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MISSILE TELEMETRY SYSTEM DESIGN AND PERFORMANCE ANALYSIS

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MISSILE TELEMETRY SYSTEM DESIGN AND PERFORMANCE ANALYSIS

ABSTRACT

Telemetry is either wired or wireless remote monitoring or control of a system. It is also used in the sense of 'receiving remote measurement' as a word meaning. Thanks to the telemetry system, various data belonging to a system are collected from a certain distance and this data is transmitted to a point to be displayed. Telemetry system is used in many application areas. Within the scope of this study, the focus is on the missile telemetry system.

During the development phase of the missiles, various External Store Certification tests are carried out. These tests are very important for collecting data and determining the working limits for the design of the weapon system and its subcomponents under development. The more ground and flight tests performed, the more accurately the design works. A telemetry system is needed at the stage of collecting this data. Thanks to the test head part placed instead of the warhead, data is collected from the electronic card and various sensors in the missile.

In this study, the missile telemetry system design and the Telemetry System Performance Calculator Interface program developed in line with this design are emphasized. Thanks to this interface, Link Margin of the Signal to Noise Ratio value is calculated by taking into account the Radio Frequency communication values used in the telemetry system on both the transmitting and receiving sides and the modulation types. According to these modulation types, telemetry communication performances are compared. As a result of the study, Link Margin of the Signal to Noise Ratio in Binary Phase Shift Keying and Quadrature Phase Shift Keying modulations are better than other modulations.

As a result of these studies, we provide a more reliable environment for pre-flight by pre-determining the communication parameters of the telemetry equipment required for missile telemetry system design.

Keywords: Telemetry, missile telemetry system, modulation, Link Margin, Telemetry System Performance Calculator Interface.

FÜZE ÜSTÜ TELEMETRİ SİSTEM TASARIMI VE PERFORMANS ANALİZLERİ

ÖZ

Telemetri bir sistemin kablolu veya kablosuz olarak uzaktan izlenmesi veya kontrol edilmesidir. Kelime anlamı olarak da ‘uzaktan ölçüm alma’ anlamında kullanılır. Telemetri sistemi sayesinde, bir sisteme ait çeşitli veriler belli bir mesafeden toplanır ve bu veriler görüntülenecek bir noktaya iletilir. Telemetri sistemi birçok uygulama alanlarında kullanılır. Bu çalışma kapsamında, füze telemetri sistemi üzerinde yoğunlaşılacaktır.

Füzeleri geliştirme aşamasında çeşitli Harici Yük Sertifikasyonu testleri gerçekleştirilir. Bu testler, geliştirilmekte olan silah sistemi ve alt bileşenlerinin tasarımına yönelik veri toplanması ve çalışma sınırlarının belirlenmesi için oldukça önemlidir. Ne kadar çok yer ve uçuş testi olursa tasarım o kadar yüksek doğruluk ile çalışır. Bu verilerin toplanması aşamasında telemetri sistemine ihtiyaç duyulur. Harp başlığı yerine yerleştirilen deneme başlığı kısmı sayesinde füze içerisinde bulunan elektronik kart ve çeşitli sensörlerden veri toplanır.

Bu çalışmada, füze telemetri sistem tasarımına ve bu tasarım doğrultusunda geliştirilen Telemetri Sistem Performans Hesaplayıcı Arayüz programı üzerinde durulmuştur. Bu arayüz sayesinde, telemetri sisteminde kullanılan hem verici hem de alıcı taraftaki RF haberleşme değerleri ve modülasyon çeşitleri dikkate alınarak Sinyal Gürültü Oranı Link Marjin değeri hesaplanır. Modülasyon türlerine göre telemetri haberleşme performansları karşılaştırılır. Çalışma sonucunda, İkili Faz Kaydırmalı Anahtarlama ve Karesel Faz Kaydırmalı Anahtarlama modülasyonlarında Sinyal Gürültü Oranı Link Marjin değerleri diğer modülasyon çeşitlerine göre daha iyi çıkmıştır.

Yapılan bu çalışmalar sonucunda, füze telemetri sistem tasarımı için gerekli olan telemetri ekipmanlarının haberleşme parametrelerini önceden belirleyerek uçuş öncesi için daha güvenilir bir ortam sağlamış oluruz.

Anahtar Kelimeler: Telemetri, füze telemetri sistemi, modülasyon, Link Marjin, Telemetri Sistem Performans Hesaplayıcı Arayüzü.

CONTENTS

NOMENCLATURE

Roman Letter Symbols

A_{eff}	: Effective Area, m^2
BR	: Bitrate, Mbits/s
BW	: Bandwidth, Hz
c	: Speed of Propagation, m/s^2
E	: Electric Field, V/m
F	: Noise Factor
f	: Frequency, Hz
G	: Gain, dB
I	: Intensity, W/m^2
I_L	: Insertion Loss, W
k	: Boltzmann Constant
N	: Noise, dB
L	: Loss, dB
NF	: Noise Figure, dB
P	: Power, W
P_L	: Transmitted Power, W
P_{rx}	: Signal Level of Receiver
P_t	: Incident Power, W
R_L	: Return Loss, dB
S/N	: Signal to Noise Ratio, dBm
T_e	: Equivalent Noise Temperature, K
V	: Voltage, V
Z_L	: Load Impedance, ohm
Z_0	: Line Impedance, ohm
Γ	: Reflection Coefficient
λ	: Wavelength, m

Acronyms

AR	: Axial Ratio
ASK	: Amplitude Shift Keying
AWGN	: Additive White Gaussian Noise
BER	: Bit Error Rate
BFSK	: Binary Frequency Shift Keying
BPSK	: Binary Phase Shift Keying
CAN	: Controller Area Network
CPFSK	: Continuous Phase Frequency Shift Keying
dB	: Desibel
dBm	: Desibel Milliwatts
dBW	: Desibel Watt
EIRP	: Effective Isotropic Radiated Power
FDM	: Frequency Division Multiplexing
FS	: Frame Synchronization
4-FSK	: Four-Frequency Shift Keying
FSPL	: Free Space Path Loss
GPS	: Global Positioning System
GPRS	: Ground Penetrating Radar System
HYS	: Harici Yük Sertifikasyonu
Hz	: Hertz
IF	: Intermediate Frequency
IRIG	: Inter-Range Instrumentation Group
K	: Kelvin
km	: Kilometer
LNA	: Low Noise Amplifier
m	: Meter
MFSK	: Multiple Frequency Shift Keying
MHz	: MegaHertz
mW	: Miliwatts
NRZL	: Non-return-to-zero Level
PCM	: Pulse Code Modulation
PCM/FM	: Pulse Code Modulation/Frequency Modulation
8-PSK	: Eight- Phase Shift Keying

QPSK	: Quadrature Phase Shift Keying
RCC	: Range Commanders Council
RF	: Radio Frequency
S/N	: Signal to Noise Ratio
TDC	: Top Dead Center
TDM	: Time Division Multiplexing
TMATS	: Telemetry Attributes Transfer Standard
VCO	: Voltage Controlled Oscillator
VSWR	: Voltage Standing Wave Ratio
W	: Watt
WLAN	: Wireless Local Area Network

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CHAPTER 1

INTRODUCTION

1.1 Background

The concept of telemetry first appeared in the 19th century. In 1845, using the first wired communication, it started to be implemented with the communication between the Russian Tsar's Palace and the army. In 1874, French engineers established a telemetry system capable of transmitting data in real time to transmit the weather data on Mont Blanc Mountain to Paris [1].

In the 1930s, wireless telemetry communication studies started in parallel by Robert Bureau and Pavel Molchanov. It has been widely used in the rocket and aviation industries. It was used in test flights when the parameter of the German V-2 rocket needed to be observed. A system called Messina was developed to obtain these parameters. However, the Messina system has not been found reliable. Von Braun, the creator of the rocket, said that it would be more useful to watch the rocket with binoculars [2]. As a system similar to Messina was needed, it was quickly replaced by a better telemetry system. By the end of 1940s, the United States started to download data from the missile to the ground with PCM and the Soviets with different modulation types.

Today, the level of development of the missile is increasing with the development of technology. For example, missiles that can adapt to different environmental conditions, have the ability to successfully hit moving targets and have a long range are being developed. Telemetry systems used in missile systems help us in the development and improvement of ammunition.

In our country, TÜBİTAK-SAGE (The Scientific and Technological Research Council of Turkey- Defense Industry Research and Development Institute) and ROKETSAN continue their research and development studies in the field of missile development.

1.2 General Overview of Telemetry System

Telemetry is the wired or wireless monitoring or control of a system. The purpose of the telemetry system is to collect data from a distance that is difficult to reach or from a distance and to transmit the data to a point where the data is displayed [3]. This is done using a wireless or wired communication channel. It is needed for testing moving objects such as airplanes, missiles, launch vehicles. The missile telemetry system is a system that collects the data of the ammunition, the data of the ammunition or various sensors such as vibration, pressure, temperature measured on the aircraft, the Mux Bus data sent from the aircraft, sends them to the Ground Station in real time in the appropriate format or saves them on a recording medium for post-flight analysis. system as a whole. As a working process, the data belonging to the sensors and ammunition are collected by the data collection system and then transmitted to the antennas via RF by being modulated by the transmitter. Telemetry data is received via the receiving antenna in the ground station and demodulated at the receiver. The data is then analyzed in real time or recorded on a recording medium [4]. The general telemetry system structure is shown in Figure 1.1.

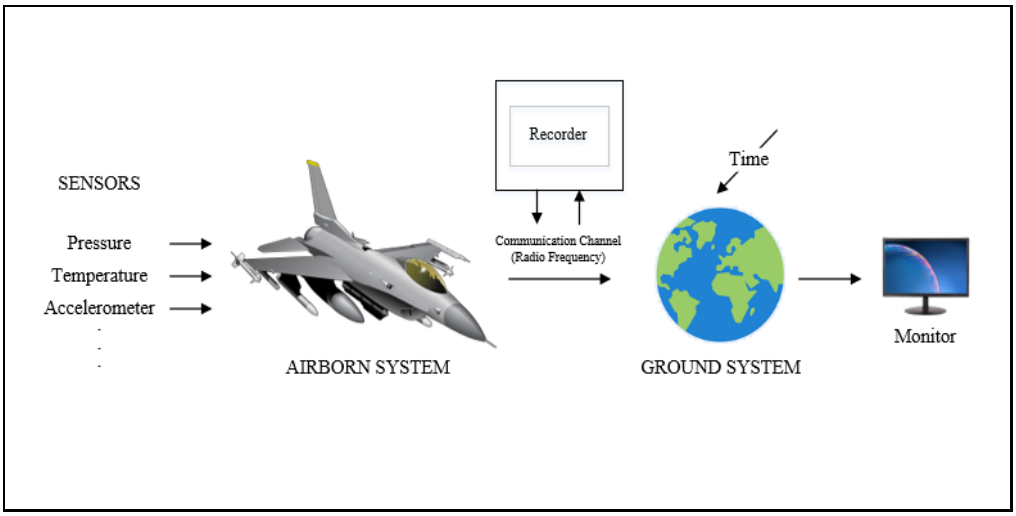

Figure 1.1 Basic Telemetry System

There are various HYS tests to ensure the compatibility between the ammunition and the platform. HYS tests are divided into 2 parts as ground and flight tests. These tests are very important for collecting data on the design of the sub-components of the

weapon system under development, verifying their designs, determining the working limits, demonstrating their compatibility with the platforms they work with, and comparing the accuracy of the requirements defined by the technical team. It is repeated under different ambient conditions and compared with previously obtained parameters. The more ground and flight tests, the more accurately the design works [5].

1.3 Telemetry Applications

Telemetry system has a wide range of applications such as [6]:

- Remote health monitoring.
- Monitoring of predators.
- Aerospace applications
- Monitoring of wastewater plants or lakes.
- Remote reading of water, natural gas, electricity meters.
- Monitoring the level of liquid tanks.

The studies carried out with the usage areas of the telemetry system are given below.

Duchrow, T. and colleagues used a telemetry system to monitor vehicle fleets as a result of their studies. They provided the communication in this system with GPRS. Data collection was done using CAN network. Thus, the information of the vehicles was collected properly and transferred to the computer [7]. Ustun, O. et al. used a telemetry system to transfer the voltage, current and battery charge rate of their solar powered vehicles to both the vehicle driver and the vehicle's computer [8]. Tucker used a telemetry system for the tracking of CarettaCaretta to find out the spawning time of A. D. CarettaCaretta turtles [9]. Durmuş, M. determined the habitat sizes and seasonal habitat selection areas by wearing a collar around the endangered gazelles. The communication of the telemetry system is provided by GPS [10]. Manir has designed an intelligent telemetry algorithm that will eliminate the communication

interruptions that may occur in the E. RF modem and end the data loss [11]. Yüksel designed a telemetry system that will measure water meters thanks to the design he made using E. ZigBee. This measurement system provides gain and convenience to many people [12].

1.4 IRIG Standard 106

The RCC was established in 1951 to find solutions to very common problems and to develop operational test standards and procedures for range use. RCC's Telemetry Group has prepared the IRIG Standard 106, known as the Telemetry Standard, to increase the compatibility of telemetry equipment during transmission, reception and processing of signals at ranges [13]. IRIG Standard is widely preferred in ammunition applications. The IRIG 106 Standard has many chapters. The most important ones are shown below.

- Chapter 4 - PCM Telemetry [13]
- Chapter 9 - TMATS [13]
- Chapter 10- Solid State On-Board Recorder Standard [13].

1.5 Telemetry PCM Frame Structure

PCM is a digital transmission system technique. The presence or absence of a pulse within a predetermined time slot indicates a logic state of 1 or 0. It is preferred in telemetry applications. It is easier to send, record and analyze digital data in PCM systems. It is less sensitive to noise than analog systems [13].

Data is transmitted in packets called Frame. Frame consists of bit strings. This array has start and end points. Telemetry PCM Frame formats are defined in accordance with the IRIG Standards. There is usually a synchronization word at the beginning or end of the frame structure. It is expressed as Frame Synchronization. The FS moves to the beginning of the next minor frame. In this way, each minor frame is separated using FS. The structure of the PCM Frame defined in Chapter 4 of the IRIG 106 Standard is shown in Figure 1.2.

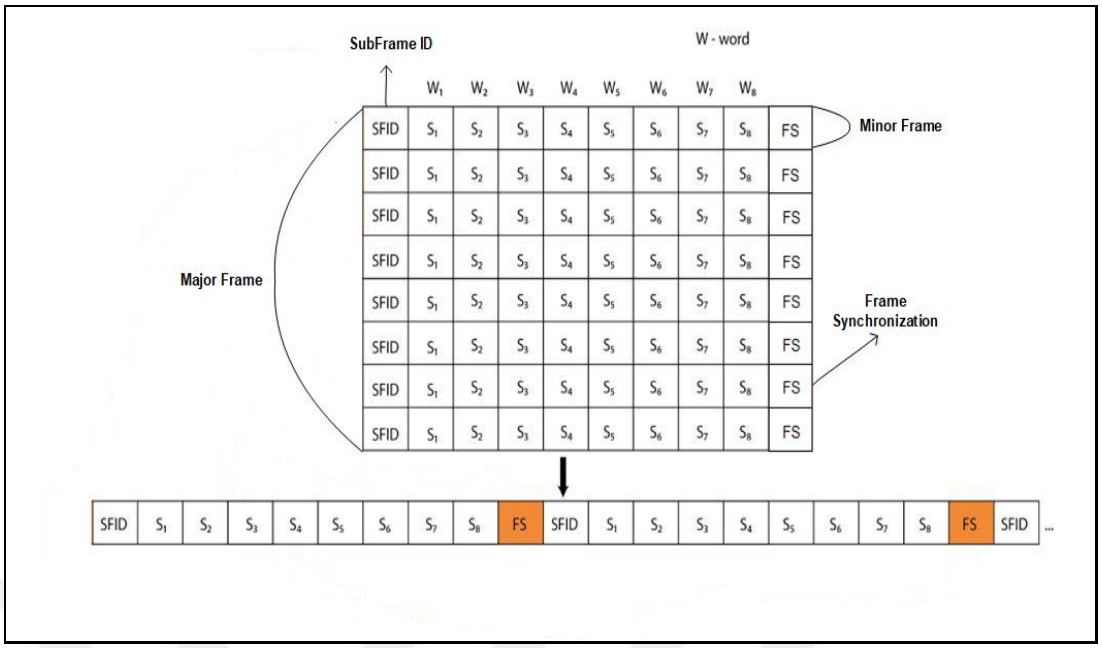

Figure 1.2 PCM Frame Structure

The FS model usually consists of 2 words. The optimum pattern values that the FS model can take are shown in Figure 1.3.

Pattern Lenght	Hex	Pattern Code															
16	eb90												1110	1011	1001	0000
17	1e6a0											1	1110	0110	1010	0000
18	3cd40											11	1100	1101	0100	0000
19	7cca0											111	1100	1100	1010	0000
20	ede20											1110	1101	1110	0010	0000
21	1dd2c0										1	1101	1101	0010	1100	0000
22	3cda80										11	1100	1101	1010	1000	0000
23	7ae680										111	1010	1110	0110	1000	0000
24	faf320										1111	1010	1111	0011	0010	0000
25	1f2dc40									1	1111	0010	1101	1100	0100	0000
26	3e9ac0									11	1110	1001	1010	1100	1100	0000
27	7d69980									111	1101	0110	1001	1001	1000	0000
28	f5e5980									1111	0101	1110	0101	1001	1000	0000
29	1ebccd00								1	1110	1011	1100	1100	1101	0000	0000
30	3ebccd00								11	1110	1011	1100	1100	1101	0000	0000
31	7f37d420								111	1111	0011	0111	1101	0100	0010	0000
32	fe6b2840								1111	1110	0110	1011	0010	1000	0100	0000
33	1f74e9498							1	1111	0111	0100	1110	1001	0100	1001	1000

Figure 1.3 Optimum frame synchronization patterns for PCM telemetry [14]

The bitrate value is calculated according to the values of the data size in the frame.

$$Words/Minor\ Frame = x \tag{1.1}$$

$$Minor\ Frame/Major\ Frame = y \tag{1.2}$$

$$Major\ Frame\ Frequency\ (Sampling\ Rate, Hz) = z \tag{1.3}$$

$$Bits/Words = 16 \tag{1.4}$$

$$Bitrate\ (Mbps) = x.y.z.16 \tag{1.5}$$

The process in which multiple bit streams with different data rates are combined in a single frame is called commutation [15]. The most important types are shown below.

1.5.1 Normal Commutation

Measurands may be sampled once every minor frame.

Normal commutation									
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7

Figure 1.4 Normal Commutation [14]

1.5.2 Sub Commutation

Measurands may be sampled less than once per minor frame.

Sub commutation									
	FS	SFID	Sensor 1	Sensor a	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor b	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor c	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor a	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor b	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor d	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7

Figure 1.5 Sub Commutation [14]

1.5.3 Super Commutation

Measurands may be multiple times every minor frame.

Super commutation								
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 1	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 1	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 1	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 1	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 1	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 1	Sensor 6	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 1	Sensor 6	Sensor 7

Figure 1.6 Super Commutation [14]

1.5.4 Random Commutation

Measurands may be sampled randomly within major frame.

Random commutation									
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor b	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor a	Sensor 4	Sensor 5	Sensor b	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor a	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor a	Sensor 4	Sensor 5	Sensor b	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor b	Sensor 7
	FS	SFID	Sensor 1	Sensor 2	Sensor b	Sensor 4	Sensor 5	Sensor b	Sensor 7

Figure 1.7 Random Commutation [14]

CHAPTER 2

RF Commutation

2.1 Components of Communication Process

Communication is the transmission of information from the source to the user through the communication channel. A communication system consists of the information source, input transducer, transmitter, communication channel, receiver, output transducer and destination source from which the information to be sent is produced. (Figure 2.1)

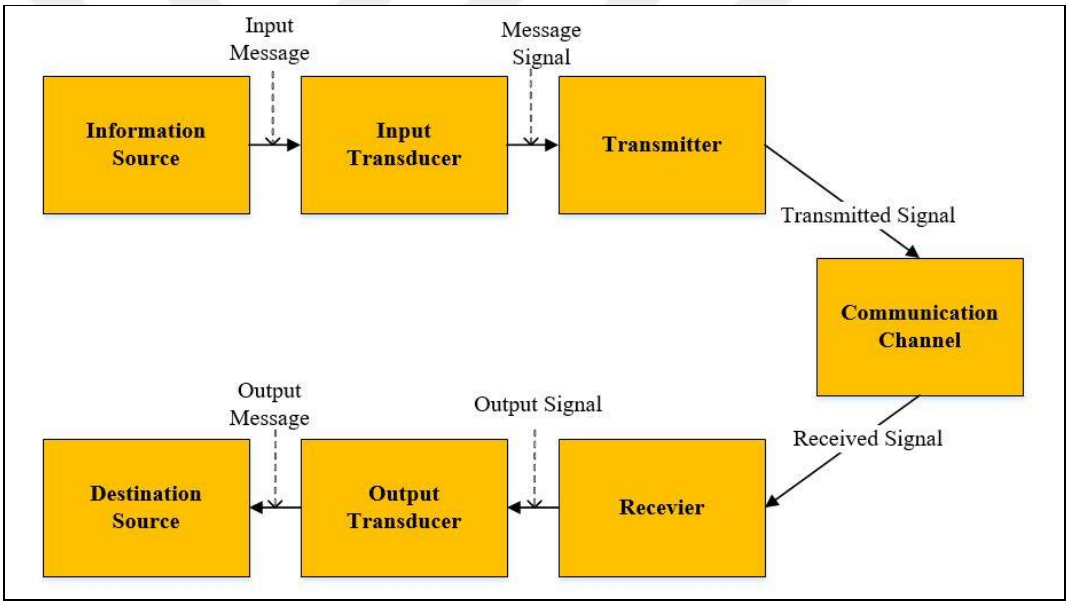

Figure 2.1 Basic Communication System

2.1.1 Types of Signal

An input message is an analog or digital signal. Analog signals are waves that amplitude and frequency are constantly changing over time. For example; sound, sine wave etc. Digital signal is a signal whose amplitude and frequency varies from one fixed level to another. For example; data, serial binary code etc.

2.1.2 Input Transducer

The devices that convert the information they perceive from the sensors into suitable for us to use and convert the sensed information into electrical energy are called. For example; the microphone converts the human voice into an electrical signal called a message signal or baseband signal.

2.1.3 Transducer

It converts the message signal to the transmission channel in order to transmit it more efficiently. For example; if the communication channel is fiber optic cable, the transmitter converts the message signal to light frequency. In this way, the transmitted signal is light. The modulation takes place at the transmitter.

2.1.4 Communication Channel

It is a physical medium used to transmit the message signal from the transmitter to the receiver. It is divided into 2 parts.

- Guided Media
- Unguided Media

Guided media is known as a wired media. For example; twisted pair, coaxial cable, fiber optic cable etc.

Unguided media is known as a wireless medium. Electromagnetic waves of different frequencies are used. For example; satellite, infrared, microwave etc.

2.1.5 Receiver

The receiver tries to convert the received signal into the original message signal sent from the source. It converts the received signal into the appropriate format for the output converter. The demodulation process takes place at the receiver.

2.1.6 Output Transducer

It converts the message signal to the original waveform.

As an example of the basic communication system, the working principle of the mobile phone can be given as an example [17].

- Person speaking on the phone (Information source).
- The microphone converts sound into an electrical signal (Input transducer).
- Sending a signal from the transmitting antenna in the base station to the receiving antenna (Communication channel).
- The speaker converts the electrical signal back to sound (Output transducer).
- Listening person (Destination source).

2.2 Link Margin Calculations

Link Margin is obtained by calculating all the gains and losses that affect the communication from the transmitter to the receiver. The signal coming to the receiver shall be at a certain power level. A link margin value is calculated according to the sensitivity of the receiver. It is also calculated based on the obtained and needed SNR value. These calculations are explained in detail in Section 8. It is done in order to ensure quality and efficient communication [24].

The decibel measurement is used to compare the 2 power levels. It is used to obtain loss or gain values. For example; If the 1 mW standard is referenced, the dBm power levels are expressed in terms of the 1 mW level. It is an absolute value. 1 W is used as the standard level in high power applications such as transmitters. dBW indicates the decibel value relative to this level [35]. dB is a relative value between 2 powers. The formulas are shown below.

$$P_{Signal,\ dBm} = 10.log\left(\frac{P\ (W)}{1\ mW}\right) = 10.log\left(\frac{P\ (W)}{10^{-3}\ W}\right) \quad (2.1)$$

$$P_{Signal,\ dBW} = 10.log\left(\frac{P\ (W)}{1\ W}\right) \quad (2.2)$$

$$P_{Signal,\ dB} = 10.log\left(\frac{P_{Ouput\ Signal}}{P_{Input\ Signal}}\right) \quad (2.3)$$

When 2 values in dBm are added, they are first converted to mW and then converted to dBm. When the different decibel expressions are added together, obtained units are mentioned below.

- ⇨ $dBm + dB = dBm$
- ⇨ $dBW + dB = dBW$
- ⇨ $dBm + dBm \neq dBm$

Table 2.1 contains values obtained from the sum of the two values in dBm.

Table 2.1 Addition of dBm (or dBW) Power Values [34]

When the difference between two added dBm powers	Combining Term added to larger power dB
0	3.0
0.1-0.2	2.9
0.3-0.4	2.8
0.5-0.6	2.7
0.7-0.8	2.6
0.9-1.0	2.5
1.1-1.3	2.4
1.4-1.6	2.3
1.7-1.9	2.2
2.9-3.1	1.7
3.2-3.4	1.6
3.5-4.0	1.5
4.1-4.3	1.4
4.4-4.6	1.3
4.7-4.9	1.2
5.0-5.5	1.1
5.6-6.1	1.0
6.2-6.4	0.9
6.5-7.0	0.8
7.1-7.3	0.7
7.4-8.0	0.6
12.0-15.0	0.2
15.0-20.0	0.1
20.3+up	0.0

2.3 Loss of RF System

2.3.1 Reflection Due to Impedance Mismatch, VSWR

It is the ratio of back reflections resulting from the impedance difference between the source and the receiver in a system. It is considered a measure of how efficiently the RF power is transmitted. The VSWR value range is from 1 to ∞. A VSWR value below 2 is a good match, and above 2 is a poor match.

As voltage;

$$VSWR = V_{max}/V_{min} \tag{2.4}$$

As impedance;

$$VSWR = Z_L/Z_0 \tag{2.5}$$

An ideal VSWR is 1:1. It is considered as 1. In this case, the power reflected from the load to the source is 0. Reflection coefficient is obtained using equation 2.6

$$\Gamma = (Z_L - Z_0)/(Z_L + Z_0) = (VSWR - 1)/(VSWR + 1) \tag{2.6}$$

Reflection coefficient calculations for line impedance and load impedance values are given in Table 2.2.

Table 2.2 Reflection Coefficient Calculation [34]

VSWR	Γ	Z_0	Z_L	P_L/P_t	R_L	**Power Lost (%)**	F	Te	NF
1	0	50	50	1	None	0.0	1.0000	0.00	0.00
1.1	0.0476	50	55	0.998	-26.44	0.2	1.0023	0.66	0.01
1.2	0.0909	50	60	0.992	-20.83	0.8	1.0083	2.42	0.04
1.3	0.1304	50	65	0.983	-17.69	1.7	1.0173	5.02	0.07
1.4	0.1667	50	70	0.972	-15.56	2.8	1.0286	8.29	0.12
1.5	0.2	50	75	0.960	-13.98	4.0	1.0417	12.08	0.18
1.6	0.2308	50	80	0.947	-12.74	5.3	1.0563	16.31	0.24
1.7	0.2593	50	85	0.933	-11.73	6.7	1.0721	20.90	0.30
1.8	0.2857	50	90	0.918	-10.88	8.2	1.0889	25.78	0.37
1.9	0.3103	50	95	0.904	-10.16	9.6	1.1066	30.91	0.44
2	0.3333	50	100	0.889	-9.54	11.2	1.1250	36.25	0.51
2.1	0.3548	50	105	0.874	-9.00	12.6	1.1440	41.77	0.58
2.2	0.375	50	110	0.859	-8.52	14.1	1.1636	47.45	0.66
2.3	0.3939	50	115	0.845	-8.09	15.5	1.1837	53.27	0.73
2.4	0.4118	50	120	0.830	-7.71	17.0	1.2042	59.21	0.81
2.5	0.4286	50	125	0.816	-7.36	18.4	1.2250	65.25	0.88
2.6	0.4444	50	130	0.802	-7.04	19.8	1.2462	71.38	0.96
2.7	0.4595	50	135	0.789	-6.76	21.1	1.2676	77.60	1.03
2.8	0.4737	50	140	0.776	-6.49	22.4	1.2893	83.89	1.10
2.9	0.4872	50	145	0.763	-6.25	23.7	1.3112	90.25	1.18
3	0.5	50	150	0.750	-6.02	25.0	1.3333	96.67	1.25

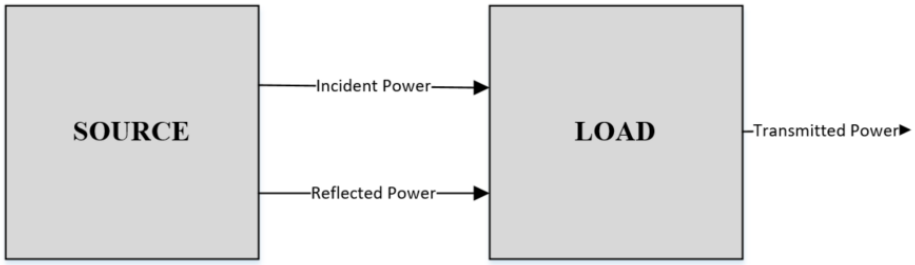

Figure 2.2 Reflection from Source to Load Impedance Mismatch

$$R_{L,\ W} = P_{incident}/P_{reflected} = 20.log((VSWR-1)/(VSWR+1)) \quad (2.7)$$

$$R_{L,\ dB} = 10.log\left(P_{incident}/P_{reflected}\right) \quad (2.8)$$

$$I_{L,\ W} = P_{incident}/P_{transmitted} = \frac{(VSWR+1)^2}{4.VSWR} \quad (2.9)$$

$$I_{L,\ dB} = 10.log(P_{incident}/P_{transmitted}) \quad (2.10)$$

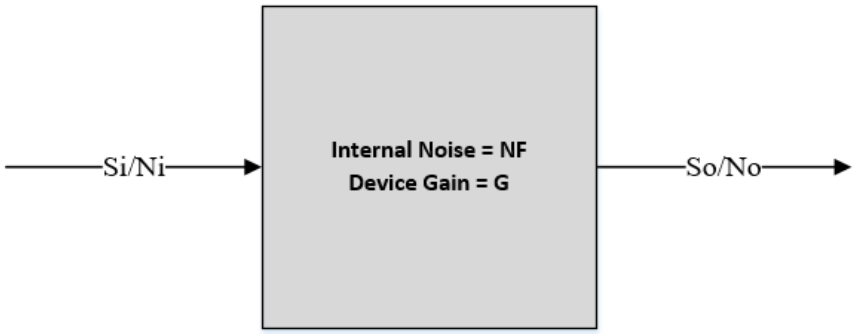

Figure 2.3 Noise Figure of System

The Noise Factor is the ratio of the input S/N value in a system to the output S/N value. It is denoted by “F”. The Noise Figure is defined as the noise number, gain. It is denoted by “NF”. Thanks to NF, we find out how much a device contributes to system noise internally. The smaller the NF, the better the device performance. NF is equal to Insertion Loss in passive devices (bandpass filter etc.).

$$F = (S_i/N_i)/(S_0/N_0) \quad (2.11)$$

$$NF = 10.log(F) \quad (2.12)$$

$$T_e = (Room\ temperature + 273).(F - 1) \quad (2.13)$$

2.3.2 Polarization

Polarization mismatch losses occur when the polarizations of the received wave and the receiving antenna do not match. Polarization is used to determine the vector direction of the magnetic and electric field. E and H are orthogonal to each other. As a rule, the polarization of a wave is defined by the direction of the electric field [18].

The electric field radiated from the antenna is named according to the type of vector. (Figure 2.4)

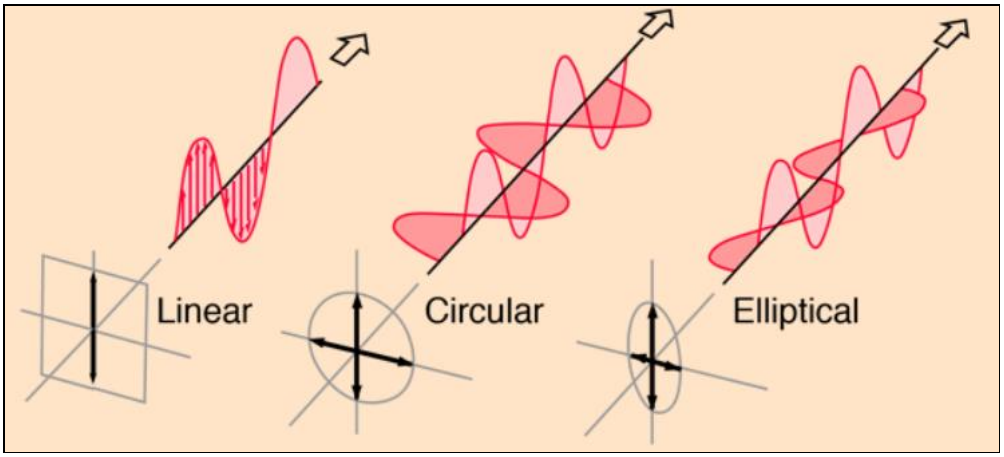

Figure 2.4 Types of Polarization [19]

As shown above, the electromagnetic wave is called linear polarization that electric field vectors are reduced to one direction.

The beam sent in circular and elliptical polarization reaches by scanning the entire area.

AR is the ratio of the maximum and minimum amplitudes of the electric field. It is used in polarization expression [20].

Circular Polarization Axial Ratio;

$$AR = E_y/E_x = 1 \tag{2.14}$$

Elliptic Polarization Axial Ratio;

$$AR = E_y/E_x > 1 \tag{2.15}$$

2.3.3 Free Space Path Loss

FSPL is a loss that occurs when the power density decreases as a result of the propagation of ectromagnetic waves in vacuum. FSPL is the ratio of the power output from the transmitting isotropic antenna to the power received from the receiving isotropic antenna (Figure 2.5).

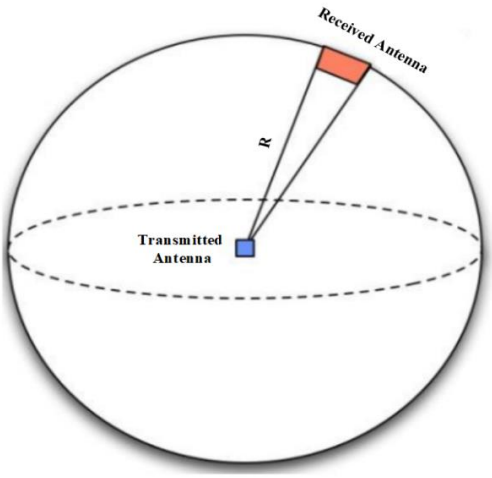

Figure 2.5 FSPL on the Spherical Surface

$$FSPL = P_{from\ Transmitted\ Antenna}/P_{to\ Received\ Antenna} \tag{2.16}$$

$$G_{Received\ Antenna} = \frac{4\pi.A_{eff}}{\lambda^2} = 1\ (Assuming\ that\ isotropic\ antenna) \tag{2.17}$$

$$A_{eff} = \frac{\lambda^2}{4\pi} \tag{2.18}$$

$$I = \frac{Total\ Power}{Area} \tag{2.19}$$

$$FSPL = \frac{I.4\pi.R^2}{I.(\lambda^2/4\pi)} = \left(\frac{4\pi.R}{\lambda}\right)^2 \quad (2.20)$$

$$FSPL\ (dB) = 32.5 + 20.log(R, km) + 20.log(f, MHz) \quad (2.21)$$

2.3.4 Noise

It is used to express the unwanted and random signal that does not carry a message and affects the message signal. The higher the noise level, the greater the message signal loss [21]. It is divided into 2 parts.

- External Noise
- Internal Noise

The sources of external noise are external. Atmospheric, space and human-induced noises can be given as examples.

Internal noise is produced by electronic circuits inside the communication system. It is divided into 2 as shot and thermal noise. Shot noise is found in all electronic circuit elements. The movement of electrons and holes in the device causes this noise. Thermal noise is caused by the random and rapid movement of electrons. It is found in resistive circuit elements. The thermal noise equation is given below [21].

$$N_{Watt} = K.T.B \quad (2.22)$$

$$N_{dBm} = 10\,log(K.T.B/mW) \quad (2.23)$$

2.3.5 Multipath

While the RF signal reaches the receiving antenna from the transmitting antenna, it hits obstacles such as mountains, buildings, trees and reaches the receiver. The RF signal arriving at the receiving antenna arrives at different amplitudes and delay times. This causes distortions in the signal. This event is called "Multipath". Multipath signals arrive later than direct signals because they cover an additional distance compared to “Line-Of-Sight” [22] (Figure 2.6).

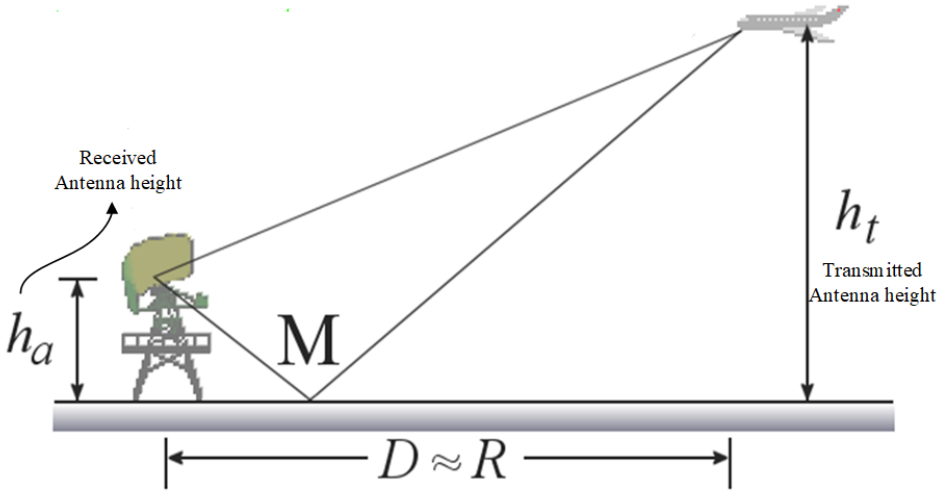

Figure 2.6 Multipath Signal Model [23]

2.3.6 Attenuation

Signals attenuate when they travel over the transmission line. These transmission lines are copper cable, coaxial cable, fiber optic cable, aerial etc. These attenuated signals are re-amplified by repeaters and given to the line [21].

The attenuation ratio is expressed as the ratio of the input signal power to the output signal power. It is mostly expressed in dB.

2.4 Gain of RF System

2.4.1 Antenna

We need antennas the RF signals sent from the transmitter on the missile so that can be received by the telemetry ground station. Patch, blade or helical antenna is generally preferred on the missile telemetry test. These antennas have low gain. In order to receive the telemetry broadcast from the missile throughout the entire orbit, the antenna used by the telemetry ground station must have special equipment that can automatically track and have a high gain [24]. As seen in Figure 2.7, a parabolic reflector antenna is used in the telemetry ground station. These antennas have a high directivity value. As long as its placement is suitable, it has the ability to follow the missile along the entire trajectory.

The equation for the gain of the parabolic reflector antenna is shown below.

$$G(dB) = 7.5 + 20.log(D, ft) + 20.log(f, GHz) \quad (2.24)$$

Figure 2.7 Antenna of Telemetry Ground Station

2.4.2 Low Noise Amplifier

The features of LNA are listed below.

- Amplifies to low power signal.
- Minimizes to additional noise.
- Reduces to S/N.

Generally, LNA is used between the receiving antenna and the receiver. It should be close to the receiver for minimum loss.

2.4.3 S/N, BER and E_b/N_0 Definitions

S/N is the ratio of signal power to noise power. It is one of the most used metrics when designing a telecommunications system and evaluating the performance of the system.

$$S/N(dB) = log(P_s/P_N) \quad (2.25)$$

BER is the ratio of the number of bit errors transmitted to all transmitted data. It is considered as a performance criterion in communication systems. Effects such as noise, distortion, bit synchronization problems and attenuation in the transmission channel affect the BER. It can be improved according to the chosen modulation technique and the used line coding.

$$BER = Number\ of\ Bit\ Errors/Total\ Number\ of\ Bits \tag{2.26}$$

E_b/N_o is energy per bit to noise power spectral density ratio. It is used when comparing the BER in different modulation types in digital data transmission.

$$E_b/N_o = S/N + BW/BR \tag{2.27}$$

2.4.4 Multiplexing, Demultiplexing

Multiplexing enables multiple signals to be combined into a single signal to be transported over a single transmission medium. Thanks to multiplexing, the number of transmission lines is minimized. The advantages of multiplexing are mentioned below.

• Thanks to multiplexing, more than one signal is sent over a single transmission.

• Bandwidth is used more effectively.

Demultiplexing is the acquisition of multiple signals from a single signal. Multiplexing and demultiplexing concept is shown in Figure 2.8. The most used types are FDM and TDM.

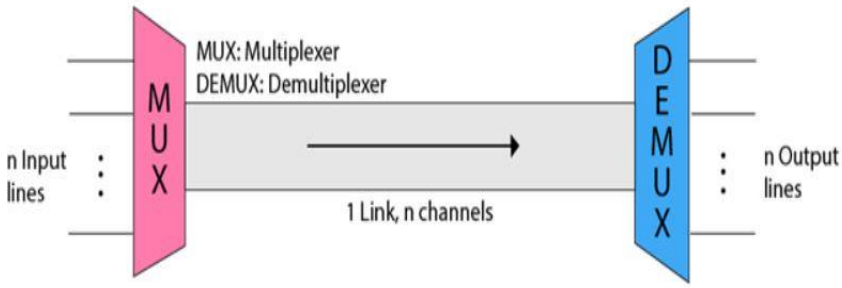

Figure 2.8 Concept of Multiplexing and Demultiplexing [25]

2.4.5 Frequency Division Multiplexing

The features of FDM are given below.

• More than one signal can be sent at the same time.

• Provides frequency sharing in communication channels. Each signal is modulated with a different carrier frequency.

• By using a different frequency band for the transmission of each signal, crosstalk is avoided.

• Channel is allocated even if there is no data.

• It is used in multiplexing of analog signals.

Figure 2.9 Frequency Division Multiplexing [26]

2.4.6 Time Division Multpilexing

TDM allows information from multiple sources to be transmitted in the same environment and at different times. Time slots are pre-allocated to resources. Time slots are allocated even if there is no data. It is divided into 2 as Synchronous and Asynchronous TDM.

In synchronous TDM, the data of each source is divided into units. The sum of the time intervals used by the source data in the transmission medium forms the TDM frame. In short, a TDM framework consists of combining 1 unit of data from all sources (Figure 2.10).

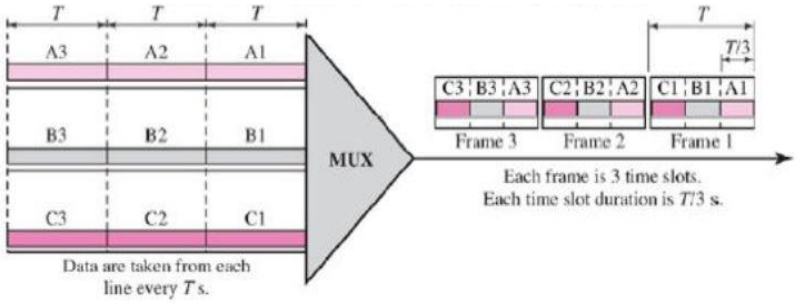

Figure 2.10 Senkron TDM [27]

In asynchronous TDM, sources may not have data to send. In this case, the time slot assigned for the resource remains empty and other resources cannot be used (Figure 2.11).

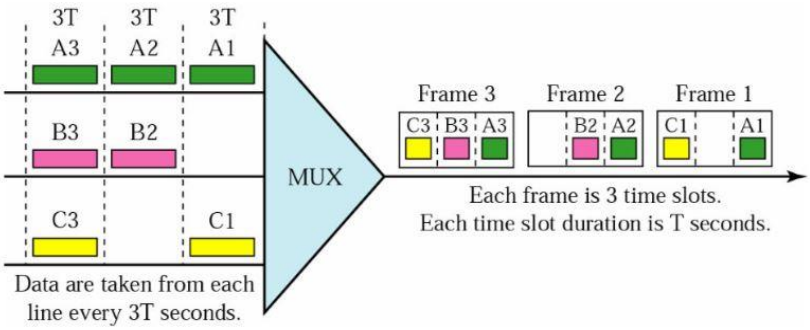

Figure 2.11 Asenkron TDM [27]

CHAPTER 3

Coding Types

3.1 Line Coding Methods

Line coding defines the ways in which data bits are expressed in the physical communication medium. The purposes of line coding are expressed below.

• Firstly, digital data is converted into a physical signal. The physical signal is defined as line code. Line encoders use the terminology mark for binary "1" and space for binary "0" [28].

• To ensure that the signal is less affected by the distortion effects such as noise and distortion in the transmission environment [28].

• More bitrate is obtained with lower baudrate [28].

Line coding block diagram is shown in Figure 3.1.

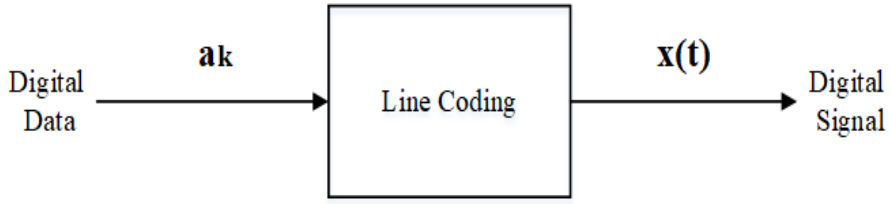

Figure 3.1 Line Coding Block Diagram

Line Coding formula is given below.

$$x(t) = \sum_{k=-\infty}^{\infty} a_k . p(t - k.T_b) \quad (3.1)$$

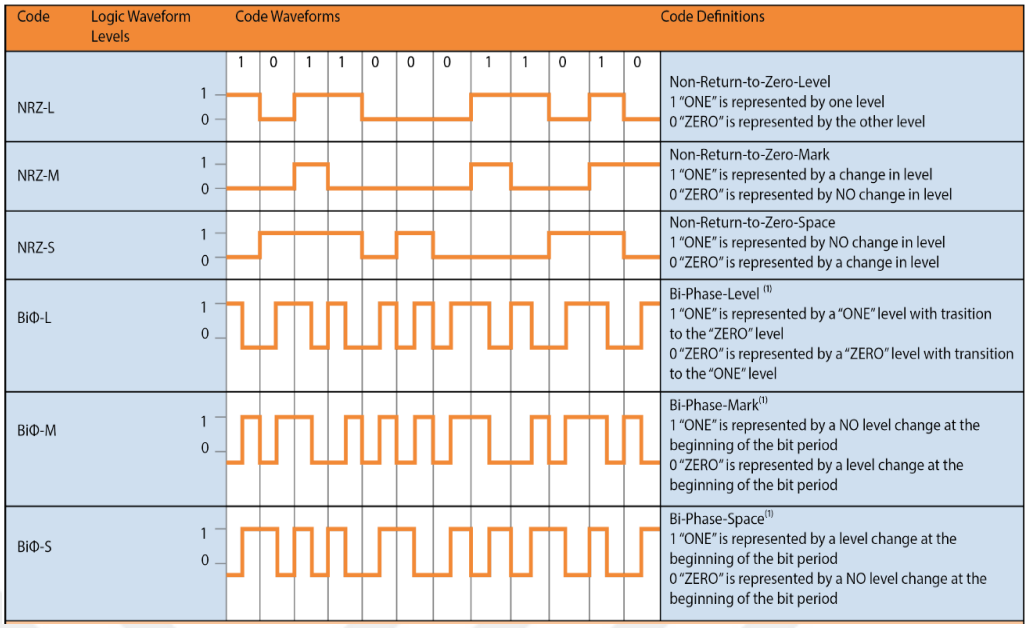

Figure 3.2 PCM code types and their definitions [13]

3.1.1 RNRZ-L

As can be seen in Figure 3.3, RNRZ-L consist of 2 adders (XOR gates) and a network of shift registers. RNRZ-L is obtained by adding the NRZ-L PCM data and outputs of the 14th and 15th bits of the shift register. The input of the shift register is RNRZ-L [29].

The RNRZ-L is called a randomizer. The prefix "R" means randomized. The term "randomized" is a bit of a misnomer. Normally, random data contains no usable information. "Randomize" term is used circuit acts on the data to make the data more spectrally flat, which make it easier to reconstruct the clock [30].

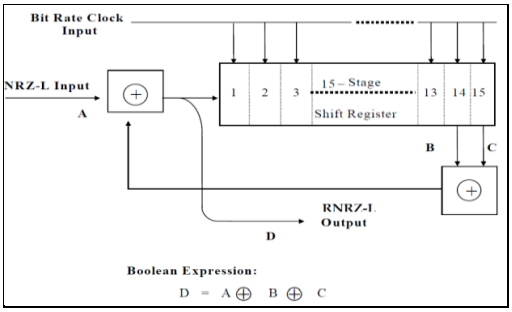

Figure 3.3 RNRZ-L Block Diagram [29]

3.1.2 NRZL

NRZ-L is called non-return-to-zero-level. Each bit value is represented by a logical high or low. The bit remains at one of the same levels throughout the all bit periods [30].

The NRZ-L is used as Derandomizer. Looking at the block diagrams of Randomizer and Derandomizer, we notice that Derandomizer is the inverse of Randomizer. The logic of this is shown in Figure 3.4 [30].

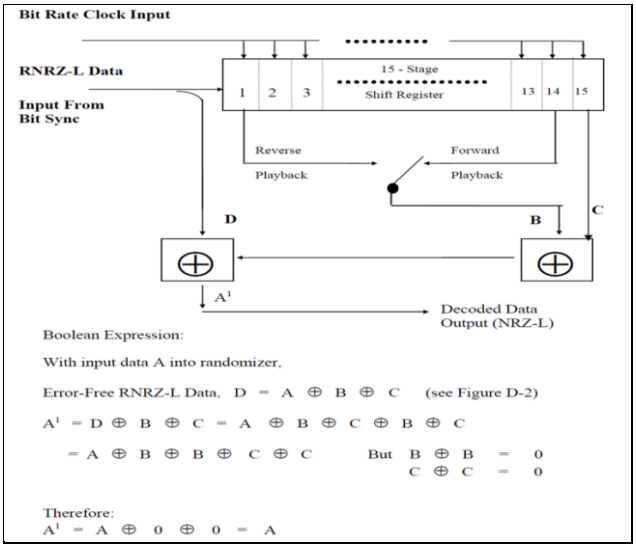

Figure 3.4 NRZ-L Block Diagram [29]

3.2 Source Coding Methods

It is a type of encoding used to compress data. Source coding has 2 main advantages.

- Require smaller storage space when storing data.
- Require less time while sending data due to lower bandwidth.

As shown in Figure 3.5, the compression ratio is found when the number of bits of the Encoder output C(M) is divided by the number of bits of the original message(M). Displaying the decoder output message with a different expression from original

message (M') is because there may be some loss of data as a result of the compression process.

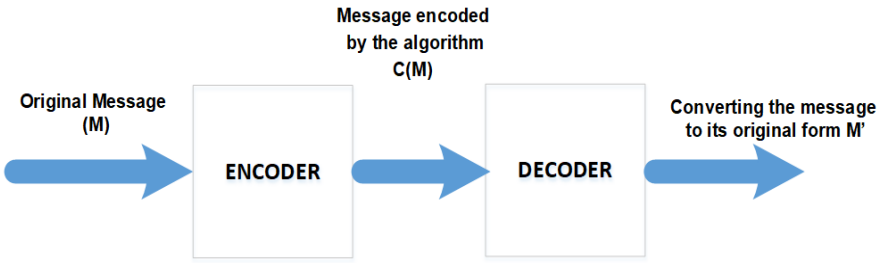

Figure 3.5 Data Compression Encoder and Decoder Method

Source Coding method is divided into 2 types as Lossy Source Coding and Lossless Source Coding.

3.2.1 Lossy Source Coding

There is a difference between the original message (M) and the reconstructed message (M') due to the loss of some data in the Lossy Source Coding method. The reason for choosing this method is to achieve higher compression ratios. In short, thanks to lossy source coding, it provides high compression of the data by risking the quality of the data to decrease.

3.2.2 Lossless Source Coding

There is a difference between the reconstructed version of the message (M') and the original message (M'). This method is used when data loss is not tolerated.

Source coding saves bit. It reduces the number of bits that we send. It tries to encode the source with as few bits as possible approaching entropy. As it is understood, the entropy term is important in the source coding process. Entropy is the minimum number of bits required to encode information using an appropriate encoding.

$$H = -\sum_{i=1}^{n} P(s_i).log_2 P(s_i) \quad (3.2)$$

As can be seen from the formula, the more uncertainty, the higher the H. Entropy coding principles are used in data compression coding.

• Huffman Coding

• Arithmetic Coding

• Run-Length Coding

• Lempel-Ziv Algorithm can be given as an example.

3.3 Channel Coding

There may be some errors that may occur in the channel while transmitting data packets. Even if 1 bit is corrupted in the packet, it may cause misunderstanding of the all data. Channel coding provides protection against channel errors by adding redundant bits. Error Detection and Error Correction techniques are used to determine whether there is a corruption during communication. The most used Error Detection and Error Correction techniques are shown in Figure 3.6.

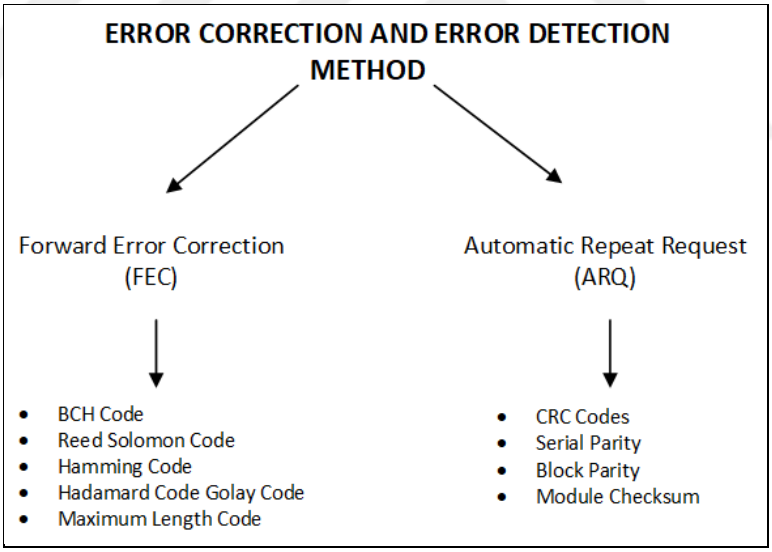

Figure 3.6 Error Correction and Detection

FEC are control bits added to the packets in the data stream in order to correct the errors that occur during transmission in digital signals on the receiving device end. For example, 5/6 FEC, 5 of the 6 bits sent are original and the others are control bits. A higher quality data transfer occurs in a communication with a lower FEC value. A high

FEC value increases the bandwidth, while a low FEC value decreases the bandwidth. Figure 3.7 shows the operation of the FEC.

ARQ is the process of detecting the error and making a request on the receiving end so that the corrupted data can be retransmitted.

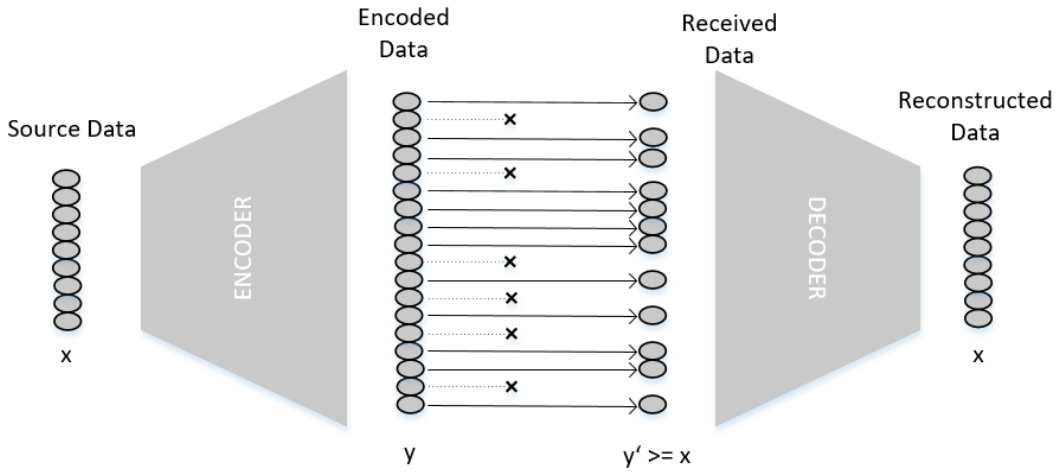

Figure 3.7 FEC Working Principle

CHAPTER 4

Modulation Methods used for Telemetry Systems

Modulation is the process of switching a low-frequency signal to a high-frequency and transmitting a high-frequency signal. The low frequency signal carrying the original information is called a modulation signal or message signal. High frequency signal is called carrier signal. The signal formed by the modulation of the carrier signal and the message signal is called the modulated signal.

Modulation takes place at the transmitter to ensure reliable and efficient information transfer. It reduces negative effects such as noise and distortion.

The most commonly used modulation techniques in telemetry systems are FSK and PSK. These modulation techniques are used to convert digital signals into waveforms suitable for communication channels. It is the modification of the characteristic features of the analog carrier according to the digital information.

It is assumed that the AWGN channel model is used when BER formulas are given according to the modulation types shown in Table 6.1. Modulated signals are exposed to noise signals in the environments in which they are transmitted. Receivers receive the modulated signal with noise added. In this model, it adds White Gaussian Noise to the signal passing through the channel. There is no distortion in the amplitude and phase of the signal [38].

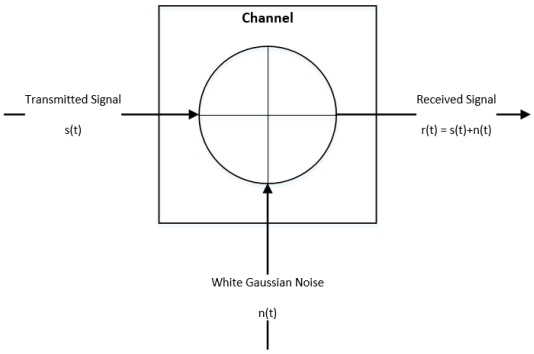

Figure 4.1 Block diagram of AWGN channel model [36]

The AWGN channel structure is given in Figure 4.1. It is modeled with a Gaussian probability density function. The power spectral density function of this channel structure is given in Equation 4.1 and is shown in Figure 4.2.

$$p(r) = \frac{1}{\sigma.\sqrt{2\pi}} e^{\left[\frac{-(r-\mu)^2}{2\sigma^2}\right]} \quad -\infty < r < \infty \tag{4.1}$$

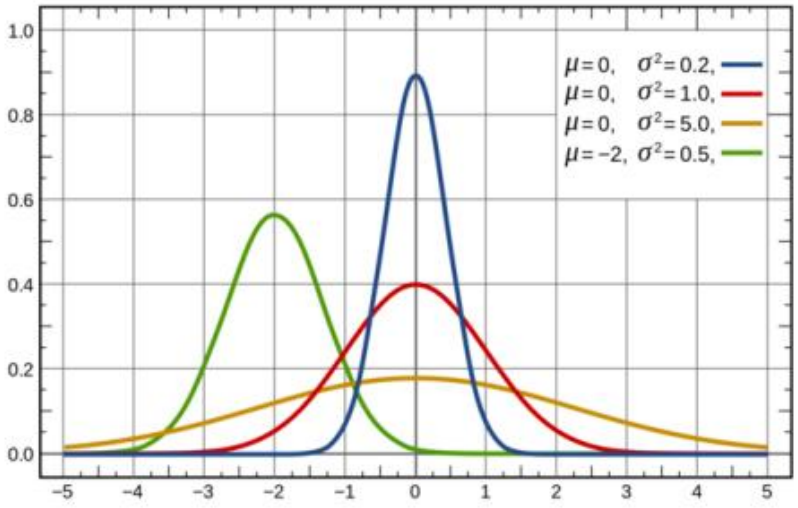

Figure 4.2 Power Spectral Density in AWGN

4.1 FSK

FSK is known as Frequency Shift Keying. The frequency of the carrier signal is changed. The modulation signal includes a digital message signal and an analog carrier signal generated from an oscillator. As seen in Figure 4.3, FSK modulation can be generated by the VCO.

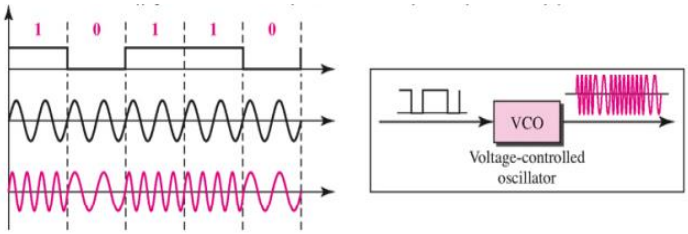

Figure 4.3 BFSK Modulation [27]

FSK features are listed below.

• Less errors occur compared to ASK.

• It is widely used in telemetry applications. Especially telemetry applications can be given as an example.

• Generally, it is used at data rates of 1200 bps and below.

The most commonly used FSK type is BFSK. Thanks to BFSK, 2 different frequency signals are used. The equation used in BFSK modulation is expressed.

$$x(t) = \begin{cases} A.cos(w_1 t) & for\ logic\ 1 \\ A.cos(w_2 t) & for\ logic\ 0 \end{cases} \quad (4.2)$$

2 applications are used in the demodulation process of BFSK: Cohorent and Non-cohorent. In cohorent BFSK, there is no phase discontinuity between the 2 signals. Non-cohorent BFSK is a phase discontinuity when one signal ends and the other signal begins. BER value is higher than Cohorent BFSK.

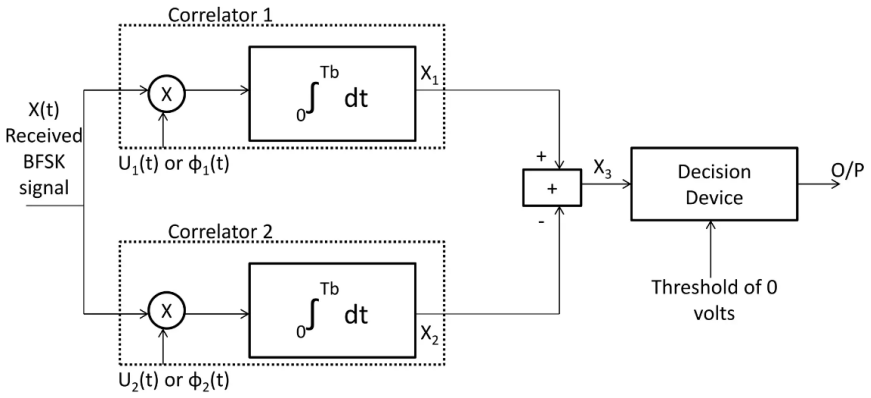

Figure 4.4 Cohorent FSK Receiver

The theoretical BER for BFSK with cohorent detection is given by

$$BER = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_o}}\right) \tag{4.3}$$

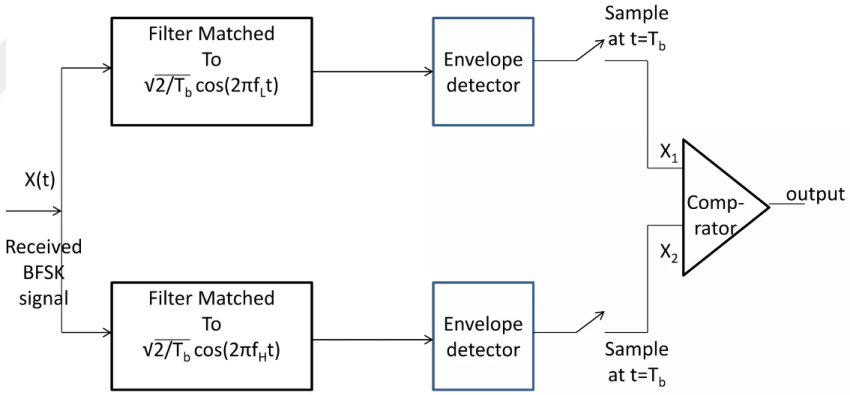

Figure 4.5 Non-cohorent FSK Receiver

The theoretical BER for BFSK with non-cohorent detection is given by

$$BER = \frac{1}{2} e^{\left(-\frac{E_b}{2.N_o}\right)} \tag{4.4}$$

The FSK type that can send 3, 4 or even 5 bits of data at the same time using more than 2 frequencies is called MFSK. It provides efficiency in the frequency spectrum by reducing the bandwidth. But it is prone to error. The formula used in MFSK modulation is given below.

$$s_i(t) = A.cos(2\pi f_i t) \qquad 1 \le i \le M \tag{4.5}$$

The theoretical BER for MFSK with non-cohorent detection is given by

$$BER = \frac{2^{k-1}}{2^k-1} \sum_{n=1}^{M-1} (-1)^{n+1} \binom{M-1}{n} \frac{1}{n+1} e^{\left(\frac{-E_b nk}{N_{0.(n+1)}}\right)} \tag{4.6}$$

The following equation is used for 4-FSK with k = 2 and M = 4.

$$BER = e^{-\frac{E_b}{N_0}} - \frac{2}{3} e^{-\frac{4E_b}{3N_0}} + \frac{1}{6} e^{-\frac{3E_b}{2N_0}} \tag{4.7}$$

PCM/FM has been the most popular telemetry modulation since about 1970. This method can also be called CPFSK. Therefore, it is explained under the title of FSK.

The PCM/FM modulation signal is produced by filtering the NRZL signal and frequency modulating a VCO [13].

Figure 4.6 shows the power spectrum of a random 5 Mbps PCM/FM signal.

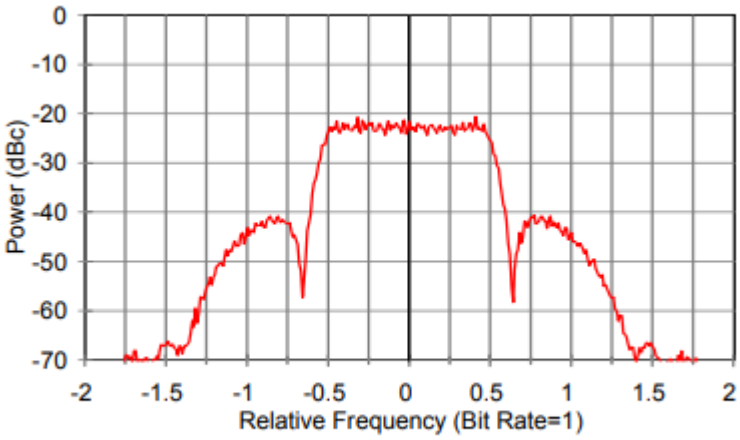

Figure 4.6 Power spectrum of 5 Mb/s PCM/FM signal [13]

The PCM/FM modulation method is highly insensitive to phase noise. Figure 4.7 shows the Eb/No performance of a 5 Mbps PCM/FM versus BER with a multi-symbol bit detector and 3 different receivers/ detectors [13].

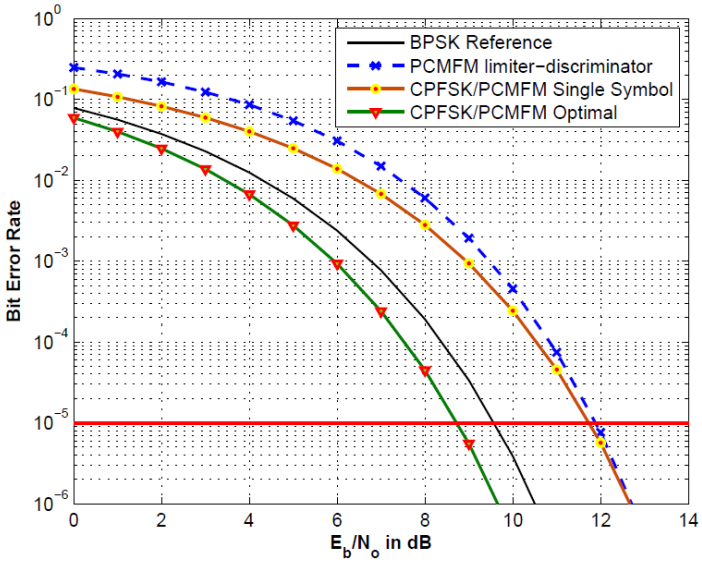

Figure 4.7 Performance comparison of different demodulation methods for PCM/FM [31]

Most implementations of PCM/FM use a modulation index of h ≅ 0.7 which provides good error performance. The minimum squared Euclidean distance as a function of modulation index is given by [31]

$$d^2{}_{min} = 2\left[1 - \frac{sin2\pi h}{2\pi h}\right] \tag{4.8}$$

For this, $d^2{}_{min} = 2.43$ when h = 0.715. Best achievable BER for PCM/FM is [31]

$$BER = Q\left(\sqrt{\frac{E_b}{2N_0} d^2{}_{min}}\right) = Q\left(\sqrt{\frac{E_b}{2N_0} 2.43}\right) = \frac{1}{2}.erfc\left(\sqrt{\frac{E_b}{4N_0} 2.43}\right) \tag{4.9}$$

The equation mentioned above is used to calculate the BER of the CPFSK/PCM-FM single symbol.

4.2 PSK

PSK is known as Phase Shift Keying. The phase of the carrier signal is changed. It is less affected by noise compared to ASK. It is generally used in bluetooth technology, telemetry applications, WLAN which is used in biometric passport and contactless payment systems.

BPSK and QPSK are commonly used PSK types. In BPSK, 0 degree and 180 degree phase different signals are used. As shown in Figure 4.8, the NRZ bipolar signal is multiplied by a carrier signal. Bit 1 represents a phase at 0 degrees and bit 1 represents a phase at 180 degrees.

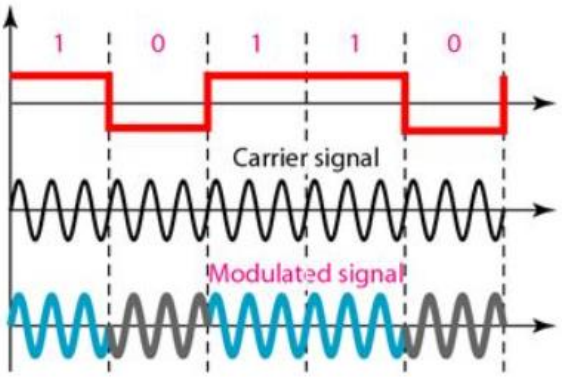

Figure 4.8 BPSK Modulation [27]

The equation used in BPSK modulation is expressed below.

$$\begin{cases} s_1(t) = A_c\, cos(2\pi f_c t)\,, & 0 \le t \le T_b \quad for\ binary\ 1 \\ s_0(t) = A_c\, cos(2\pi f_c t + \pi)\,, & 0 \le t \le T_b \quad for\ binary\ 0 \end{cases} \tag{4.10}$$

The BER of the signal with BPSK in AWGN can be calculated as given in equation 4.11.

$$BER = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_o}}\right) \tag{4.11}$$

Thanks to QPSK, 2 bits are sent with 1 signal. In the M encoding system, it takes the values $N = 2$, $M = 4$ in the $2^N = M$. As seen in Figure 4.9, 2 separate multipliers are applied to each 2 bits. By collecting 2 signals, signals in -135°, -45°, 45°, 135° phases are formed. A single carrier frequency provides 4 different outputs.

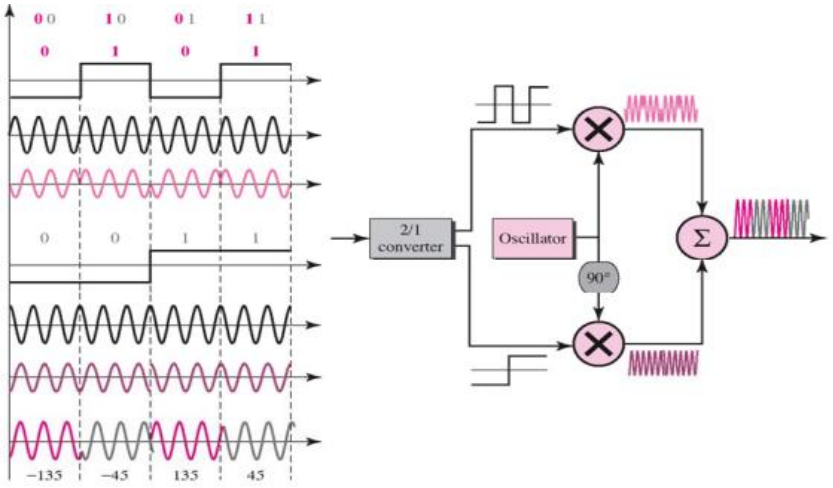

Figure 4.9 QPSK Modulation [27]

The BER of the signal with QPSK in AWGN can be calculated as given in equation 4.12.

$$BER = erfc\left(\sqrt{\frac{E_b}{N_0}}\right)\left[1 - \frac{1}{4}erfc\left(\sqrt{\frac{E_b}{N_0}}\right)\right] \approx \frac{1}{2}erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \quad (4.12)$$

In 8-PSK, each symbol is represented by 3 bits. It provides %50 more bit transmission rate than QPSK. The BER of the 8-PSK signal in the AWGN can be calculated as given in equation 4.13

$$BER = \left(\frac{1}{3}\right).erfc\left(\sqrt{\frac{3.E_b}{N_0}}.sin\left(\frac{\pi}{8}\right)\right) \quad (4.13)$$

4.3 Constellation Diagram

It is used to show the amplitude and phase values of the signal. As shown in Figure 4.10, “I” signal represents the cosine signal and “Q” signal represents the sine sine with a 90 degree phase difference from the cosine. PSK is also used in orthogonal BFSK.

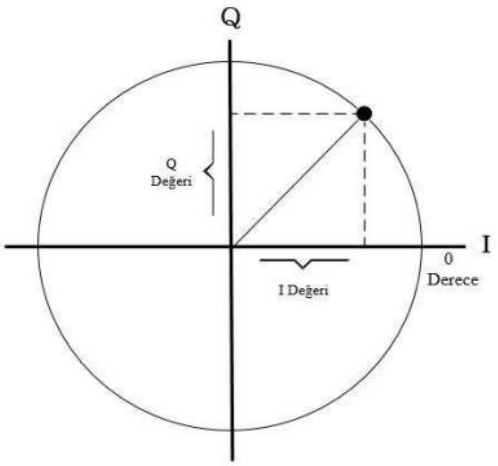

Figure 4.10 Constellation Diagram [32]

Assuming that the So and S1 signals are orthogonal, the constellation diagram of BFSK is shown in Figure 4.11.

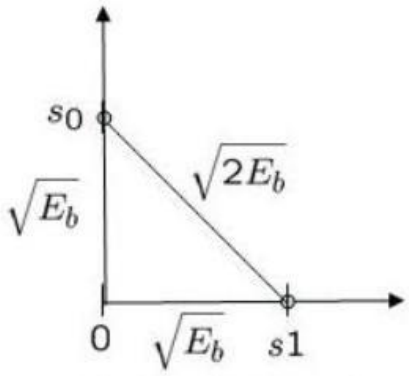

Figure 4.11 Orthogonal BFSK Constellation Diagram

BPSK modulation has no sinus component. Q values are zero. Because the cosine components are of opposite sign, they are 1 and -1. Therefore, when the constellation diagram is expressed it is shown as two points with opposite signs. The BPSK constellation diagram is shown in Figure 4.12 [33].

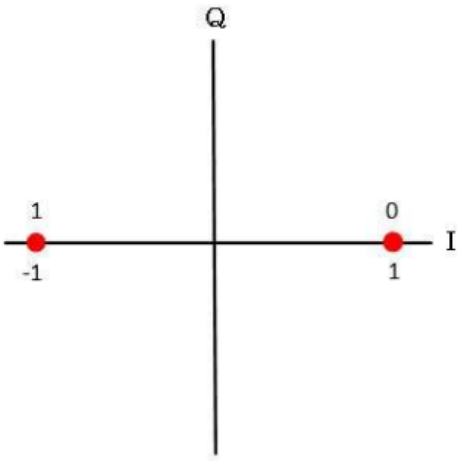

Figure 4.12 BFSK Constellation Diagram [33]

The constellation diagram points of the QPSK symbols are shown in Figure 4.13. It contains four different symbols that represent sequences of bits 00, 01, 11, and 10 respectively.

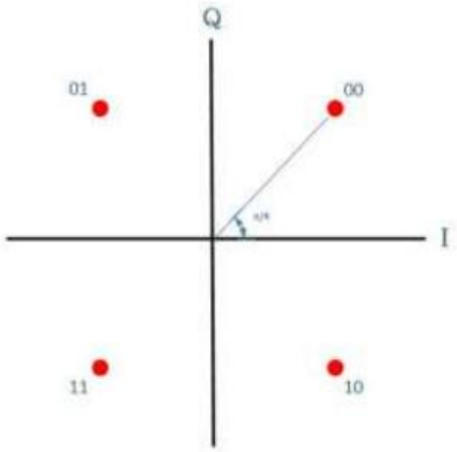

Figure 4.13 QPSK Constellation Diagram [33]

In 8-PSK, bits are represented by 8 phase angles. There are 4 differences between each phase. A gray coded 8-PSK constellation diagram is given in Figure 4.14.

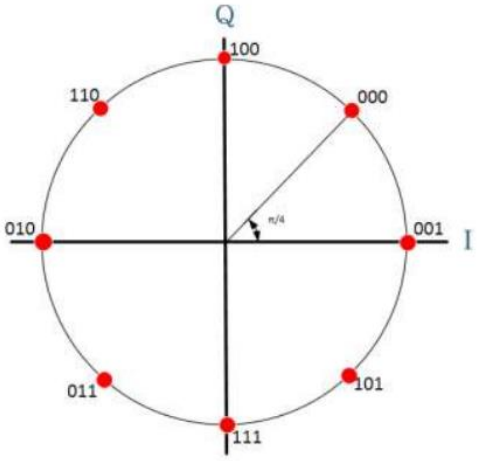

Figure 4.14 8-PSK Constellation Diagram [33]

CHAPTER 5

Design of Telemetry System

5.1 Airborne Telemetry System

Various analog and digital data are collected over the missile by means of telemetry equipment. If the collected data is an analog signal, it shall be converted into a digital signal by PCM. Thanks to PCM, the message signal is sampled with an appropriate sampling frequency. These sample values are then quantized at certain quantization levels. That is, the amplitude of the signal is rounded to certain values. Finally, each quanta level is represented by a binary code(1, 0). Thus, the message to be transmitted by PCM is converted to digital. If the collected data is a digital signal, no conversion is required. These digital signals are collected by the data commutator. There are TDM and PCM Generator structures in the data commutator. TDM collects each sensor data. PCM creates the major frame. The PCM Generator takes each minor frame and lines up in a continuous data stream. If it is necessary to compress the digital data obtained from the data commutator, source coding is used.

Some bits may be corrupted while transmitting data packets. Even if 1 bit is corrupted in the packet, it may cause misunderstanding of the all data. For this, error detection and correction techniques of channel coding are used to understand whether there is distortion during communication. Channel coding provides protection against channel errors by adding redundant bits.

Source coding and channel coding are not mandatory. However, line coding is needed to convert a digital data into a physical signal. After the digital signal is obtained by line coding, the premodulation filter is used before modulation to limit the bandwidth of the signal. Thus, it eliminates unwanted harmonics by reducing noise and BER. The Premodulation Filter is a lowpass filter. After the digital signal passes through the filter, the modulation process takes place. The modulated signal obtained as a result of the modulation is transmitted to the antennas to be sent to the ground.

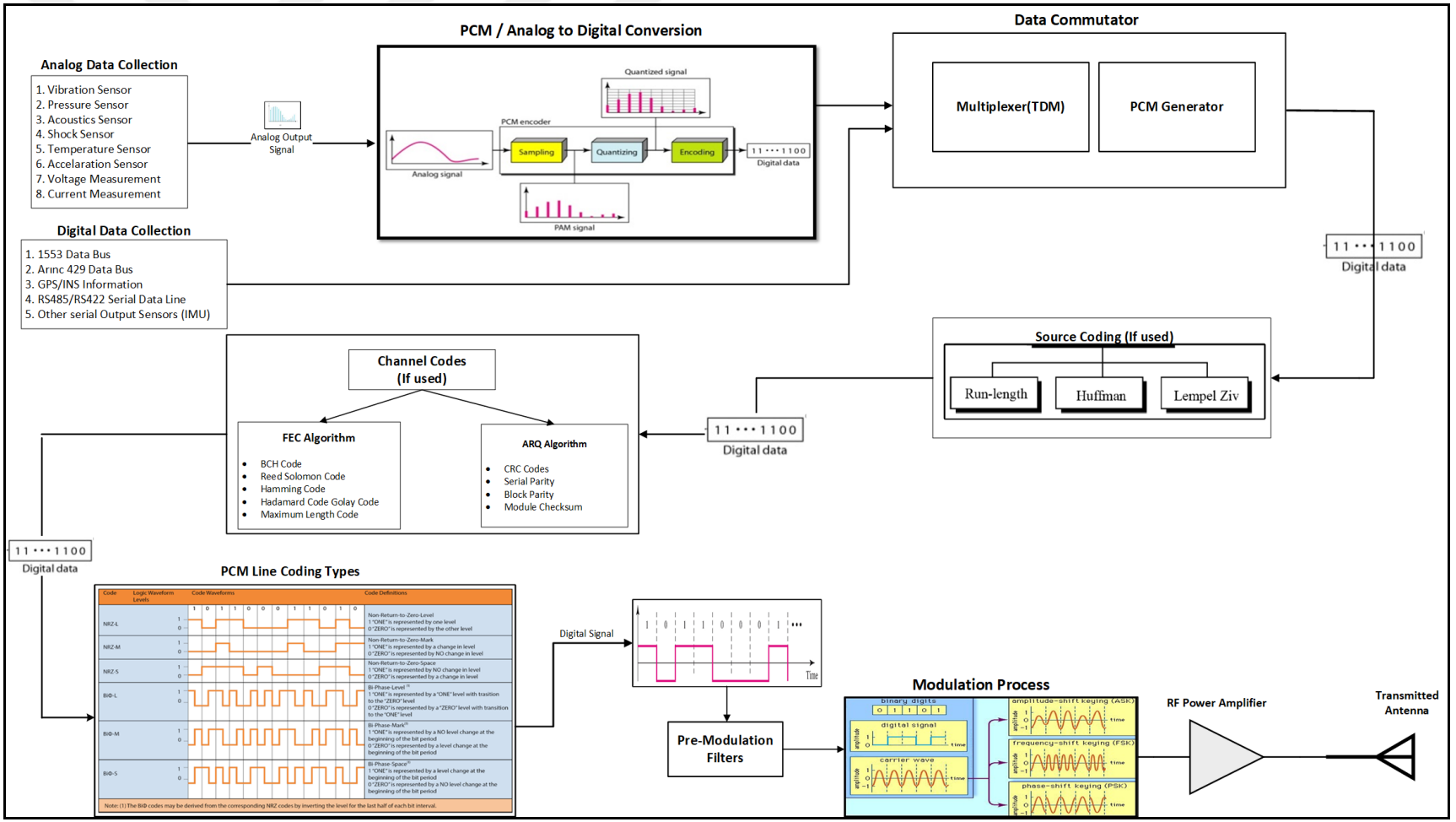

Figure 5.1 Airborne Telemetry System

The working principle of the telemetry system on the missile has been described above. Figure 5.1 shows the structure of the airborne telemetry system.

5.2 Telemetry Ground Station

The telemetry ground station is used for receiving, processing, displaying and recording the RF signal coming from the onboard telemetry transmitter, thanks to its reflector antenna. The working principle of the telemetry ground station is shown in Figure 5.2.

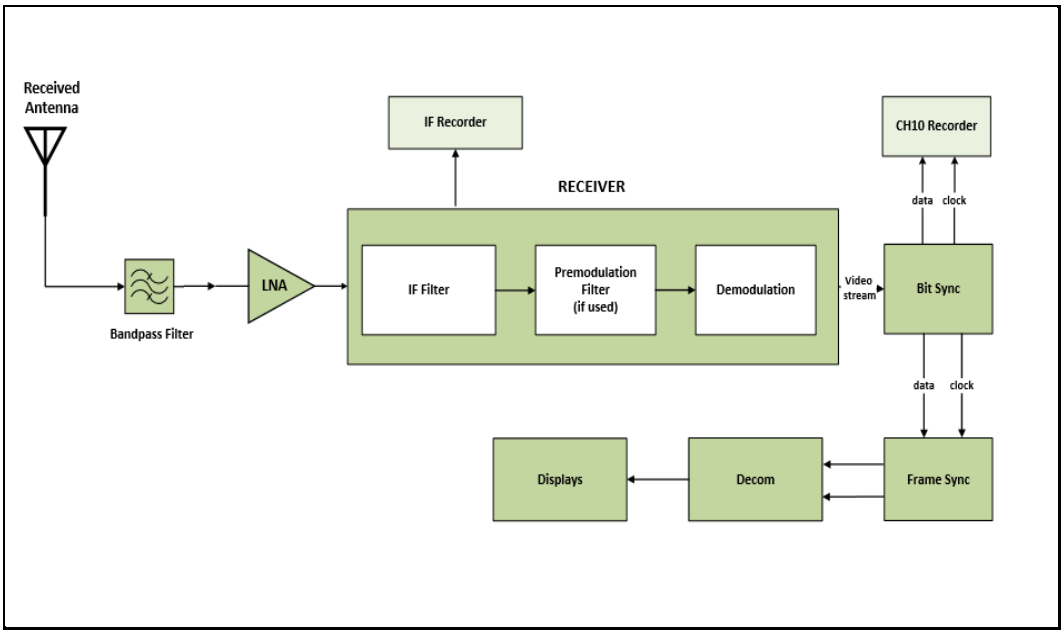

Figure 5.2 Telemetry Ground Station

Thanks to the antenna in the telemetry ground station, RF signals sent from the missile are received. The RF signal received from the antenna is sent to the Receiver. In order to receive telemetry broadcasts from every orbit of the missile, reflector antennas with high gain and automatic tracking of the missile are preferred [24]. The RF signal coming to the receiver goes through various processes. Thanks to IF, the RF signal is shifted to be fixed in a certain frequency range. If the bitrate is greater than 50 Mbits/sec, the IF values are 460 MHz, 760 MHz etc. If the bitrate is below 50 Mbits/sec, IF value is 70 MHz [34]. Here is the down conversion process. If the bandwidth of the signal is to be limited, the Premodulation filter is used. Then, the

message signal is freed from carrier frequency by demodulation. Bit synchronization operations are performed by creating a copy of the message signal by the receiver. As shown in Figure 5.3, the output of the Bit Synchroniser consists of 2 analog signals the data and the clock.

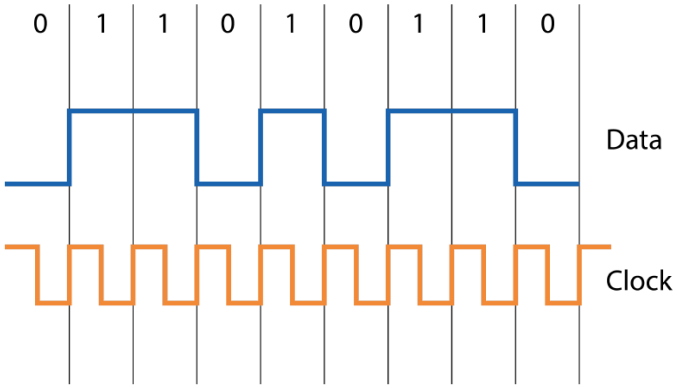

Figure 5.3 Bit Sync Diagram [14]

As shown in Figure 5.4, minor frame per major frame lined up according to FS turns into PCM Major Frame structure.

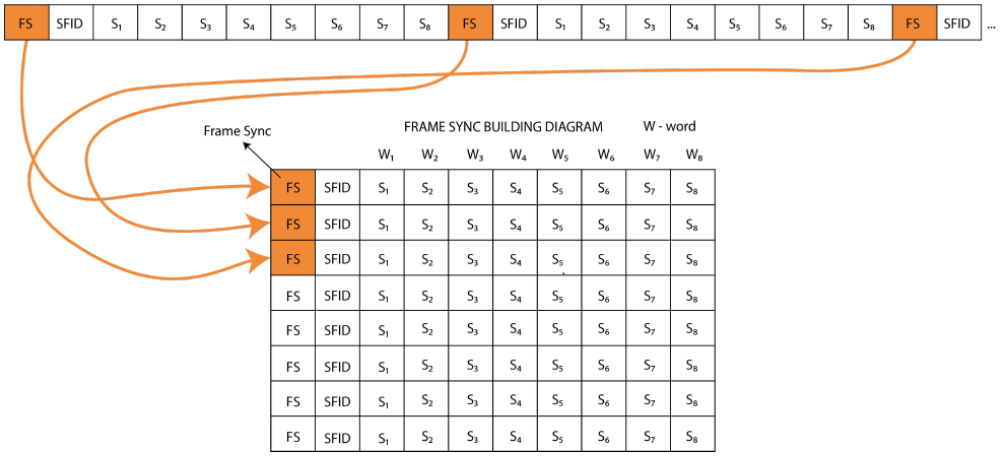

Figure 5.4 Frame Sync Building Diagram [14]

Then, by reversing the operations applied on the missile, decommutate the individual data parameters by Decom. Thus, the received signals are ready for processing. Then, after the signals are decoded, the data is displayed on the monitors in the Mobile

Telemetry Station shown in Figure 5.5 for analysis and recorded in the IF Recorder. If the user wants, record data in CH10 Recorder format without the need for Decom.

Figure 5.5 Mobile Telemetry Station

CHAPTER 6

A Complete End to End Link Margin Calculations

This section includes end to end link margin calculations according to S/N and receiver sensitivity in Figure 6.1. S/N is expressed as C/N in IRIG standards.

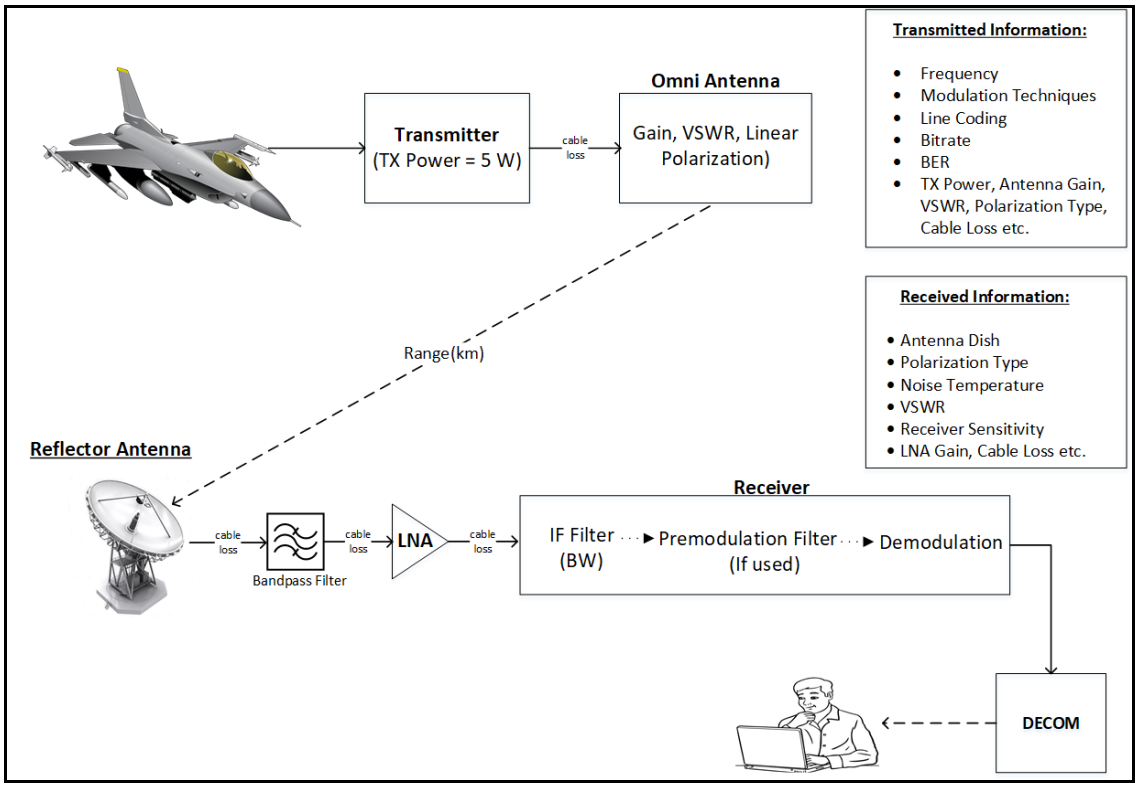

Figure 6.1 Airborne and Ground System Diagram

Using equation 6.1 and equation 6.2, equation 6.3 is obtained. Equation 6.3 shows how to obtain Noise Factor of Transmitted Antenna.

$$P_L = P_t * a\frac{4.VSWR}{(VSWR+1)^2} \tag{6.1}$$

$$G = \frac{P_L}{P_t} \tag{6.2}$$

$$F = \frac{1}{G} \tag{6.3}$$

Equation 6.4 is obtained Noise Figure of Transmitted Antenna using equation 6.3 logarithmically.

$$NF = 10.\log F \tag{6.4}$$

Effective Isotropic Radiated Power is the effective power radiated by an antenna in the direction in which it is oriented. It depends on transmitter output power, antenna gain and other losses. In Equation 6.5, EIRP is given by

$$EIRP = P_{Transmitter\ Output,\ dBm} + G_{Transmitter\ Antenna,\ dB} - L_{Transmitter\ Cable,Connector\ etc.\ (dB)} \tag{6.5}$$

The signal level coming to the receiver is shown in equation 6.6.

$$P_{rx(total)} = EIRP_{dBm} - FSPL_{dB} - L_{Receiver\ Antenna\ Polarization,\ dB} + G_{Receiver\ Antenna\ Gain,\ dB} + G_{LNA,\ dB} - L_{Receive\ Side\ Connection\ (cable/connector),\ dB} - L_{Other\ (between\ LNA\ and\ receiver\ if\ any),\ dB} \tag{6.6}$$

Considering the receiver sensitivity, the following equation 6.7 is obtained so that the receiver can be made to obtain the link margin.

$$Link\ Margin\ of\ Receiver = P_{rx(total)} - (Receiver\ Sensitivity)_{dBm} \tag{6.7}$$

The thermal noise obtained after LNA is obtained in equation 6.8. Front-end noise temperature value prior to LNA is used instead of "T".

$$N_{received} = (k.T.B)_{dBm} + G_{LNA,\ dBm} \tag{6.8}$$

BER and E_b/N_0 formulas according to modulation types are shown in Table 6.1. If the BER value is known, the E_b/N_0 value can be calculated. The S/N value is obtained in equation 6.9.

$$\frac{S}{N} = \frac{E_b}{N_0} - \frac{BW}{BR} \tag{6.9}$$

Equation 6.10 is obtained using equation 6.11 and equation 6.12.

$$Needed\frac{S}{N} = Needed\frac{E_b}{N_0} - \frac{BW}{BR} \tag{6.10}$$

$$(Link\ Margin\ of\ S/N)_{dB} = \ Obtained\frac{S}{N} - Needed\frac{S}{N} \tag{6.11}$$

$$(Link\ Margin\ of\ S/N)_{dB} = \ Obtained\frac{S}{N} - Needed\frac{E_b}{N_0} + \frac{BW}{BR} \tag{6.12}$$

Table 6.1 Needed Eb/ N0 and BER formulas according to modulation types in AWGN

Modulation Type	**Needed E_b/N_0 Formula**	**BER Formula**
BPSK	$(erfcinv(2.BER))^2$	$\left(\frac{1}{2}\right).erfc\left(\sqrt{\frac{E_b}{N_0}}\right)$
QPSK	$\approx (erfcinv(2.BER))^2$	$\approx \left(\frac{1}{2}\right).erfc\left(\sqrt{\frac{E_b}{N_0}}\right)$
8-PSK	$\left(\frac{1}{3}\right)((erfcinv(3.BER)/\sin(\frac{\pi}{8}))^2$	$\left(\frac{1}{3}\right)erfc\left(\sqrt{\frac{3.E_b}{N_0}}.\sin(\frac{\pi}{8})\right)$
(M – PSK)	$\left(\frac{1}{k}\right)((erfcinv(k.BER)/\sin(\frac{\pi}{M}))^2$	$\left(\frac{1}{k}\right)erfc\left(\sqrt{\frac{k.E_b}{N_0}}.\sin(\frac{\pi}{M})\right)$
B-FSK (Noncoherent)	$(-2).\ln(2.BER)$	$\left(\frac{1}{2}\right).e^{\left(-\frac{E_b}{2.N_0}\right)}$
4-FSK (Noncohorent)	$\approx (-1).\ln(BER)$	$\approx e^{\left(-\frac{E_b}{N_0}\right)} - \left(\frac{2}{3}\right).e^{\left(-\frac{4E_b}{3.N_0}\right)} + \left(\frac{1}{6}\right).e^{\left(-\frac{3E_b}{2.N_0}\right)}$
MFSK (Noncohorent)	-	$\frac{2^{k-1}}{2^k-1}\sum_{n=1}^{M-1}\binom{M-1}{n}(-1)^{n+1}\frac{1}{n+1}e^{(-n.k.E_b)/(No.(n+1))}$
PCM/FM	$(1.646).(erfcinv(2BER))^2$ [31]	$\frac{1}{2}.erfc\left(\sqrt{\frac{E_b}{4N_0}2.43}\right)$ [31]
$M = 2^k$	M = signal level number k = number of bits per signal element	

CHAPTER 7

Analyzes

Thanks to the developed "Telemetry System Performance Calculator Interface" program, the signals coming from the missile to the telemetry ground station are simulated. Multipath effect is not considered. RF communication values and modulation types on the missile, range and ground station side are taken into account. Thus, telemetry communication performances are compared by calculating the S/N Link Margin value according to the distance. BFSK, 4-FSK, BPSK, QPSK, 8-PSK, PCM/FM are used as modulation types. In order to increase the performance of the telemetry system, modulation techniques are emphasized.

In this section, modulation types and distance from the communication parameters on the missile and ground station sides vary, and other parameters are kept constant. However, thanks to the Telemetry System Performance Calculator Interface program, we can improve the performance of the telemetry system by changing all communication parameters.

Simulation outputs are also available according to Range-FSPL, BER-Eb/No and Range-Link Margin of Received Signal parameters. Range-FSPL and Range-Link Margin of Received Signal parameters do not depend on modulation types. Therefore, the simulation outputs of these parameters are only shown in the BFSK subtitle.

7.1 BFSK Simülasyon Çıktıları

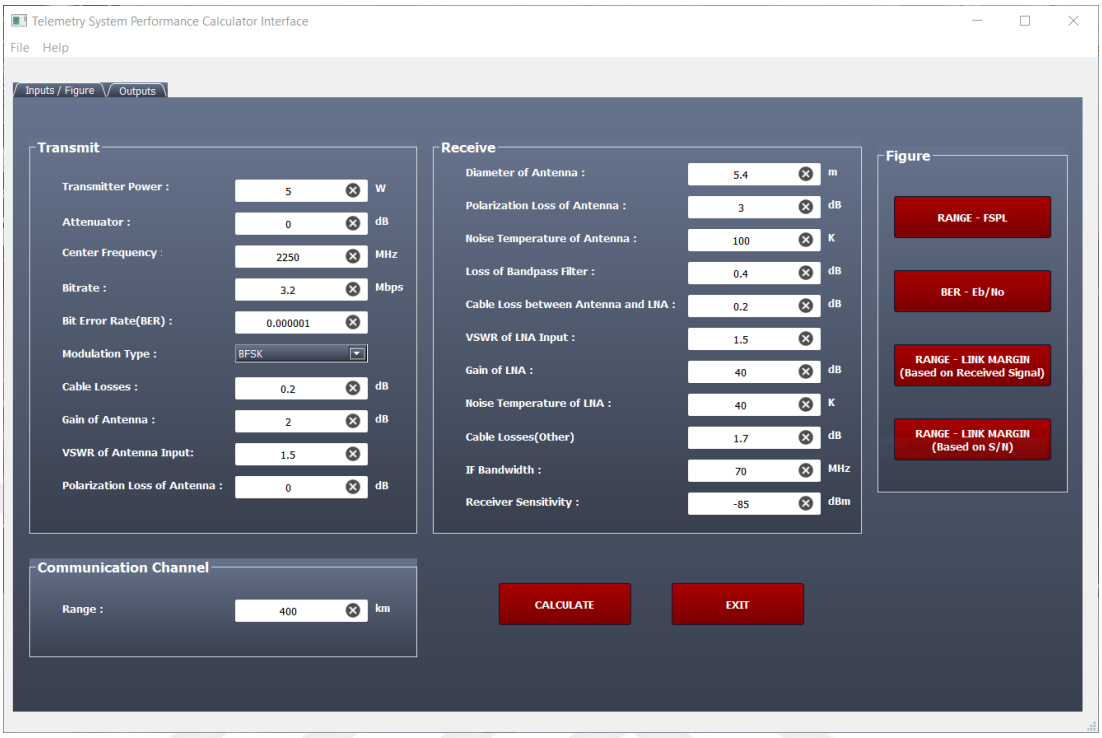

Figure 7.1 Telemetry System Performance Calculator Interface Input Screen for BFSK

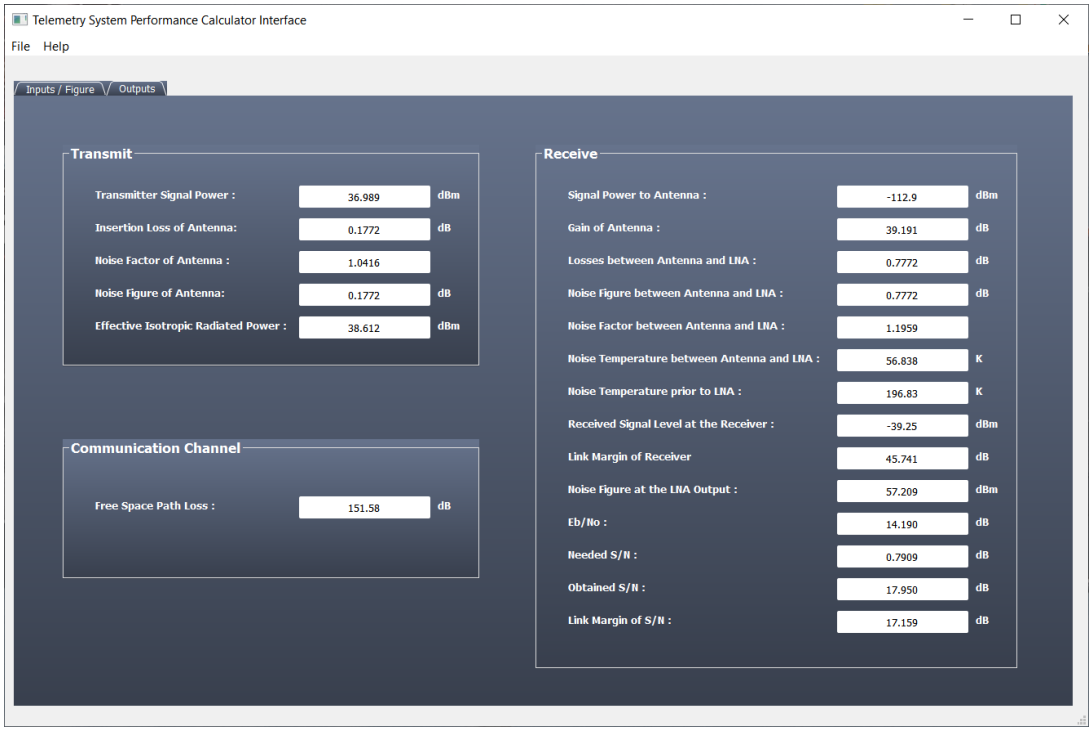

Figure 7.2. Telemetry System Performance Calculator Interface Output Screen for BFSK

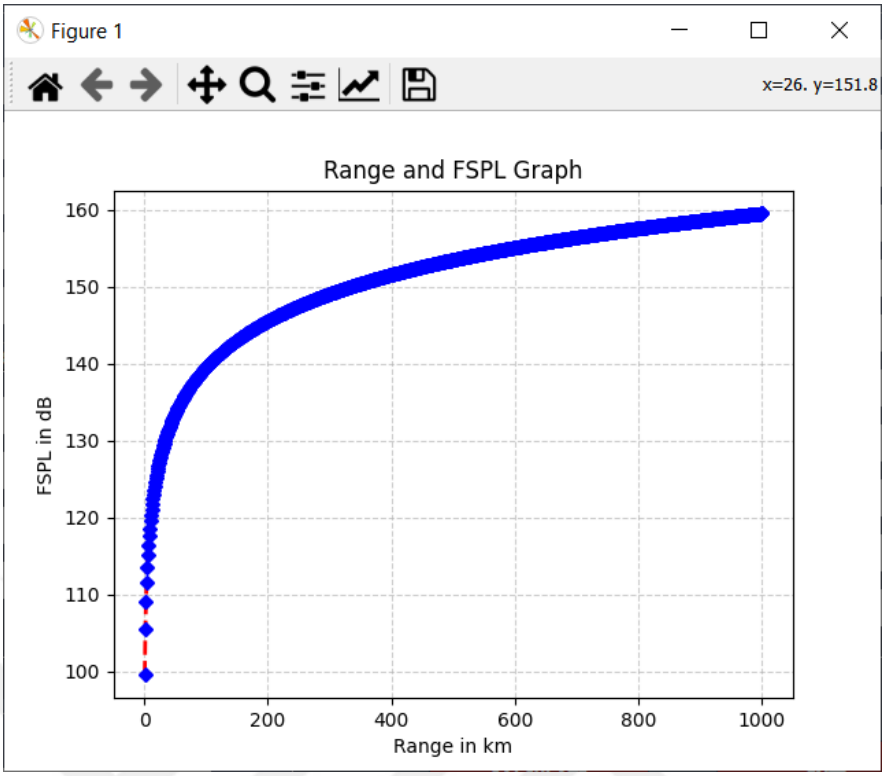

Figure 7.3 Range-FSPL Graph

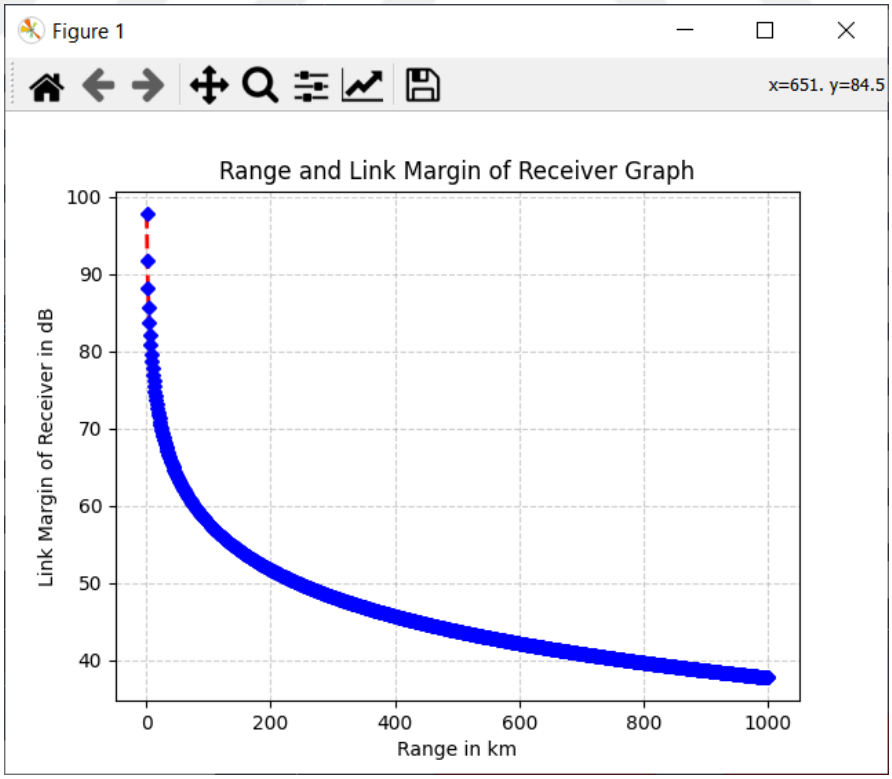

Figure 7.4 Range-Link Margin of Received Signal

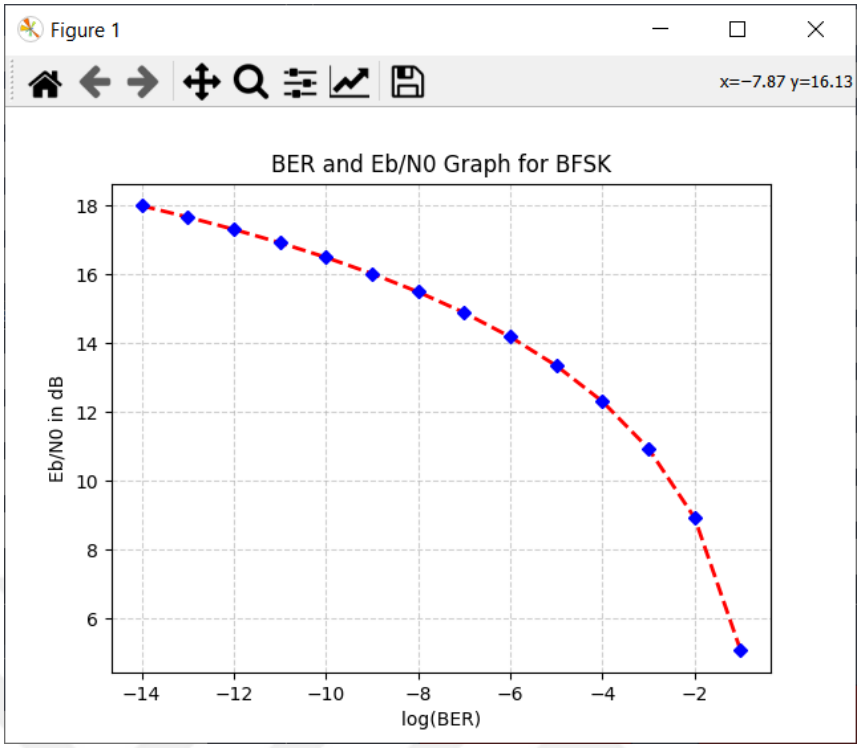

Figure 7.5 BER-E_b/N_0 Graph for BFSK

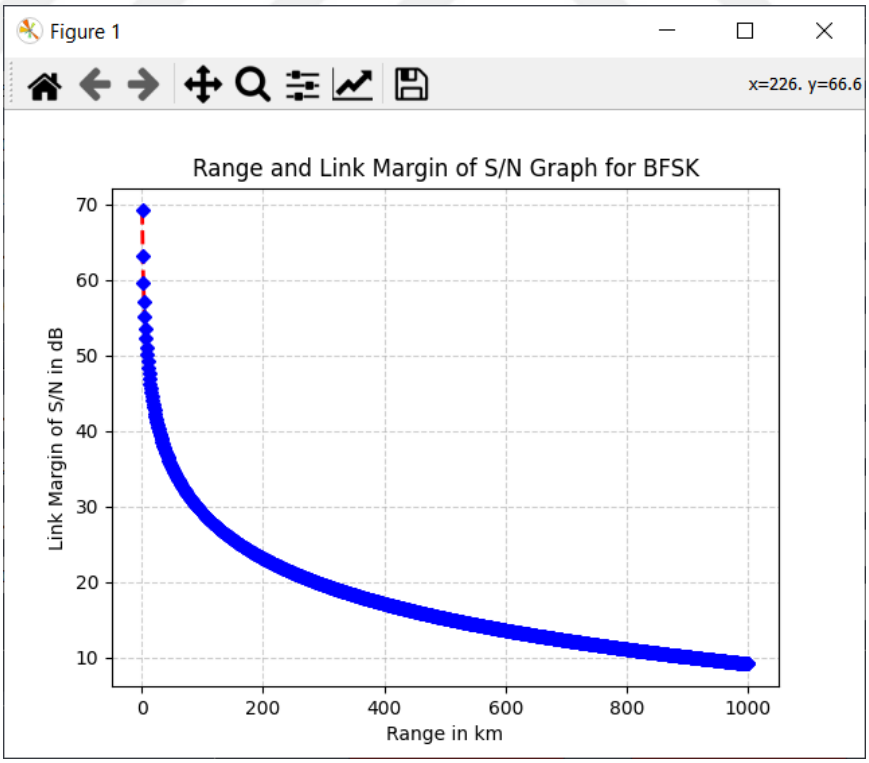

Figure 7.6 Range-Link Margin of S/N Graph for BFSK

7.2 4-FSK Simülasyon Çıktıları

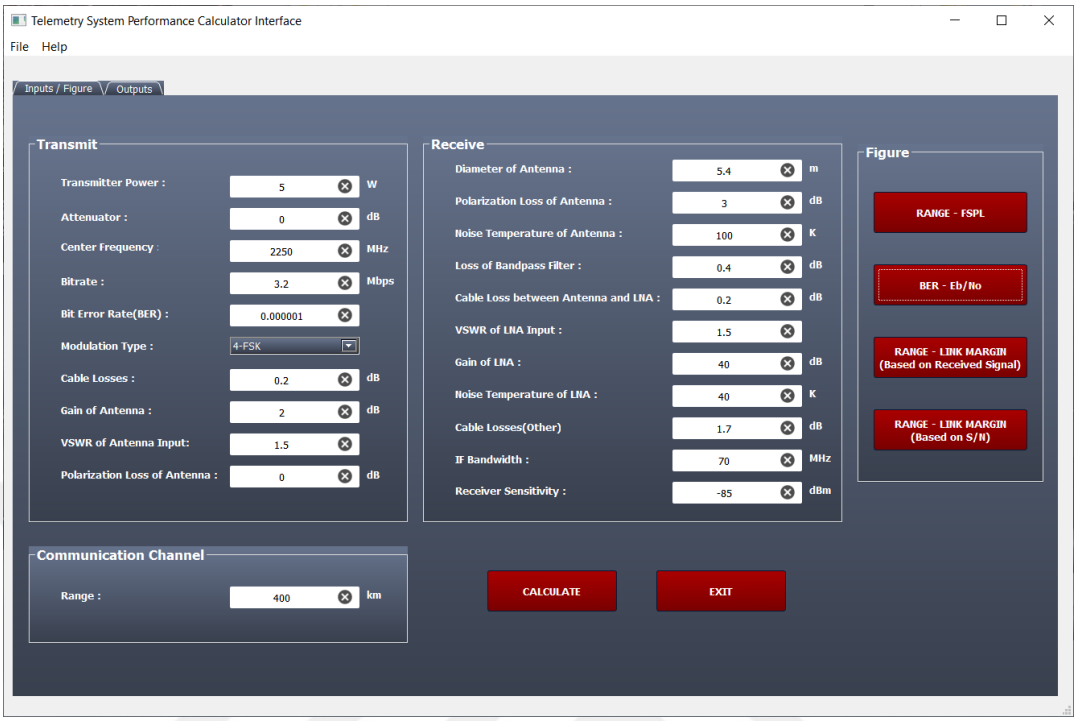

Figure 7.7 Telemetry System Performance Calculator Interface Input Screen for 4-FSK

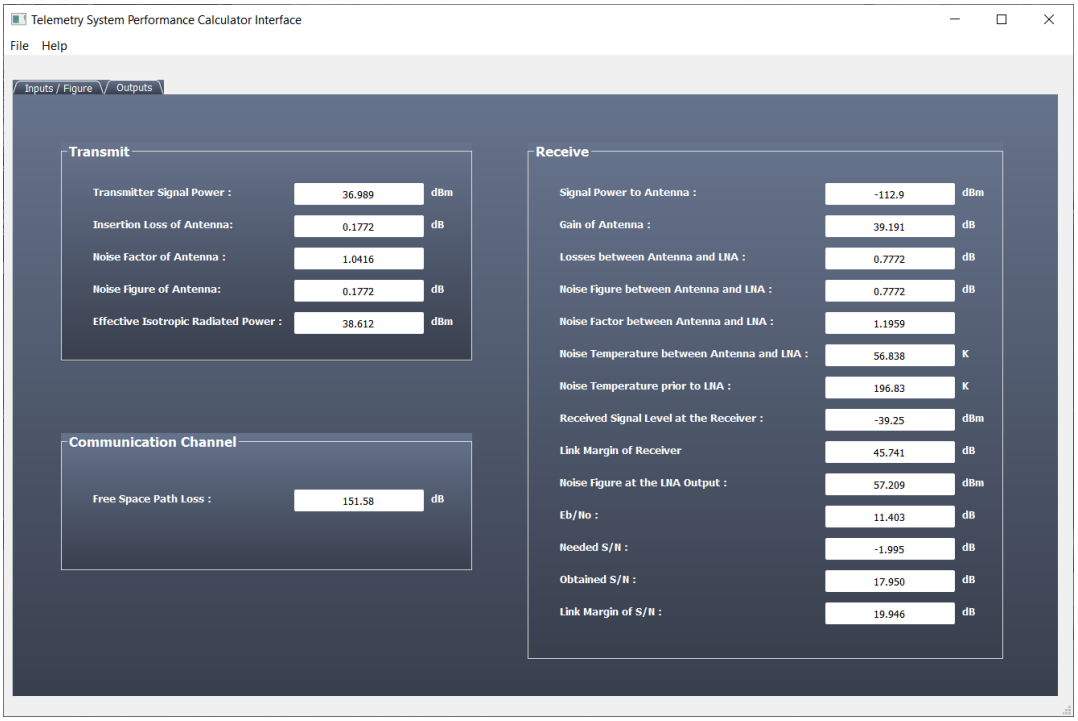

Figure 7.8 Telemetry System Performance Calculator Interface Output Screen for 4-FSK

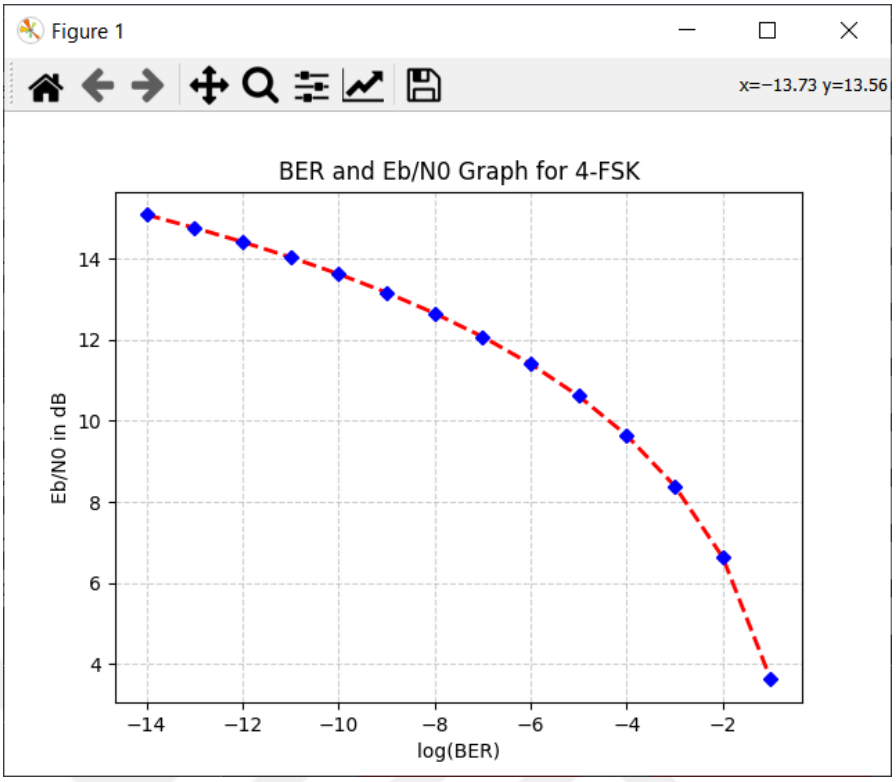

Figure 7.9 BER-E_b/N_0 Graph for 4-FSK

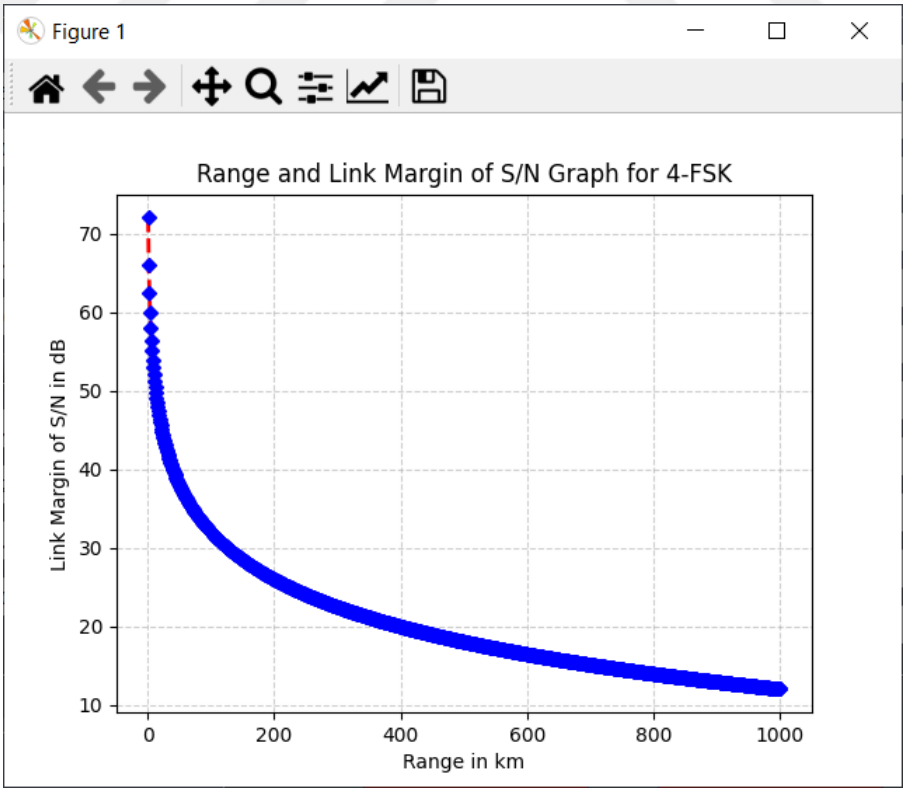

Figure 7.10 Range-Link Margin of S/N Graph for 4-FSK

7.3 PCM/FM Simülasyon Çıktıları

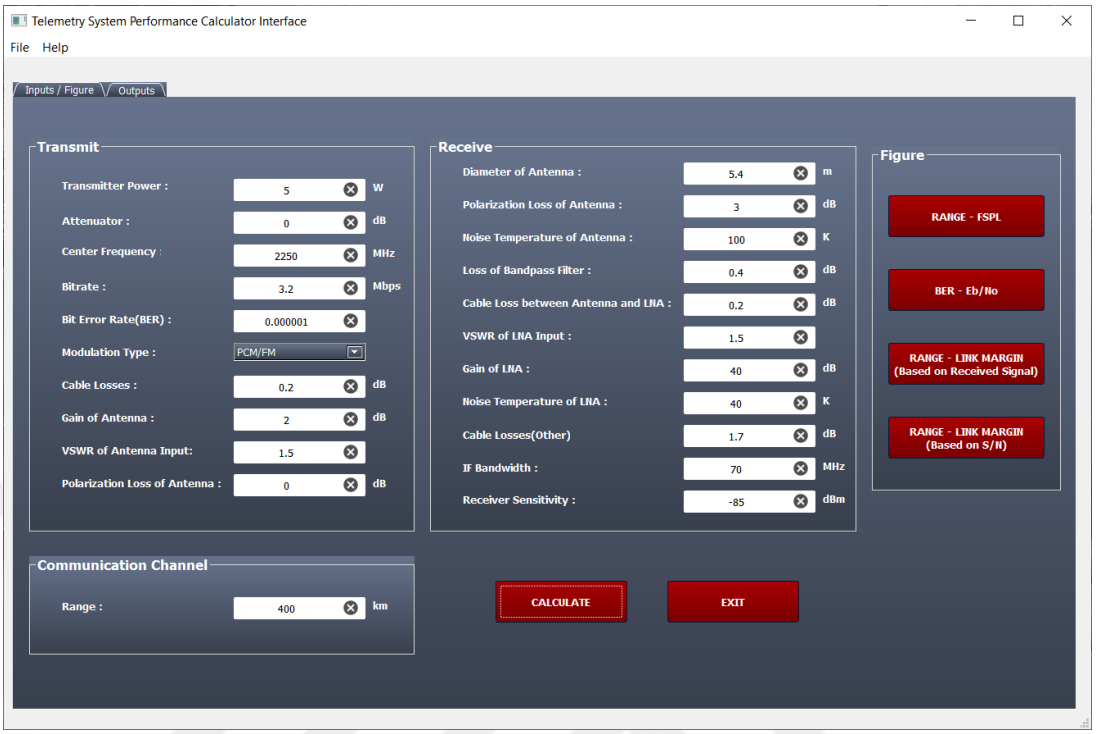

Figure 7.11 Telemetry System Performance Calculator Interface Input Screen for PCM/FM

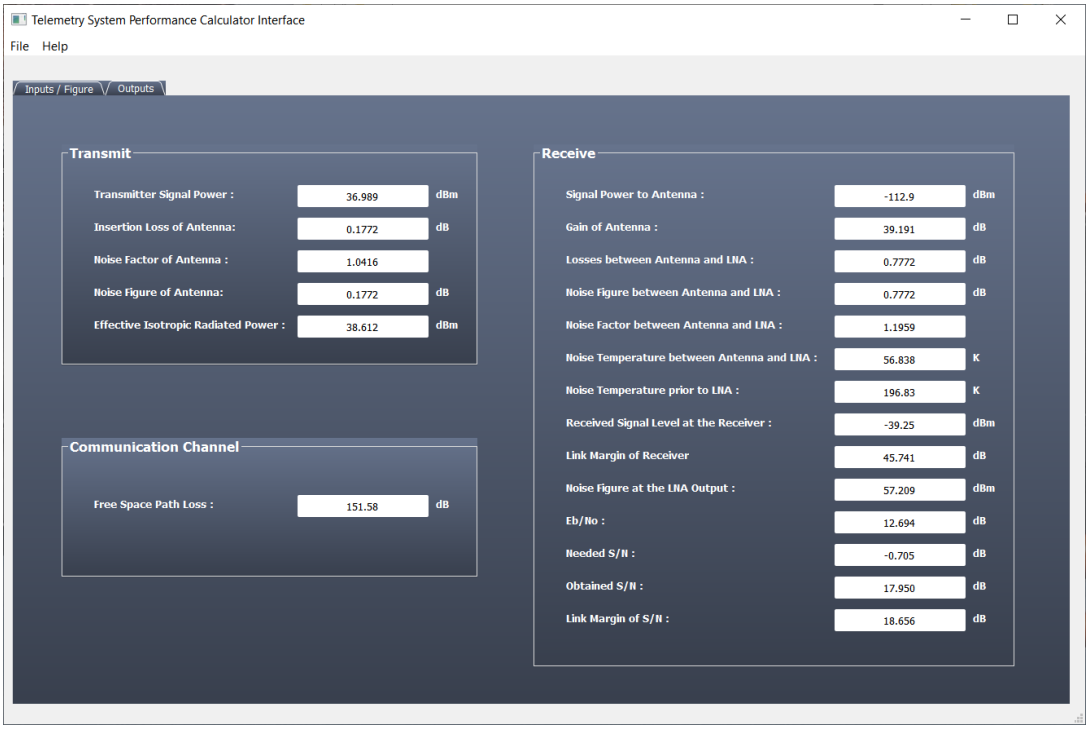

Figure 7.12 Telemetry System Performance Calculator Interface Output Screen for PCM/FM

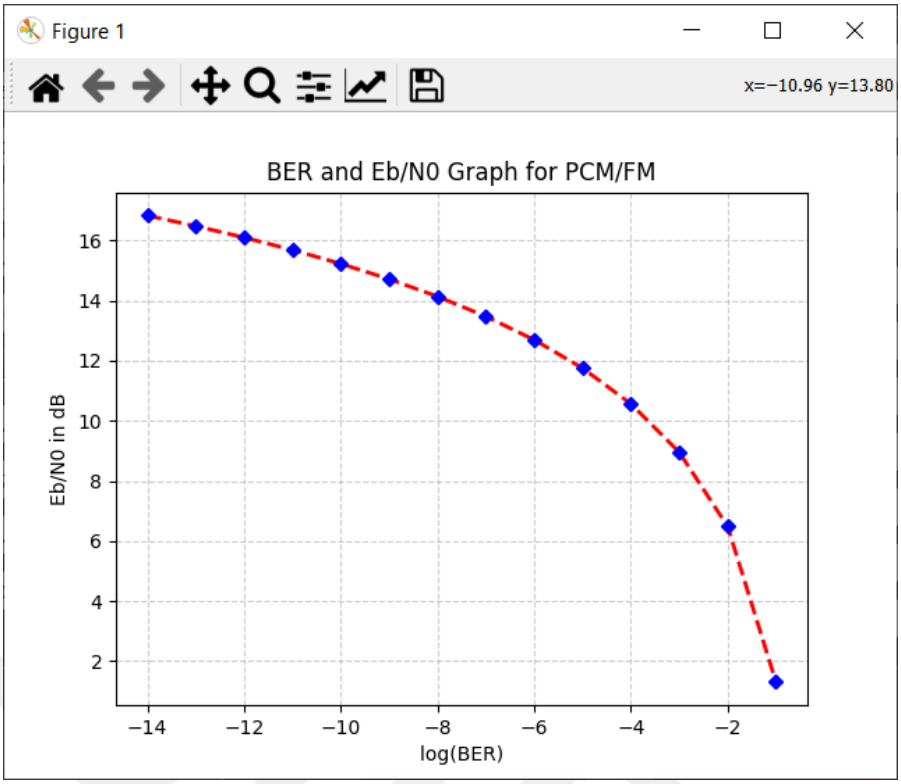

Figure 7.13 BER-E_b/N_0 Graph for PCM/FM

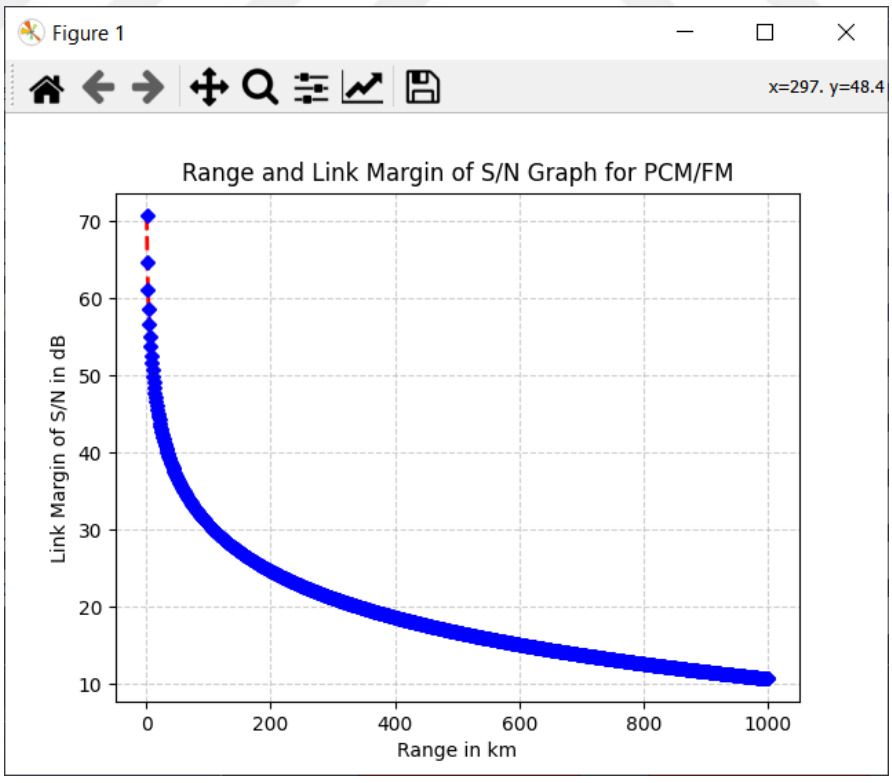

Figure 7.14 Range-Link Margin of S/N Graph for PCM/FM

7.4 BPSK Simülasyon Çıktıları

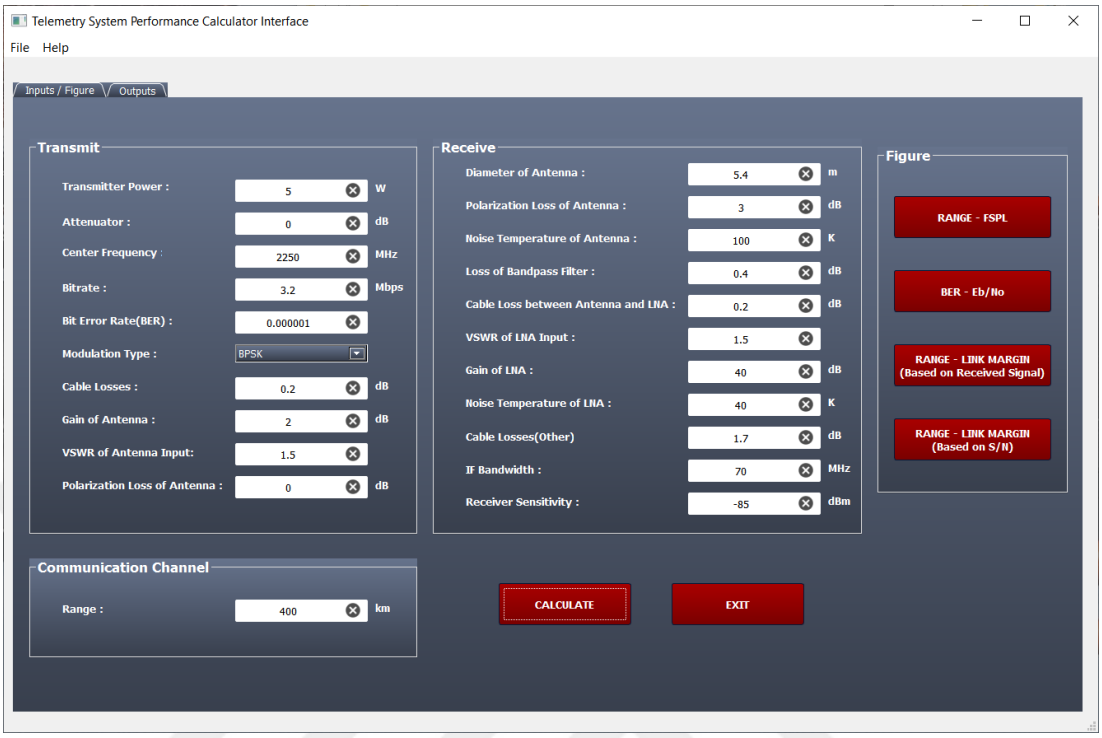

Figure 7.15 Telemetry System Performance Calculator Interface Input Screen for BPSK

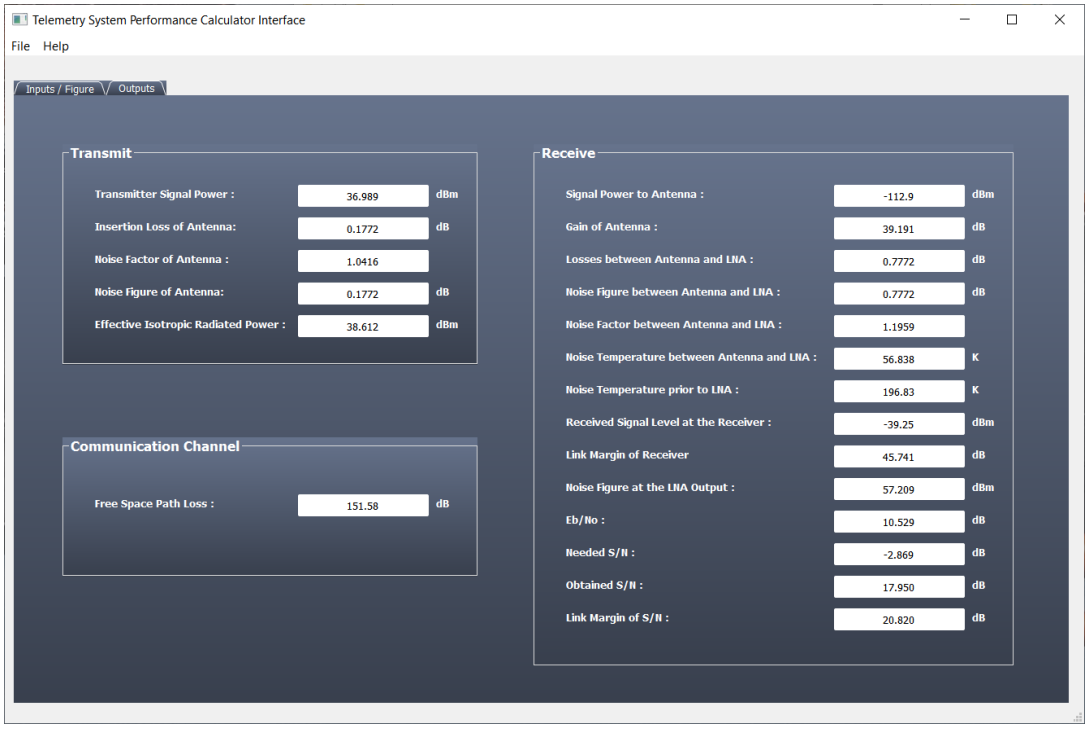

Figure 7.16 Telemetry System Performance Calculator Interface Output Screen for BPSK

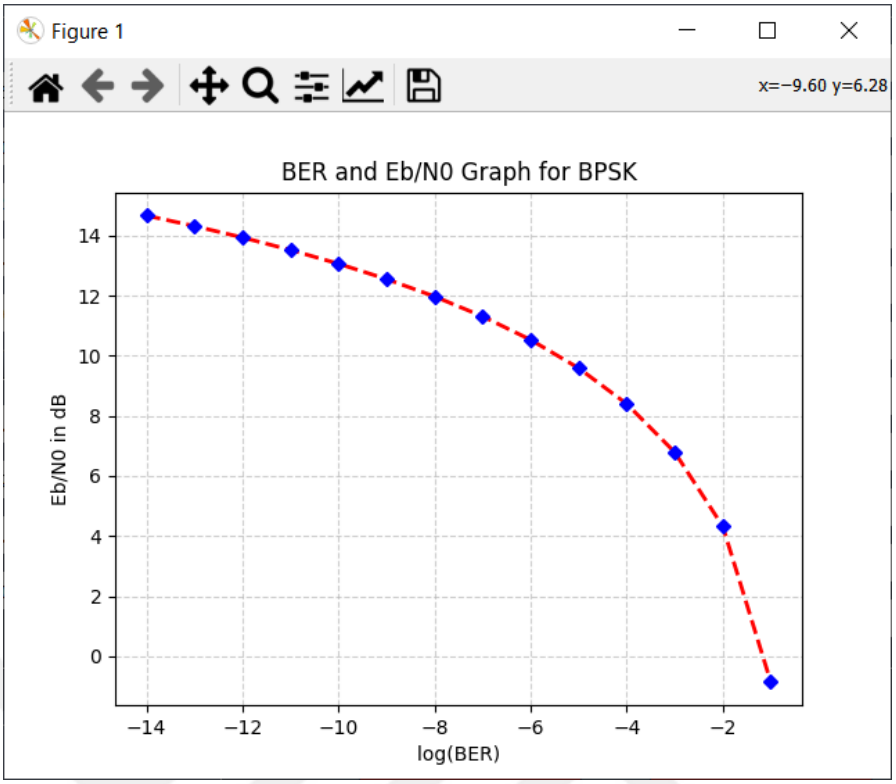

Figure 7.17 BER-E_b/N_0 Graph for BPSK

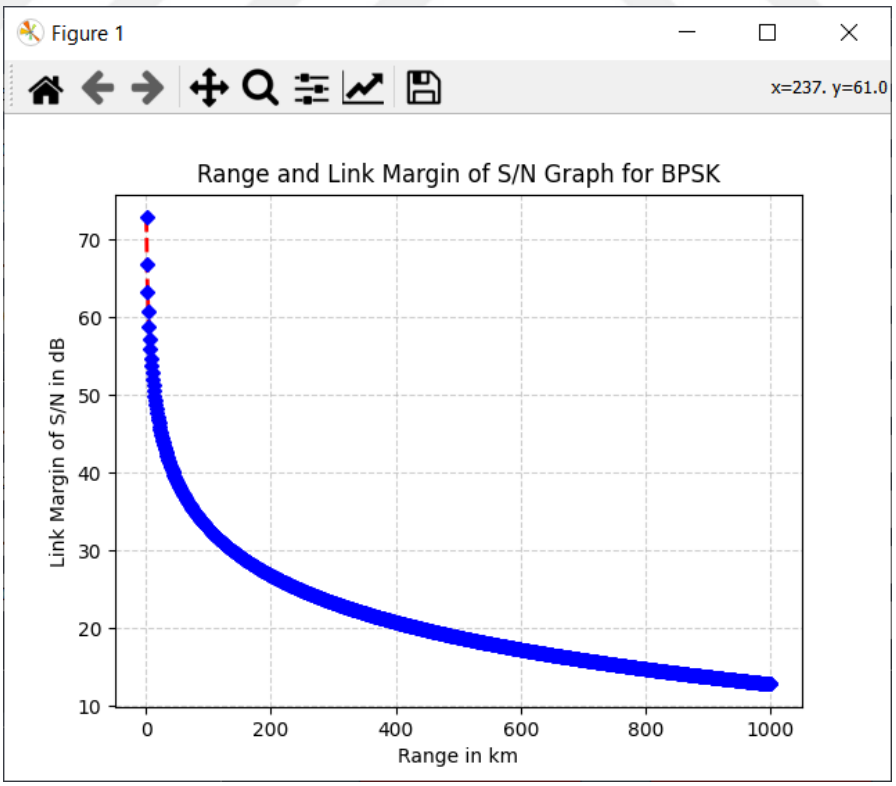

Figure 7.18 Range-Link Margin of S/N Graph for BPSK

7.5 QPSK Simülasyon Çıktıları

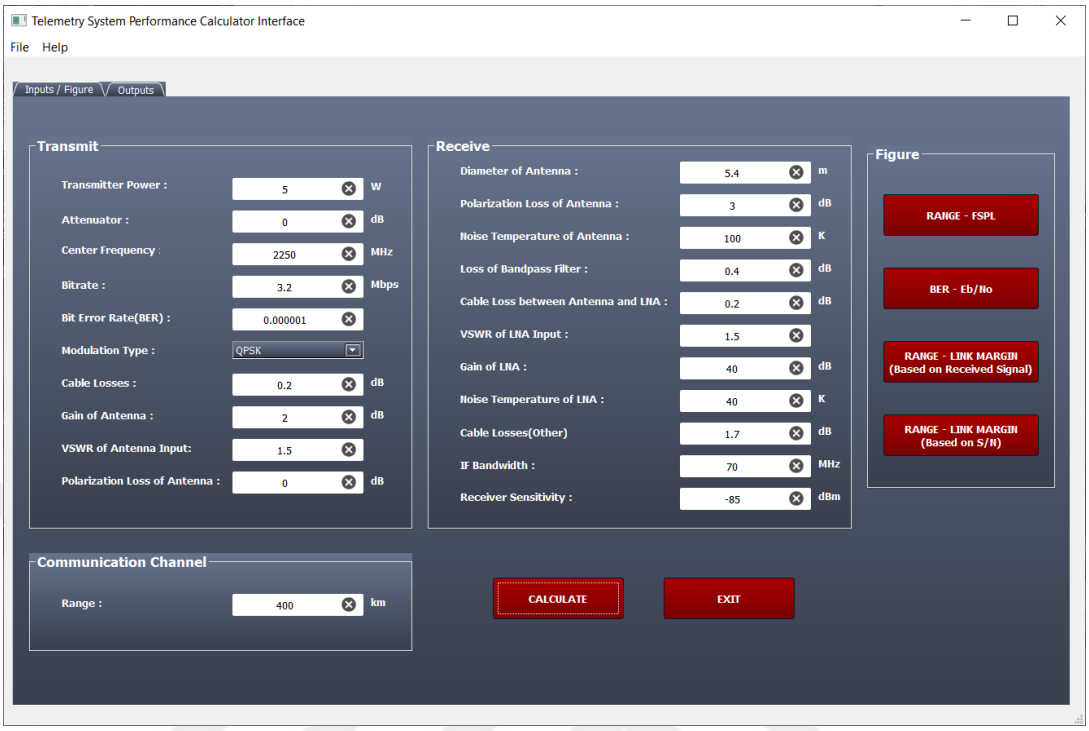

Figure 7.19 Telemetry System Performance Calculator Interface Input Screen for QPSK

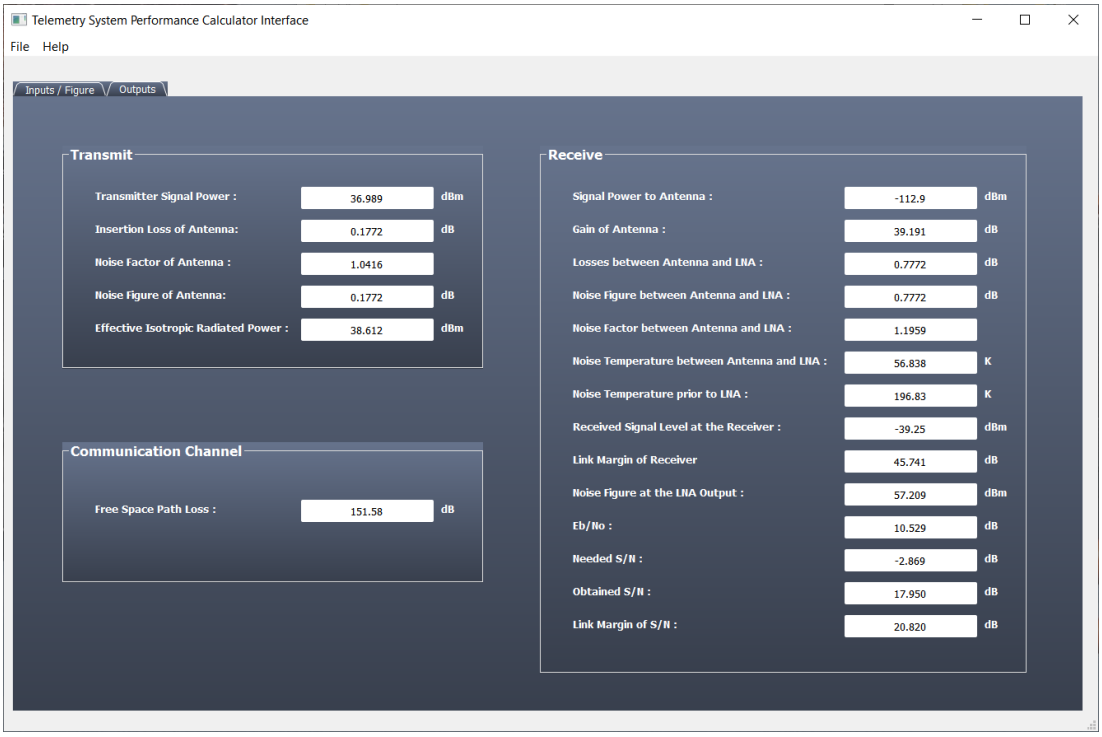

Figure 7.20 Telemetry System Performance Calculator Interface Output Screen for QPSK

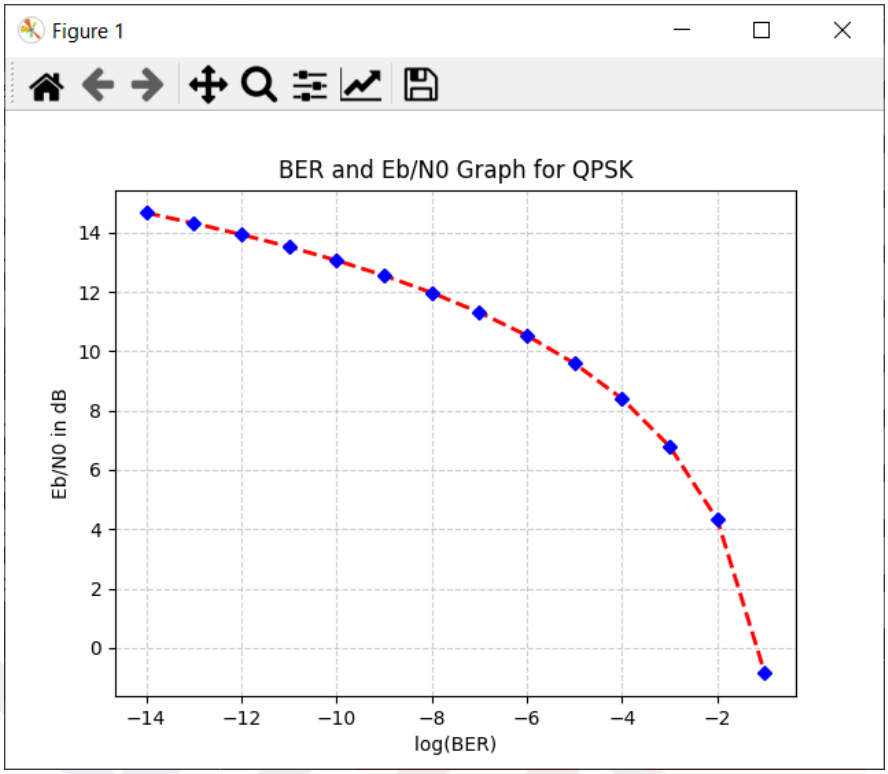

Figure 7.21 BER-E_b/N_0 Graph for QPSK

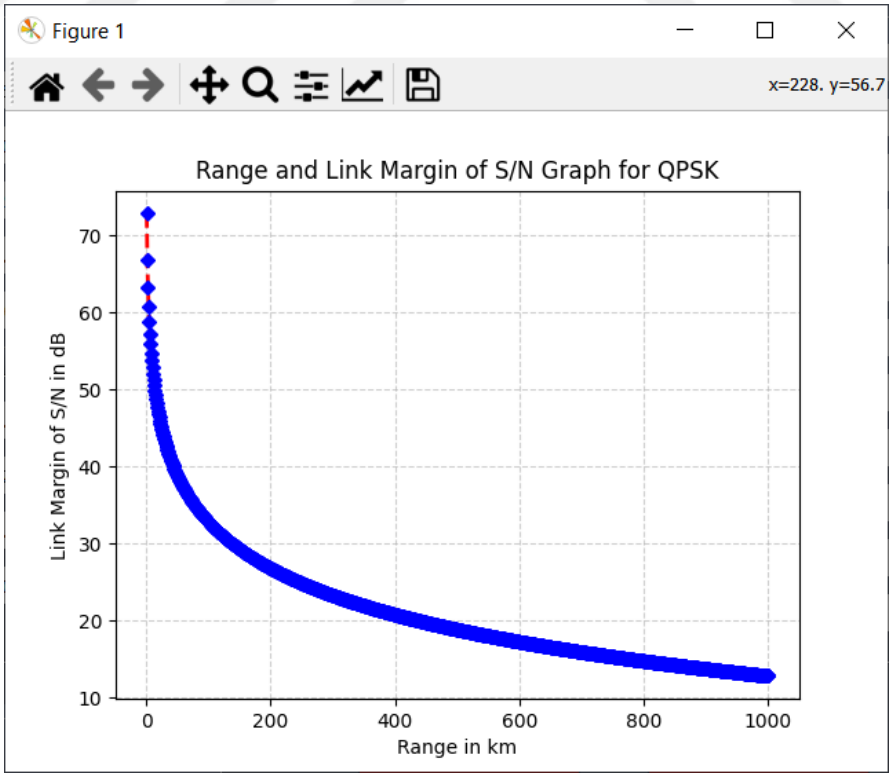

Figure 7.22 Range-Link Margin of S/N Graph for QPSK

7.6 8-PSK Simülasyon Çıktıları

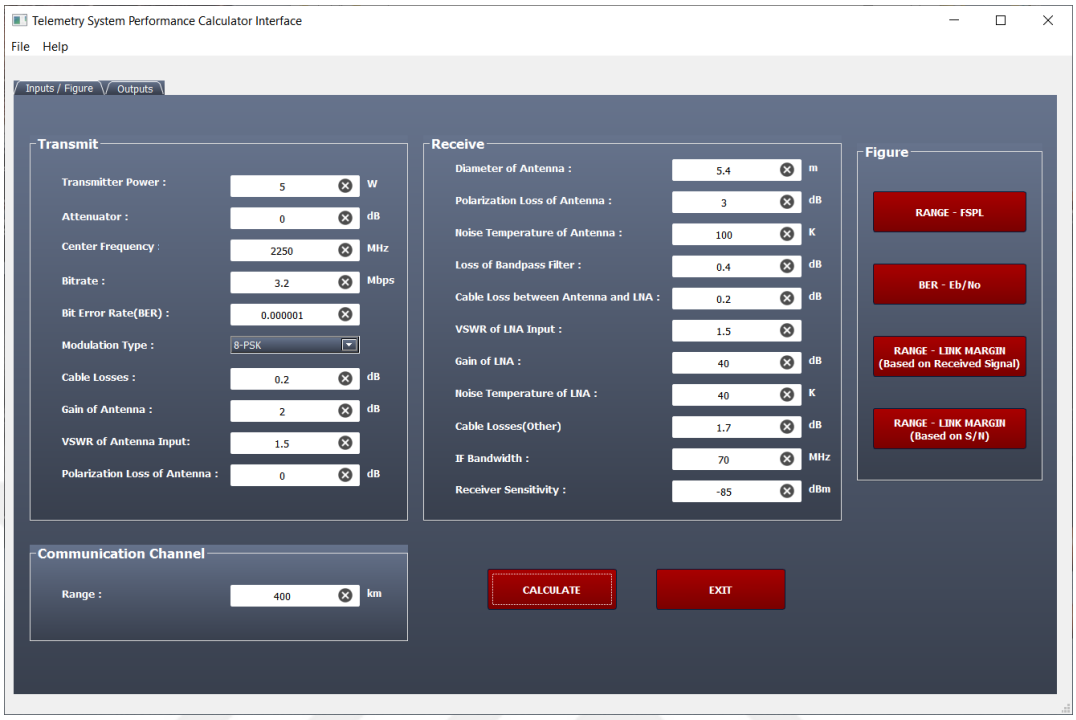

Figure 7.23 Telemetry System Performance Calculator Interface Input Screen for 8-PSK

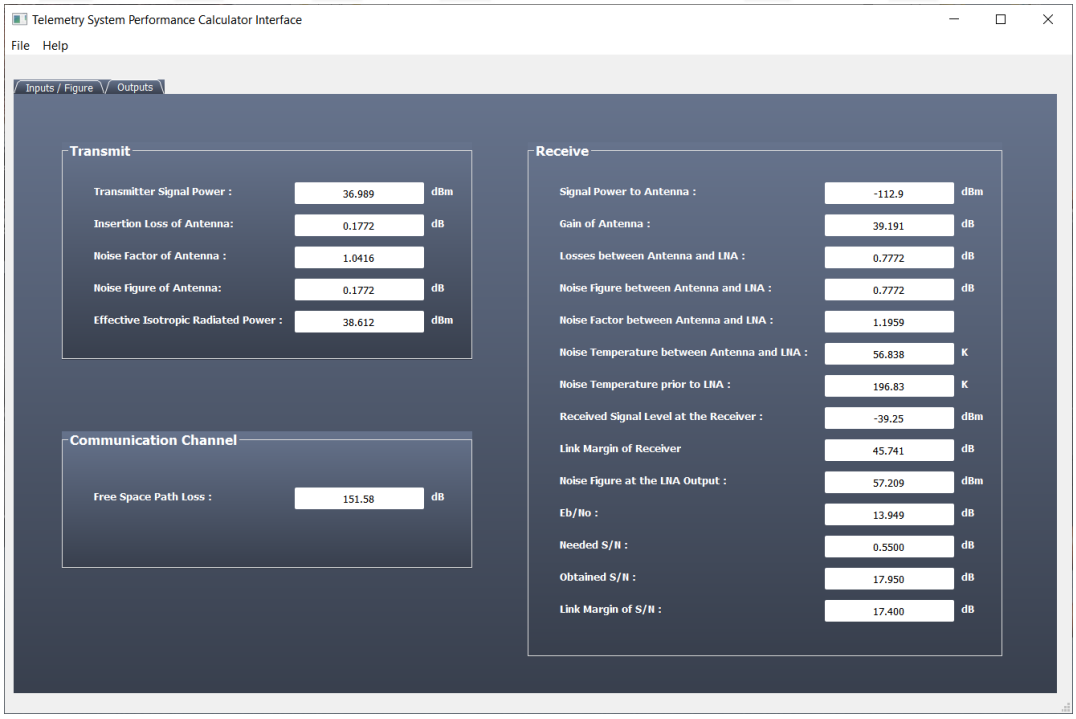

Figure 7.24 Telemetry System Performance Calculator Interface Output Screen for 8-PSK

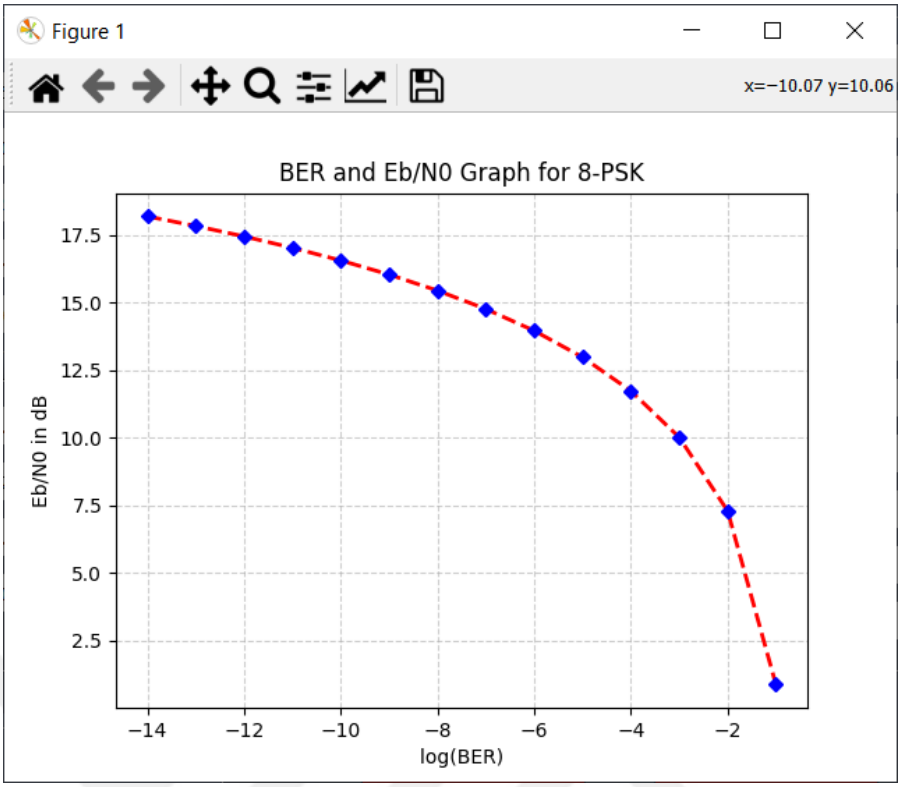

Figure 7.25 BER-E_b/N_0 Graph for 8-PSK

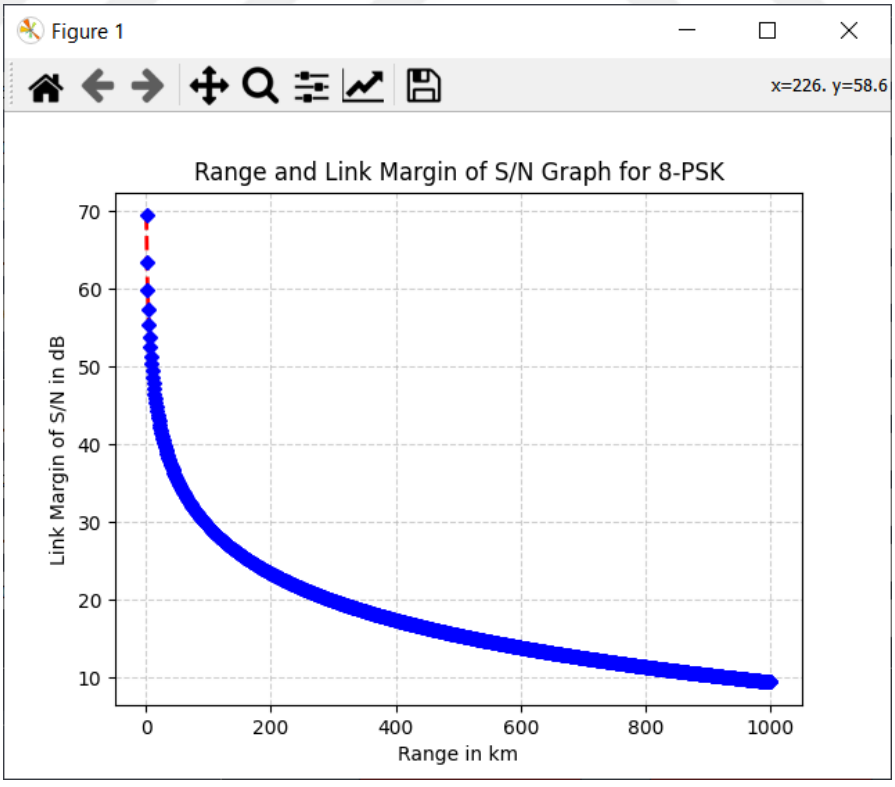

Figure 7.26 Range-Link Margin of S/N Graph for 8-PSK

CHAPTER 8

Conclusions

8.1 Advices and Future Works

In this study, other communication parameters are kept constant by changing the modulation types and distance from the communication parameters on the missile and ground station side. However, thanks to the developed Telemetry System Performance Calculator Interface program, we can improve the performance of the telemetry system by changing all communication parameters.

S/N is one of the most important parameters affecting the communication quality in telecommunication communication. Link Margin of S/N value is an important metric for evaluating communication quality in transmitting and receiving systems. Communication can be interrupted frequently if the Link Margin of S/N is less than 6 dB. The higher the value, the better the line quality. Link Margin of S/N value should be 6 dB and above. Thanks to the developed interface, the Link Margin of S/N value is calculated according to the distance and telemetry communication performances are compared according to the modulation types.

Suppose that communication parameters are in Table 8.1. When BPSK and QPSK modulation techniques are used at a distance of 400 km, the Link Margin of S/N value is calculated as 20,820 dB. As shown in Table 8.2, Link Margin of S/N decreases by 6 dB when the range is doubled, and increases by 6 dB when divided by 2. The Link Margin value for the modulation technique used at a distance of 400 km is 17.159 dB for BFSK, 19.946 dB for 4-FSK, 18.656 dB for PCM/FM, and 17.40 dB for 8-PSK. As a result of the study, BPSK and QPSK should be preferred as modulation techniques in order to get the best performance in telemetry system design.

As a result of these studies, we provide a more reliable environment for pre-flight by pre-determining the communication parameters of the telemetry equipment required for missile telemetry system design.

For future works, we can develop the Telemetry System Performance Calculator Interface program and turn it into an optimization tool to provide better communication quality.

Table 8.1 Airborne and Ground Station Communication Parameters

TRANSMIT	Transmitter Power	5 W
	Attenuator	0 dB
	Center Frequency	2250 MHz
	Bitrate	3.2 Mbps
	Bit Error Rate (BER)	10^{-6}
	Cable Losses	0.2 dB
	Gain of Antenna	2 dB
	VSWR of Antenna Input	1.5
	Polarization Loss of Antenna	0 dB
RECEIVE	Diameter of Antenna	5.4 m
	Polarization Loss of Antenna	3 dB
	Noise Temperature of Antenna	100 K
	Loss of Bandpass Filter	0.4 dB
	Cable Loss between Antenna and LNA	0.2 dB
	VSWR of LNA Input	1.5
	Gain of LNA	40 dB
	Noise Temperature of LNA	40 K
	Cable Losses (Other)	1.7 dB
	IF Bandwidth	70 MHz
	Receiver Sensitivity	-85 dBm

Table 8.2 Range-Link Margin of S/N for Modulation Type

	MODULATION TYPES					
	BFSK	**4-FSK**	**PCM/FM**	**BPSK**	**QPSK**	**8-PSK**
Link Margin of S/N for 100 km	29.201 dB	31.987 dB	30.697 dB	32.861 dB	32.861 dB	29.442 dB
Link Margin of S/N for 200 km	23.180 dB	25.967 dB	24.676 dB	26.841 dB	26.841 dB	23.421 dB
Link Margin of S/N for 400 km	17.159 dB	19.946 dB	18.656 dB	20.820 dB	20.820 dB	17.40 dB
Link Margin of S/N for 800 km	11.139 dB	13.926 dB	12.635 dB	14.799 dB	14.799 dB	11.38 dB

REFERENCES

[1] Mayo-Wells, W. J. The origins of space telemetry. *Technology and Culture*, *4*(4), 499-514. 1963.

[2] Wikipedia contributors. (2022, November 28). Telemetry. In Wikipedia, The Free Encyclopedia. Retrieved 19:51, December 4, 2022, from https://en.wikipedia.org/w/index.php?title=Telemetry&oldid=1124316202.

[3] F. Carden, R. Jedlicka, R. Henry, "Telemetry Systems Engineering", Artech House, 2002.

[4] Arasan, A., & Ertugrul, C. A Frame Based Combining Method for Telemetry Data. Proceeding-etc2016, 244-247. 2016.

[5] Ufelek, M., Yoruk, O., & Cakici, M. E. 3.3 Real Time Data Visualization in Telemetry Systems. Proceedings-ettc2020, 107-112. 2020

[6] Manir, E., & Çinar, S. M. (On the investigation of a designed smart telemetry control algorithm. In *2016 National Conference on Electrical, Electronics and Biomedical Engineering (ELECO)* (pp. 650-654). IEEE. 2016.

[7] Duchrow, T., Schröer, M., Griesbach, B., Kasperski, S., Bermpohl, F. M. G., Kramer, S., & Kirchner, F. Towards electric mobility data mining. In *2012 IEEE International Electric Vehicle Conference* (pp. 1-6). IEEE. 2012.

[8] Ustun, O., Yilmaz, M., Gokce, C., Karakaya, U., ve Tuncay, R. N."Energy management method for solar race car design and application", Electric Machines and Drives Conference, 2009, 804-811.

[9] Tucker, A. D., "Nest site fidelity and clutch frequency of loggerhead turtles are better elucidated by satellite telemetry than by nocturnal tagging efforts:

implications for stock estimation", Journal of Experimental Marine Biology and Ecology, 383.1., 48-55, 2010.

[10] Durmuş, M., Şanlıurfada Ceylanların (Gazella subgutturosa) Yaşam Alanı Büyüklüğü Ve Habitat Seçimlerinin GPS Telemetri İle Belirlenmesi, Yüksek Lisana Tezi, Fen Bilimleri Enstitüsü, ODTÜ, Ankara, 2010.

[11] Manir, E., & Çinar, S. M. On the investigation of a designed smart telemetry control algorithm. In 2016 National Conference on Electrical, Electronics and Biomedical Engineering (ELECO) (pp. 650-654). IEEE, 2016.

[12] Yüksel, E. *Uzaktan Ölçüm İçin Zigbee Mimarisi Kullanan Sistem Tasarımı* (Doctoral dissertation, Yüksek Lisans Tezi, İstanbul Üniversitesi Fen Bilimleri Enstitüsü). 2010.

[13] Standard, I. R. I. G. 106-04 (Part I). Published by the Secretariat Range Commanders Council (RCC). 2004.

[14] Aerospace Telemetry (IRIG 106 PCM & CHAPTER 10 intro). (n.d.). Retrieved from https://training.dewesoft.com/online/course/telemetry

[15] Wikipedia contributors. (2022, December 14). Commutation (telemetry). In *Wikipedia, The Free Encyclopedia*. Retrieved 11:04, December 14, 2022, from https://en.wikipedia.org/w/index.php?title=Commutation_(telemetry)&oldid=1127335046.

[16] Sağlam, A. Increasing transmission range of missile telemetry data with compression techniques. MS thesis. Baskent University Graduate School of Natural and Applied Sciences, 2017.

[17] Proakis, J. G., Salehi, M., Zhou, N., & Li, X. *Communication systems engineering* (Vol. 2). New Jersey: Prentice Hall. 1994.

[18] Kolawole, M.,“Satellite Communication Engineering”, Marcel Dekker, Melbourne, 16-35 (2002).

[19] Classification of Polarization. (n.d.). Retrieved from http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/polclas.html.

[20] Kurt, T. Effect of modulation techniques on link equations at satellite communication systems. MS thesis. Gazi University Graduate School of Natural and Applied Sciences, 2013.

[21] Lathi, B. P., Ding Z. *Modern Digital and Analog Communication Systems*. Oxford University Press, 2009.

[22] Tiryakioğlu, İ., Güllü, M., Baybura, T., & Erdoğan, S. The Study of GPS Signal Reflection(Multipath) Effects on Point Position. 2. Mühendislik Ölçmeleri Sempozyumu on ITU (pp. 534-543), November 2005.

[23] Multipath Height Finding Method. (n.d.). Retrieved from https://www.radartutorial.eu/01.basics/rb63.en.html.

[24] Sağlam, B. Performance analysis of telemetry receiver applications. MS thesis. Baskent University Graduate School of Natural and Applied Sciences, 2014.

[25] Consept of Multiplexing. (n.d.). Retrieved from https://www.javatpoint.com/multiplexing-in-computer-network.

[26] Frequency Division Multiplexing. (n.d.). Retrieved from http://www.myreadingroom.co.in/notes-and-studymaterial/68-dcn/775-frequency-division-multiplexing.html.

[27] The McGraw-Hill Companies, Inc., 2004.

[28] Data Communications (n.d.). Retrieved from http://ceng.gazi.edu.tr/~ozdemir/

[29] Range Commanders Council Telemetry Group, Range Commanders Council, White Sands Missile Range, New Mexico, IRIG Standard 106-17: Telemetry Standards, Annex A.2, 2017. (Available on-line at http://www.irig106.org/docs/106-17/annexa-2.pdf).

[30] Graham, A., Richard, Jr. Software Randomized NRZ-L Decoder. International Telemetering Conference Proceedings , 2018, June 1.

[31] Punnoose, R. J. *Re-Engineering PCM/FM as a Phase Modulation Scheme* (No. SAND2008-3557C). Sandia National Lab.(SNL-CA), Livermore, CA (United States). 2008.

[32] Agilent, Digital Modulation in Communications Systems -An Introduction, Application Note 1298, 5965-7160E, 2001.

[33] Kırkaya, E.. *Sayısal haberleşme sistemlerinde esnek karar verme demodülasyon yöntemlerinin FPGA üzerinde etkin bir şekilde gerçekleştirilmesi* (Doctoral dissertation, Sakarya Universitesi. 2016.

[34] Altan, H. Telemetry Communications Systems Simplified. Independently published. 2018.

[35] Kayran, A. H. *Analog haberleşme*. Birsen Yayınevi. 2002.

[36] Benarji, B., Rao, G. S., & Setty, S. P. (2015). BER Performance of OFDM System with various OFDM frames in AWGN, Rayleigh and Rician Fading Channel. *International Journal of Computer Sciences and Engineering*, *3*(4), 6-11.

[37] Atila, O. (2016). *Dikgen frekans bölmeli çoklu erişim sistemlerinde kanal kestirimi ve performans analizi* (Master's thesis, Fen Bilimleri Enstitüsü).

[38] Aygün, E. (2007). *Uyarlamalı İşbirlikli Çeşitleme* (Doctoral dissertation, Fen Bilimleri Enstitüsü).

APPENDICES

Appendix A: Use of Telemetry System Performance Calculator Interface

Appendix A – Use of Telemetry System Performance Calculator Interface

After entering the communication parameters in the Transmit, Receive and Communication Channel section in the 'Input/Figure' tab of the interface screen, the 'CALCULATE' button is clicked (Figure A. 1). Then click on the 'Outputs' tab. This tab contains the outputs of the calculated values (Figure A. 2).

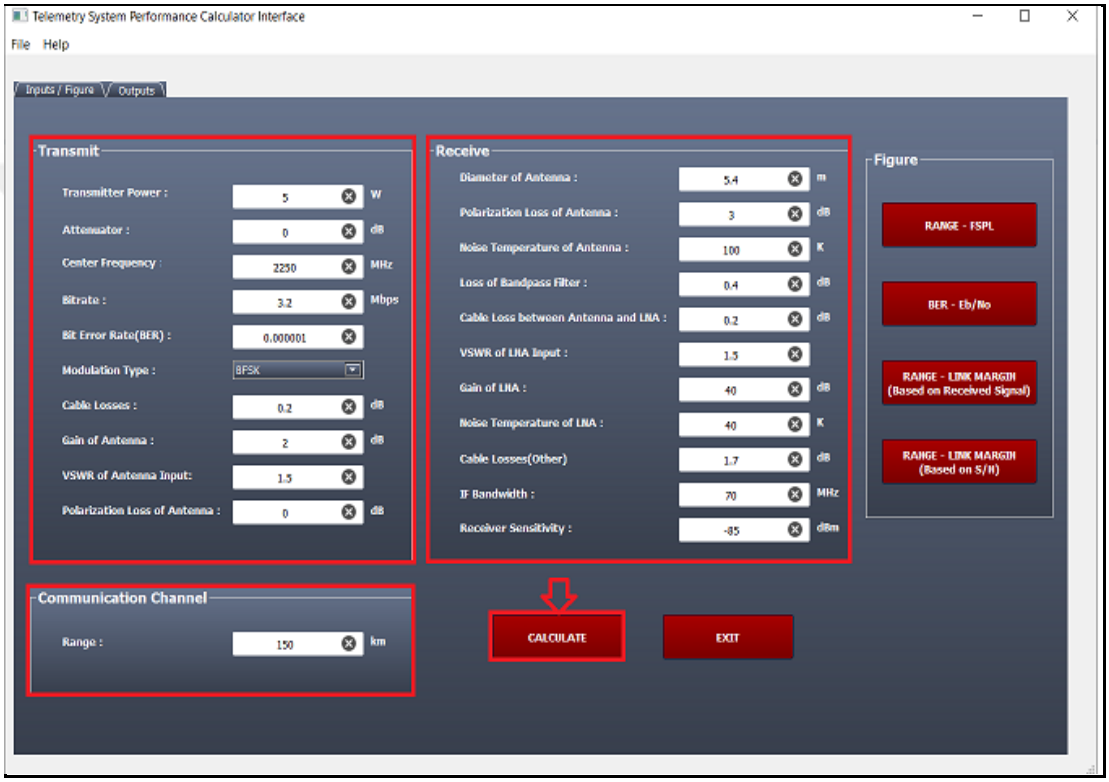

Figure A. 1 Telemetry System Performance Calculator Interface Screen (1)

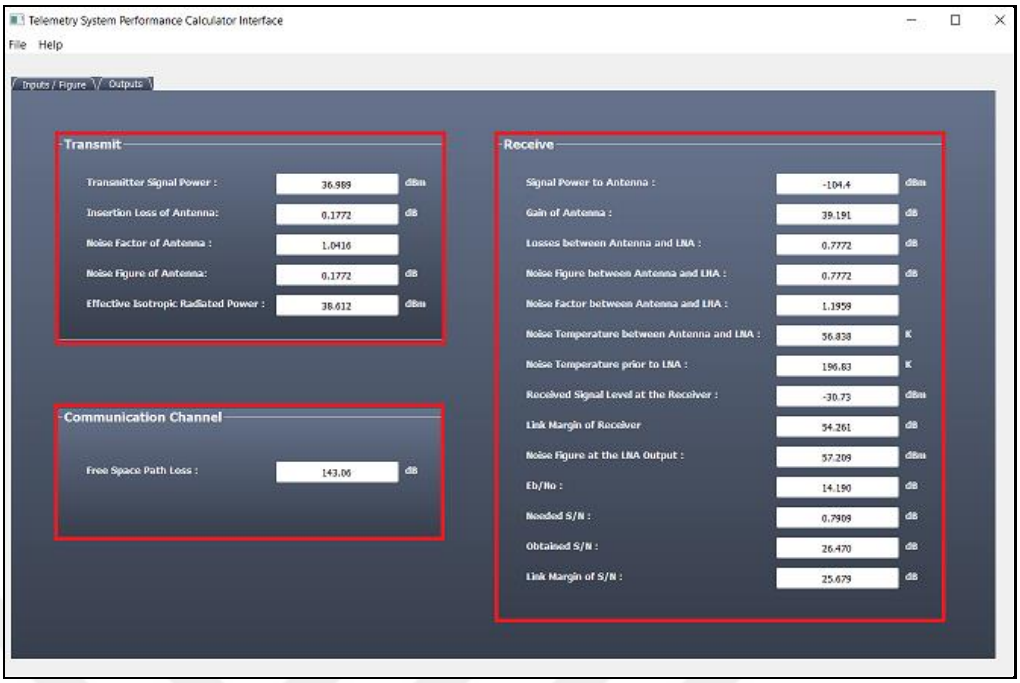

Figure A. 2 Telemetry System Performance Calculator Interface Screen (2)

Returns to the 'Input/Figure' tab. As shown in Figure A. 3, all buttons are pressed in order. When the 'Range-FSPL' button is clicked, Figure A. 4 opens.

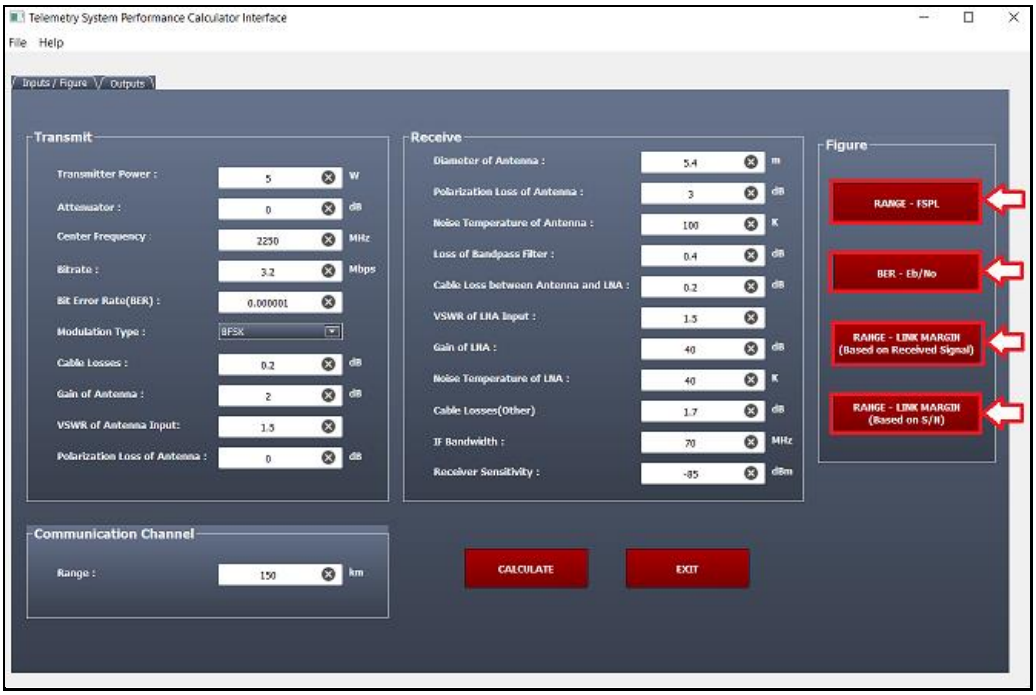

Figure A. 3 Telemetry System Performance Calculator Interface Screen (3)

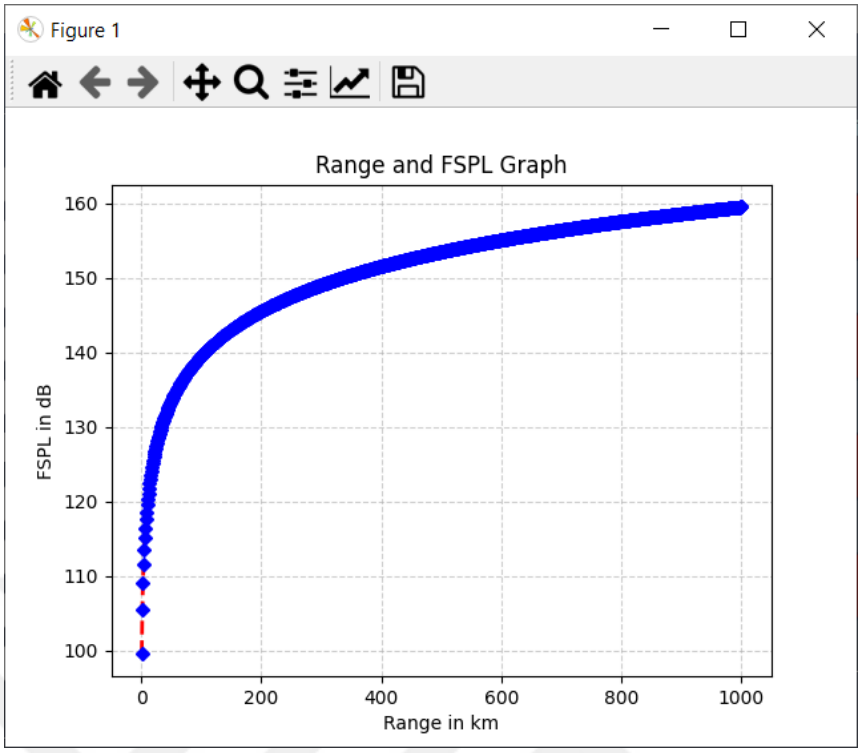

Figure A. 4 Telemetry System Performance Calculator Interface Screen (4)

When the 'BER-Eb/No' button is clicked, Figure A. 5 opens.

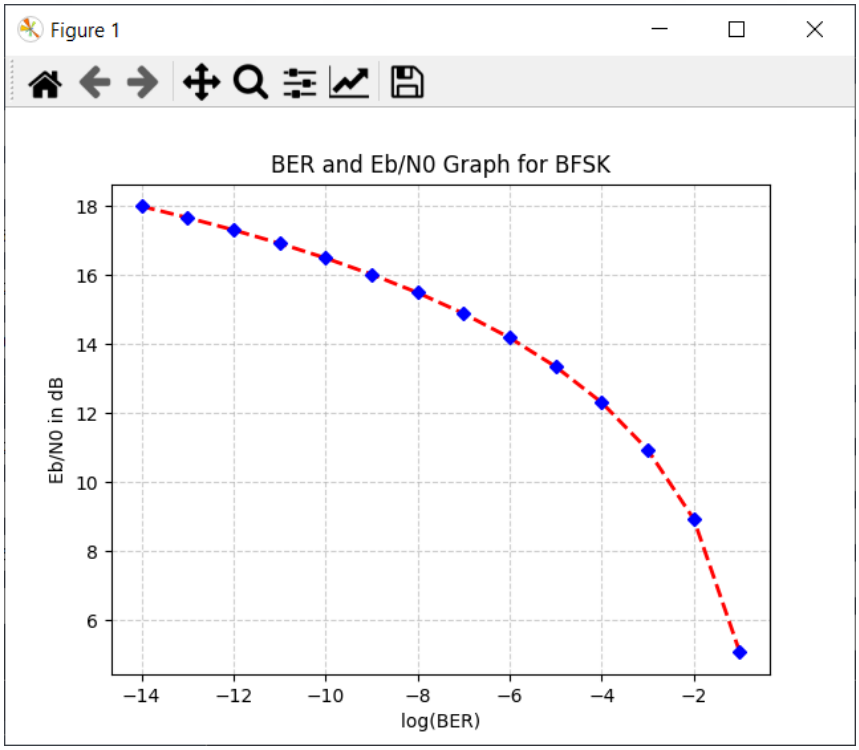

Figure A. 5 Telemetry System Performance Calculator Interface Screen (5)

When the 'Range-Link Margin (Based on Received Signal)' button is clicked, Figure A. 6 opens.

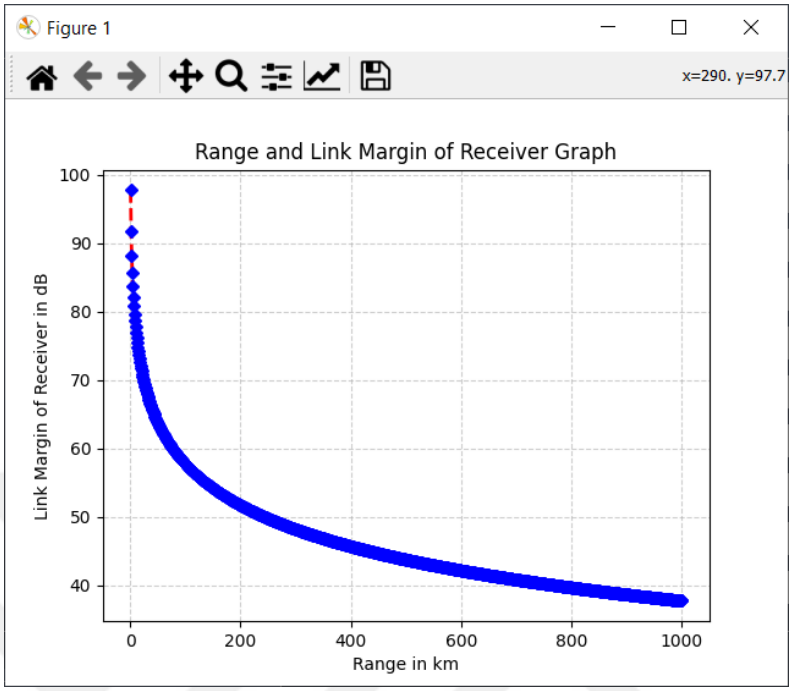

Figure A. 6 Telemetry System Performance Calculator Interface Screen (6)

When the 'Range-Link Margin (Based on S/N)' button is clicked, Figure A. 7 opens.

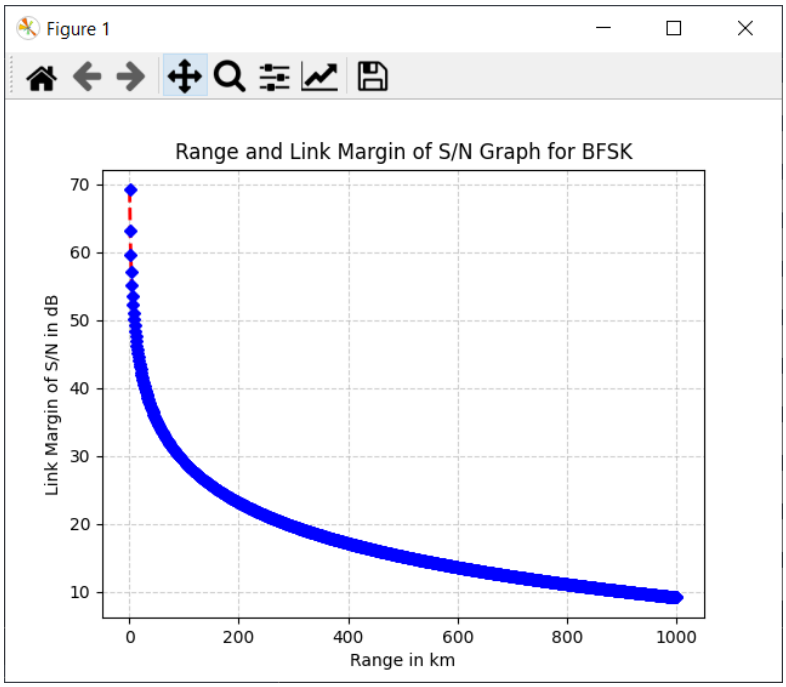

Figure A. 7 Telemetry System Performance Calculator Interface Screen (7)

As shown in Figure A. 8, we can import values in the 'Input/Figure' tab in any file format by clicking the 'Save As' button on the top tab of the interface screen (Figure A. 9).

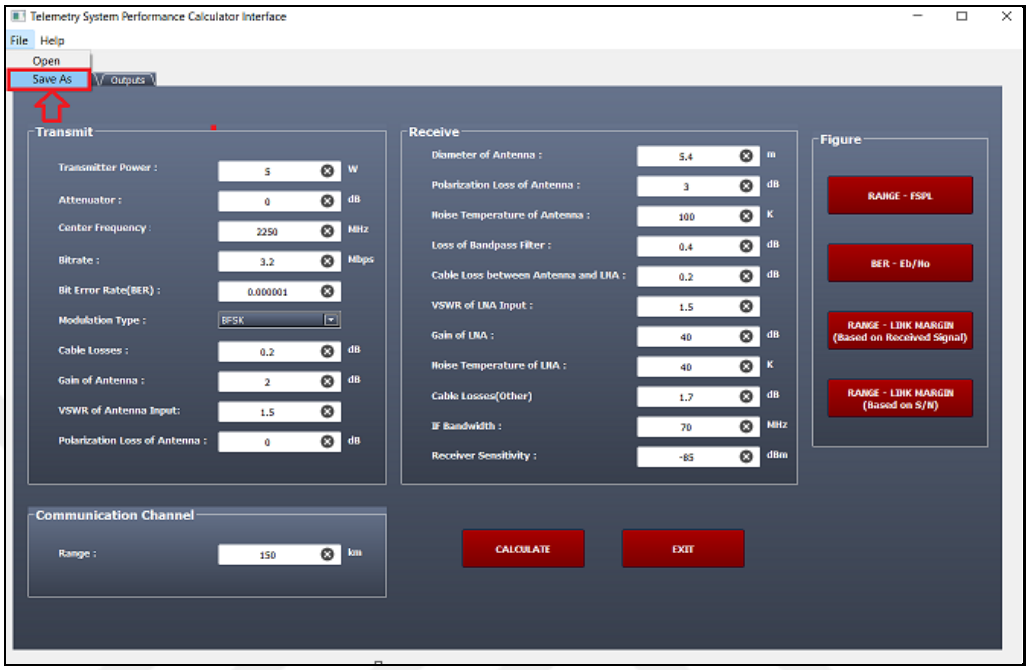

Figure A. 8 Telemetry System Performance Calculator Interface Screen (8)

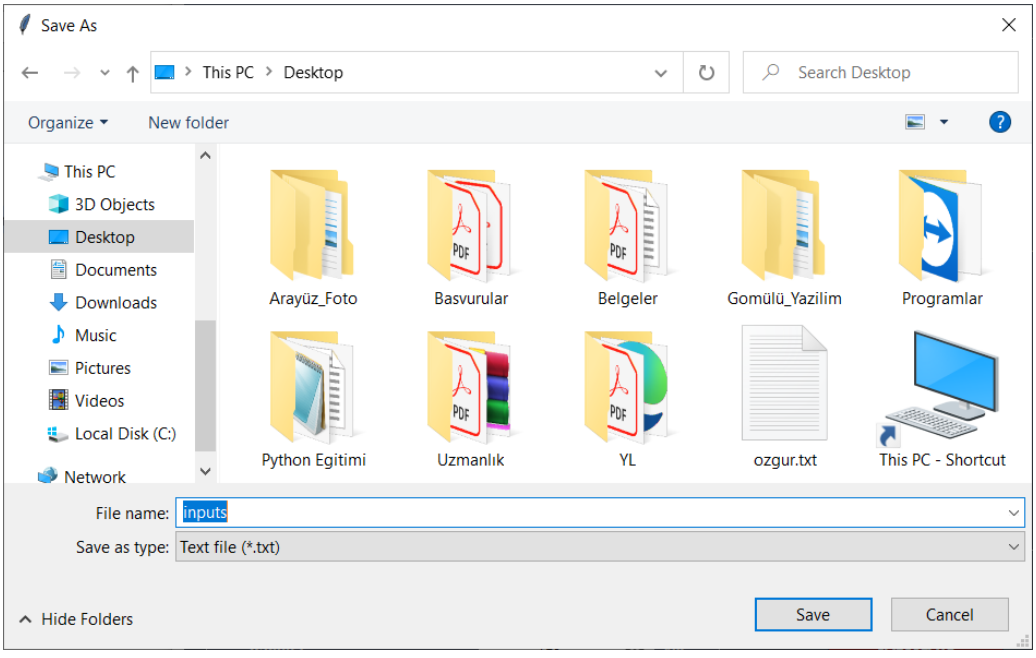

Figure A. 9 Telemetry System Performance Calculator Interface Screen (9)

As shown in Figure A. 10, we can export values in any file format by clicking the 'Open' button (Figure A. 11).

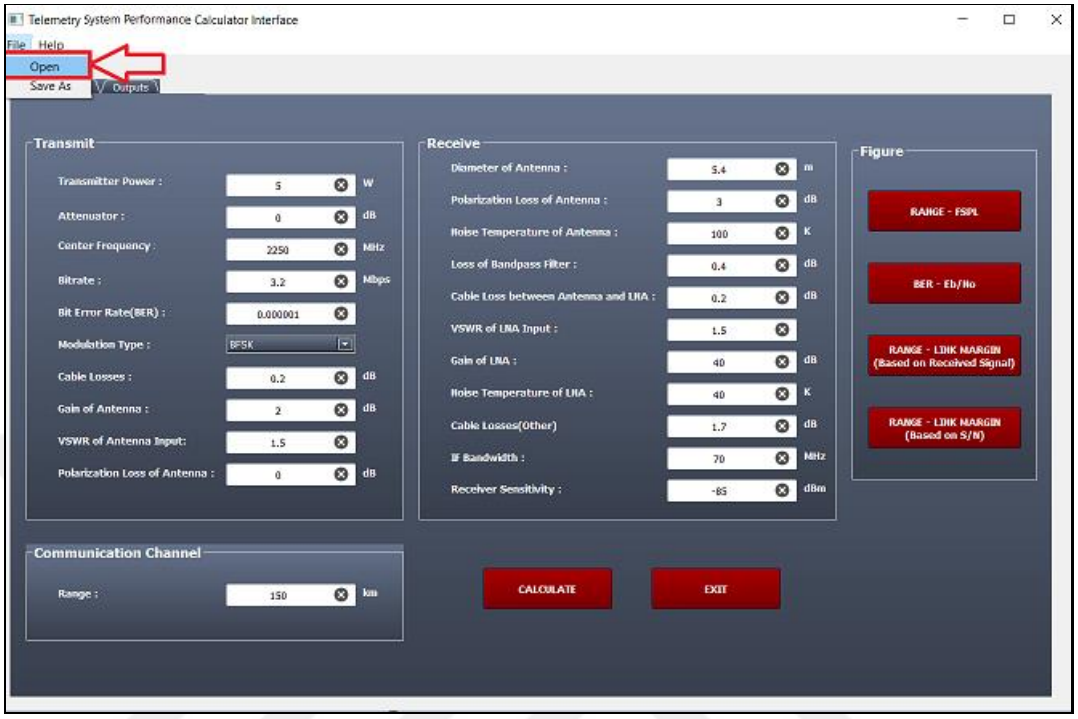

Figure A. 10 Telemetry System Performance Calculator Interface Screen (10)

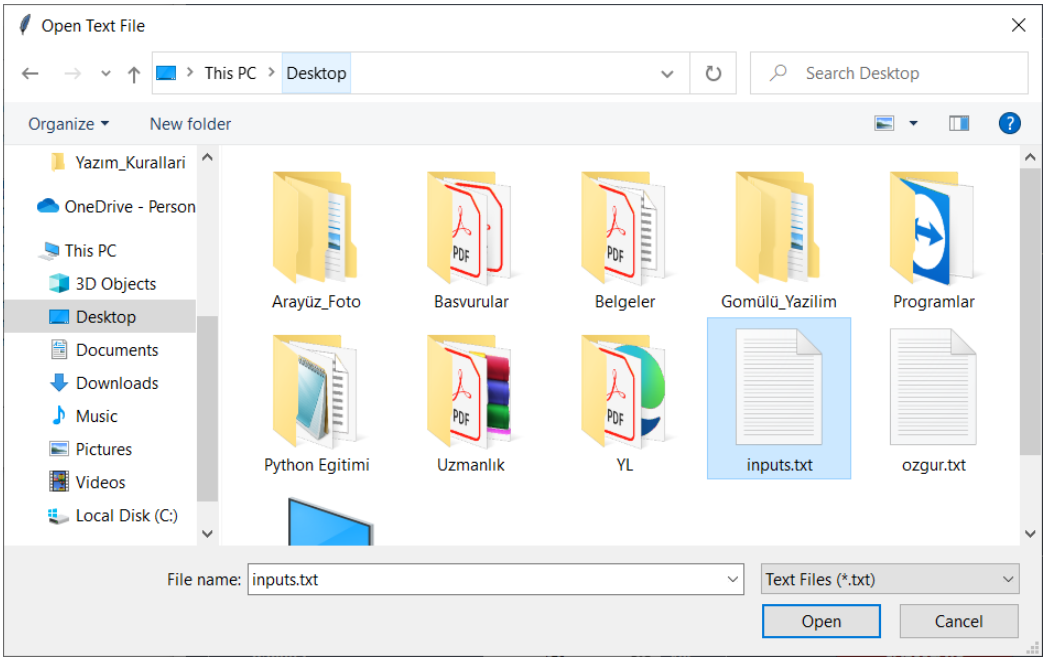

Figure A. 11 Telemetry System Performance Calculator Interface Screen (11)

As shown in Figure A. 12, when the ‘About’ button is clicked in the 'Help' tab, Figure A. 13 opens.

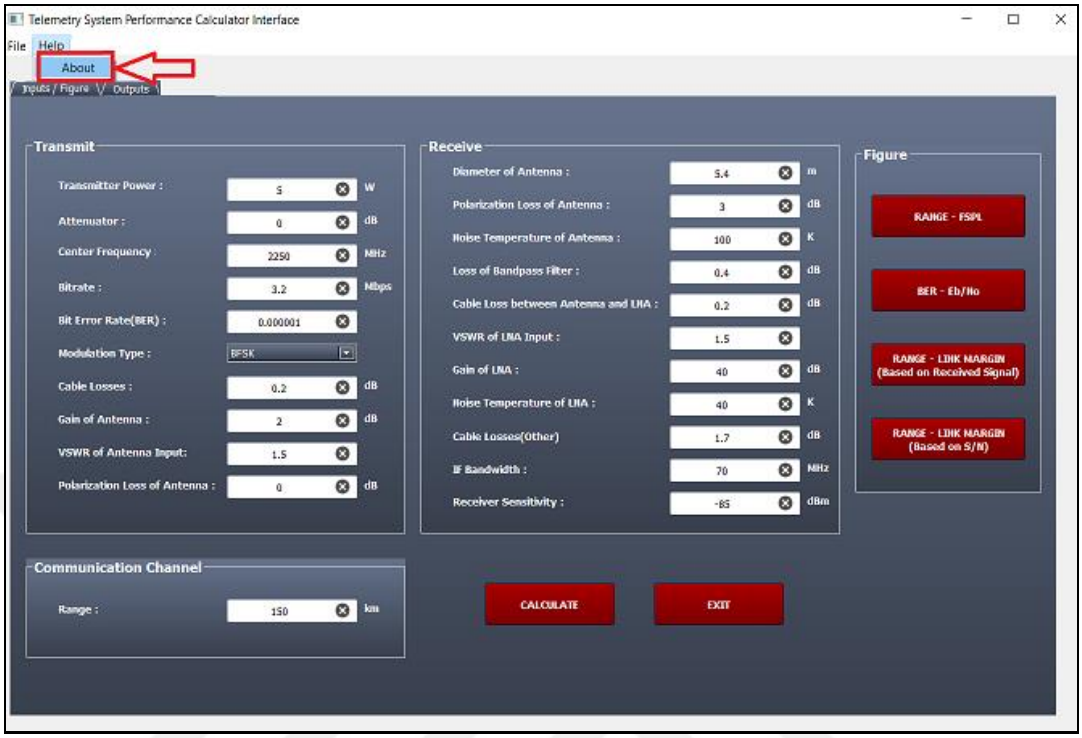

Figure A. 12 Telemetry System Performance Calculator Interface Screen (12)

Figure A. 13 Telemetry System Performance Calculator Interface Screen (13)

When ‘EXIT’ button is clicked in the 'Input/Figure' tab, exit Telemetry System Performance Calculator Interface (Figure A. 14).

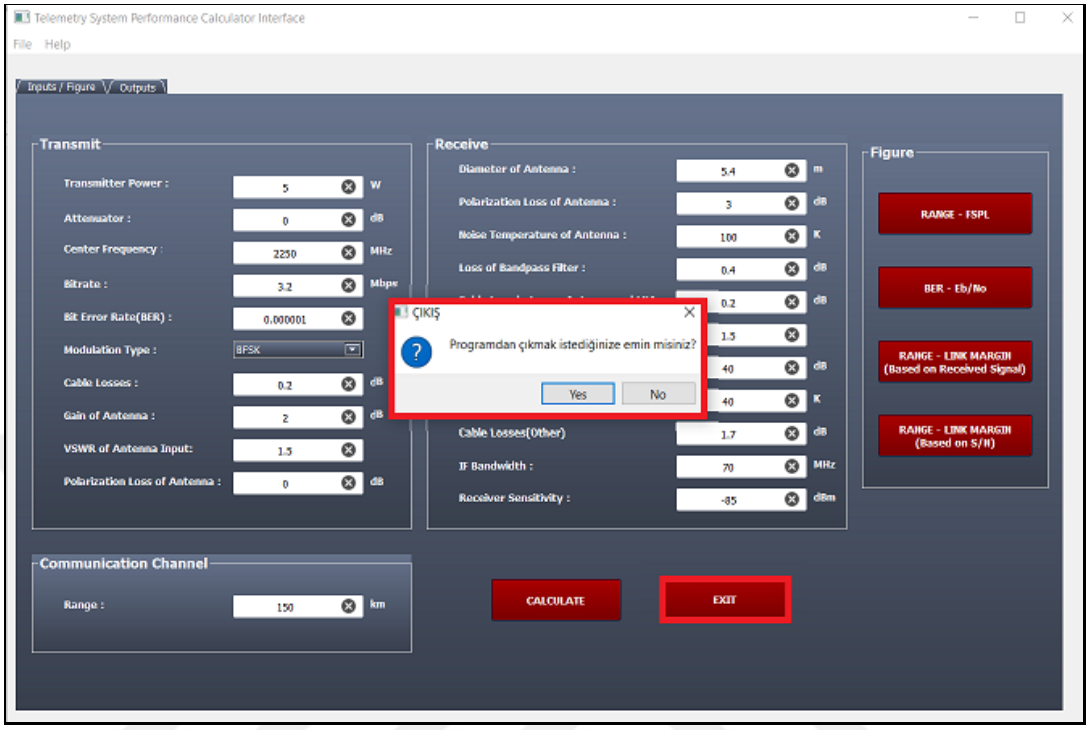

Figure A. 14 Telemetry System Performance Calculator Interface Screen (13)

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