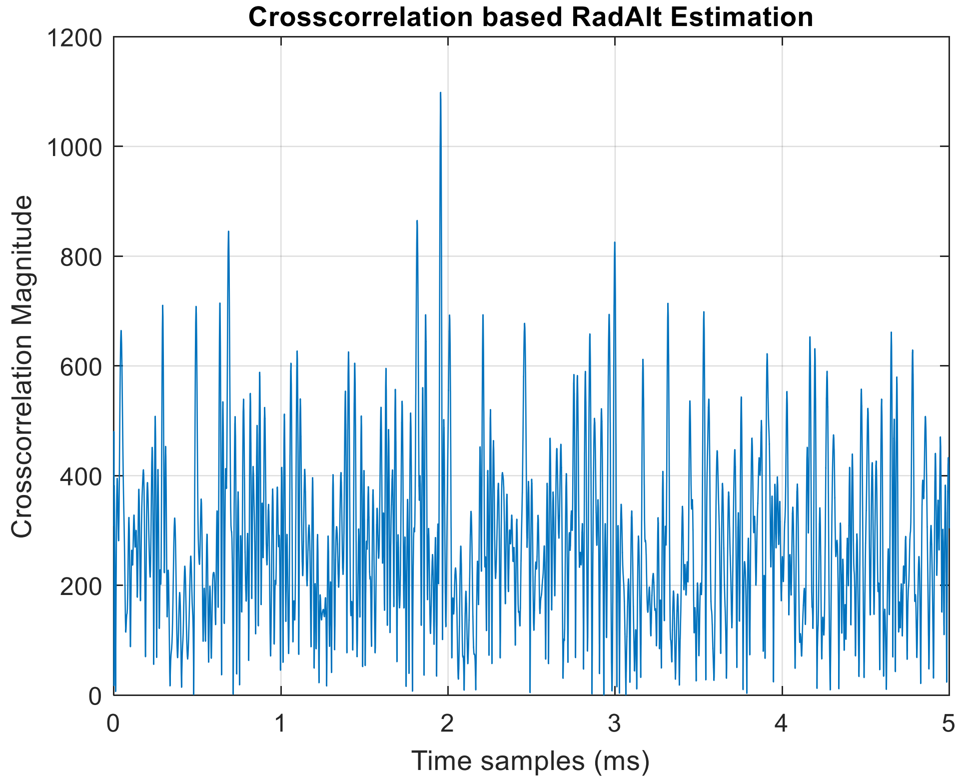

Figure 9: Radio Altimeter Estimation with SNR 10 dB

Fig. 9 is the observation from the same experiment done earlier, but with SNR of 10 dB, in other words in a noisier environment. It shows that there is a larger probability of incorrectly estimating another peak which results from the high AWGN component.

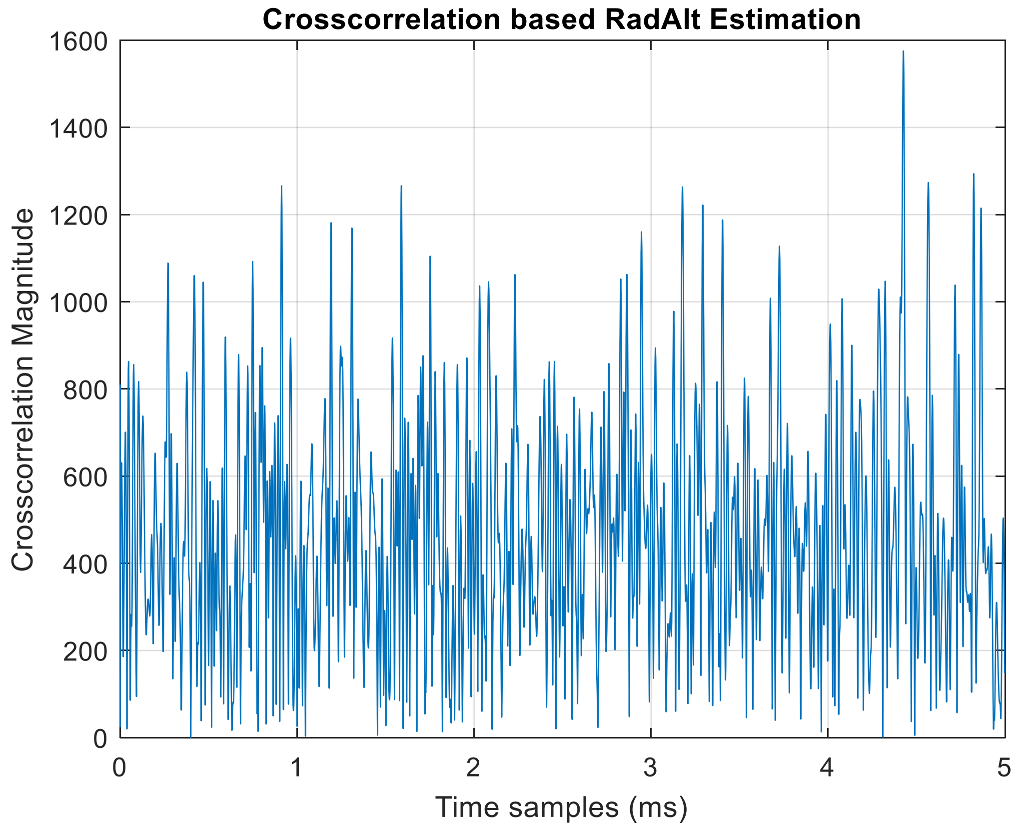

Figure 10: Radio Altimeter Estimation with SNR 5 dB

For Fig. 10, the SNR was further reduced to 5 dB in order to show how the peak estimation effort suffers when strong AWGN is present in the environment. The peak near 2ms is overwhelmed by the noise and the peak is estimated to be near 4.5ms, which is clearly a contribution of the noise.

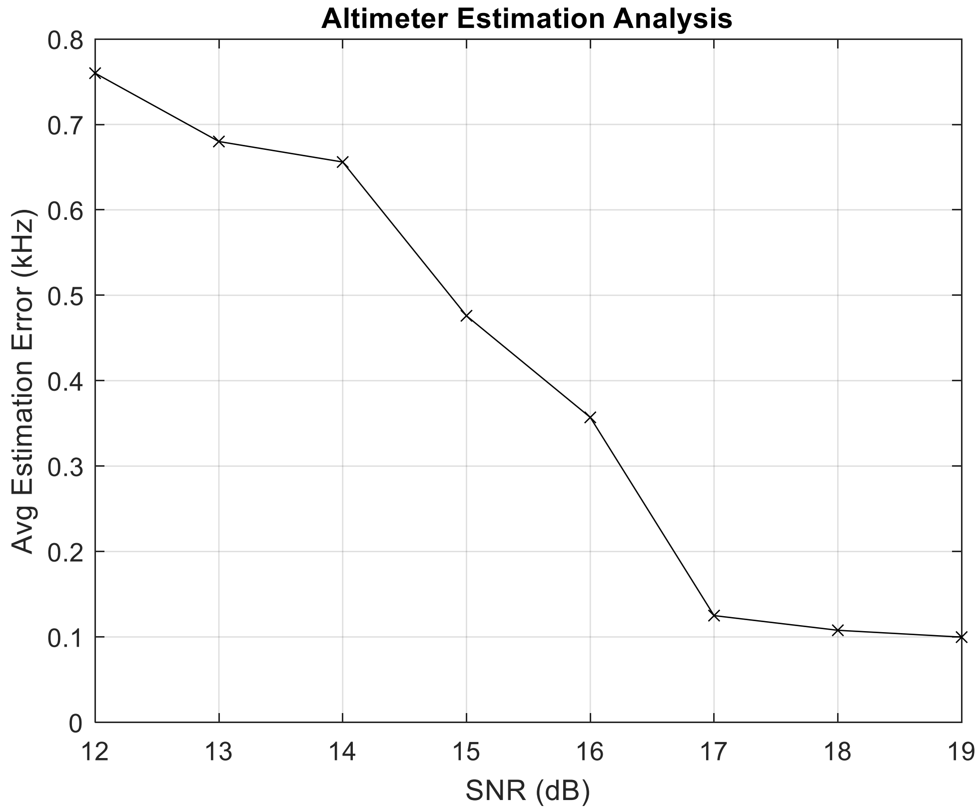

Figure 11: Average Estimation Error (kHz) with Varying SNR

The exercise in Fig. 11 was done to identify a reasonable range for altimeter estimation errors. It is seen that in all iterations (1000) run for every SNR input, average estimation error falls between 0-1 kHz. However, the simple estimation technique discussed above is not able to detect the altimeter signal well for noisy environments (<12 dB). With more sophisticated estimators, it is expected that the range of estimation errors seen in Fig. 11 could be achieved even with lower SNR values. With this assumption, going forward, this work takes altimeter estimation error of 1 kHz for all decorrelator based demodulation analysis for all noise levels shown in the following figures.

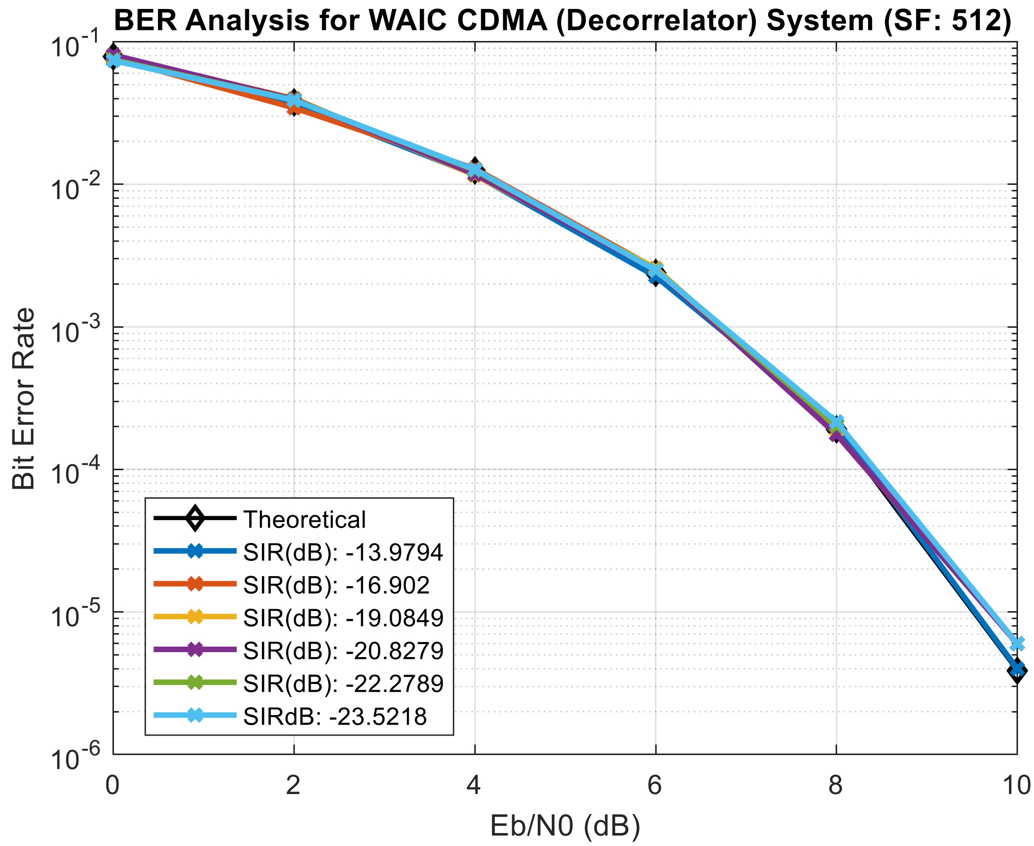

Figure 12: BER Performance Decorrelator based Demodulation

Fig. 12 shows BER performance for WAIC CDMA system based on decorrelator based demodulation. The test set up is same as the one explained earlier below Fig. 6. Just the demodulation for these tests were done using the decorrelator function. With altimeter estimation of 1 kHz, all ranges of altimeter signal strengths tested result in negation of almost all of the interference, due to the use of codes at RX that are orthonormal to the closely estimated RA signals. The bit errors in all cases shown are contributed only by the AWGN, as evidenced by the proximity of all curves to the theoretical BER curve for the AWGN levels.

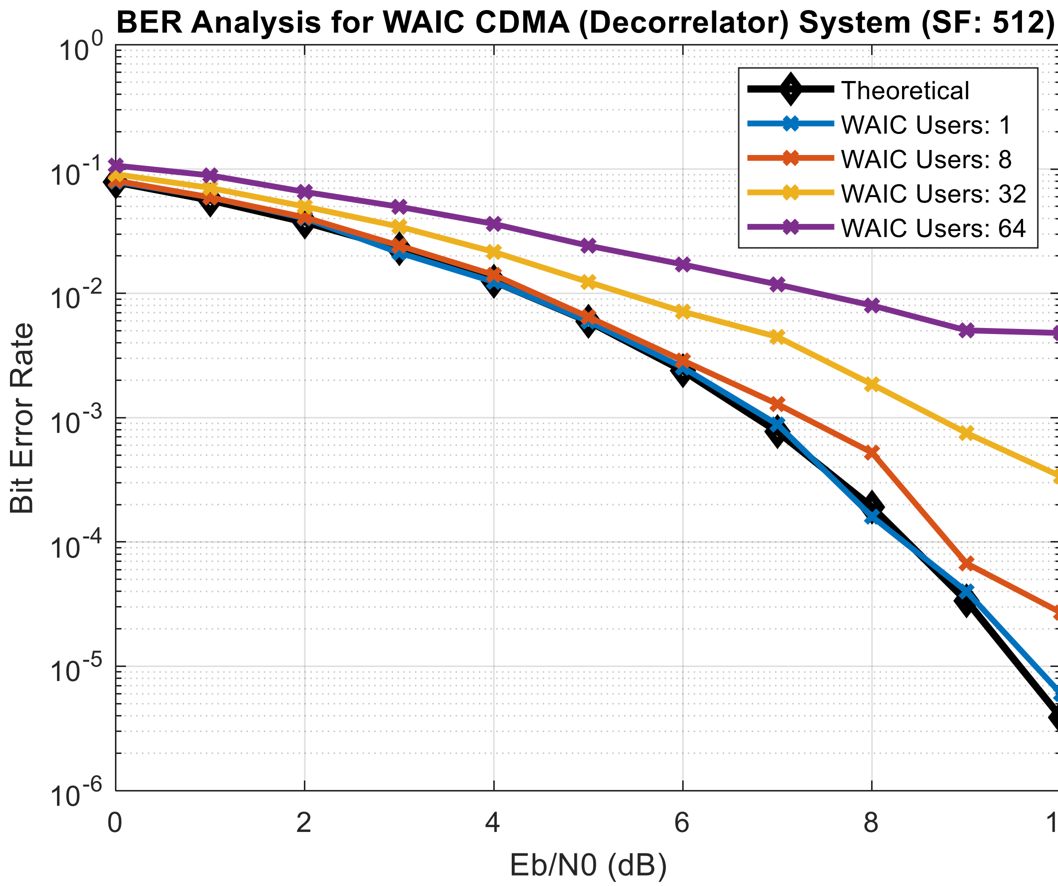

Figure 13: BER Analysis with multiple WAIC users

The tests in Fig. 13 were evaluated by taking the average BER across multiple simultaneously functioning users, for the Eb/N0 level inputs. Asynchronous detection was used in this experiment. As the number of simultaneous users increase in the system, there's increase in interference between users which affects the system performance on top of the altimeter interference. SIR of -23.5 dB was used for this experiment. As seen earlier, with 1 kHz altimeter estimation error, the decorrelator effectively suppresses the interference from the altimeter. So, the increase in BER observed with increasing number of users must be a result of the inter-user interference, which obviously increases with number of users.

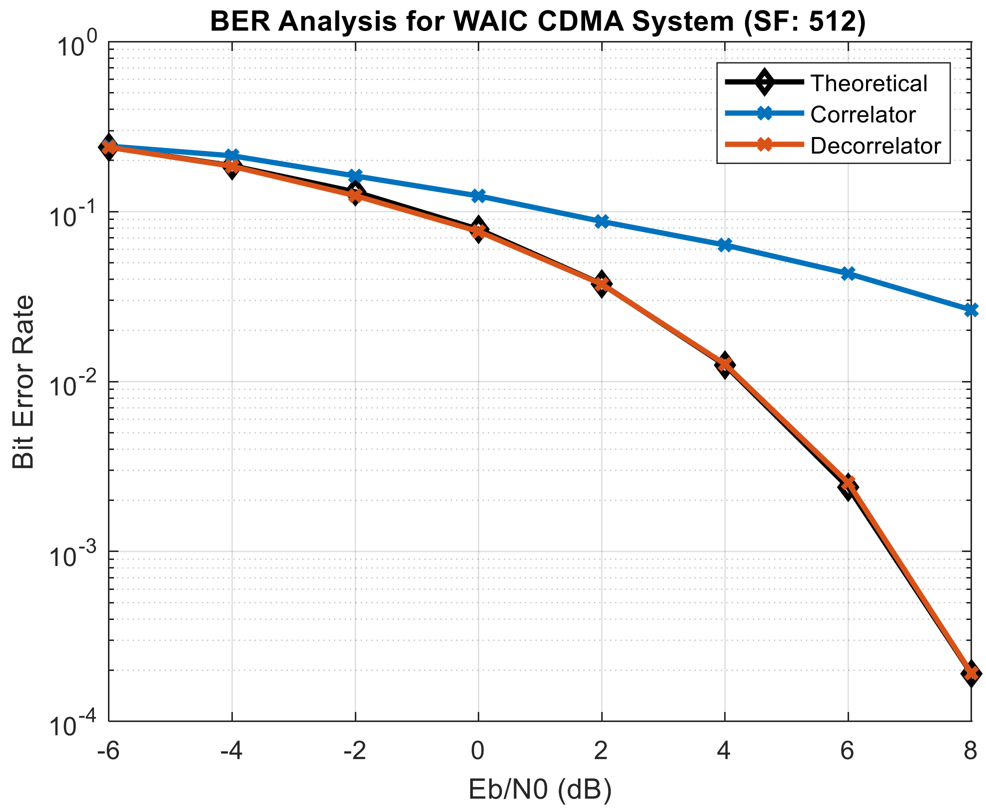

Figure 14: Correlator v/s Decorrelator BER Performance

Fig. 14 shows BER performance between the correlator and the decorrelator based demodulation techniques explained in the previous sections. SIR used was -23.52 dB. As mentioned earlier, altimeter estimation error is taken as 1 kHz for the decorrelator based function. It is seen that the decorrelator based CDMA WAIC system performs as good as the theoretical curve shown, which means all of the altimeter interference is negated by the orthonormal code generated at RX using the estimate of the altimeter signal. So, given a good altimeter signal estimation, the decorrelator based system performs much better in removing the altimeter interference than the correlator based system.

2.3 Spreading Sequence Selection

The codes to be utilized for modulation and demodulation were analyzed for their performance for different use cases. They did not show any significant differences in performance. As a result, this work does not prescribe any particular code for usage in a CDMA based WAIC system.

2.3.1 Walsh-Hadamard Sequences

A square matrix of order k containing values ± 1 in which both rows and columns are orthogonal to each other are known as Hadamard matrices of order k.

$$H(2^1) = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$H(2^2) = \begin{bmatrix} H(2) & H(2) \\ H(2) & -H(2) \end{bmatrix}$$

$$H(2^k) = \begin{bmatrix} H(2^{k-1}) & H(2^{k-1}) \\ H(2^{k-1}) & -H(2^{k-1}) \end{bmatrix} \tag{19}$$

These matrices were first worked on by Sylvester (1867). These matrices are associated with Walsh functions [18], which are discrete orthogonal functions. Hadamard matrices can be used to generate Walsh functions, and due to this associated between the two, these matrices used in telecommunications as spreading sequences are known as Hadamard-Walsh Sequences. For a synchronous DS-CDMA, with say a spreading factor of 1024, a Hadamard matrix of size 2^{10} is generated. Assuming number of users < 1024, any code can be used as signature sequence by a user.

2.3.2 Zadoff-Chu Sequences

Zadoff-Chu sequences are complex-valued sequences which are known to be cyclic orthogonal [19-21]. This means that cyclically shifted versions of a sequence are orthogonal to each other. The original non-shifted sequence is known as the root sequence.

The ZC Sequence is given by equation 20,

$$z_u(n) = e^{-j\left(\frac{\pi u n\left(n+C_f+2q\right)}{N}\right)} \tag{20}$$

where

$0 \le n < N$,

$0 < u < N$ and $gcd(N, u) = 1$,

$C_f = N \bmod 2$,

$q \in \mathbb{Z}$,

N = sequence length = spreading factor used in DS-CDMA.

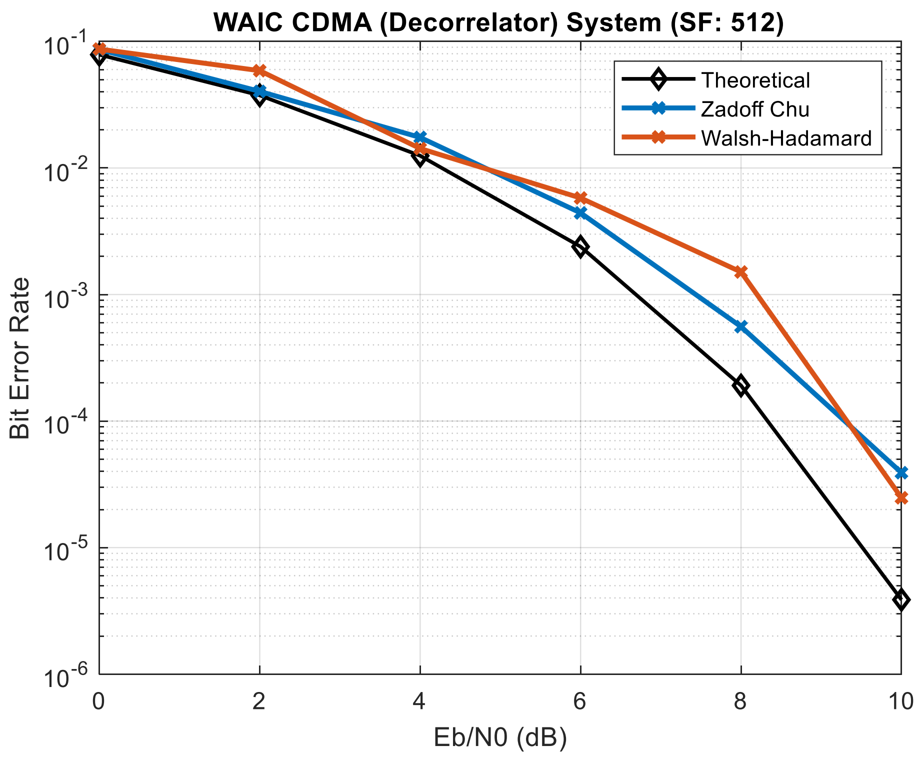

Figure 15: Codeword BER Analysis (Decorrelator), Multiple Users

In Fig. 15, the decorrelator based system with multiple (16) WAIC users was tested to see if either the Zadoff-Chu or the Walsh-Hadamard sequence shows better performance. It was plotted with SIR -23.52 dB. It can be seen that no one code can be said to strictly perform better.

CHAPTER 3
ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

OFDM is a broadband digital modulation technique which is widely used in various communications systems [5]. Robert Chang [23] explained the idea first in 1966, however it wasn't until 1971 that Weinstein and Ebert [24] presented a practical approach that presented OFDM as a viable option. OFDM has become a very popular technique on which many current day systems in cellular technologies such as LTE, LTE-Advanced as well as WLAN technologies such as IEEE 802.11 a/g/n/ac are based on. It presents convenient implementation of these key technologies. In this technique, the band allocated for operation is divided into orthogonal sub-carriers/sub-channels on which samples are sent concurrently. It is known to be robust in environments with interference, as data on only the sub-carriers affected by interference get corrupted. Appropriate error correction techniques can be employed to recover from a portion of the data corruption. It leads to more efficient use of the available bandwidth, compared to simple Frequency Division Multiplexing, where adjacent bands need to be padded with guard bands in order to avoid inter symbol interference. The orthogonality between the sub-channels ensure that a large portion of a sub-channel can be utilized in transmitting data symbols. The aforementioned properties of OFDM make it an interesting solution to the problem of operating a robust WAIC communication system in the presence of Altimeter interference.

3.1 Mathematical Derivation of OFDM

This section will present the mathematical derivation of the OFDM transmit and receive signals.

3.1.1 OFDM TX

A system in which the communication bandwidth is divided such that multiple sub-bands (and multiple sub-carriers) are modulated instead of the single wide band, is known as a Multi-Carrier Modulated (MCM) system. This forms the basis for OFDM. Consider a wide frequency band of B Hz and total sub-carriers as N. That means the spacing between sub-carriers would be B/N Hz.

Then fundamental frequency is $F_0 = B / N$. So, there will be N sub-carriers like …., $-2F_0, -F_0, 0, F_0, 2F_0, \ldots$. Then k^{th} sub-carrier will be $kF_0 = kB/N$. Let k^{th} symbol be X_k. Then the transmitted signal on the k^{th} sub-carrier will be,

$$s_k(t) = X_k e^{j2\pi k F_0 t} \tag{21}$$

The net transmitted MCM across all sub-carriers N would therefore be,

$$x(t) = \sum_k X_k \, e^{j2\pi k F_0 t} \tag{22}$$

3.1.2 OFDM RX

Ignoring noise in the channel for now, from equation 22, the composite signal received is therefore,

$$y(t) = s(t) = \sum_k X_k \, e^{j2\pi k F_0 t} \tag{23}$$

It is interesting to note that the received signal looks like the Fourier series with X_k being the k^{th} Fourier series coefficient. So, in order to recover the symbol on the l^{th} sub-carrier, X_l the l^{th} Fourier coefficient can be recovered in the following manner,

$$X_l = F_o \int_0^{1/F_0} e^{-j2\pi l F_0 t} y(t) \, dt \tag{24}$$

$$= F_o \int_0^{1/F_0} e^{-j2\pi l F_0 t} \sum_k X_k \, e^{j2\pi k F_0 t} \, dt \tag{25}$$

$$= \sum_k X_k \, F_o \int_0^{1/F_0} e^{-j2\pi (k-l) F_0 t} \, dt \tag{26}$$

Now, the term $F_0 \int_0^{1/F_0} e^{-j2\pi (k-l) F_0 t} \, dt$ is 1 if $k = l$ and 0 if $k \neq l$ as it is an integration of a sinusoid over its fundamental period $1/F_0$. Then equation 26 reduces to,

$$X_l = \sum_k X_k \delta(k - l) \tag{27}$$

This is the coherent demodulation with $e^{-j2\pi l F_0 t}$ to extract X_l.

This can be done for recovering the symbols corresponding to all N sub-carriers.

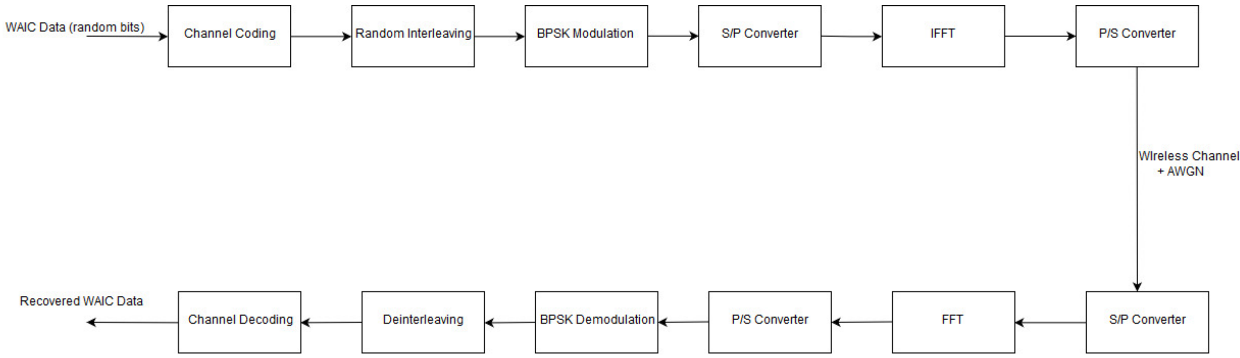

Figure 16: OFDM System

3.2 WAIC OFDM System Model

This section will explain how the OFDM system is implemented for the WAIC setup. The wireless channel is assumed to only have AWGN. Interference will be caused by the presence of the Altimeter signal in the same frequency range (4.2 GHz – 4.4 GHz). Each block shown in Fig. 16 is explained in detail in the following subsections.

3.2.1 Channel Coding/Decoding

3.2.1.1 Convolution Coding

The WAIC system model based on OFDM was designed with a forward error correction coding scheme for which convolution coding was used. They were introduced by Elias first in 1955 [25]. [26] In 1967, Viterbi presented a maximum likelihood based decoding scheme, which carved the path for modern convolution codes.

Convolution encoding is basically done by passing a sequence of input/data bits into a linear finite-state shift register. The constraint length K determines the number of stages of the shift register. A $(K-1)$ bit shift register would be needed. It also comprises of logic function entities. For the WAIC model, a constraint length of $K=7$ was chosen. Assume k to be the number of bits input into the encoder module at a time, and n to be the number of encoded bits output. The code rate is determined by $R_c = k\,/\,n$. In the WAIC context, k was chosen as 1, whereas n was chosen to be

2, which means every data bit is encoded with an additional redundant bit for protection. This means the code rate $R_c = 0.5$.

To illustrate how the machinery works, a simple example with $K = 4$, $k = 1$ and $n = 2$ is presented below in Fig. 17.

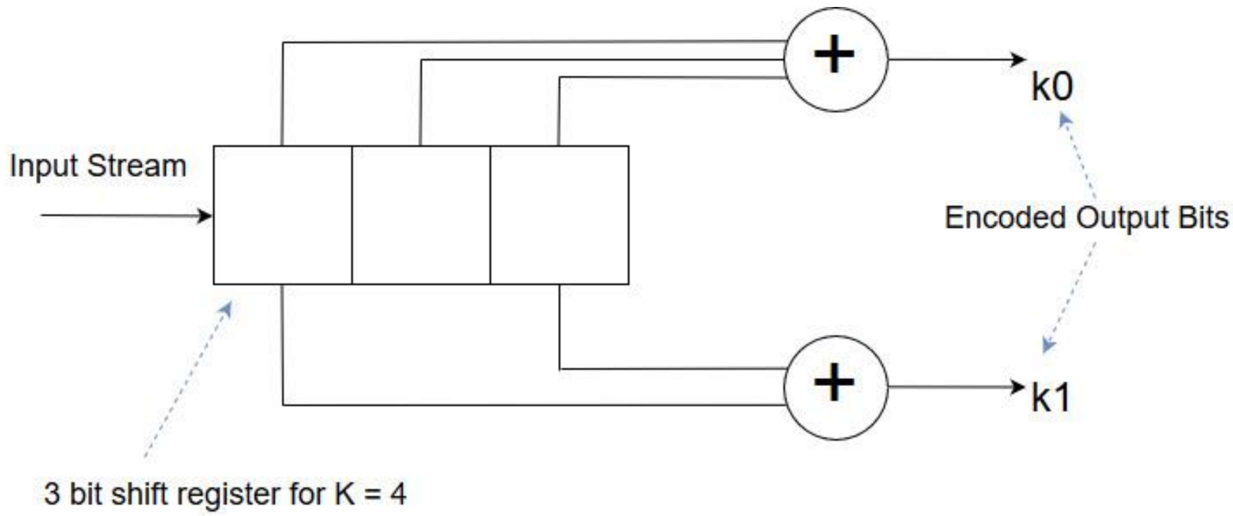

Figure 17: Convolution Coding Implementation

The illustration suggests that a bit is encoded based on knowledge of its two previous input bits and the current bit (that just moved into the shift register). The function that determines which of the current shift register entries produce the encoded output bits are given by generator polynomials. They were taken as $1 + x^3 + x^4 + x^5 + x^6$ and $1 + x + x^3 + x^4 + x^6$ for the convolution coding.

3.2.1.2 Viterbi Decoding

A major task of the error correction technique is the decoding process. Viterbi decoding was used as the decoding technique in the WAIC OFDM system model. If the channel does not induce any errors in transmission, the original data can be recovered by removing the redundant bits added in the encoding process, using something like the Viterbi algorithm. However, the task becomes challenging when data bits get corrupted in transmission. There are two ways in which decoding can be performed. Both are explained below.

3.2.1.2.1 Hard Decision Decoding

Hard decision decoding is performed by sampling received pulses and comparing them to threshold values. Depending on whether voltage values are greater or lesser than the threshold value, decision is taken to qualify them as a 1 or a 0. The decoding does not take into account the proximity of the voltage values to the threshold, and take a "hard" decision based on where they simply lie with respect to the threshold value.

3.2.1.2.2 Soft Decision Decoding

Soft decision decoding is performed by decoding a block of bits and qualifying them in a possible range of values. This leads to better estimates of the original data as the reliability of every pulse received is taken into account. The WAIC OFDM system model employs soft decision decoding.

3.2.2 Interleaving/Deinterleaving

Interleaving is a technique employed in error correction methods. It is especially important when the propagation medium causes burst errors. The intention is to spread the encoded bits out so that after the deinterleaving process at the receiver, the decoder perceives the supposedly contiguous errors as random errors. In the WAIC OFDM system model, block interleaving/deinterleaving was performed. A permutation mapping was used by the interleaver to randomly spread the bits out. The deinterleaver function which had access to the mapping inverses it and restores the original symbol sequence.

3.2.3 Modulation/Demodulation

The modulation scheme employed was Binary Phase Shift Keying (BPSK). Data symbols were interpreted as either +1 or -1. At the receiver side, in the BPSK demodulation they were mapped down to the original data symbol values of 0 and 1.

3.2.4 IFFT/FFT

Looking at equation 22 once again,

$$x(t) = \sum_k X_k \, e^{j2\pi k F_0 t}$$

Practically implementing this would be difficult if there are large number of sub-carriers intended to be transmitted on. For example, if there are 1000 sub-carriers, there would be a need of placing 1000 oscillators for transmitting at precisely the 1000 sub-carrier frequencies. Now, the frequency band was considered as B Hz earlier. So, let $F_{max} = B \,/\, 2$ and since the signal is bandlimited to F_{max}, it can be sampled at the Nyquist rate of $2F_{max} = B$ Hz. So, the Nyquist sampling interval is $\frac{1}{B} = T$. Then, l^{th} sampling instant is $lT = l/B$.

Now,

$$x(l) = x(lT) = \sum_k X_k \, e^{j2\pi k F_0 lT} \tag{28}$$

$$= \sum_k X_k \, e^{j2\pi k (\frac{B}{N}) l (\frac{1}{B})} \tag{29}$$

$$= \sum_k X_k \, e^{j2\pi (k/N) l} \tag{30}$$

Equation 30 shows $x(l)$ to be the l^{th} Inverse Discrete Fourier Transform (IDFT) of $X_0, X_1, X_2 \dots \dots . X_{N-1}$. Hence the composite transmitted signal can be generated by an Inverse Fast Fourier Transform (IFFT) engine. IFFT is just an efficient way of performing the IDFT.

Similarly, at the receiver the symbol transmitted on l^{th} sub-carrier, X_l can be recovered from the received signal with the Discrete Fourier Transform (DFT) process which can be efficiently implemented using a Fast Fourier Transform (FFT) engine.

3.2.5 WAIC System

The WAIC system used for OFDM evaluation can be explained with assistance from the following figure.

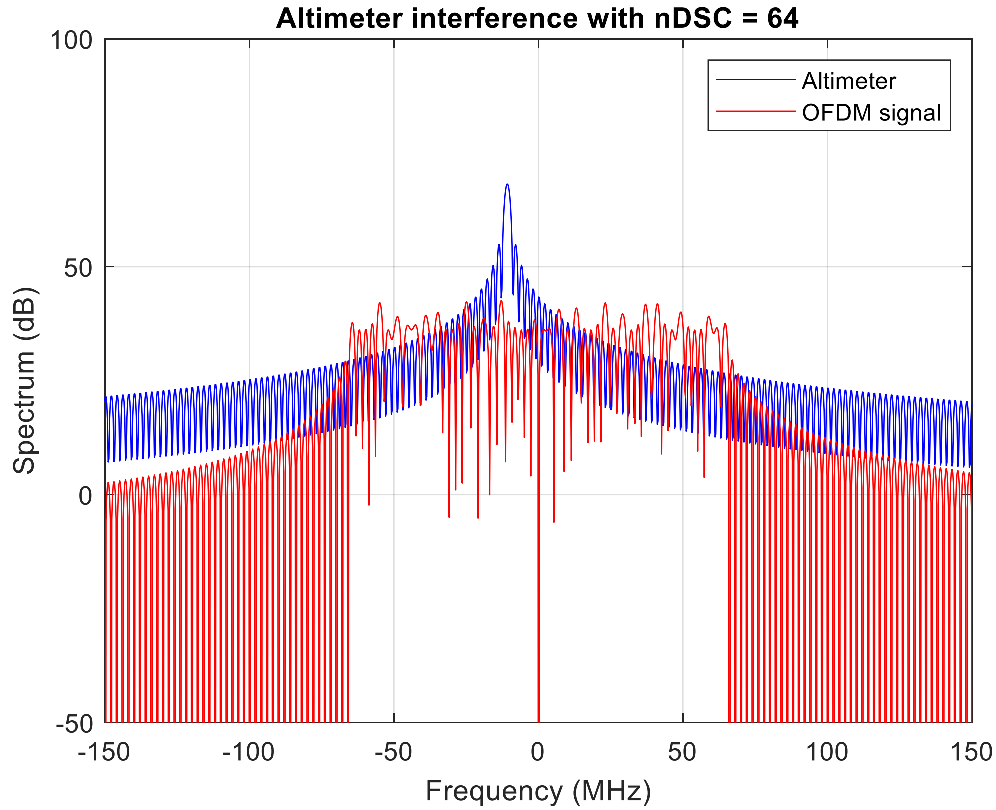

Figure 18: Altimeter Interference with SIR -14 dB

The plot in Fig. 18 is generated using the following parameters.

Number of data symbols (Nsymb) = 10,000

Altimeter sweep period (SP) = 5ms

Altimeter BW @baseband (B) = 100 MHz

Sampling frequency (Bs) = 10*B = 1000 MHz

Data Symbol Time (T) = SP/Nsymb = 0.5 us

OFDM BW (W) = 1/T = 2 MHz

FFT points (nFFT) = 2^ceil(log2(ceil(Bs/W))) = 512

OFDM sub-carrier spacing (df) = W/nFFT = 4 kHz

Number of data subcarriers (nDSC) depends on number of bits desired to be transmitted. This would determine how many of the 512 (nFFT) subcarriers are used for transmitting data. In a case where it is decided to use 64 data subcarriers, as in Fig. 18, 32 bits in total can be transmitted, as the rest of the 32 subcarriers would carry the appended bits for protection against errors (for coderate 1/2 as described in section 3.2.1.1). Fig. 18 shows operation of an OFDM symbol. The figure also shows the interference from the altimeter signal (with SIR -14 dB) affecting the OFDM symbol. The effect of varying the altimeter strengths on subcarriers will be seen in the following sections.

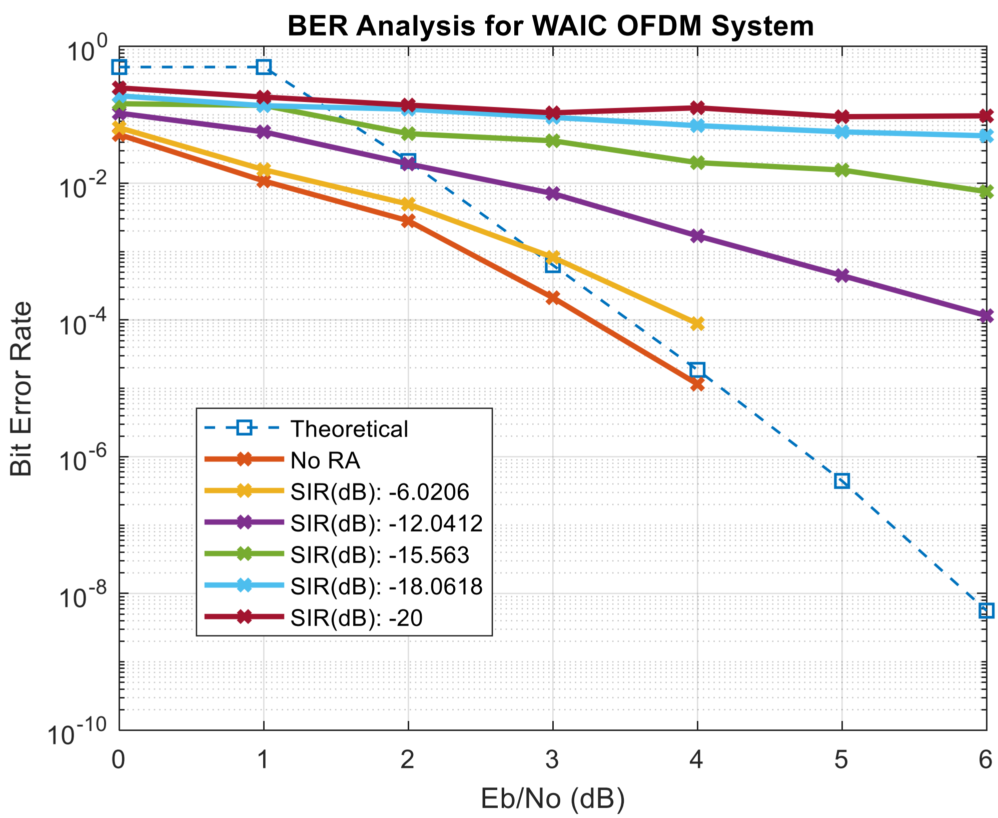

Figure 19: OFDM with Different RA Signal Strengths

Fig. 19 shows the BER performance of a WAIC OFDM system described above with 64 data subcarriers. The BER is calculated by running the simulation till 200 bits are seen in error or till 320000 WAIC data bits are transmitted in total, whichever occurs first. The ‘Theoretical’ curve seen as a dotted line on the plot shows the theoretical upper bound for convolution coding, generated using the same parameters that were used in WAIC system. It is seen in the plot that BER performance suffers as the altimeter strength increases. That can be explained with the following figure.

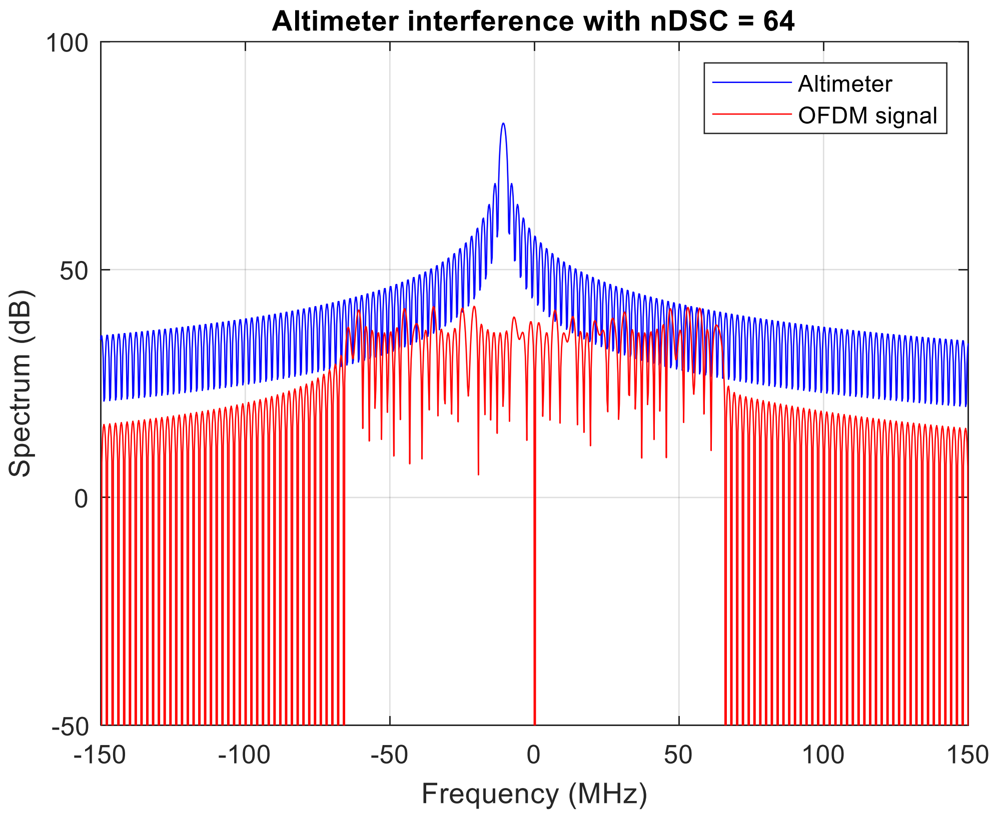

Figure 20: Altimeter Interference with SIR -28 dB

Fig. 20 shows how with a stronger altimeter interference (compared to Fig. 18), the effect of the interference becomes more pervasive across the data carrying subcarriers. That is the reason why in Fig. 19, curves spread out further from the ideal with higher altimeter signal strength.

3.3 Performance Improvement Techniques

Cognitive Radio [27][28] is a technique used by devices to intelligently sense communications channels in order to adjust their transmission/reception for improving the efficiency of their communications. In [29] the authors discuss a number of techniques for protection of primary user (PU) communications in a cognitive OFDM environment in which there exists high interference for PUs transmitting partly in bands occupied by a secondary user (SU).

In [30] and [31], the authors discuss the use of multiple-choice sequences and constellation expansion techniques, both of which exhibit the need for relaying sideband information to the receiver that results in overheads. Approaches such as ones presented in [32-36] discuss active interference cancellation (AIC) schemes where the receiver is not dependent on side channel information for reducing the interference. A couple of intuitive schemes were studied for performance benefits in a WAIC system environment.

3.3.1 Transmission Turnoff of Potentially Affected Subcarriers

This approach presents an enhancement technique on the transmission side. It requires an adaptive understanding of the interference caused by the SU (the altimeter in the WAIC context). Depending on the portion of the sweep cycle where the altimeter lies, a particular set of the sub-carriers of the WAIC user would be affected most. The idea is to switch off transmission on the affected sub-carrier set. In other words, no data symbols are modulated on the set of identified sub-carriers.

This exercise causes notches in those sub-carriers as they contain no data, as can be observed in Fig. 21. SIR used was -20 dB. Realtime sensing of the set of affected sub-carriers is beyond the scope of this work.

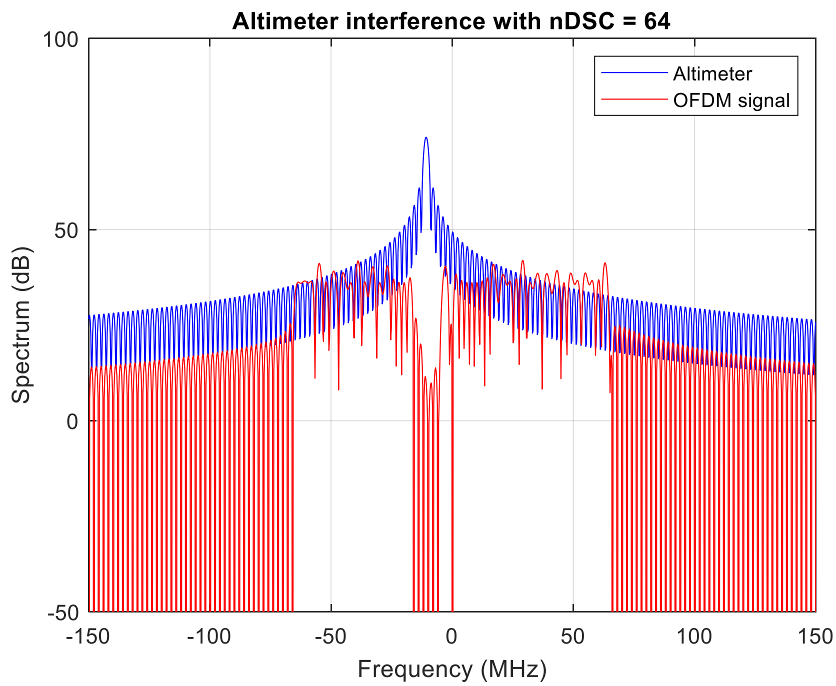

Figure 21: Notched Out Subcarriers at TX

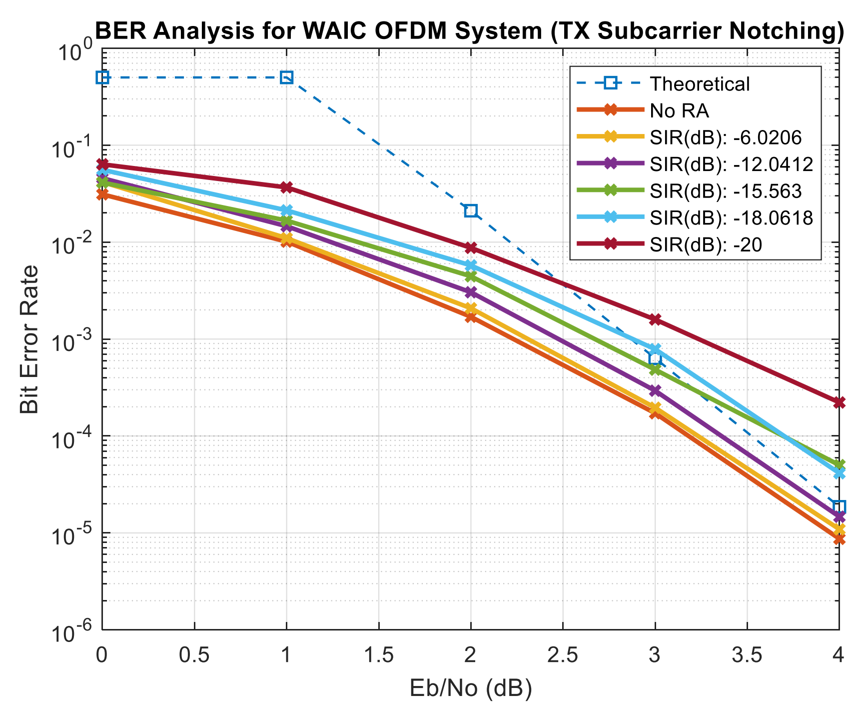

Figure 22: OFDM Performance with Subcarrier Notching at TX

Fig. 22 shows that when potentially harmed subcarriers are left unutilized during transmission, curves corresponding to stronger altimeter signals are observed to be moving closer to the ideal curve. This shows that this cognitive radio technique helps remove the altimeter interference, thus making the WAIC communications more robust.

3.3.2 Assume Null Reception at Potentially Corrupt Subcarriers

Another approach that depends on sensing the medium is to make adjustments on the receiver side. Sensing the positioning of the altimeter signal, an estimation of the sub-carriers suffering from the maximum interference can be made. Fig. 23 shows that data symbols on approximately the 25^{th} to 30^{th} sub-carriers suffer from maximum interference from the altimeter. Those potentially corrupt sub-carriers are assumed to be carrying 0s (as seen in Fig. 24) and after deinterleaving the entire stream is fed into the decoder. The process of intelligent estimation of region of maximum interference is beyond the scope of this work.

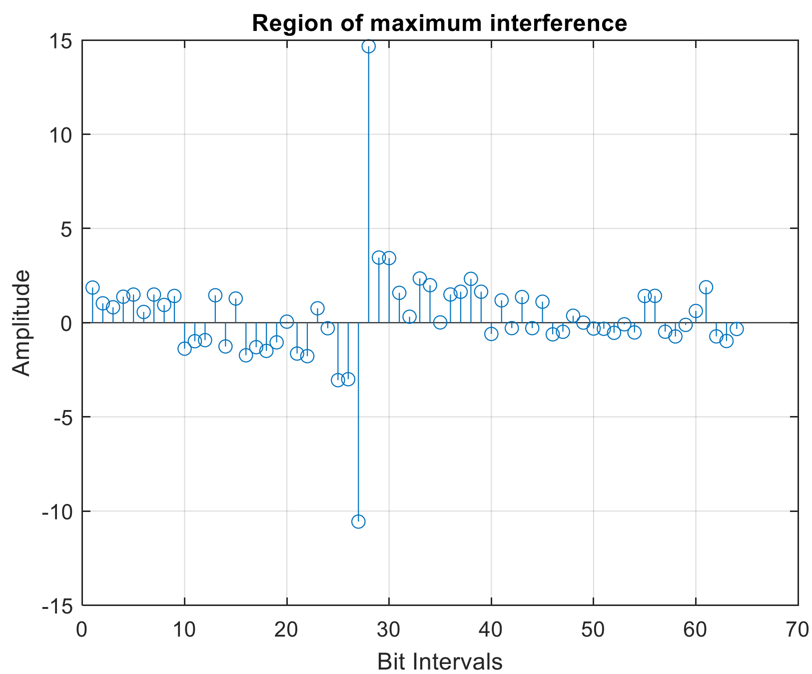

Figure 23: Most Affected Bit Intervals from RA Interference

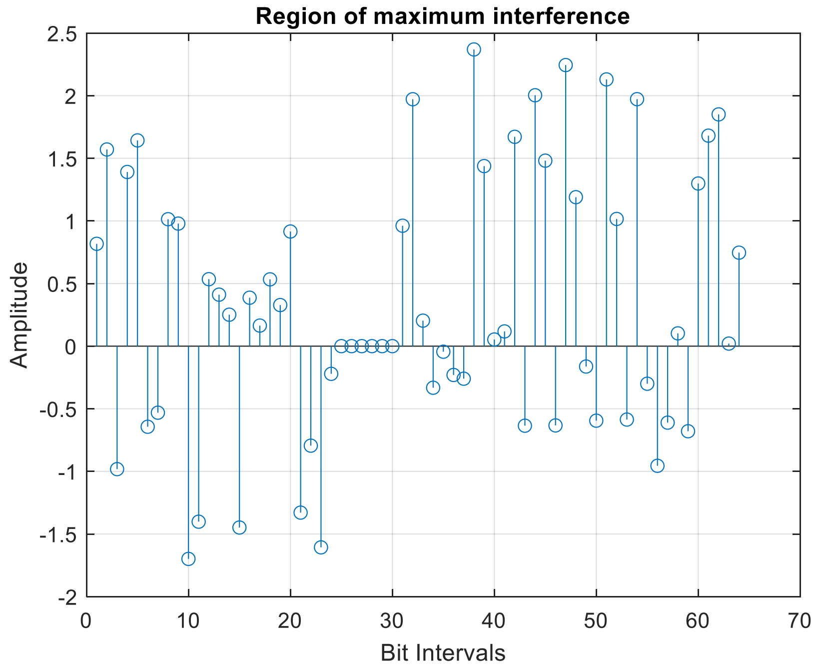

Figure 24: Interference Mitigation by Nulling Affected Subcarrier Reception

The simulations for Figs. 23 and 24 are performed with SIR of -29.5 dB. Fig. 24 shows subcarriers 25 – 30 having zeros. This is from the processing at RX. These were the subcarriers carrying the maximum bit energies.

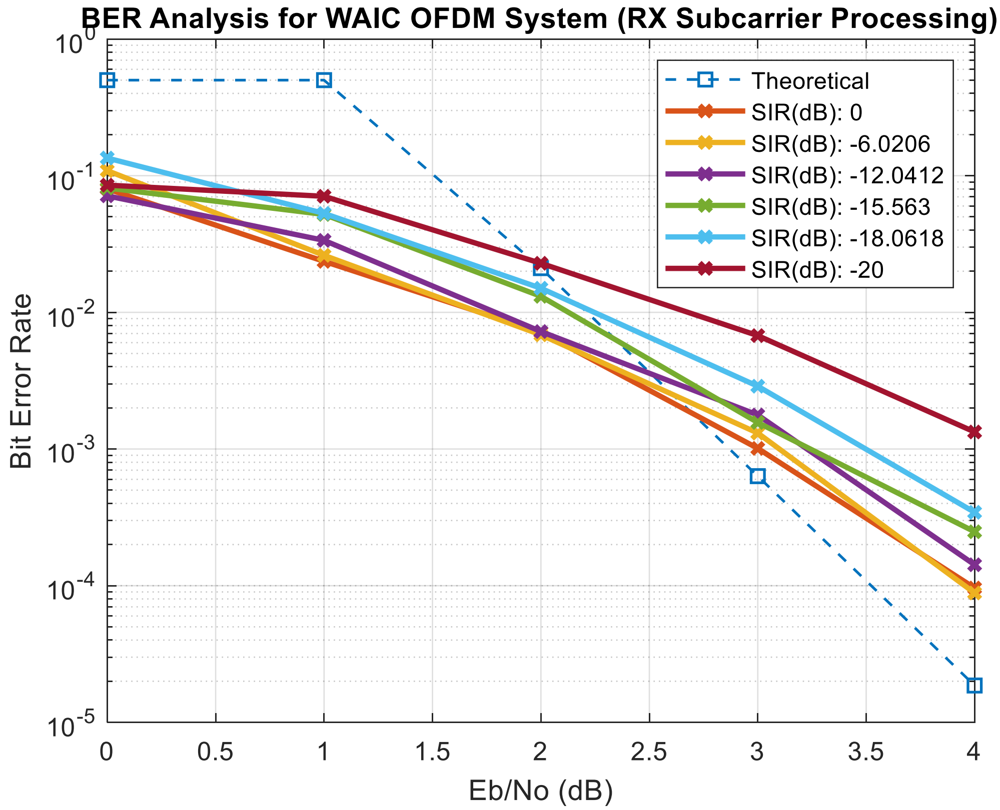

Figure 25: OFDM with Nulling Affected Subcarrier Reception Performance

Similar to the plot for TX notching of subcarriers (Fig. 22), effects of altimeter interference seem to get nullified even in this enhancement procedure. Now, which enhancement scheme performs better is analyzed in the next couple of figures.

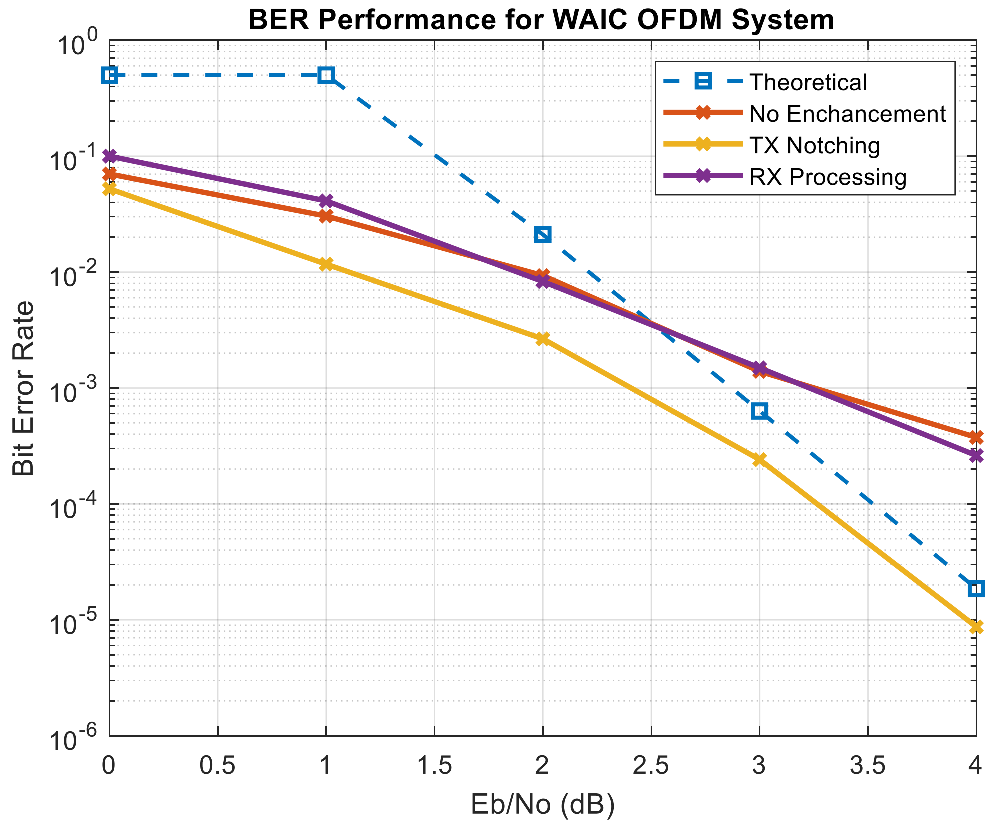

Figure 26: Performance Comparison between OFDM Techniques (weak RA)

Fig. 26 shows a performance comparison between the different OFDM techniques discussed till now. It uses a relatively weaker altimeter interference with SIR of - 9.5 dB. It is seen that intelligent subcarrier notching at TX to leave faulty subcarriers unutilized performs better than the other techniques.

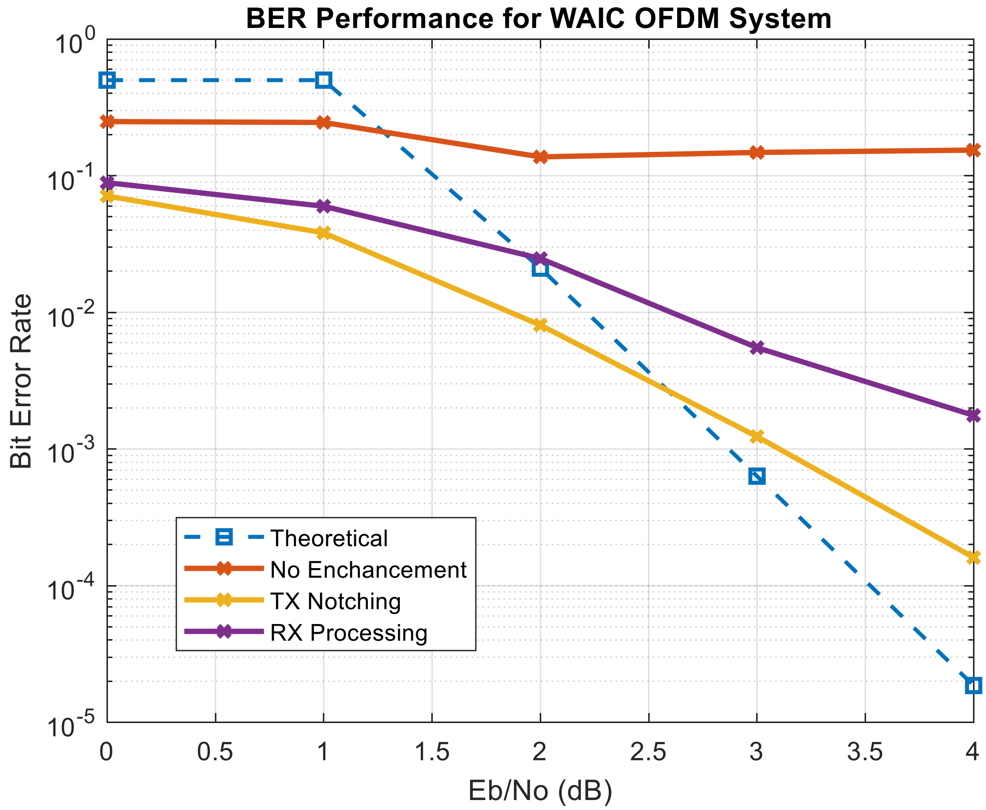

Figure 27: Performance Comparison between OFDM Techniques (strong RA)

Fig. 27 shows a performance comparison between the different OFDM techniques using a relatively stronger altimeter interference with SIR of -20 dB. Even in this case, intelligent TX subcarrier notching performs better than other techniques.

CHAPTER 4

COMPARISON BETWEEN WAIC OFDM AND WAIC DS-CDMA

A comparison of the WAIC systems based on OFDM and DS-CDMA is shown in Figs. 28 and Figs. 29. The better performing techniques from both the systems were picked for this analysis. For the DS-CDMA system the decorrelator based mechanism was used whereas for OFDM the subcarrier notching at TX method was used. To ensure fair comparison between the two techniques, FEC functionality was added to the DS-CDMA WAIC system using the same parameters as the OFDM system (described in section 3.2.1).

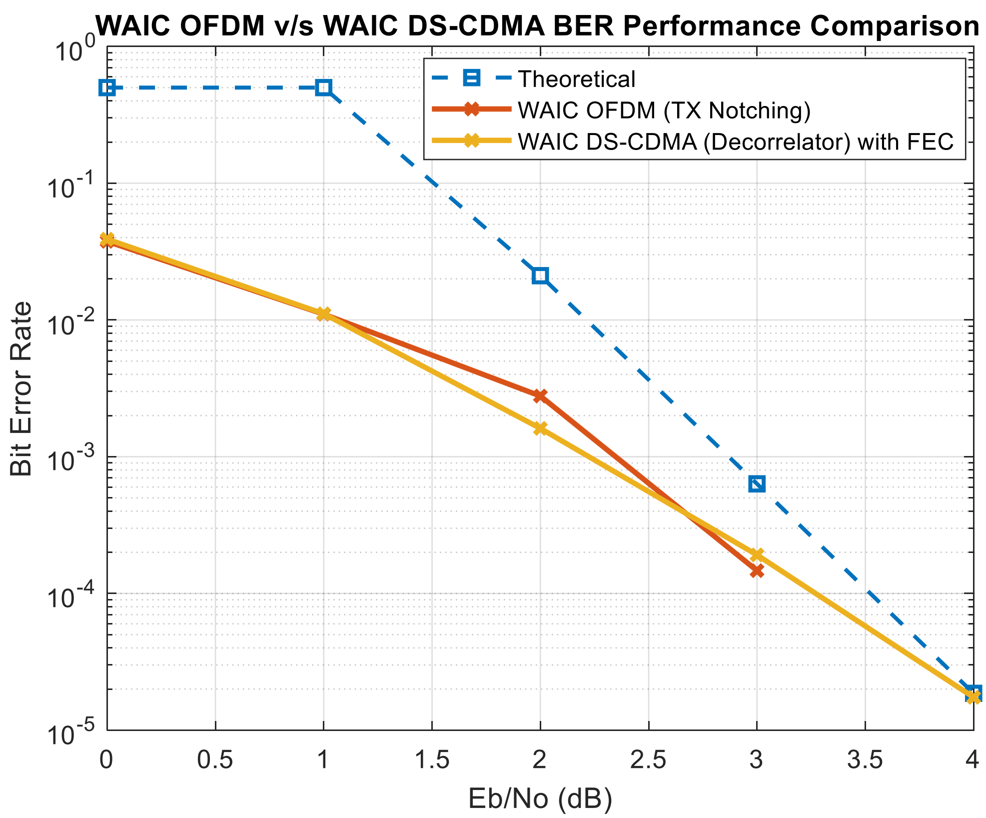

Figure 28: BER Performance OFDM v/s CDMA (weak RA)

The experiment in Fig. 28 takes a weak altimeter interference (SIR -9.54 dB) for the comparison simulations. The DS-CDMA technique performs slightly better than OFDM for a weak altimeter signal.

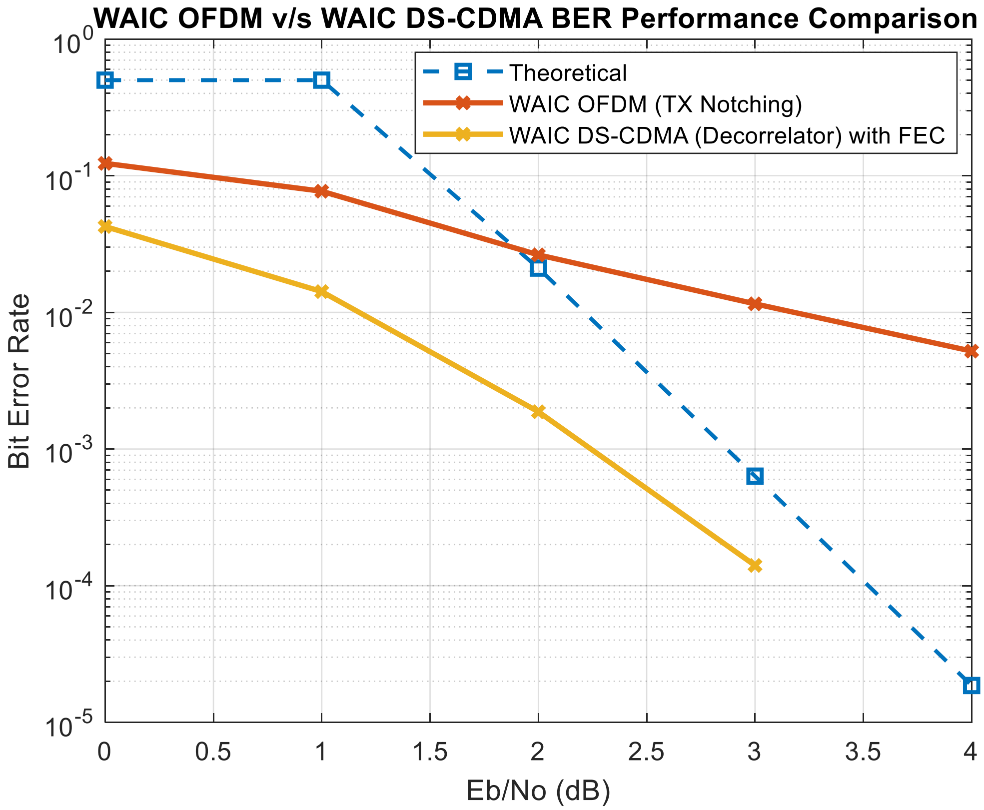

Figure 29: BER Performance OFDM v/s CDMA (strong RA)

The simulation in Fig. 29 uses a strong altimeter interference (SIR -24 dB) for causing interference. The property of the decorrelator based CDMA system, in which a good altimeter estimation technique makes sure that even interference from strong altimeter signals are negated, clearly gives an advantage to the WAIC DS-CDMA system compared to the OFDM based system. It can hence be said that the CDMA system is more robust to increase in altimeter signal strength than the OFDM based WAIC system.

CHAPTER 5
CONCLUSION AND FUTURE WORK

This work has presented techniques for building wireless communications systems for facilitating WAIC communications. The widely popular CDMA and OFDM wireless communications techniques were evaluated for their feasibility in implementing WAIC systems operating in the 4.2 GHz – 4.4 GHz frequency band. Since the same band is also used for the radio altimeter service, the framework for all analysis was the influence of different altimeter strengths on the proposed WAIC systems. In CDMA, the decorrelator based demodulation technique was compared with the correlator based technique and it was identified that given a good altimeter estimator, the former successfully negates the interference from different altimeter strengths. In the future, work can be done to design a more sophisticated altimeter estimation technique in order to make the device robust in noisier environments. In OFDM, different enhancement techniques were studied for their performance benefits in tackling altimeter interference. All modulation/demodulation in this work was done using simple BPSK. In the future, other modulation schemes can be evaluated with the presented communications schemes. A performance evaluation of the systems described can also be done with fading channels.

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