ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

COMPRESSION OF ON BOARD TELEMETRY DATA USING DIFFERENT FRAME STRUCTURES

M.Sc. THESIS

Damla ÇOLAK

Institute of Science Engineering and Technology

Defense Technologies Programme

JULY 2021

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

COMPRESSION OF ON BOARD TELEMETRY DATA USING DIFFERENT FRAME STRUCTURES

M.Sc. THESIS

Damla ÇOLAK
(514171025)

Department of Defence Technologies

Defense Technologies Programme

Thesis Advisor: Asst. Prof. Ramazan Yeniçeri

JULY 2021

ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

FÜZE ÜSTÜ TELEMETRİ VERİLERİNİN FARKLI ÇERÇEVE FORMATLARI KULLANILARAK SIKIŞTIRILMA ALGORİTMALARI İLE SIKIŞTIRILMASI

YÜKSEK LİSANS TEZİ

Damla ÇOLAK
(514171025)

Savunma Teknolojileri Anabilim Dalı

Savunma Teknolojileri Programı

Tez Danışmanı: Dr. Öğr. Üyesi Ramazan YENİÇERİ

TEMMUZ 2021

Damla ÇOLAK, a M.Sc. student of İTU Graduate School student ID 514171025, successfully defended the thesis/dissertation entitled "COMPRESSION OF ON BOARD TELEMETRY DATA USING DIFFERENT FRAME STRUCTURES", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Asst. Prof. Ramazan Yeniçeri** İstanbul Technical University	....
Jury Members :	**Prof. Dr. Müştak Erhan Yalçın** Istanbul Technical University	....
	Dr. Emre Göncü Istanbul Technical University	....

Date of Submission : 8 JUNE 2021
Date of Defense : 9 JULY 2021

To my family and friends,

FOREWORD

I would like to thank my advisor, Dr. Ramazan Yeniçeri for encouraging me from the very beginning and for his guidance through the years of my master's study. I feel fortunate to have the opportunity to work in defence topics which led me to a very exciting field for my future work.

Also, I am very thankful to my colleague,my old manager and my elder brother Zafer Eraslan to support me during my lecture terms. My manager Merve Hanköylü has supported me whenever I needed to work on my thesis term. I am very pleased to both of them for their valuable conversations and advice.

I would like to thank to my colleague Merve Nar, my elder sister in heart Duygu Çolak, my cute friends Ayşen Akdemir,Ebru Tendürüs, Anıl Özgür and Tolga Doğan for their all support and friendships.

Moreover, I would like to thank my dear friend Can Selim Yılmaz for his huge supports and motivating speeches. Whenever I need, he was always there.

I would like to thank my brother Ahmet Çolak for being the most inspirational person not only my thesis studies but also my whole life.

Lastly, I would like to thank my father Kerim Çolak, my mother Fatma Çolak for their endless support and love.

June 2021

Damla ÇOLAK
(Electrical and electronics engineer)

TABLE OF CONTENTS

Page

FOREWORD ... **vii**
TABLE OF CONTENTS ... **ix**
ABBREVIATIONS ... **xi**
SYMBOLS ... **xiii**
LIST OF TABLES ... **xv**
LIST OF FIGURES ... **xvii**
SUMMARY ... **xix**
ÖZET ... **xxi**
1. INTRODUCTION ... **1**
1.1 General Overwiev of Telemetry System ... 3
1.1.1 Importance of Telemetry ... 3
1.1.2 Essential Points of Telemetry ... 4
1.1.3 Conceptual Design of Telemetry Systems ... 5
1.1.4 Subsystems of Airborne Data Acquisition Systems ... 6
1.1.5 Types of Modulation ... 7
1.1.6 Basics PCM (Pulse Code Modulation) ... 8
1.1.7 IRIG Telemetry Standards ... 8
1.2 Telemetry Frame Structures ... 9
1.2.1 Basic Commutation ... 9
1.2.2 Super Commutation ... 11
1.2.3 Sub Commutation ... 11
2. RF COMMUNICATION AND LINK BUDGET CALCULATION ... **13**
2.1 Important Specifications for RF Communication ... 13
2.1.1 Frequency Allocations ... 13
2.1.2 Synchronization Word Allocations ... 13
2.1.3 Designating Output Power Occurance Value ... 13
2.2 Link Budget Calculations ... 14
2.2.1 Losses of RF Systems ... 14
2.2.2 Gains of Rf Systems ... 18
3. DATA COMPRESSION ALGORITHM ... **21**
3.1 Lossy Compression Algorithm ... 22
3.2 Lossless Compression Algorithms ... 22
3.2.1 Huffman Algorithm ... 23
3.2.2 Lempel- Ziv Welch Coding Algorithm ... 26
4. DATA COMPRESSION ALGORITHM ... **29**
4.1 Construction of Data Acquisition System on Hardware Level ... 30
4.1.1 Test Set-up of Hardware Supporting Subcommutation Frame ... 32
4.1.2 Test Set-up of Harfware Supporting Super Commutation Frame ... 36
4.1.3 Demodulation Process of Test Data ... 38
4.2 Evalutaion of Data Compression Techniques ... 39
4.2.1 Compression of Total Frame Data ... 40
4.2.2 Compression of categorized data placing on the frame ... 42

4.3 Link Budget Calculations 51
5. CONLUSION AND RECOMMENDATION 55
REFERENCES 59
APPENDICES 63
Appendix A: Huffman Compression Algorithm Matlab Code 63
Appendix B: LZW Algorithm Matlab Code 64
Appendix B.1: LZW Encoding Function on Matlab 64
Appendix B.2: LZW Decoding Function on Matlab 66
Appendix C: Parameters on Link Budget Calculation 68
Appendix D: Pressure Sensor Properties Used in Test Set-up 69
Appendix E: Vibration Sensor Properties Used in Test Set-up 70
Appendix F: Data Acquisition System Properties Used in Test Set-up 1 71
CURRICULUM VITAE 73

ABBREVIATIONS

GPS	**:** Global Positioning System
RCC	: Range Commanders Council
TG	: Telemetry Group
IRIG	: Inter-Range Instrumentation Group
DoD	: Department of Defence
COTS	: Commercial Off The Shelf
DAS	: Data Acquisition System
TDM	: Time Division Multiplexing
NRZ_L	: Non-Return-to-Zero-Level
RNRZ_L	: Randomized Non-Return-to-Zero-Level
PCM	: Pulse Code Modulation
PAM	: Pulse Amplitude Modulation
AM	**:** Amplitude Modulation
FM	: Frequency Modulation
PAL	: Phase Alternating Line
LZW	: Lempel Ziv Welch
TV	: Television
NASA	: National Aeronautics and Space Administration
CCDS	: Consultative Committee for Space Data Systems
ESA	: European Space Agency

SYMBOLS

Pt	: Sent power
Pr	: Power received
Λ	: Wavelength (found with c/f)
c	: speed of light,
f	: frequency of the signal
t	: Time
αC	: Loss due to metal conductivity
αD	: Dielectric loss tangent
αG	: Loss due to dielectric conductivity
αR	: Loss due to radiation
εR	: Antenna efficiency
D	: Antenna directivity

LIST OF TABLES

Page

Table 3.1: Probability and frequency for Huffman algorithm **24**
Table 3.2: Coded words for each symbol using Huffman tree.................................. **26**
Table 3.3: First part of the dictionary... **28**
Table 3.4: The dictionary of message 'DADADADA' **28**
Table 4.1: Frame structure of received data from hardware supporting subcommuttaion. **34**
Table 4.2: Frame structure of received data from hardware supporting subcommuttaion. **37**
Table 4.3: Compression percentages... **41**
Table 4.4: Compression percentage of guidance data **43**
Table 4.5: Constant parameters for link budget calculation...................................... **53**
Table 4.6: Link budget calculation before/after compression................................... **54**
Table D.1: Pressure sensor properties used in test set-up. **69**

LIST OF FIGURES

Page

Figure 1.1 : Scope of thesis **3**
Figure 1.2 : A telemetry system. **5**
Figure 1.3 : Airborne data acquisition system. **6**
Figure 1.4 : RF commumication process **7**
Figure 1.5 : PCM data coding in binary order **8**
Figure 1.6 : Data stream of the telemetry data packages **9**
Figure 1.7 : Basic commutation working procedure. **10**
Figure 1.8 : Super commutation methods working procedure **11**
Figure 1.9 : Super commutation methods working procedure **12**
Figure 2.1 : Atmospheric absorption losses (by frequency) **17**
Figure 2.2 : Polarization types in electromagnetic waves **18**
Figure 3.1 : Data encoding and decoding process **22**
Figure 3.2 : Probability of repeated symbols **24**
Figure 3.3 : Huffman tree from root to the leaves. **25**
Figure 4.1 : Hardware set-up of data acquisiton system. **31**
Figure 4.2 : Test Set-up of data acquisition with hardware 1. .... **33**
Figure 4.3 : Guidance/Serial data distrubution on frame with subcommutation method. **36**
Figure 4.4 : Guidance/Serial data distrubution on frame with supercommutation Method. **38**
Figure 4.5 : Demodulation code for syntetic pcm data file. **39**
Figure 4.6 : Compression rates of subcommutative hardware data. **40**
Figure 4.7 : Compression rates of suppercommutative hardware data. **41**
Figure 4.8 : Compression rates of guidance data. **43**
Figure 4.9 : Data compression rates of telemetry video data. **44**
Figure 4.10 : Pressure data of hardware 1. .... **45**
Figure 4.11 : Zoomed version of pressure data. **46**
Figure 4.12 : Pressure data at 1900 psi **46**
Figure 4.13 : Compressedpressure data. **47**
Figure 4.14 : Compression ratio pressure data. **48**
Figure 4.15 : Vibration data ofhardware 1. .... **49**
Figure 4.16 : Zoomed version of vibration data. **49**
Figure 4.17 : Vibration data at a specific time interval. **50**
Figure 4.18 : Compressed vibration data. **51**
Figure 4.19 : Compression ratio pressure data. **51**
Figure A.1 : Huffmancompression algorithm Matlab code.. .... **63**
Figure B.1 : LZW algorithm Matlab code.. .... **64**
Figure B.2 : LZW encoding function on Matlab. **64**
Figure B.3 : Contiuning LZW encoding function on Matlab. **65**
Figure B.4 : LZW decoding function on Matlab **66**
Figure B.5 : Contiuning Lzw decoding function on Matlab **67**
Figure C.1 : Parameters on link budget calculation **68**

Figure E.1 : Vibration sensor properties ued in test set-up.. **70**
Figure E.2 : Data acquisition systems Properties used in test set-up........................ **71**

COMPRESSION OF ON BOARD TELEMETRY DATA BY USING DIFFERENT FRAME STRUCTURES

SUMMARY

Considering the first use of the word 'telemetry' in history, its equivalent is 'remote measurement'. The word telemetry is used both literally and conceptually to describe applications that aim to remotely control any system, and to collect and save instant data obtained from these systems in a data center. Telemetry is used in many systems used today. For example, power plants, civil aviation industry, natural gas production facilities, communication systems, biomedical systems, space stations and vehicles are the main areas that use telemetry for data measurement and collection. In addition, telemetry applications are a necessity since the design phase of specific aircraft, spacecraft, some types of submarine vehicles, rockets and missiles requires verification of the design by comparing the performance data obtained from these vehicles with the actual values.

The telemetry data of an on-board vehicle in the design phase includes measurements of various onboard sensors, GPS (Global Positioning System) data, guidance commands generated by the missile computer, and image data collected when necessary. This data is collected by an internal unit and then transmitted via wireless communication to a ground station. These collected data are evaluated by the design engineers and interpreted according to whether the simulated flight environment before the flight and the characteristics of the flying unit are compatible with the real ones. This data is then used to obtain the optimum in-flight health of the on-board unit by trial, to find and minimize errors as required. As it turns out, this critical role of telemetry tests shows the importance of collecting as much data as possible with minimum error.

Compressing telemetry data before transmission will allow to increase the amount of data obtained per flight as it can make room for more data. As a result of the literature research, it has been seen that the compression methods applied to the data are mostly evaluated in the data storage phase for on-board systems. However, the data bandwidth in telemetry tests of the on-board system is one of the main parameters limiting the communication range of the test.

This study aims to evaluate the effects of data bandwidth reduction on RF communication range as a result of data compression techniques in on-board telemetry tests. Apart from this, it is aimed to evaluate the differences that may occur between telemetry structures in different formats used after being subjected to the same compression process. For these purposes, different data compression methods are applied on on-board telemetry data. The results to be encountered as a result of both the compression of the data transmitted to the ground station as a whole packet and the compression of each data type separately are evaluated. As a result of these processes, the reduction rates in the amount of data are compared. Their effects on RF parameters are evaluated using link budget calculations. Other communication

parameters such as signal modulation type, receiver characteristics, transmit power value, antenna types are considered constant only to see the effect of change in data size. The obtained results are compatible with the hypothesis, since the communication distance is increased due to the decrease in the data bandwidth. It was expected that different telemetry structures gave different results with the same compression algorithm.

KEYWORDS: Telemetry, Data compression, Subcommutation, Supercommutation, Huffman algorithm, Lempel-Ziv-Welch algorithm.

FÜZE ÜSTÜ TELEMETRİ VERİLERİNİN FARKLI ÇERÇEVE FORMATLARI KULLANILARAK SIKIŞTIRILMA ALGORİTMALARI İLE SIKIŞTIRILMASI

ÖZET

'Telemetri' kelimesinin tarihte ilk kullanımını değerlendirildiğinde karşılığı 'uzaktan ölçüm'dür. Telemetri kelimesi hem kelime anlamı hem de kavramsal olarak herhangi bir sistemi uzaktan kontrol etmeyi hedef alan uygulamaları tanımlamak, ve bu sistemlerden elde edilen anlık verileri bir veri merkezinde toplamak ve kaydetmek için kullanılmıştır. Günümüzde kullanılan pek çok sistemde telemetri kullanılmaktadır. Örneğin elektrik tesisleri, sivil havacılık sektörü, doğalgaz üretim tesisleri, iletişim sistemleri, biyomedikal sistemler, uzay istasyonları ve araçlar, veri ölçüm ve toplama amacıyla telemetri kullanan başlıca alanlardır. Ayrıca spesifik olarak uçakların, uzay araçlarının, denizaltı araçlarının bazı çeşitlerinin, roketlerin ve füzelerin tasarım aşaması, bu araçlardan alınan performans verilerinin gerçek değerleriyle karşılaştırılarak tasarımın doğrulanması gerektirdiğinden telemetri uygulamaları bir ihtiyaçtır.

Veri ölçüm ve toplama amacıyla kullanılan telemetri birimlerinin tasarımı toplanacak verinin türüne, örnekleme ihtiyacına bununla parallel olarak veri miktarına göre RF gereksinimleri de gözetilerek donanımsal ve yazılımsal olarak gerçekleştirilmektedir. Tasarım aşamasındaki bir on-board sistemin telemetri verileri, çeşitli yerleşik sensörlerin ölçümlerini, GPS (Küresel Konumlandırma Sistemi) verilerini, füze bilgisayarı tarafından oluşturulan güdüm komutlarını, gerekli durumlarda toplanan görüntü verilerini içerir. Bu veriler dahili bir birim tarafından toplanır ve daha sonra kablosuz iletişim yoluyla bir yer istasyonuna iletilir. Toplanan bu veriler tasarım mühendisleri tarafından değerlendirilerek uçuş öncesi simule edilen uçuş ortamı ve uçan birimin karakteristiğinin gerçektekiyle uyumlu olup olmamasına göre yorumlanır. . Analog veri olarak basınç, titresim sensörlerinden elde edilen verilerle uçan bir yapıdan elde edilecek uçuş verileri sentetik olarak simüle edilir. Daha sonra, bu veriler gereksinimlere uygun olacak şekilde hataları bulmak ve minimize etmek için on-board birimin uçuştaki sağlığının en optimum düzeydeki deneme ile elde edilmesi amacıyla kullanılır. Anlaşıldığı üzere telemetri testlerinin bu kritik rolü, mümkün olduğu kadar çok veriyi minimum hata ile toplamanın önemini göstermektedir.

Telemetri verilerinin iletilmeden önce sıkıştırılması, daha çok veriye yer açabileceğinden uçuş başına elde edilen veri miktarının arttırılmasına olanak sağlayacaktır. Literatür araştırması neticesinde verilere uygulanan sıkıştırma yöntemlerinin on board sistemler için çoğunlukla veriyi saklama aşamasında değerlendirildiği görülmüştür. Ancak on-board sistemin telemetri testlerindeki veri bant genişliği, testin iletişim menzilini sınırlandıran başlıca p

arametrelerden biridir.

Bu çalışma, on-board telemetri testlerinde veri sıkıştırma teknikleri neticesinde veri bant genişliğinin azalmasının RF iletişim menzili üzerindeki etkilerini değerlendirmeyi amaçlamaktadır. Bunun dışında kullanılan farklı formatlardaki telemetri yapılarının aynı sıkıştırma işlemine maruz kaldıktan sonra birbirleriyle aralarında oluşabilecek farklılıkların değerlendirilmesi hedeflenmiştir. Bu amaçlar doğrultusunda sentetik on-board telemetri verileri üzerinde farklı veri sıkıştırma yöntemleri uygulanmaktadır. Yer istasyonuna iletilen verilerin hem bütün paket olarak sıkıştırılması hem de her veri türüne göre ayrı ayrı sıkıştırılması neticesinde karşılaşılacak sonuçlar değerlendirilmektedir. Bunun yanısıra tüm telemetri verilerinin sıkıştırılması dışında bir telemetri paketindeki verilerin sıkıştırılması ve telemetri paketine etkisi incelenmiştir. Bunun dışında farklı çerçeve yapılarını destekleyen donanımlar üzerinde toplanan veriler, belirli kurallar dahilinde paketlenecek şekilde veri yapısına yerleştirilir. Telemetri genel kuralları öncülüğünde yere indirilecek telemetri verilerinin paket içindeki yerleşimi tasarımcının belirleyeceği komütasyon türüne göre yapılır. Süper komütasyon ve alt komütasyon yöntemi, normal komütasyon yönteminden farklı çerçeve yapısı oluşturan bir teoriye dayanmaktadır. Bu çalışma kapsamında farklı komütasyon tekniklerini destekleyen donanımlardan farklı telemetri çerçeve yapıları oluşturulmuştur. Her bir çerçeve yapısıyla toplanan very paketleri analiz edilerek sıkıştırma algoritmalarıyla sıkıştırılmıştır. Alt komütasyon yöntemiyle küçük çerçevelere bölünen sayısal verilerin matris yapısını tamamlayabilmesi için veri dışında ortak kelimelere ihtiyacı vardır. Bu durumun sıkıştırmada veri çeşitliliğinin artmasına neden olduğu anlaşılmıştır. Süperkomütasyon yönteminin kullanımının sıkıştırmada alt komütasyon çerçeve yapısına göre sıkıştırıldıktan sonra veri boyutundaki etkisi incelenmiştir.

Sıkıştırma uygulanacak veriler analog kaynaktan gelen veriler ve dijital kaynaktan gelen veriler olarak gruplandırılarak kaynağına göre sıkıştırma algoritmalarının verimliliği değerlendirilmektedir. Bu işlemler neticesinde veri miktarındaki azalma oranları karşılaştırılmaktadır. Veri miktarlarındaki azalma bant genişliği ile ilişkilendirilmektedir. Bant genişliğindeki azalmanın hesaplanan RF haberleşme hızına etkisinin analizi link bütçesi hesabı ile yapılabilmektedir. Bu çalışma kapsamında Link bütçesi hesaplamaları kullanılarak RF parametreleri üzerindeki etkiler değerlendirilmektedir. Sinyal modülasyon türü, alıcı özellikleri, gönderici güç değeri, anten türleri ve kazançları gibi diğer iletişim parametreleri, yalnızca veri boyutundaki değişimin etkisini görmek için sabit olarak kabul edilmektedir. Elde edilen sonuçlar, veri bant genişliğindeki azalmadan dolayı iletişim mesafesinde artış gözlenmesi sebebiyle hipotezle uyumludur. Farklı telemetri yapılarının aynı sıkıştırma algoritması ile farklı sonuçlar vermiş olması beklendiği gibi sonuçlanmıştır.

ANAHTAR KELİMELER: Telemetri, Veri Sıkıştırma, Subkomütasyon, Süperkomütasyon, Huffman algoritması, Lempel-Ziv-Welch Algoritması.

1. INTRODUCTION

The concept of telemetry emerged in the 19th century and these conceptual engineering applications were first made with wired communication. Its first application was the establishment of a system capable of real-time data transmission between the cities of Mont Blanc and Paris to collect some airborne data by French engineers in 1874 [1]. The first worldwide uses in rocket and missile technologies emerged due to the monitoring of the parameters needed to carry out the tests of the German V-2 rocket. In this activity, which is called the Messina system, it was stated that it would be more beneficial to monitor the flight with binoculars, even by the creator of the rocket, Von Braun [2]. For the first time in history, the Messina system was the first to state the need for a system with the aforementioned features. For this reason, the design of telemetry systems has been emphasized, and the concept of telemetry has started to develop rapidly and become widespread. In the last quarter of the 1940s, the Soviets started to download data from the missile with different modulation types. On the other hand, America continued its telemetry studies with pulse code modulation (PCM). Today, it has become a standardized method to receive data from the subsystems in the system and the sensors on them during the flight test of an on-board system, especially of missile systems [3]. In the design process of any system, the requirements that must be met as a priority are determined and it is completed with a verification process in which all requirements are met after the product is released. In order for an on-board system to be carried out in accordance with the design study, it is a standardized need to perform rangefinder tests before and after design verification. Verification of the results obtained in certain steps of the design with telemetry tests ensures the correct progress of the relevant design and the use of all resources in maximum efficiency. If the engineering workforce, cost and human resources are used efficiently, the system approaches the correct design and verification process [4]. With the rapid development of technology in recent years, the level of detail included in the designs has been increasing the level of sophistication and complexity of the on-board system that needs to be produced. For this reason, each on-board system developed is subjected to various tests and the telemetry data collected from these systems is examined. The data collected through these aforementioned tests are used to confirm the accuracy of the design studies and to make improvements where necessary. Due to the great influence of telemetry data in the design process, it is important to conduct tests by collecting as much data as possible. However, current telemetry systems are insufficient to support large data sizes. For this reason, it is a necessity to improve and develop an on-board telemetry system to be able to transfer more data at a lower cost. Compressing telemetry data and making room for more data should be considered as a solution to this situation.

When the preferred applications in on-board systems in the literature are examined, it is seen that the data compression method in telemetry is preferred for archiving and storing the data delivered to the ground station [5]. In parallel, in a study conducted by NASA and Stanford University, these telemetry data are analyzed as pieces with various properties and compression techniques are applied to each of them in order to store the data after downloading [5].

In another study, in an archive, in a study conducted by the University of Paris and NASA to increase the storage capability of the database on the ground, it saves time and storage space by compressing satellite data [6].

These studies generally aim at an improvement in a different area. Live data obtained in all these studies are not studied and RF gain parameters are not emphasized. The methods in which this approach is used in the studies carried out by defense industry companies in our country are not known. This situation creates an obstacle to data collection with high bandwidth in on-board systems with high range. Compressing the data before it is sent to the ground in the defense industry is an issue that needs to be developed to evaluate which data types would be a better choice. If the effect on the distance is evaluated by calculating the link budget after applying the data compression algorithm in different telemetry systems, it is possible to obtain gains such as less loss in signal transmission, reduction in thermal noise, and improvement in communication capability of the same systems. It is thought that this study will also contribute to communication systems such as data link used in on-board systems in order to make telemetry systems more efficient. In Figure 1.1, the study titles that will be included in this thesis are presented as an outline.

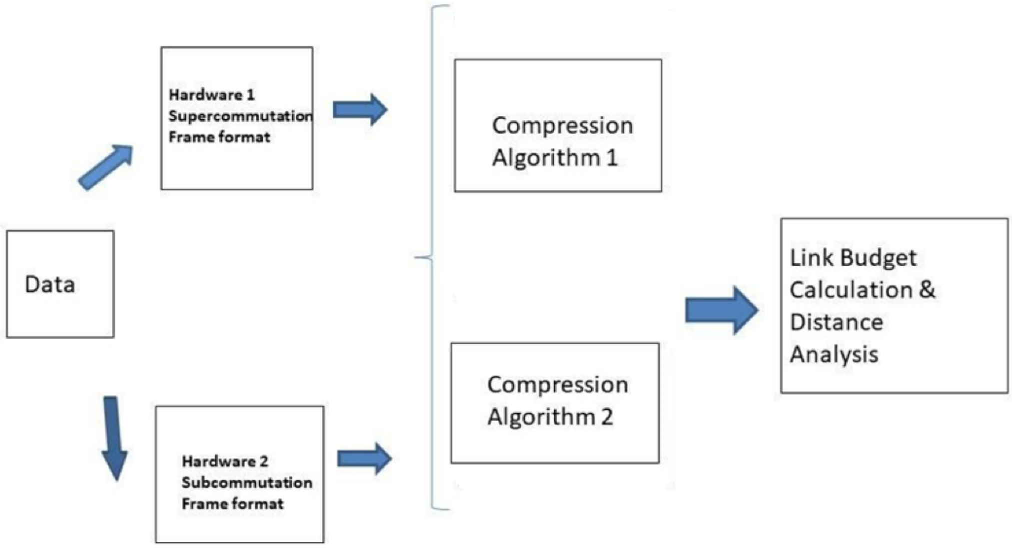


Figure 1.1: Scope of thesis.

1.1 General Overwiev of Telemetry System

Telemetry is the process in which certain features of an on-board system are measured and the results are recorded and transmitted to a ground station on the ground for analysis. The telemetry data transmission medium for satellite, rocket and missile, spacecraft applications can be air and space. However, since telemetry can be used in some cases with black box technology in underwater vehicles, the transmission medium is water.

Today's telemetry applications support a large number of measured physical quantities. However, using separate transmission channels for the measurement of each physical quantity is very costly. To be more practical, telemetry requires that these physical quantity measurements, such as pressure, strain, vibration, digital data, and video data, be grouped in a format that can be transmitted as a single data stream [1]. The received data stream is decomposed into the original measured data components for analysis..

1.1.1 Importance of Telemetry

Telemetry provides the user stay in a safe location while monitoring what's taking place in an unsafe location. On- board systems like missile development, for instance, is a major application for telemetry systems [7]. During initial flight testing, a missile performs a variety of test maneuvers. The critical flight data from a maneuver is transmitted to a ground station where results are viewed in real time or analyzed within seconds of the maneuver. Real-time monitoring allows the controller to make instant decisions on whether to proceed with or terminate the test.Therefore, telemetry has a vital importance in terms of critical maneuver. On the other hand, real-time data is also captured to storage media for later analysis and archiving.

1.1.2 Essential Points of Telemetry

Timing

Timing is one of the main building blocks of Telemetry [1]. Determining and maintaining the appropriate and correct time in the airborne system is very important in terms of transmitting the parameters sent by the system over the telemetry network in a synchronous time period and in the correct time step. Accurate timing allows the system to send commands to the ground station and transmit telemetry information. When time synchronization cannot be achieved, the meaning of the collected data can lead to results that are close to impossible.

Correlating Multiple Systems

Working with more than one test object, for example, when there is an airborne system, a target, and a positioned ground station in the environment, it will be a matter of looking and analyzing from a flight test point. In this way, flights should contain parameters that must be shared for each object in the test environment.

Telemetry Standarts

Telemetry applications needed a standart in orde to resolve common problems and develop test procedures. For these purposes, a council called ***Range Commanders Council (RCC)*** have been established in 1951. The Telemetry Group (TG) of the RCC maintains telemetry system standards that they used. Documents of these standards are known as the IRIG Standards. IRIG Document 106 Telemetry Standards contains most of the standards used in the flight test industry [8]. The missile applications also prefer to be depended on IRIG Standarts. In addition, DOD uses a task guide for the development of the digital recorder standard known as IRIG 106 Chapter 10.

IRIG Standarts

Purpose of IRIG standards is to promote test range interoperability and it has a number of chapters and appendices. Most important chapters and their relevants issues are showed belowed.

- Chapter 4 – PCM Telemetry [8]
- Chapter 9 – TMATS [8]
- Chapter 10 – Digital Data Recorder [8]

1.1.3 Conceptual Design of Telemetry Systems

Today's telemetry systems are consisted of COTS products. However, while they all have many common elements, they are each uniquely configured to satisfy specific application requirements. A telemetry system is generally viewed as two components, the Airborne System and the Ground System. In actuality, either or both may be in the air or on the ground like showing on Figure 1.2.

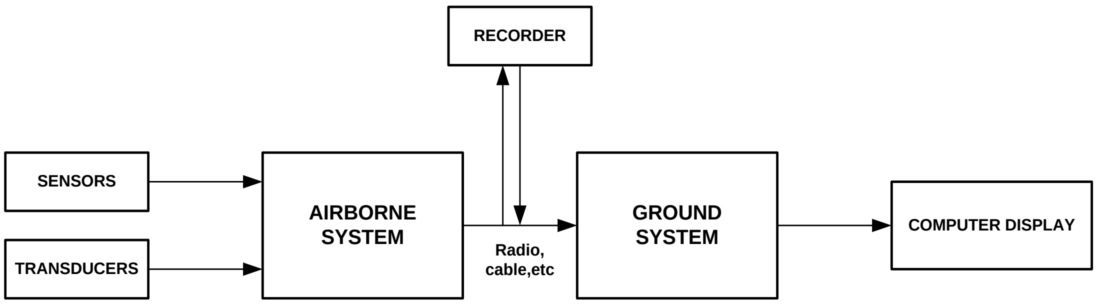


Figure 1.2: Telemetry system.

An airborne or a missile uses the telemetry systems inside the data acquisition system that they include.General concept of DAS's are obtaining the data from external system as analog or digital format. An airborne or an on-board data acquisition systems are showed in Figure 1.3.

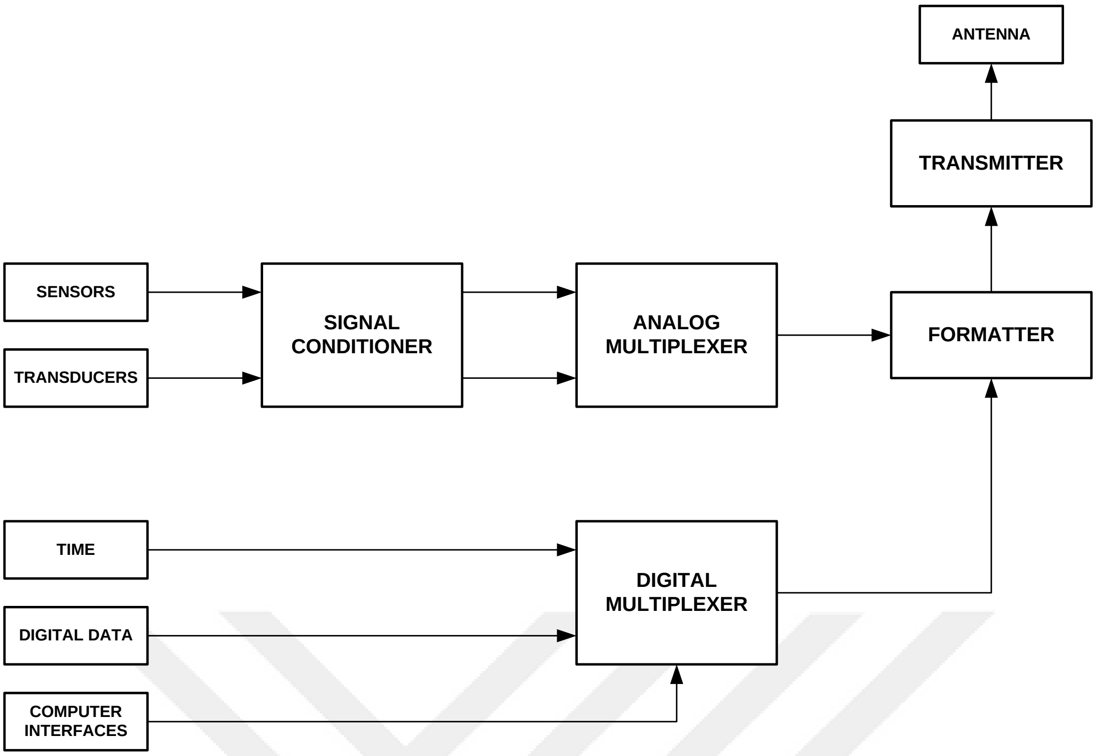


Figure 1.3 : Airborne data acquisition system.

1.1.4 Subsystems of Airborne Data Acquisition Systems

Sensors

Data collection begins in the measurement process of a quantity perceived and before a production is completed. Some sensors produce a flame, such as thermocouples for temperature or piezoelectric strain gauges for pressure. But some sensors require excitation such as strain gauges, potentiometers for rotation. Persons attached to signalers provide the power to train sensors to be compatible with an acquisition. A multiplexer (known as a commutator) is used because a separate path means is targeted and contained for each source. Analogues of single pulses according to the measured channel and those measuring as output series. The collection of data in one or rigorous way is called Time Division Multiplexing TDM [9]. RF communication process step by step in Figure 1.4.

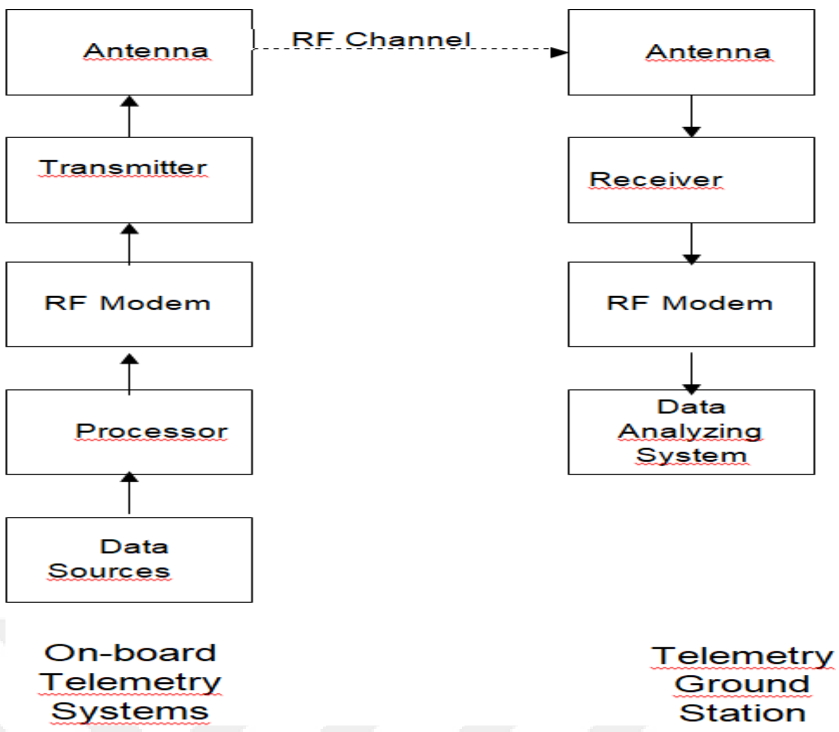


Figure 1.4 : RF commumication process.

1.1.5 Types of Modulation

Modulation is the technique where the value of each sample (i.e., the modulating signal) systematically changes the characteristics of a carrier signal (e.g., amplitude (height) or frequency (timing). The resulting modulated wave "carries" the data. Conversely, removing the carrier signal results in the return of the original measurement.The TDM stream produced by the basic multiplexer scheme is accomplished via Pulse Code Modulation or PAM.The scheme where the pulse height of the TDM stream is proportional to the measured value is called Pulse Amplitude Modulation (PAM). A unique set of synchronization pulses is added to identify the original measurands and their value. PAM has many limitations, including accuracy, constraints on the number of measurands supported, and the poor ability to integrate digital data.

- The PAM data stream signal is transmitted from the multiplexer in a uniformly spaced sequence of constant-width pulses. The intensity of each pulse is modulated by amplitude. This is similar to AM radio broadcast, except the carrier is a pulse rather than a sine wave.
- Since amplitudes are degraded by noise, the multiplexed data stream is usually converted to a constant amplitude pulse modulation scheme. PDM

carries the information in the pulse width, which varies directly to the amplitude of the signal.

- PPM results if the PDM waveform is differentiated, then rectified. The distance between the two pulses represents the sampled amplitude of the sine wave, with the first pulse as the zero time reference.

Pulse Code Modulation (PCM) is today's preferred telemetry format for the same reasons that PAM is inadequate.

1.1.6 Basics PCM (Pulse Code Modulation)

As a result of telemetry application most of the operator prefers PCM codes on their studies over the years. Therefore, a number of PCM codes have been designed to represent logic one and zero levels while achieving the greatest performance for a given application. These are shown below (Figure 1.5).

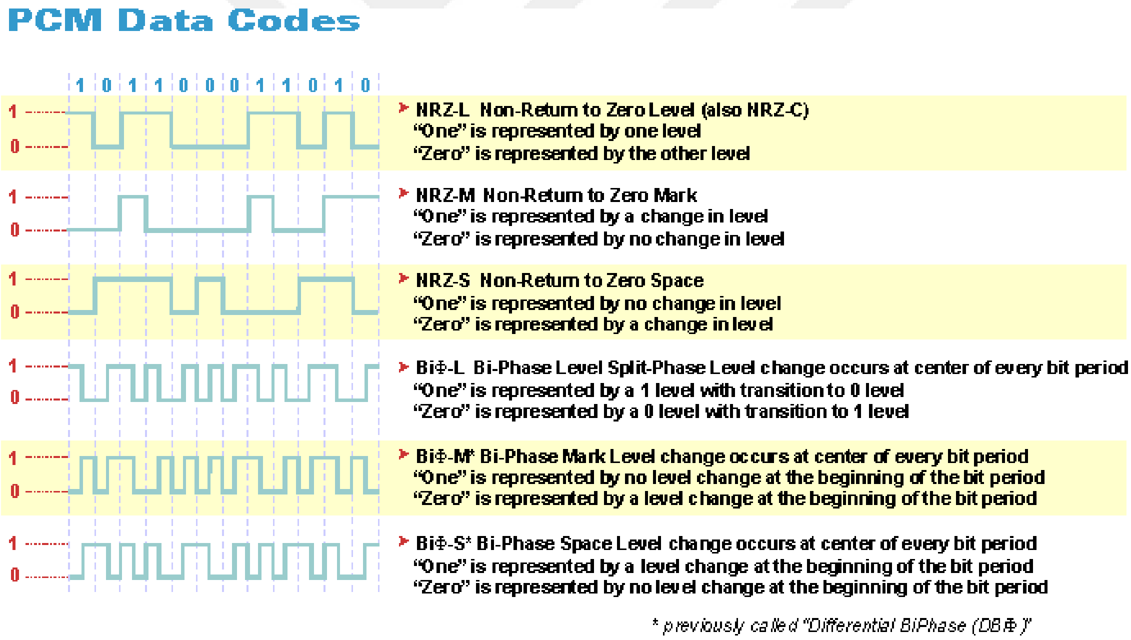


Figure 1.5 : PCM data coding in binary order [9].

1.1.7 IRIG Telemetry Standards

The Range Commanders Council (RCC): Worked together to form the Range Commanders Conference in 1951. Its name was changed to the Range Commanders Council in 1963 [8]. RCC was established to solve the following issues:

• Solving common problems

• Discussing common range issues in a regular forum

• Exchange of information to minimize duplication

• Coordinating large or special purchasing actions

• Developing and publishing test procedures and standards

Interrange Instrumentation Group (IRIG): RCC's Telemetry Group (TG) maintains the telemetry system standards used by RCC members. These standards documents are known as the IRIG Standards. IRIG Document 106 Telemetry Standards includes most of the standards used in the flight test industry, also in the defense industry. For example, IRIG 106 Chapter 10 determines the design parameters of the receiver systems to be used in standard telemetry systems.

1.2 Telemetry Frame Structures

An easier way to visualize data is presented in the table below and is defined in Chapter 4 of the IRIG-106 Standard [8].The standard includes both naming and numbering conventions of words and frames as seen Figure 1.6.

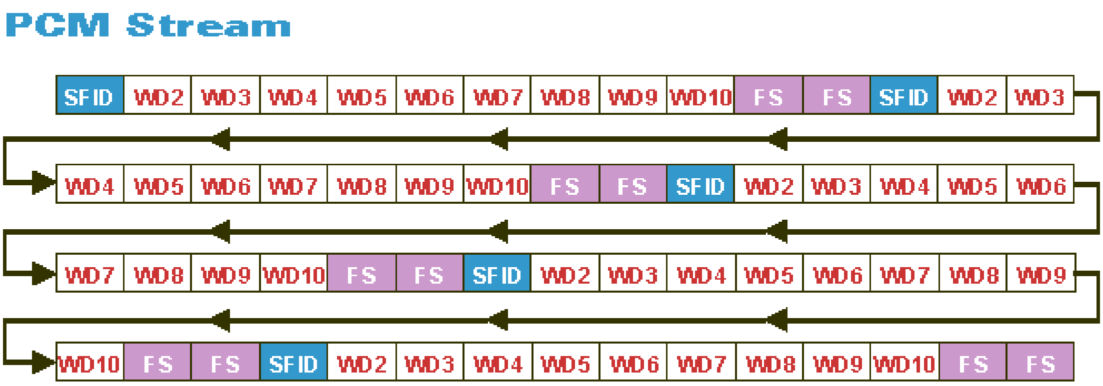


Figure 1.6 : Data stream of the telemetry data packages [9].

1.2.1 Basic Commutation

In sending data to be presented by the multiplexer to the external system, one revolution of the commutator produces a frame of the word stream containing the information of each measurand. Each scan cycle essentially produces the same string of words. At this point, only the value of the measurand is captured, rather than the address. If only the data contained in the measurand is captured, it is very difficult to distinguish who owns a value from others. It is therefore necessary to find a reference point for parsing the data of the value stream. For this purpose, a unique word called frame synchronization is added to the end of each frame.

Today, the most popular form of telemetry multiplexing (originally called commutation, as in an electric motor's commutator) is TDM (Time Division Multiplexing). Here, each channel is serially sampled for an instant by the multiplexer. A unique 3-t-33 bit code that marks the end of the commutation frame period.

In a simple commutator, each data word is sampled once per revolution at a rate compatible with the measurand with the fastest changing data. Since the rate of change of a measurand's value varies tremendously, the sampling frequency rate must accommodate it. As an example, to characterize vibration requires many more samples per second (thousands) than temperature (fractions).

According to the Nyquist Theorem, you must sample data at twice the maximum frequency component for the signal to be acquired.

Sampling rates of 5 times the maximum frequency component are typical.

A low pass filter is used to eliminate any frequencies that you cannot accurately digitize to prevent aliasing (Figure 1.7).

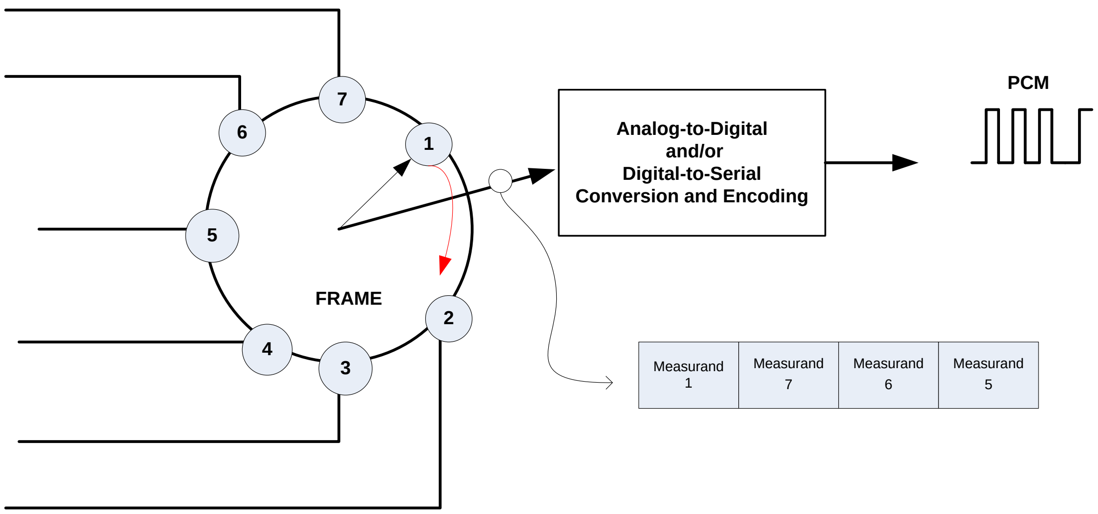


Figure 1.7 : Basic commutation working procedure.

1.2.2 Super Commutation

It is necessary to adopt a worst-case approach to sample all measured physical quantities at the highest possible rate. At this point, we are faced with a lot of redundant data pile up in the carrier frequency spectrum and power. Therefore, sampling rates should be adjusted by the designer according to the frequency content. It should be considered independent of other measured physical quantities or digitized data with different periodic data repetition rates. Quantities sampled at a high sampling rate are improved by including the measurand more than once in each frame. This is called supercommutation. Supercommutation fills the frame structure by adding multiple instances side by side, as shown in Figure 1.8. This changes according to the need for repetition of the data and the behavior of the data source.

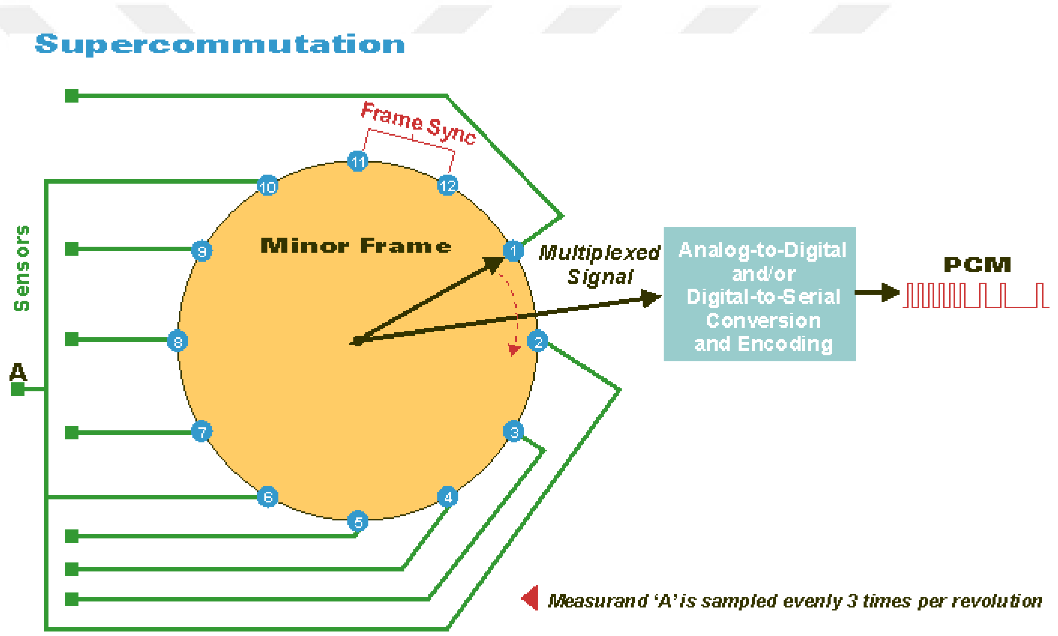
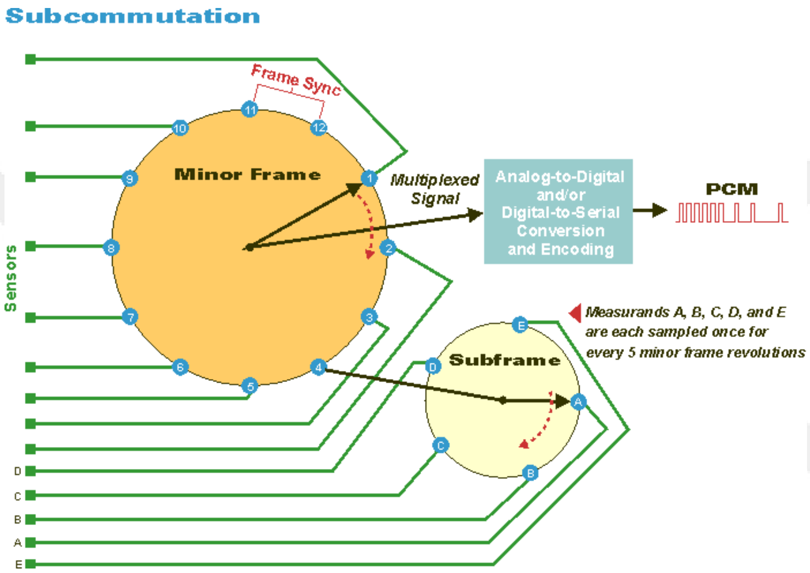


Figure 1.8 : Super sommutation methods working procedure [9].

1.2.3 Sub Commutation

In most telemetry applications, the measurand values vary from each other at different rates and in roughly an order of magnitude. Physical quantities that change slowly do not need to be sampled as often as data that change in size faster. Because of the behavior of the sample, the sampling frequency should be lower because the pressure data varies less per unit time than the vibration data. Even for data that changes very slowly, sampling once per frame will be sufficient when collecting within the time cycle. For this reason, major frame structures have been developed to include multiple subframes, each of which is called a minor frame. Some data may share a single frame identification word, as one-time sampling is sufficient, data that changes slowly. Working with sub-frame structures in parallel with such a slow sampling rate is called subcommutation. This shared location between minor frames is illustrated in the diagram in figure 1.9. In the use case of this construct, each subframe synchronization word is required. Another word in the frame is assigned the task of identifying the current small frame and it is called sub frame identifier. In sub frame frame structures, the frame structure can be thought of as a matrix, since the data will be distributed to each sub frame.



Şekil 1.9: Sub commutation methods working procedure [9]

2. RF COMMUNICATION AND LINK BUDGET CALCULATION

RF communication is a type of communication that is generally made by air by making antenna connections between the transmitter and the receiver wirelessly. There are some important parameters in order for this communication to be affected by the environmental effects at least and to transmit the meaningful information carried without deterioration. These parameters are essential both in the design phase of the communication units and in the software installation of the technical values required for communication.

2.1 Important Specifications for RF Communication

2.1.1 Frequency Allocations

Carrier frequency, also known as center frequency, is the most important Rf parameter. Determination of carrier frequency in international electronic warfare issues is a study in itself. The reason for this is that if the carrier frequency is known, the data carried on that frequency can be obtained or interferences.

It is the fact that it can be prevented from being transmitted in a healthy way by providing deterioration with Each country has a frequency band range that it chooses for military work. For example, according to the national frequency plan, Turkey's air telemetry band range is determined ,as between 2300 MHz. and 2450 MHz. [10].

2.1.2 Synchronization Word Allocations

The word synchronization is very important in terms of separating the data string carrying meaningful information from other data in the same frequency band. In international telemetry studies, synchronization words have been standardized taking into account certain rules. Within the scope of this study, while creating synthetic telemetry data, the word synchronization is added to the beginning of this data, preventing data loss and data drift.

2.1.3 Designating Output Power Occurance Value

The output power of the rf communication transmitter is a very important parameter for the healthy establishment and transmission of the link. Because the output power value provides the biggest gain to the link budget. It is essential for the designer and the operator performing the telemetry tests to prefer to use the minimum output power that will meet the need. The output power values used within the scope of this study were kept constant. However, in the link calculation part, different power values were tried and compared in the link budget.

2.2 Link Budget Calculations

‘’Link budget’’ is a a kind of design that takes into account all gains and losses from the transmitter to the receiver affecting the communication. In order to ensure quality data communication, the power level of the received signal is important.

For RF systems, power is declared by decibel-Watt which is symbolized with dBW. The decibel is a logarithmic unit that deserves the ratio of the power of the system to a reference. There is approximately twice the output power for every 3dBm increase, and every 10 dBm increase causes a 10-fold increase in power .Since the Watt unit is used for power in other electrical-electronic calculations, it will be useful to know how to convert between dB and W at this stage:

$$P(dBm) = 10\log_{10} 10\big(P(dBm)\big) \tag{2.1}$$

$$P(mW) = (10^{\frac{P(dBm)}{10}}) \tag{2.2}$$

2.2.1 Losses of RF Systems

Distance Loss

Distance Loss is called the decrease in power density when the radio wave is formed over a distance.

Noise in RF Systems

The component in the receiver part at RF communication, that is, the receiver in the telemetry ground station for this study, also performs the process of removing the noise added on the channel. Added unwanted signals while the data frequency is raising and moving on the position are defined as a noise. Noise can occur due to different sources. However, in link budget calculations, a random Gaussian noise is used, which is associated with the bandwidth of the signal and is generated by the temperature emitted by the objects. The power of the noise is found and treated as a negative value in the budget, while the communication bandwidth, Boltzman constant and system temperature values are used [11].

Another definition used for RF systems other than noise power is the noise factor. This value is found by measuring the ratio of the information-carrying signal to noise (SNR; Signal-to-Noise Ratio) at the input and output points of the system:

$$\mathrm{F} = \mathrm{SNRinput} \div \mathrm{SNRoutput} \tag{2.3}$$

The definition of the noise figure (NF) is found by calculating the logarithm base 10 of the noise difference and multiplying it by 10:

$$\mathrm{NF} = 10\log(\mathrm{F}) \tag{2.4}$$

Loss of Free Space

In RF communication systems, if there is no reflection or refraction in the direction of the signal, and the line of sight between the receiver and the sender system is provided, in short, free space loss is observed under ideal conditions. This loss can be defined as the weakening of the power of the information signal depending on the communication range. In Equation (2.3), the necessary equation for calculating the amount of power reaching the receiver system is shown.

$$\mathrm{S} = \mathrm{Pt} \,/\, (4 \times \boldsymbol{\pi} \times \boldsymbol{R}2\,) \tag{2.5}$$

S: The amount of power per unit area for the calculated distance.
R: Distance between sender and receiver.
Pt: Power sent from the sender system.

The free-space path loss (FSPL) can be calculated using the equation in Equation 2.4 [12].

$$\mathrm{FSPL} = \mathbf{P}\boldsymbol{t}\ \mathbf{P}\boldsymbol{r} = (4 \times \boldsymbol{\pi} \times \boldsymbol{R}2\,) \,/\, \lambda\, 2 \tag{2.6}$$

Pt: Sent power
Pr: Power received
λ: Wavelength (found with c/f)
c: speed of light,
f: frequency of the signal

In short, the free space loss increases in direct proportion to the square of the distance (communication range). This loss is generally used in the calculations in decibels and for the dB case, the base 10 logarithm of the above ratio is multiplied by 20.

Transmission Line Losses

At the level of radio frequencies, wave characteristics are taken into account in order to transfer the signal from the transmitting and receiving systems to the antennas, and cabling or other structures suitable for high frequency currents are used. Many different transmission lines such as coaxial cables, microstrip structures, waveguides are examined during the design process, and the selection is made according to the suitability of the systems. At this point, one of the most important criteria is transmission line losses.

While finding the attenuation created by a transmission line in the system-wide signal, the losses due to different reasons are summed [13].

$$\boldsymbol{\alpha} = \boldsymbol{\alpha}\mathrm{C} + \boldsymbol{\alpha}\mathrm{D} + \boldsymbol{\alpha}\mathrm{G} + \boldsymbol{\alpha}\mathrm{R} \tag{2.7}$$

αC : Loss due to metal conductivity
αD : Dielectric loss tangent
αG : Loss due to dielectric conductivity
αR : Loss due to radiation

The unit of these losses is Nepers/meter and they need to be multiplied by 8.69 to convert to dB/meter.

For military telemetry applications, coaxial cable is generally used in the transmission line and the total loss for the sender-receiver system is calculated separately and included in the link budget calculation.

Atmospheric Losses

In cases where information signals are transmitted wirelessly by antenna, as in telemetry applications, it is necessary to evaluate how electromagnetic waves are affected in the atmosphere according to their wavelength. The two main substances that cause signals to be absorbed by the atmosphere are oxygen and water vapor [14].

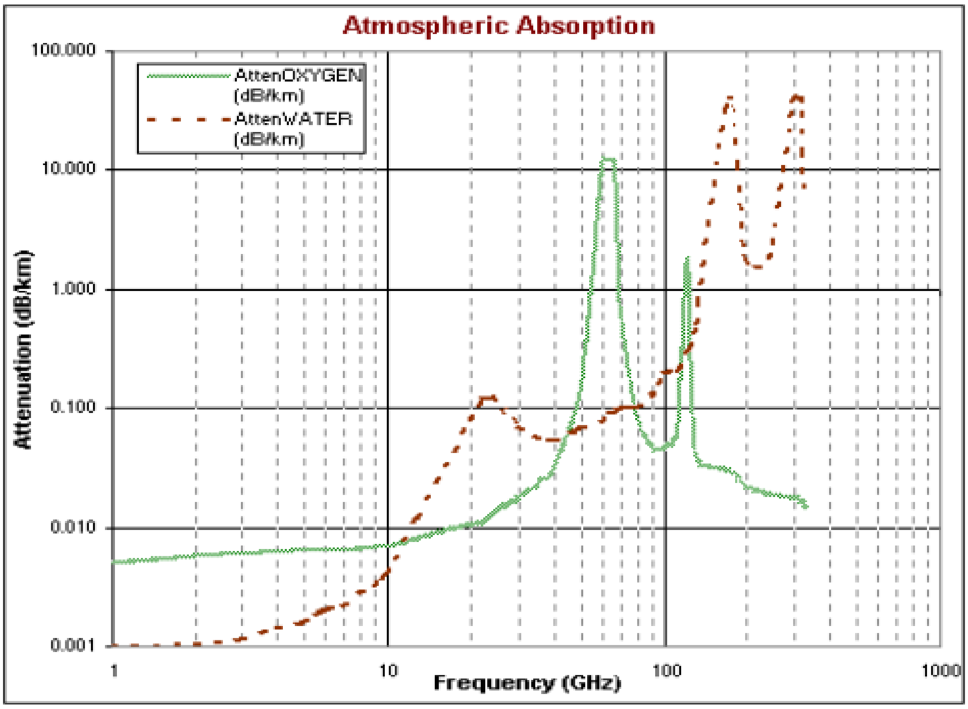


Figure 2. 1: Atmospheric absorption losses (by frequency) [8].

As observed in the graph in Figure 2.1, gases in the atmosphere also have a weakening effect on RF signals and are taken into account during the design process. In addition, natural events such as rain and snow also cause weakening, but since meteorologically suitable days are selected in telemetry tests, they are not considered necessary within the scope of this thesis study.

Polarization Loss

Antennas that provide wireless transmission of data have a basic characteristic feature called polarization. The antenna converts the radio frequency electric current into electromagnetic waves and radiates these waves into space [15,16]. Every electric field creates a magnetic field perpendicular to itself, and magnetic fields create an electric field perpendicular to itself; electromagnetic wave travels in this way. Although the direction in which the wave is traveling is towards the receiver antenna, it has linear, circular or elliptical polarization according to the path followed. Figure 2.2 shows the different types of polarization.

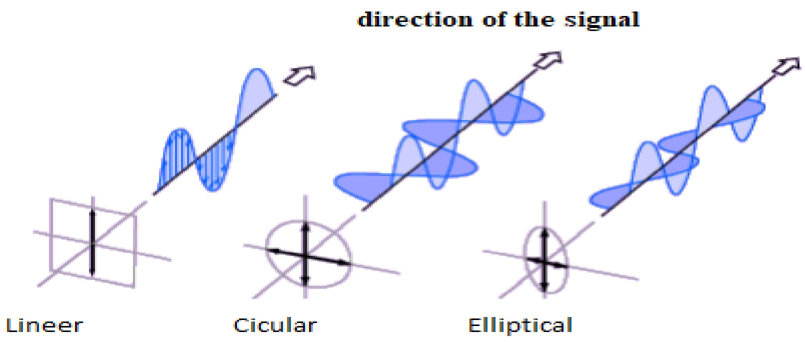


Figure 2. 2: Polarization types in electromagnetic waves [16].

In cases where the polarizations of the transmitting and receiving antennas are different, the polarization loss should be added to the link budget calculation. This loss can be found by squaring the cosine of the angle difference between the electric fields (cos2φ). When budgeting the link for telemetry applications, the polarization loss between antennas is usually taken into account as a loss of 3dB.

2.2.2 Gains of Rf Systems

Transmitter Output Power

In wireless communication systems, the RF signal strength at the output of the sender system becomes positive and is written as a positive value in the gains section when making the link budget. This gain can also be defined as the power generated on the resistor when a 50 Ohm resistor is connected to the antenna port at the RF transmitter output.

The transmitter output power may differ depending on the products used in the system. As defined in the telemetry standard document IRIG Standard 106-04 [8], it is essential to select the lowest possible output power in these applications.

In addition, output power over 25 W is also prevented by the same standard. Within the scope of the study, this value has been accepted as 10 dBW (10*log10(10 W/1W)) considering the technical document of an S-Band COTS product [17-20].

Antenna Gains

In cases where electromagnetic signals are transmitted to another antenna by means of an antenna, a gain value of the antenna is defined according to the directionality and electrical efficiency of the antenna.

The directionality is a parameter dependent on the design of the antenna and is defined according to the system requirements. Helical and 360-degree coverage antennas are generally used on the missile for telemetry tests. Example shapes are shown in Figure 2.3. This is because; The fact that the missile is mobile and it is designed to rotate around itself in some cases and it must be able to communicate with the ground station antenna LOS (Line Of Sight) throughout the flight.

Such omnidirectional antennas have low gain since they cannot concentrate the output power in one direction. [21].

$$\text{Antenna Gain} = \text{G} = \varepsilon\text{R.D} \tag{2.8}$$

εR: Antenna efficiency
D: Antenna directivity

The value displayed as the antenna efficiency parameter (εR); It varies depending on the metal used, the antenna type, the effective area of the antenna and the wavelength of the frequency at which it operates. Ground station antennas on the ground in the missile tests are selected from high-gain dish antennas since there is no space constraint [22]. These antennas are directional, that is, antennas with high directivity and are rotated by mast according to the direction in which the missile is moving.

3. DATA COMPRESSION ALGORITHM

Nowadays, the computer-aided processes increase, so the volume decrease of data which needs to be recorded, processed and sent has been increased. So as to control te mentioned volume increase, the necessity of data compression processes has increased. A file could be converted to another file thanks to the data compression process. Thus it is possible to reach the original data (lossless compression) or approximately similar data (lossy compression) when the reverse process of conversion is applied to compressed data file.

Data compression includes two main advantages. First one of these advantages is to need smaller storage space for storing data. Second advantage is to need less time while sending data due to reduced bandwidth. It is possible to encode them with data compression algorithms because most of the files contain redundant and repetitive data. Data compression issues has been started to be evaluated in the 1950s, and with the advancement of technology, the requirement for data compression various application areas has increased.A simple block diagram for data compression techniques is shown in following Figure 3.1. The binary message, M, come to a block that acts as an encoder, then it comes out being encoded as C (M). Post-coding message which symbolized by C (M) can be decoded into M. This function generates by decoder having the same information about coding as the encoder. As a result of this process, it is possible to return to the original message or with minor changes. Obtaining original message is only ensured by lossless data compression methods. The key point of this work is compression ratio of data. It could be found when the total bit number of the encoder output C (M) is divided by the total number of bits of the original message M. The decoder output message is displayed with a different representation (M ') than the original message, and there may be some losses in the data as a result of the compression process [23-25].

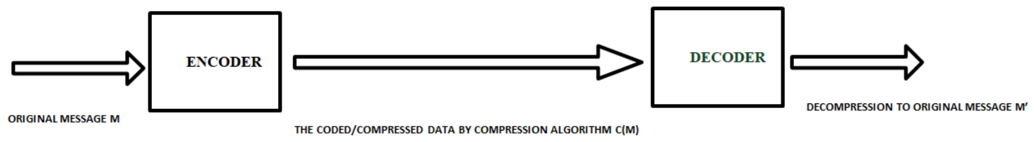


Figure 3.1 : Data encoding and decoding process

3.1 Lossy Compression Algorithm

Lossy data compression techniques causes some data lose. Namely, there is a difference between the original message M and its reconstructed version M. The reason why these techniques are preferred considering the data loss is that higher compression ratios can be obtained by neglecting this loss. For instance, lossy data compression algorithms ensure good advantages in data such as video or speech. Human sensory organs and the brain could be able to complete some missing frames on their own. Thus, this loss may remain at an unnoticeable level. In shortly, taking risk about decrease in the quality of the data provides that the data is highly compressed. However, missile concept requires every minor data gathering from data acquisition system. Missing some of data can not be acceptable for missile test systems.

3.2 Lossless Compression Algorithms

Lossless data compression techniques ensure no difference between the reconstructed version of the message M and the original message M. These methods and produced algorithms are generally preferred for times when data loss is not tolerated. In example; Files such as security and safety records are sensitive data to errors in. The main scope of this study is that lossless data compression techniques have been used for a system used in the military field.

Lossless data compression techniques are separated to 2 main titles which are static compression techniques and dynamic compression techniques [26,27]. Entropy coding techniques are members of lossless data compression techniques. They provide compression of digital data by allocating code words which are fewer of bits to the symbols with higher frequency (chance of encountering). The most used lossless entropy coding techniques are Huffman algorithm, Shanon-Fano algoritms, arithmetic coding and LZW techniques. Huffman algrorithm and Lempel-Ziv Welch techniwues were applied within the scope of the study [28,29].

3.2.1 Huffman Algorithm

This algorithm is an entropy coding algorithm which is one of the main applications of lossless data compression. David Huffman named for the method and he developed the algorithm for a lecture in 1950 while he was a student at MIT (Massachusetts Institute of Technology) [30]. He aimed generating the shortest code for the most common characters in the data flow which means the characters with the highest probability. He declared this characters' highest probability as frequency. The codes which have variable-length are generated and the average code length is decreased. Therefore compression has provided.

The decoding process of the codes is that the code of any character is not prefixed by another symbol in the purpose of avoiding confusion in the receiving system. This feature claims that Huffman algorithm is a prefix code.

First step off Huffman code is creating a tree is and sorting the characters by probability size. After that the symbols of the binary system (1 or 0) are assigned to the characters with the lowest probability and the lowest two probabilities are added to eachother. Then the second lowest probability is added one more tree branch and that will proceed in the same system. Eventually, the codes for each character are gathered by moving backwards [30].

The Huffman algorithm could be expressed more bright with an example. Imagine that we have a text file of 50 characters. We consider the alphabet which will be symbolized with "A"depicted with 5 different symbols used in this text. We aim to encode 5 different symbols from k to u in the alphabet of A. We let the message to be compressed as "KKKKKKKKLLLLMMMMNNOO". Firstly we calculate the total number of occurrences of these symbols in the text. After that we show the probability values in a chart like first branch of the Huffman Tree (Figure 3.2).

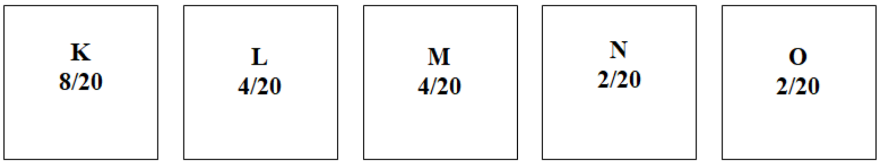


Figure 3. 2 : Probability of repeated symbols

The frequency of each symbol is determined in following table. From the Table 3.1, it can be understood that the symbols 'N' and 'O' are the least common. Therefore, the codewords belonging to these symbols will be setted up by the longest ones. 'N' and 'O' will take place on the bottom leaves of the Huffman tree.

Table 3.1 : Probability and frequency for huffman algorithm.

Symbols of Alphabet	**K**	**L**	**M**	**N**	**O**
Probability Value	0.4	0.2	0.2	0.1	0.1
Frequency Value	4	2	2	1	1

In the following step, the least probability 'N' and 'O' symbols are combined and continue to be treated as a single node. The last digit in the code words of these symbols will be ‘0’ for one and will be ‘1’ for the other.The possibilities continue to add up and at every step. A new symbol is added to the node. When the probability is completed to 1, the adding processes are completed and the codes are obtained by descending from the root of the tree to the leaves like showing on Figure 3.3 below.

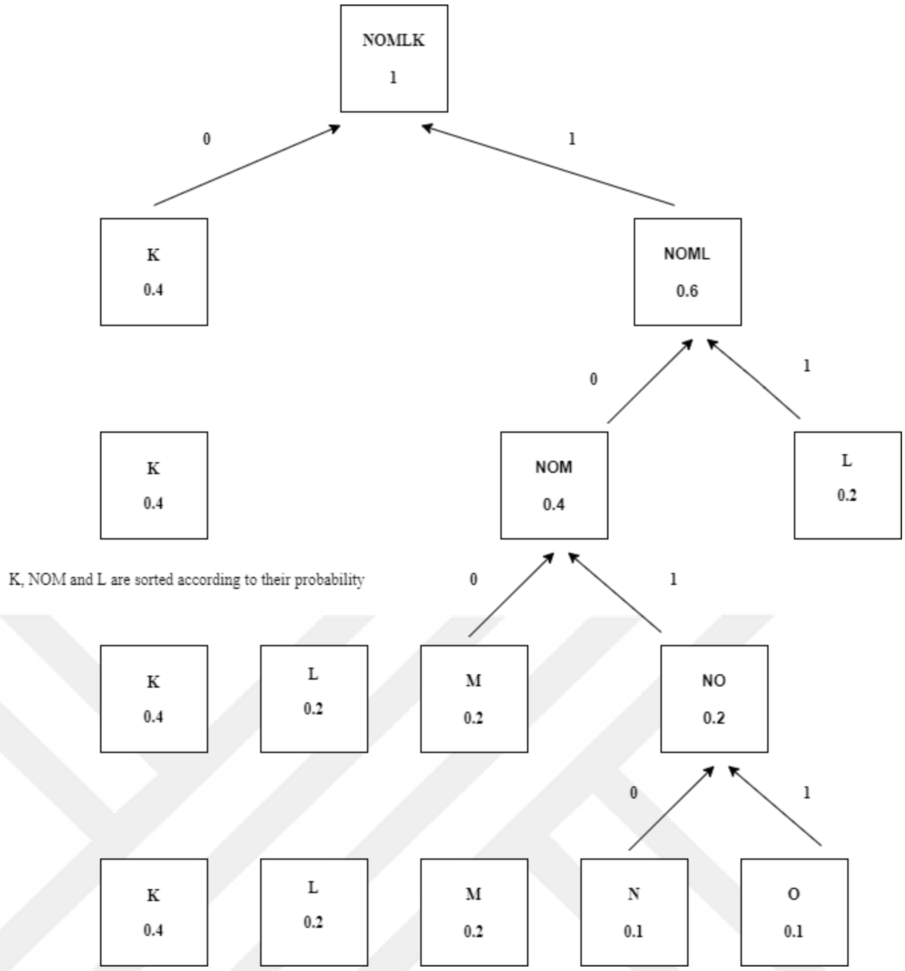


Figure 3. 3 : Huffman tree from root to the leaves.

Following Table 3.2 shows the coded words gathered for the situation using the Huffman tree method. The average length of a code could be calculated with 2 steps. Fistly, frequency of each symbol and number of bits of coded word are multiplied. Then the result divided by total message length) calculation. The calculation of the the mentioned example is showed below.

$$total\ length\ of\ the\ code = frequency\ of\ each\ symbol \times number\ of\ bits$$

$$Average\ length = total\ length\ of\ the\ code \div total\ message\ length$$

$$Average\ length = [(4 \times 1) + (2 \times 2) + (2 \times 3) + (1 \times 4) + (1 \times 4)] \div 10$$

$$Average\ length = 2.2$$

Table 3.2 : Coded words for each symbol using huffman tree.

Symbol	K	L	M	N	O
Coded Words	**1**	**01**	**000**	**0010**	**0011**

3.2.2 Lempel- Ziv Welch Coding Algorithm

Lempel-Ziv (LZ) algorithms are lossless data compression algorithms which were developed by Abraham Lempel and Jacob Ziv. These algorithms are defined as dictionary-based methods on data compression ways. Repeating symbol groups in a file are determined with these methods. After that, the corresponding code words are created. Then a dictionary is created containing these code words [31].

LZ77 is the first founded member of the LZ data compression family. This method was defined specificially for text-based data files. This method also was introduced in the article published in 1977 named “A Universal Algorithm for Data Compression” [30,31].

The LZ77 algorithm generally uses a kind of floating window that moves with the cursor. The window in the question could be separated into two items. First one of them is called the "search buffer" which could also be defined as a dictionary.Second of them is a "lookahead buffer" starting from the cursor location. The sizes of these parts are aimed to be staying constant during the operations of the algorithm. The algorithm evaluates with a basic logic and it requires some steps to be performed in a loop. These steps could be listed as below [32,33]:

- The longest string starting at the cursor location in the forward buffer is matched with the string that starts in the search buffer .The longest section needed to be chosen like this process.
- Distance in the search buffer for matching could be symbolized with ‘K’.
- The length of the matched section could be determined as ‘L’
- The code or message of the first character after matching could be symbolized with ‘M. Thus outcomes of the process would be on triple output form like (K, L, M)
- The cursor is taken one step ahead like L + 1 charachters.

Although the LZ78 is very close to LZ7 in terms of application, it differs from LZ77 in the way of not using buffers in the algorithm. The data compression principle of the LZ78 algorithm recommends that the dictionary should be created in the same way by not only encoder but also decoder system. As a result, the dictionary of the LZ78 contains unlimited previously ecompared expressions.While evaluating the LZ78 technique, the dictionary is created with progressing in coding. Thus, it is suitable to analyze the data for one time. Thus, there is not a need that all data to be available before coding. This situation ensures the advantage of using the LZ78 in terms of approaching to real-time data. The LZW technique was generated by Terry Welch in 1984 as a result of the developments on the studies of Lempel and Ziv [34]. Eventually, LZW is considered as one of the most efficient algorithms that assures the best compression ratio. The LZW algorithm is known as the youngest member of this code family. It gives more advantages according to both LZ77 and LZ78 in terms of compression performance. The coding steps for this algorithm are listed below.

- K is determined as the position in the window. M is determined as the first character after pairing.
- Firstly, all the elements belonging to the alphabet of the statement to be encoded in the dictionary.
- K is the empty set. The letter M refers the character to be processed next in the symbol section.
- It is checked whether the K + M sequence is included in the dictionary or not.If it is included, the K set is extended to K + M. If it is not included, the dictionary equivalent code of K is accepted as outcomes. The K + M section is added to the dictionary. K is updated to M. that means next character becomes M.
- The steps written above are iterated in a loop until the message aiming to be encoded is finished.
- In order to make brighter, we can go on to an example.For instance, the dictionary prepared at the beginning for the 'DADADADA' message is as follows.The first part of the Dictionary is shown at Table 3.3.
- The letter D is a subtented character in the dictionary.When the letter A is switched, the value of K becomes D, and C becomes A. Hence, DA is written

as the K + M value. The expression DA is added to the dictionary. The K value is D and its numbering becomes 1. Result is added to the code section.

- When it comes to the second letter D result becomes K = A, M = D and K + M = AD. The expression AD is added to the dictionary. Corresponds of A is 2 and it ise added to the code section.
- When it comes to the second letter A, the characters D and A have already placed in the dictionary. So that K becomes DA.The dictionary equivalent of DA is 3, and it is added to the code section.
- The procedure could be completed in the same way, the code representing the entire message and the generated dictionary are constructed as shown in Table 3.4 .
- As a result of the obtained dictionary, the encoded version of the message is founded as "12352".

Table 3.3 : First part of the dictionary.

Row Number	Dictinary Input
1	**D**
2	**A**

Table 3.4 : Dictionary of message ‘DADADADA’.

Row Number	Dictinary Input
1	**D**
2	**A**
3	**DA**
4	**AD**
5	**DAD**
6	**DADA**

4. DATA COMPRESSION ALGORITHM

Within the scope of the thesis, the size reduction amounts provided by the selected compression methods in the process of compressing the telemetry data generated on the missile before sending it to the telemetry ground station were examined. For this purpose, two types of data acquisition system which have different frame structure topology have been chosen as syntetic data source of telemetry. After usage of these 2 DAC, syntetic data and their compression gains were analyzed. In this context, MATLAB program was used and data compression techniques were applied to synthetic telemetry data.

First of all, the test set-up of the data acquisition system promoting subcommutation frame structure has been constructed and snytetic data were collected by this hardware. Secondly, the test set-up of the data acquisition system including supercommutation frame structure has been constructed on desktop. Snytetic data collection process is applied much the same as first hardware. After that, collecting telemetry data were encoded and separated according to inner data types. The Huffman algorithm and LZW methods were chosen as applied compression techniques and these techniques are evaluated on both total frame and inner data separately for each data acquisition systems. The reason for choosing lossless data compression algorithms is that the missiles are products of the defense industry sector. In such critical technologies of military importance, the information-carrying telemetry data becoming different from the original data after compression may cause an intolerable situation. For instance the images taken by the seeker or the pressure data collection for the specific military purposes are analyzed within the scope of telemetry data. However, it may cause much trouble where numerical values are monitored instantly if some bits are lost or changed. All of the methods chosen for analysis in this study must be lossless data compression techniques.

After the outcomes of the compression were examined, it was observed that the LZW technique gave more successful results compared to the Huffman algorithm.

In short, synthetic telemetry data produced from harwares having different frame structures are examined in the first part of the study. The telemetry frame structure have been analyzed on PCM form before sending to ground station.Then the data limits according to their types have been determined.

Second part of this study has been considered to compression using lossless data compression techniques. Each categorized data in fram and total frame data were compressed. So, it is analyzed which technique provides more efficient compression. Compressing the data reduces its size. In parallel with size reduction, the bandwidth needed to transmit the data is also decreased. This situation has been examined in the link budget analysis. In this study we intented for assuming that the other parameters of the receiver and transmitter systems remain the same and only the bandwidth changes. As the bandwidth decreases, the strength and the impact of the noise signals will also decrease, so a longer communication range will be gathered with the same systems.

On the other hand, communication bandwidth is a costly parameter and it requires a specific frequency range allocation.Therefore, there is a necessity for a proper design of RF systems. Modern day telemetry test engineers endeavor to select the lowest bandwidth allowing healthy communication. For this reason, decreasing the bandwith and increasing the communication range will become more and more important every day.

4.1 Construction of Data Acquisition System on Hardware Level

Data Collection Systems are units that allow collecting multiple data over the system they are connected to in on board applications. Both of the hardware used in this study was selected as units capable of collecting both analog and serial data.

Sensors that collect analog signals or measure voltage differences are digitized by an analog to digital converter (ADC). Then they are sent to the compiler to be placed in the data packet to be downloaded to the ground station.

Synthetic digital data representing the guidance data were collected over the RS-485 line by means of a serial data generator. Data simulated as guidance data and the data simulated as seeker data are already in digital form. They are sent to the compiler to be placed in the data packet to be downloaded to the ground without any converter processing.

The compiler allows the frame structure called telemetry package to be created according to the operator's ease of use or usage preference by adhering to a set of standards. For example, the user may prefer analog data to be at the beginning of the frame to be the data placed first in the packet. As a second example, the user can set the sampling rate of analog data. It may request that the serial data be placed in the frame with different commutations in accordance with the IRIG 106 Standard.

Within the scope of this thesis, analog data were collected from two types of hardwares were determined as pressure and vibration data, and the sampling rates were kept constant in tests performed with both hardwares. Since the analog data will be different in time when they are started to be collected and the applied vibration pulses will be made manually, synchronization will not be possible during the data recording period. For this reason, the dimensions of the analog data collected in both hardwares cannot be the same. Data recorded for a longer time will have a longer size. Even if they have the same size, the compression ratios will not be compared to each other, as the data content will not be exactly the same. The block diagram of data acquisition systems used as test set-up in this study is showed below.

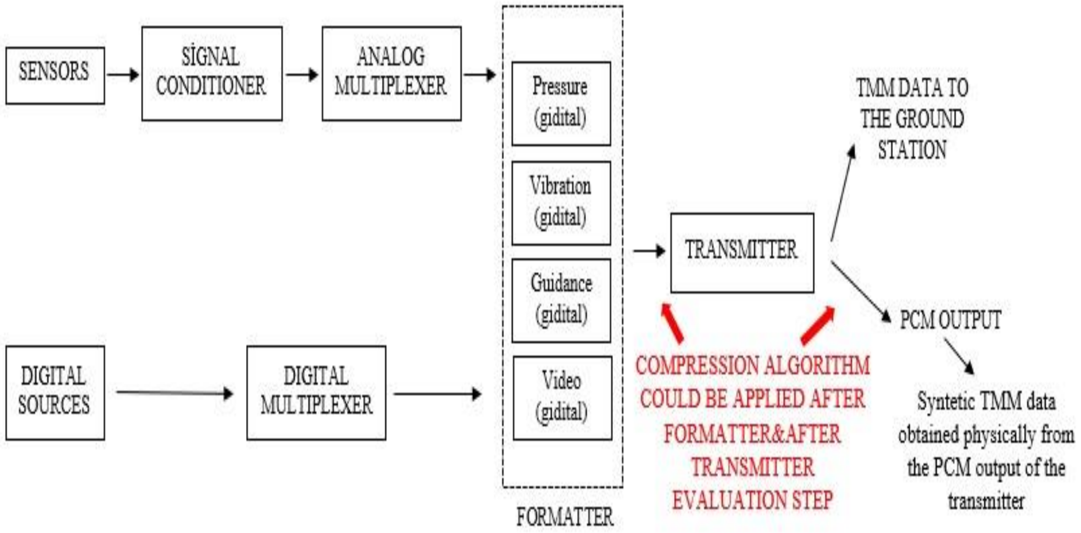


Figure 4.1 : Hardware set-up of data acquisiton system.

As can be seen from Figure 4.1, the formatter sends the data that were placed in the frame structure to the transmitter. The transmitter modulates these data. Then it encrypts them and makes them ready to be sent. These encrypted data ready to be sent are called PCM data. This modulated data is sent from the hardware to the air via RF communication and then to the receiver or ground station. The same data can be read from the transmitter as PCM output. In the tests carried out in this study, data was collected over the transmitter's PCM output ports. The reason for this situation is to prevent the data created on the systems from being lost in the air. If data is damaged or lost in the air, it may cause inaccurate results in the compression process. Since it is an important point to compress telemetry packages as they are, synthetic test data were collected over the hardware's PCM output line.

Compression algorithms can be applied both before and after the transmitter is modulated, as can be seen in Figure 4.1. Implementing compression algorithms at the compiler stage requires hardware access to the compiler. Alternatively, compression of data in the output of the compiler can be accomplished by external hardware or software. However, the data acquisition system (DAS) is a compact structure. Access to the hardware and related card is required for these operations. Applying compression by accessing the hardware is not covered in this study. Likewise, compression algorithms can be applied just after analog sensors and serial data generators, which are the sources of data. The effects of compressing each data separately on reducing bandwidth according to data types can be evaluated directly. However, if each data reaches the compiler after it has been compressed, the compiler must adopt a certain principle to put this compressed data into the frame structure. Since this feature requires access to the internal world of the hardware, it includes working on a different subject. For this reason, in this study, issues related to the inner world of the hardware have not been addressed.

The location of each data type in the resulting frame structures is known. Pressure, vibration, guidance and seeker data were obtained separately and subjected to compression algorithms. The compression rates encountered according to these data types have been studied within the scope of this study. The compression ratios obtained are aimed to shed light on which data will provide higher efficiency when compressed.

4.1.1 Test Set-up of Hardware Supporting Subcommutation Frame

The desktop set-up required for the tests performed with the hardware that allows the user to create telemetry frame structure with the subcommutation method is as shown below. While creating the test set-up, analog data were collected directly from the sensors serving the relevant purpose. The physical quantities collected from analog sensors reach the ADC on the cards inside the DAS. These data are digitized and made ready and suitable for entering the telemetry frame structure. A kind of generator that prints serial data is used as a digital data source. The TV camera is used as the video data source. These data, which are also analog magnitudes, are compressed and digitized in DAS with the image compression technique and made to be added to the telemetry frame structure (Figure 4.2).

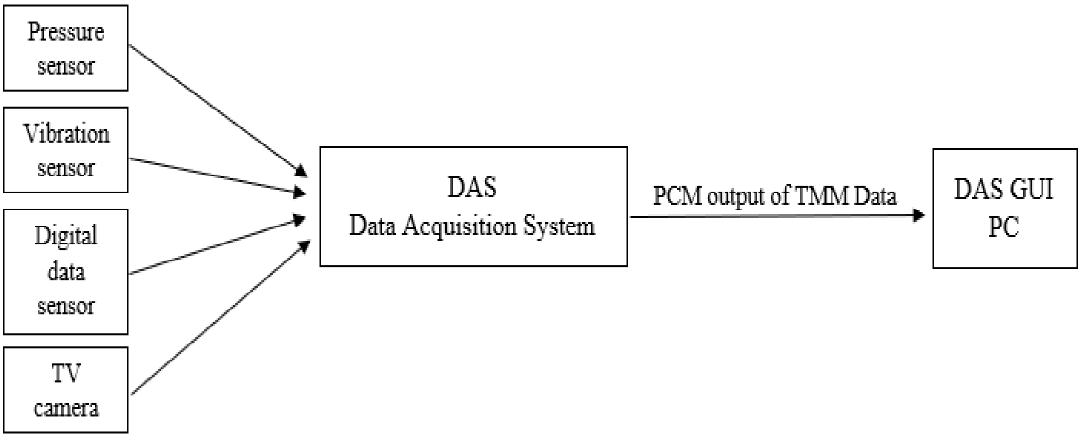


Figure 4.2 : Test set-up of data acquisition with hardware 1.

While creating syntetic tests data, the frame structure was arranged first. This structure, which was created by using the real rangefinder data and the output frequency of the sensors, is formed by combining five minor frames. 5 minor frames constitute 1 major frame. Each minor frame consists of taking samples from all sources in 0.2 milliseconds. For example, a sensor will receive the first data in 0.2 milliseconds and the second data in 0.4 milliseconds. The frequency of sending the major frame to the ground is happened in every 1 millisecond. While creating the major frame, each data is sampled every 0.2 milliseconds and placed inside the 1 millisecond major frame. Therefore, each data is sampled 5 times in the major frame. The length of each data is arranged as 1 byte and 8 bits. According to the scenario developed in this way, the outputs of the sensors are sent in 8 bit in binary order. The created frame structure is shown below (Table 4.1).

Table 4.1 : Frame structure of received data from hardware supporting subcommuttaion.

Sync. Word	***Sfid***	***Analog Data 1***	***Analog Data 2***	***Serıal Data 1***	***Serıal Data 2***	***Minor Frame Counts***	
Synchronization Word	Sub Frame Identifier	Pressure 1	Vibration 1	Guidance 1	Video 1	***First Minor Frame Data***	***MAJOR FRAME DATA***
Synchronization Word	Sub Frame Identifier	Pressure 1	Vibration 1	Guidance 2	Video 2	***Second Minor Frame Data***	
Synchronization Word	Sub Frame Identifier	Pressure 1	Vibration 1	Guidance 3	Video 3	***Third Minor Frame Data***	
Synchronization Word	Sub Frame Identifier	Pressure 1	Vibration 1	Guidance 4	Video 4	***FourthMinor Frame Data***	
Synchronization Word	Sub Frame Identifier	Pressure 1	Vibration 1	Guidance 5	Video 5	***Fifth Minor Frame Data***	
Synchronization Word	Sub Frame Identifier	Pressure 1	Vibration 1	Guidance 6	Video 6	***Sixth Minor Frame Data***	
Synchronization Word	Sub Frame Identifier	Pressure 1	Vibration 1	Guidance 7	Video 7	***Seventh Minor Frame Data***	
Synchronization Word	Sub Frame Identifier	Pressure 1	Vibration 1	Guidance 8	Video 8	***Eight Minor Frame Data***	
Synchronization Word	Sub Frame Identifier	Pressure 1	Vibration 1	Guidance 9	Video 9	***Nineth Minor Frame Data***	
Synchronization Word	Sub Frame Identifier	Pressure 1	Vibration 1	Guidance 10	Video 10	***Tenth Minor Frame Data***	

The data size used in this study can be calculated according to the formula below.

$$Total\ Bit\ Numbers = a \tag{4.1}$$

$$total\ number\ of\ minor\ frames\ on\ 1\ package = b \tag{4.2}$$

$$Data\ Lenght\ of\ Each\ Minor\ Frames = c \tag{4.3}$$

$$Sampling\ Rate\ at\ 1\ Milisecond\ = d \tag{4.4}$$

$$a = b \times c \times d \tag{4.5}$$

$$Total\ Number\ of\ Minor\ Frames\ on\ 1\ Package = 10 \tag{4.6}$$

$$Data\ Lenght\ of\ Each\ Minor\ Frames = 100\ byte \tag{4.7}$$

$$Data\ Lenght\ of\ Each\ Minor\ Frames = 800\ bits \tag{4.8}$$

$$Data\ Lenght\ of\ Each\ Major\ Frames = 1000\ byte \tag{4.9}$$

$$Data\ Lenght\ of\ Each\ Major\ Frames = 8000\ bits \tag{4.10}$$

$$\text{Sampling Rate} = 500\ Frame\ Per\ Second \tag{4.11}$$

$$Total\ Bits\ Numbers = 8000 \times 10 \times 500 \tag{4.12}$$

$$Total\ Bits\ Numbers = 40000000\ bit\ per\ second \tag{4.13}$$

That means, telemetry frame structure in this study allows 4,000,000 bits to be sended to the ground station.

For the analysis carried out within the scope of the thesis, the parameter for the number of data types in this sample frame has been increased. Today, data transfer of 10 Mbps and above is not generally used in telemetry applications [4]. However, higher sizes are analyzed in this study like 8,000,000 bps.

In hardware where subcommutation technique is applied, the data is divided into parts to fit into a rectangular frame structure. For example, as can be seen in the figure below, the digital data in 1 data packet is sent by dividing it into 5 small frames instead of being sent in a single main frame like Figure 4.3. For example, if a

42-byte data is sent in 5 lines occupying 10 bytes, it must be filled by the hardware because the data between the 42th byte and the 50th byte is over. Writes a fixed digital value, called Common Word, to complete the package in cases where the hardware cannot find data to place it in the frame. This situation causes a space occupation of 50 bytes in order to fit the matrix structure of the frame, while 42 bytes of serial data is required in the hardware.

1st Minor Frame	...	Guidance 1	Guidance 2	Guidance 3	Guidance 4	Guidance 5	Guidance 6	Guidance 7	Guidance 8	Guidance 9	Guidance 10
2st Minor Frame	...	Guidance 11	Guidance 12	Guidance 13	Guidance 14	Guidance 15	Guidance 16	Guidance 17	Guidance 18	Guidance 19	Guidance 20
3rd Minor Frame	...	Guidance 21	Guidance 22	Guidance 23	Guidance 24	Guidance 25	Guidance 26	Guidance 27	Guidance 28	Guidance 29	Guidance 30
4th Minor Frame	...	Guidance 31	Guidance 32	Guidance 33	Guidance 34	Guidance 35	Guidance 36	Guidance 37	Guidance 38	Guidance 39	Guidance 40
5th Minor Frame	...	Guidance 41	Guidance 42	Common Word	Common Word	Common Word	Common Word	Common Word	Common Word	Common Word	Common Word
	Other Data										

Figure 4.3 : Guidance/serial data distrubution on frame with subcommutation method.

4.1.2 Test Set-up of Harfware Supporting Super Commutation Frame

The desktop set-up required for the tests performed with the hardware that allows the user to create telemetry frame structure with the Supercommutation method is as described in item 4.1.1. The only difference between these two test set-ups is the hardware. In this part of the study, all other variables were kept constant and the test set-up was created by changing the hardware and test wiring. Super commutative frame includes 1000 byte elements inside since Supercommutation frame structure used in hardware is shown below (Table 4.2).

Table 4.2 : Frame structure of received data from hardware supporting subcommuttaion.

MAJOR FRAME DATA = MINOR FRAME DATA														
SYNC. Word	***SFID***	***5 Sample From Each Analog Data***		***Serial Data 1***					***Serial Data 2***					
Sync. Word	SFID	Pressure 1	Vibration 1	Guidance 1	Guidance 2	Guidance 3	Guidance 4	Guidance 5	Video 1	Video 2	Video 3	Video 4	Video 5

The data size of hardware used in supercommutation method can be calculated according to the formula below.

$$total\ number\ of\ minor\ frames\ on\ 1\ package = 1 \tag{4.14}$$

$$total\ number\ of\ major\ frames\ on\ 1\ package = 1 \tag{4.14}$$

$$data\ lenght\ of\ each\ minor\ frames = 1000\ byte \tag{4.15}$$

$$data\ lenght\ of\ each\ minor\ frames = 8000\ bits \tag{4.16}$$

$$Number\ of\ Frame\ Per\ Second = 500 \tag{4.17}$$

$$Total\ Bit\ Numbers = 8 \times 1000 \times 500 \tag{4.18}$$

$$Total\ Bit\ Numbers = 4000000\ bps \tag{4.19}$$

As can be understood from Figure 4.4, the data are repeated in major frames by adding them side by side in supercommutation frame structures. Samples of the same data are not added to the next minor frame structure. In supercommutation frame structures, the major frame is generally not divided into minor frames. Since the hardware 2 product used in this study and the supercommutation structure is used, the number of minor frames is equal to the number of major frames. Pressure and vibration data are sampled 5 times in one major frame. These examples are written side by side and added to the main frame. Serial data are written side by side since sampling is not possible. Compared to the hardware using the subcomutation method, supercommutation frames does not require filling with a common word data in the frame. As seen in Figure 10, fourthy two bytes of data simulating the guidance data are written side by side in a single line. At this stage, it does not need to be completed to fifty bytes.

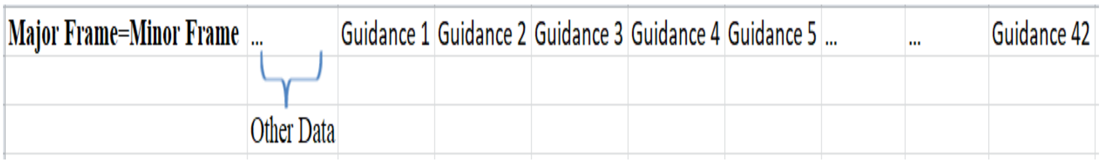


Figure 4.4 : Guidance/serial data distrubution on frame with supercommutation method.

4.1.3 Demodulation Process of Test Data

After the data collection systems are set up properly and preparing the necessary test set-up, the data are collected on the PCM reading port. The collected data is saved as a ".binary" file. This file contains the same data that will be sent to the telemetry ground station. There are two reasons for collecting data from the PCM channel. The first is that the data to be sent is not lost and its content is not changed. The second reason is to accurately simulate the phenomenon of range performance by applying the data compression algorithm before flight.

The data encrypted by modulation read from the PCM output of the Transmitter is parsed into frame structure by the decoding code below (Figure 4.5).

```
%% Damla COLAK 2021 DATA ENCODING
clc
clear all
%% RF Inputs Expected From The User:
syncronization_word =input('Please Enter the Syncronization Word in format Format [AA; AA; AA ;AA] :' );
frame_length=input('Please Enter the Frame Size of the Telemetry Package  :' );
receiver_checking_data_length=input('Please Enter the length of data would be added to Telemetry Package :');

%% Reading the Input Telemetry Data File From User:
[input_file, file_path] = uigetfile('*.*', 'Please Enter the Input Telemetry Data File');
file_name = strcat(file_path,input_file);
cd(file_path);
fid = fopen(input_file,'r') ;
raw_data = fread(fid,'uint8') ;
fclose(fid) ;
raw_data=raw_data';

%% Finding the Input  From Telemetry Data File:
syncronization_word_HEX = (hex2dec(syncronization_word))' ;
syncronization_word_length = length(syncronization_word_HEX) ;
syncronization_word_index=strfind(raw_data,syncronization_word_HEX);

%% This Part is for Receiver or PCM Recorder Specifications from Transmitter Hardware
package_length=frame_length+receiver_checking_data_length;
received_data_first=syncronization_word_index';
rx_input=0:package_length-1;
rx_func=bsxfun(@plus,received_data_first,rx_input);
rx_func_new=rx_func(1:end-1,:);
rx_colunm=reshape(rx_func_new',1,[]);
received_data=reshape(raw_data(rx_colunm),length(rx_input),[])';

%% Finding Major ve Minor Frame Data From received Data
major_frame_data_with_zero=received_data(:,1:end);
major_frame_data=major_frame_data_with_zero(:,5:end-receiver_checking_data_length);
minor_frame_data=major_frame_data;
```

Figure 4.5 : Demodulation code for syntetic PCM data file.

Major frame data is obtained from the decoded data. Data collected from both subcommuttative and supercommutative hardware can be parsed by this algorithm. First thing that the algorithm looks at is to find the "synchronization" in the modulated data. With this process, it is determined whether the frame structure is divided into smaller frames or not. The whole main frame and different data types in the frame are reached with this decoding code.

4.2 Evalutaion of Data Compression Techniques

The data in different frame structure collected from the hardware at this stage of the study were subjected to two kinds of compression algorithms. These algorithms are Huffman algorithm and LZW compression method. Data compression process has been handled as in the process items below. First, the data received from both hardwares was decoded. Then the major frame data was focused. Compressing the data received from two different hardwares as a whole frame structures have been aimed to give an almost similar result in terms of compressing the space occupied by the data in the frame and the empty areas in the frame with common words. The overall efficiency of a telemetry data when compressed regardless of the subcomponent data it contains was examined. At this stage, the whole mainframe has been compressed considering it as a matrix structure.

First, all frame structures have been compressed and checked for a difference. As the second step, Huffman and LZW compression algorithms have been applied separately, and the analysis of which compression algorithm gives better compression results have been obtained. Then, the mentioned compression algorithms have been applied respectively. The compression ratios of analog and digital data in a data acquisition system have been compared. The effect of compression on the system has been evaluated separately or with the whole framework and compared with each other.

4.2.1 Compression of Total Frame Data

At this part of the study, first a major frame data of the telemetry data has been taken and compressed with Huffman algorithm, and then the LZW compression algorithm has been applied to the same structure. The results obtained are shown below (Figure 4.6) (Figure 4.7).

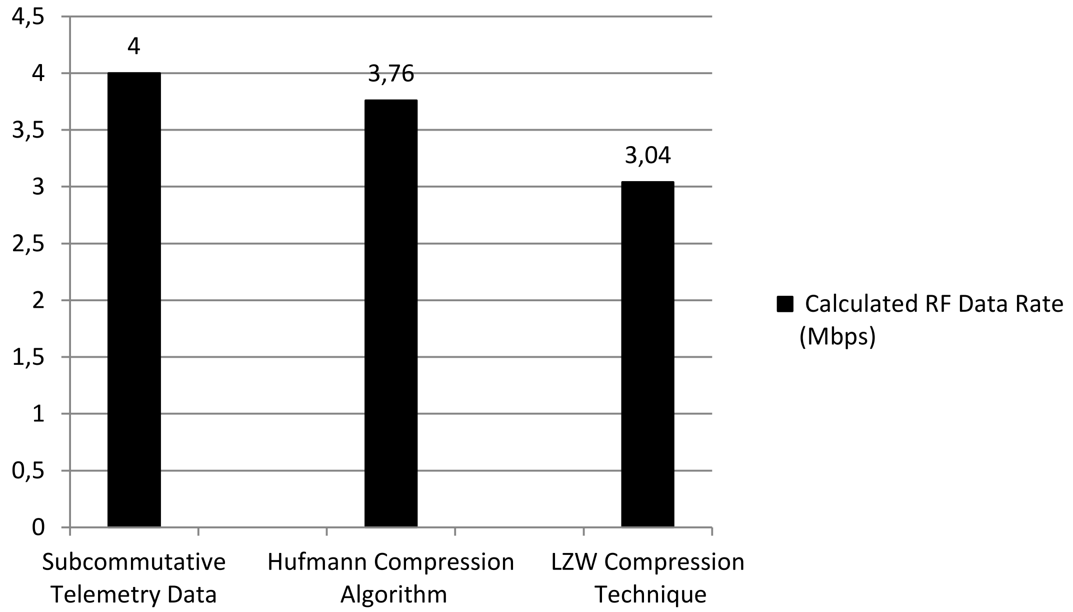


Figure 4.6 : Compression rates of subcommutative hardware data.

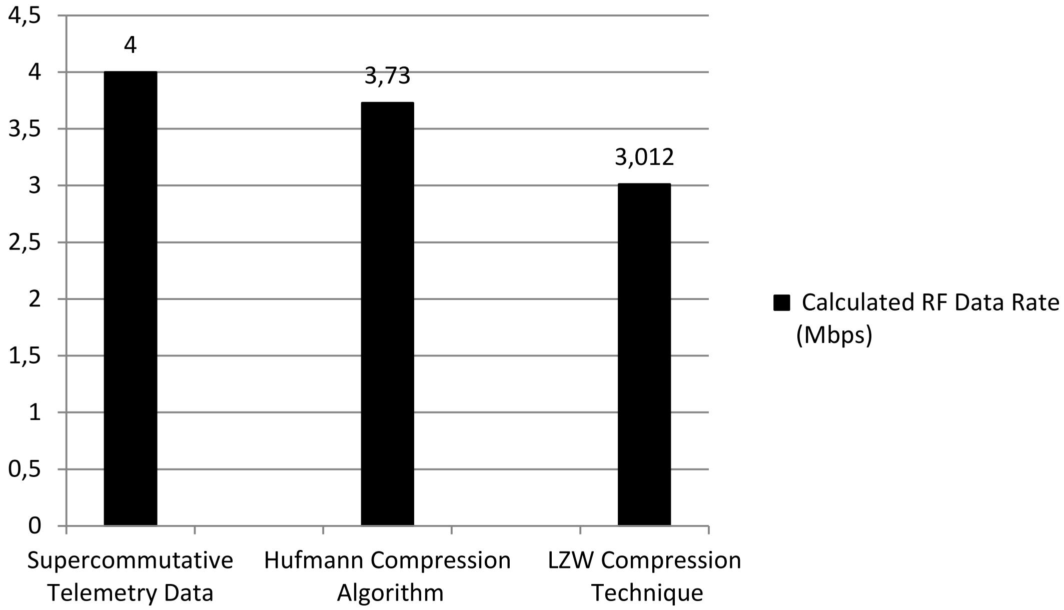


Figure 4.7 : Compression rates of suppercommutative hardware data.

According to the results of this analysis, compression of both subcommutative and super commutative data had a positive effect in terms of data speed. In both methods, the LZW algorithm has been provided better compression compared to the Huffman algorithm. The Table 4.3 shows the compression percentages.

Table 4.3 : Compression percentages.

Frame Structure	Compression Percentage with Huffman Algorithm	Compression Percentage with LZW Algorithm
Subcommuttative Frame	% 6.00	%24.00
Suppercommuttative Frame	% 6.75	%24,70

The same compression algorithm has already given a better result in the supercommutative method. The reason for this situation is that the frame structure created has been presented as an array. In this array, all data are lined up next to each other. It is the same for analog data. It is written side by side in the array as much as the sampling amounts. A single common word is written in the last spaces to complete the major frame. Therefore, the compression process is also applied to the common word in the blank fields while it is applied to the relevant data.

The situation is different in the subcommutative frame structure. In the data subcommutatively divided into minor frames, a different common word is written for each data type in the empty places. For example, a different common word is written to the empty part of the digital data section, while a different common word is written to the part where analog data is not sampled. Therefore, while the whole frame is compressed, since there are different common words in the empty part, the compression rates are different.

4.2.2 Compression of categorized data placing on the frame

In this part of the study, the datas simulating the telemetry data have been examined separately and separate compression algorithms have been applied to each of them. Then, which of the selected compression methods were more efficient has been investigated. The data contained in a package of both subcommuttaive and supercommuttative frame structures have been parsed. After that, it has been focused on the effect of data type in terms of reducing bandwidth by applying compression methods to each data type of the same size, respectively.

It is sufficient to look at the data in a single major frame while compressing digital masters such as guidance and video data, because this digital data is repeated in all data packets during the collected period. Since the sources of digital data transmit fixed data, this data will repeat itself in each packet, so when applying compression algorithms, it will be sufficient to apply it to the data in a single packet. However, this does not apply to analog data. Since the pressure and vibration data evaluated within the scope of this study are analog data, all data packets collected should be considered when evaluating the compression of these data.

Compression of Serial/guidance Data

The header information of the serial data was the same in the data received from both the supercommuttative and subcommutatvie hardware. Said synthetic batch data have had the same size and content. Therefore, it has not made a difference in terms of data compression algorithm. However, in this case, there is a situation that needs attention. If the cycle time of serial data is different with the cycle time of the frame planned to be downloaded to the receiving station, the compression rate may change. For example, if the serial data generator sends data in 10 miliseconds and the PCM output sends this data to the receiving station every 5 miliseconds, serial data repetition occurs in that frame. When viewed on a time basis, in this case, 2 times data sampling is experienced in 10 seconds. Figure 4.8 shows the compression ratios and of synthetic guidance data with subcommuttation and supercommutation methods.

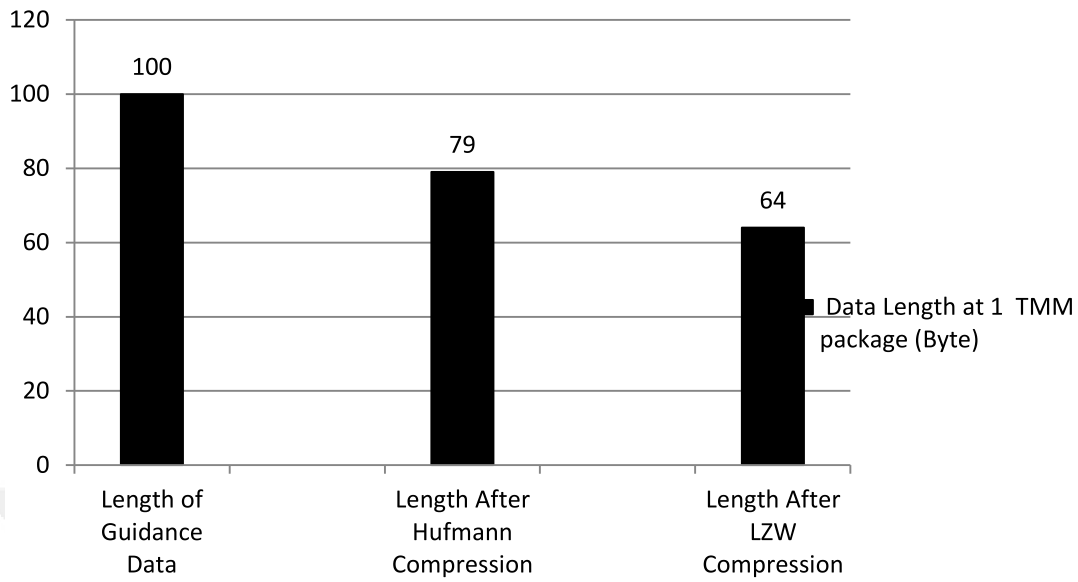


Figure 4.8 : Compression rates of guidance data.

Table 4.4 shows the compression ratios and of synthetic guidance data with subcommuttation and supercommutation methods.

Table 4.4 : Compression percentage of guidance data.

Frame Structure	Compression Percentage with LZW Algorithm	Compression Percentage with Huffman Algorithm
GuidanceSubcommuttative Frame	% 36.0	%21.0
Suppercommuttative Frame	% 36.0	%21.0

Compression of Video Data

The compression rates of two types of video data have been observed very small. Considering the reason for this, when the video data collects data from the analog video line, this data is digitized and compressed and sent to telemetry. It does not seem very possible to recompress the already compressed data. The video data in this study was simulated as follows:

- First of all, there is a unit that can collect analog video data in both hardware and the test set-up was created accordingly.
- In this thesis, the source of analog video data has been chosen as TV camera.
- The input parameter of the camera is in PAL format, and the data in this PAL format is received in the inner system of the hardware.
- Digitized data is compressed in H264 format.
- This digital video data, ready to be put into the telemetry package, is placed in frame structure on the formatter side.
- Image data is parsed from the PCM data obtained as a frame structure.
- Huffman and LZW algorithms have been applied to the obtained data.

As a result of this study, data that has already been compressed has been subjected to lossless compression methods. For this reason, it is normal for the compression ratio obtained to be low. As a result, it is clear that compression of video and image data will yield less efficiency than other data types (Figure 4.9).

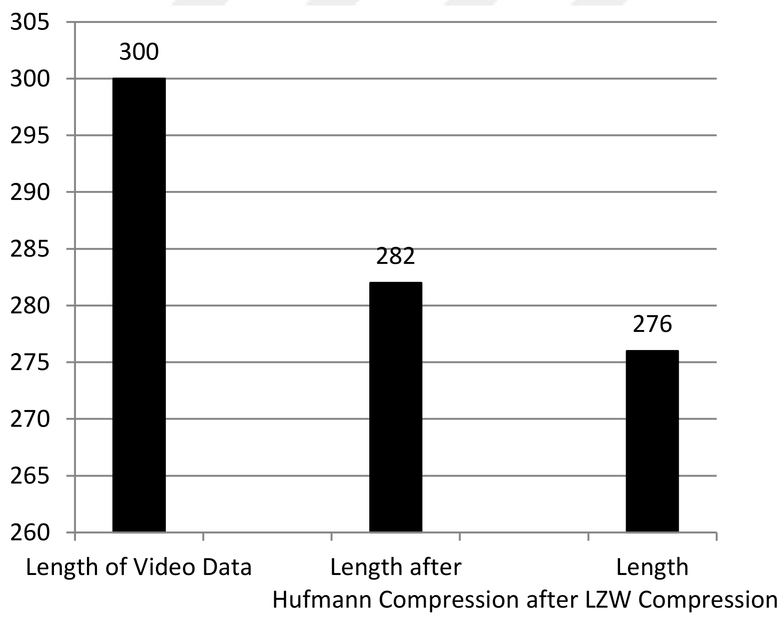


Figure 4.9 : Data compression rates of telemetry video data.

The video data in a telemetry package means the data size in 1 major frame in the collected data. This data size is 300 bytes for video data. While the size of the image data with the compression algorithm applied was 300 bytes, it became 282 bytes.

With the LZW compression algorithm, which offers better compression, it decreased from 300 bytes to 276 bytes. This is the reason why the data size is compressed at such a small rate. Recompressing an already compressed video data gave us a very small percentage of compression.

Compression of Pressure Data

In this part of the study, the steps of collecting pressure data from the data acquisition system and its effect on data size when subjected to compression algorithm are examined. When data is desired to be collected with both hardwares, the voltage difference based on the differential difference is presented as the output of the analog digital converter. This digitized data is taken by the formatter and put into the frame structure. Here, instead of evaluating over a single telemetry package in the frame structure, it was aimed to analyze the data obtained during the data collection period. The reason for this is that the pressure data changes very slowly with time. Raw pressure data are given below. Starting from 1100 psi, the pressure data increasing by 100 psi, respectively, has been reduced to zero psi value after 1500 psi measurement. Then, starting from 1600 Psi, similarly, 100 Psi has been increased. Pressure has been measured up to 2000 Psi, which is the full scale output value of the sensor. After reaching the value of 2000 Psi, the test was completed. The behavior of the pressure data received during this test is shown below (Figure 4.10).

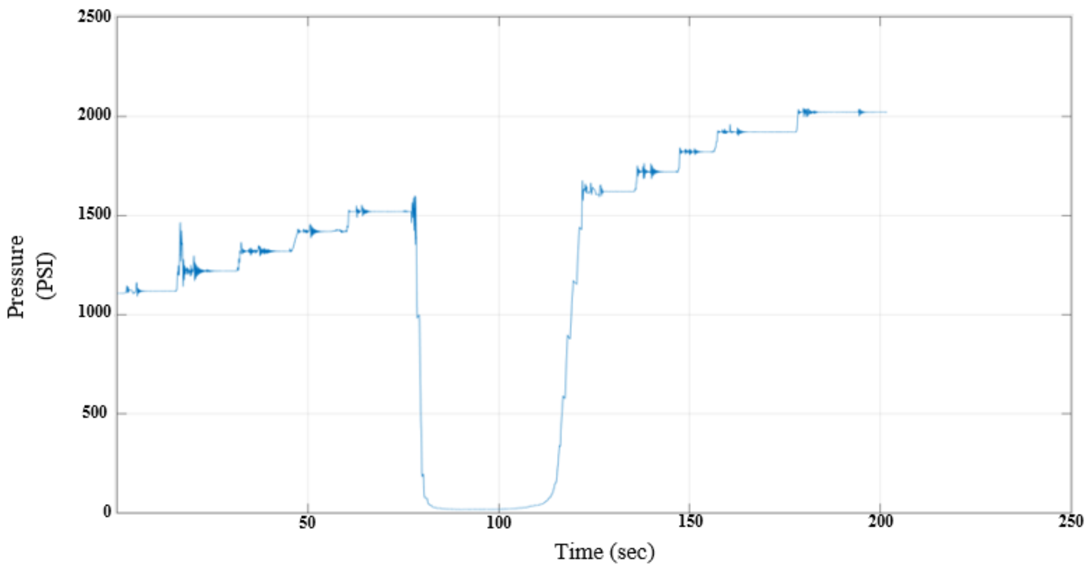


Figure 4.10 : Pressure data of hardware 1.

The scale of the data has been increased to better analyze the behavior of the pressure data. A single pressure application phase has been focused on the zoomed data. As can be seen in the figure below, pressure data samples have not changed frequently (Figure 4.11).

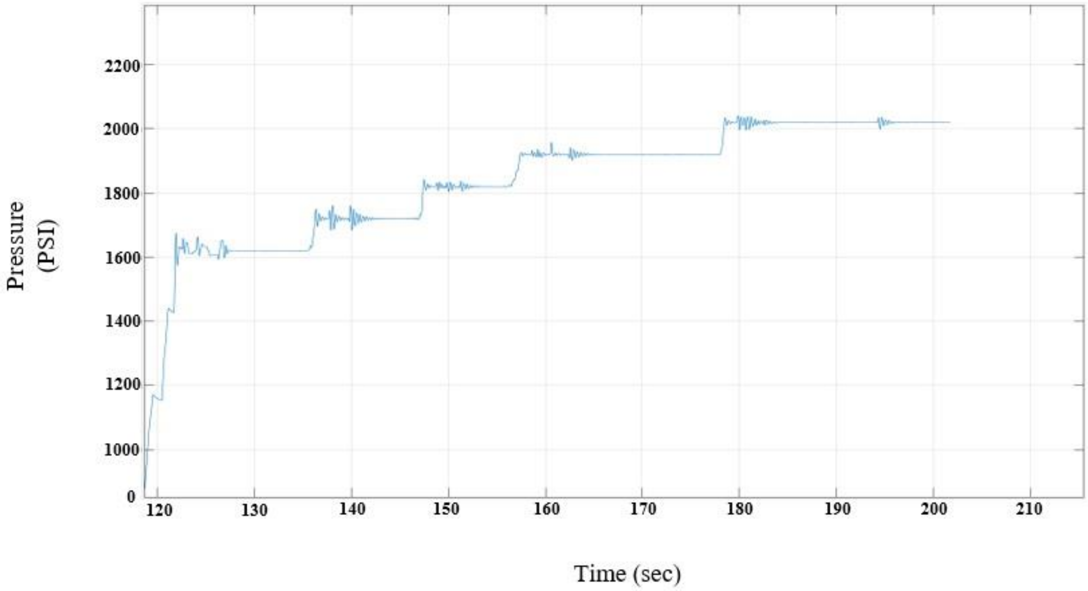


Figure 4.11 : Zoomed version of pressure data.

When the pressure data was zoomed further, the following conclusion was reached. According to the data below, it is seen that there is a data of 1900 Psi applied for about 180 seconds (Figure 4.12).

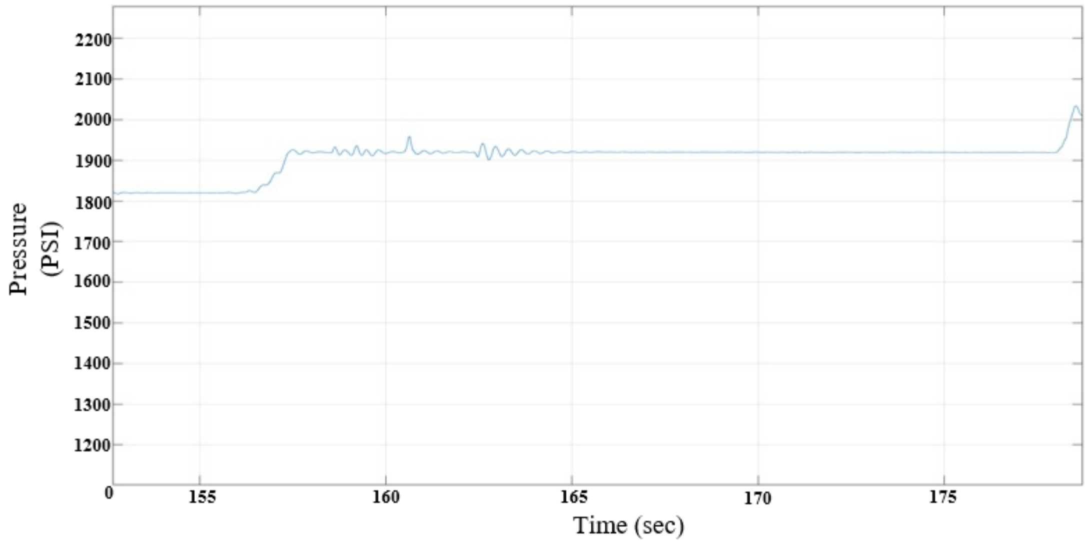


Figure 4.12 : Pressure data at 1900 psi.

LZW algorithm has been applied to all of the pressure data taken for approximately 200 seconds. The reason of this is that the LZW algorithm provides more successful compression for each data type than the Huffman algorithm. The result obtained is shown below. When the figure below is examined, it can be clearly stated that the behavior of the pressure data have not been shown a meaningful behavior after being compressed. However, the fact that the data collected for 200 seconds was reduced to a size of approximately 10 seconds (compressed) shows that a very efficient application has been made (Figure 4.13).

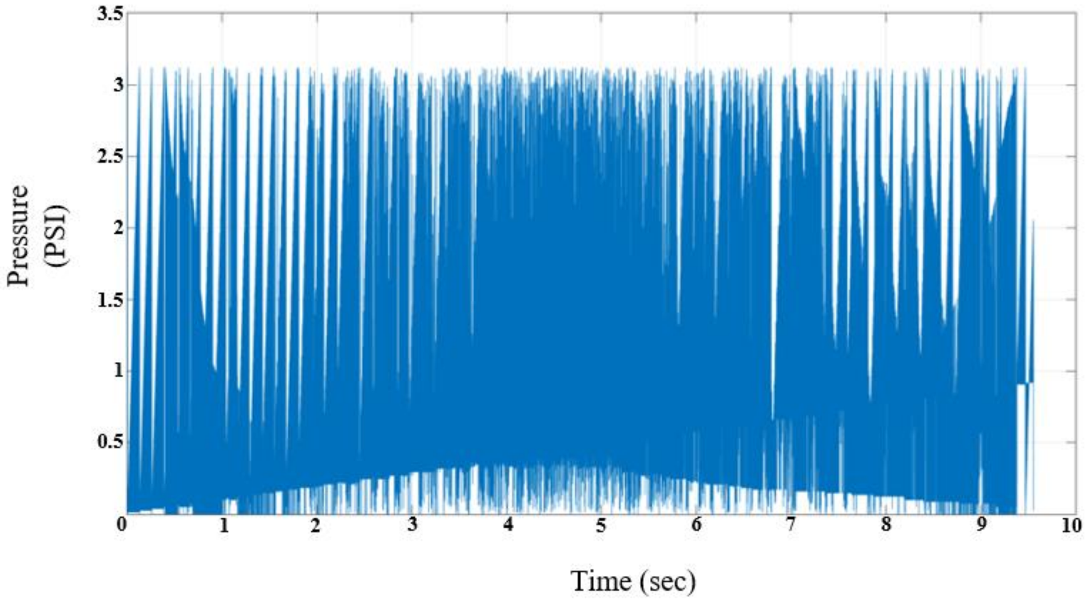


Figure 4.13 : Compressed pressure data.

Due to the sampling amount of the pressure data to be compressed in Figure 4.14, the data size is high. While analyzing the pressure data, the effect of compression on the time was examined since there is a direct proportionality between the data size and the collection time of these data. Compressing a single frame of data cannot show the behavior of the pressure data throughout the test.For this reason, the data in the time period when the pressure in the collected pressure data is applied is analyzed. When the effect of time-based compression addition is examined, the application time of the pressure applied data appears to be approximately 190 seconds. However, the space covered by this data after compression is a time interval of 9.5 seconds. Considering that there is a direct proportion between time and data size, the size of the data we collect will decrease at the same rate. Therefore, we can say that compressed pressure data achieves more efficiency from compression algorithms compared to other data. The graph below shows the compression percentage for the collected pressure data, and as in other data types, the LZW algorithm gave a more successful result in pressure one than the Huffman algorithm.

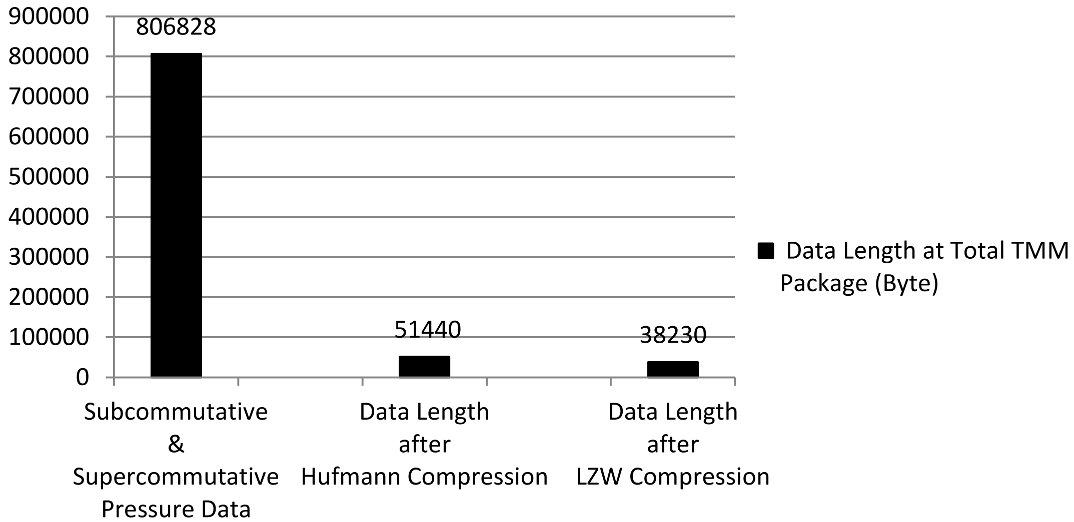


Figure 4.14 : Compression ratio pressure data.

The size of the pressure data before compression is 806828 bytes. After applying the LZW compression algorithm, the data size became 38230. The difference between the data rates before and after compression increases to approximately 21 times. Likewise, the effect on time data is approximately 21 times.

Compression of Vibration Data

In this part of the study, data was collected from the vibration sensor connected to the Test setup. The way the test was done, the sensors measured the vibration data of the surface they were on with three blows they received on the surface after they were physically connected to the hardware. The part of the collected data to be analyzed is given in the figure below (Figure 4.15).

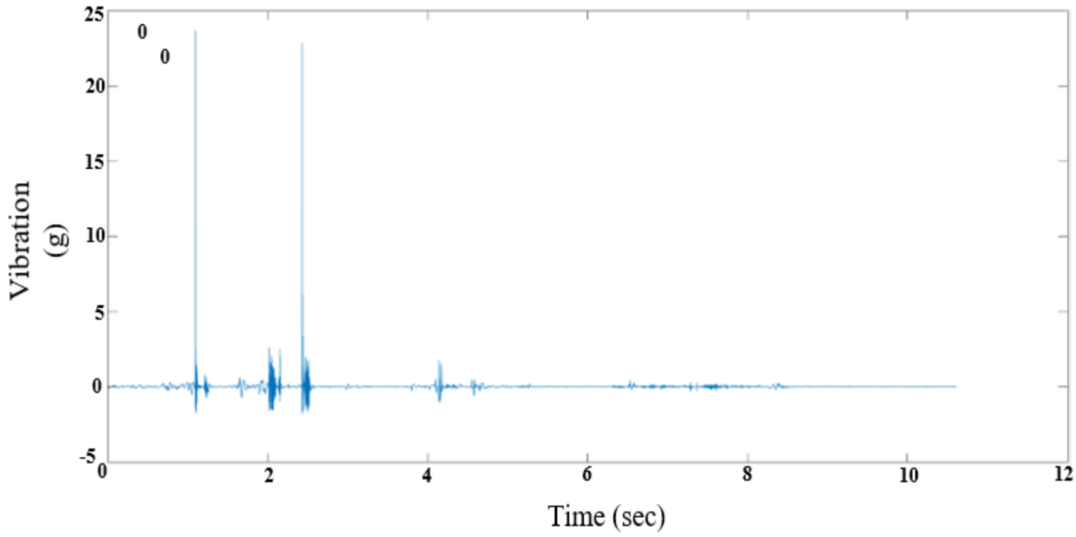


Figure 4.15 : Vibration data of hardware 1.

Vibration data was measured using vibration sensors added to Appendix while testing. Vibration data were measured at certain g levels by hitting the surface to which the vibration sensors were attached three times. In order to better analyze the behavior of these measured data below, the unmeasured parts have been omitted.

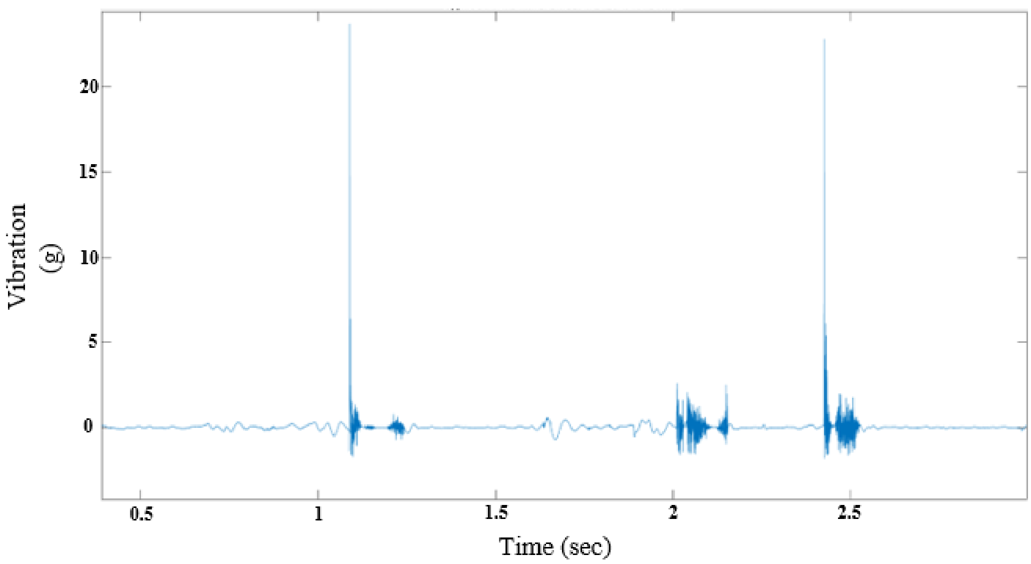


Figure 4.16 : Zoomed version of vibration data.

During the test, he focused on one of the vibration data generated by the three impacts applied to the sensor. As seen in Figure 4.16, vibration data is a data type that requires quite a lot of samples in a short period of time. When we look at the time period between two samples, this time is times and times below the data collection time. The data collected by this sensor is compressed and the compression ratio is evaluated in terms of time. The red areas marked in Figure 4.17 show the number of samples taken in the 0.03 second time frame.

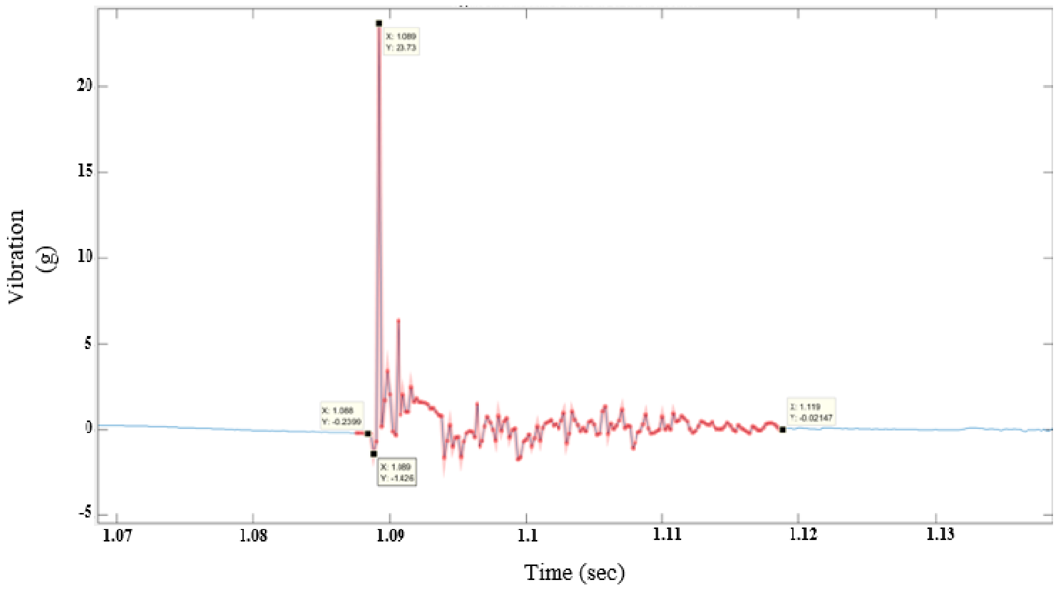


Figure 4.17 : Vibration data at a specific time interval.

The LZW compression algorithm, which has proven to provide better compression, is applied to the sampled vibration data, and the compression effect in terms of time is shown in figure 4.13. It has been observed that the vibration data, which has a data size of approximately 13 seconds, is reduced to a size of 0.23 seconds when compressed. Although the compressed data does not represent a meaningful data, the compression effect in terms of time can be understood from Figure 4.18.

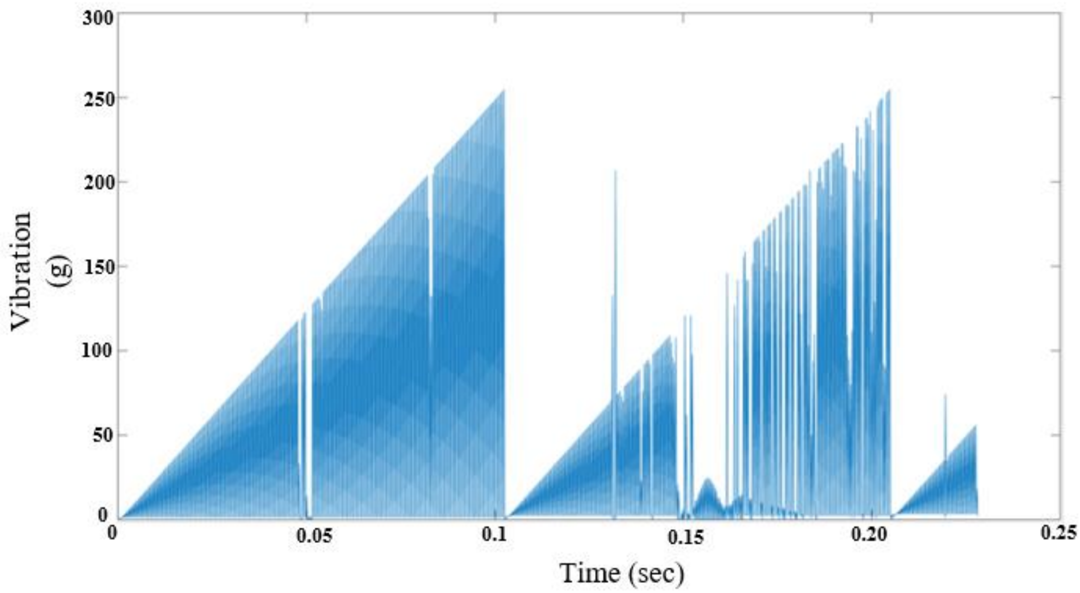


Figure 4.18 : Compressed vibration data.

The vibration data included in the telemetry package is 53043 bytes. When the LZW compression algorithm is applied, it has been reduced to a size of 1054 bytes. The compression ratio was found to be almost 50 times.

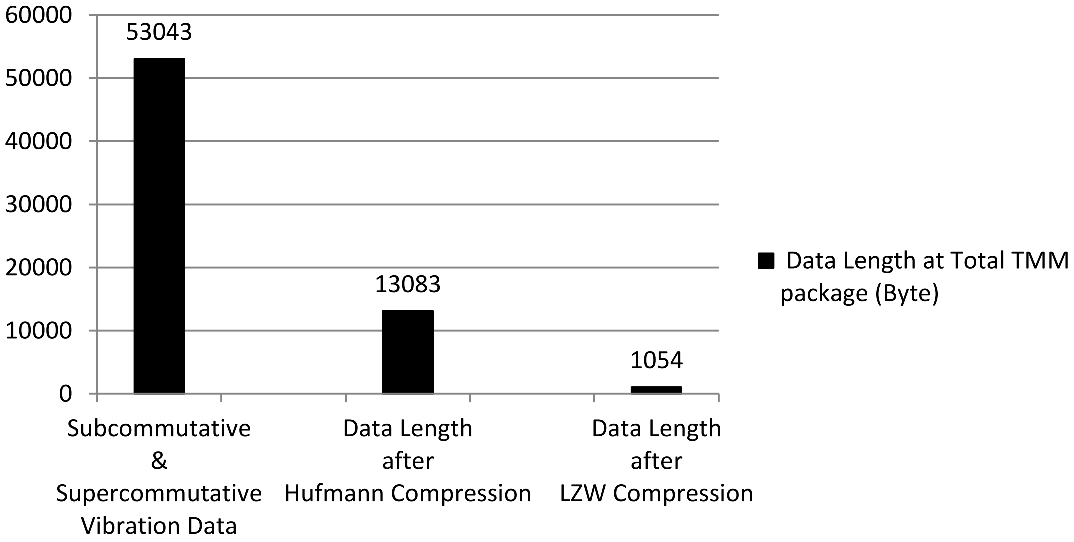


Figure 4.19 : Compression ratio pressure data.

4.3 Link Budget Calculations

In item 2 of the thesis study, the main factors affecting RF communication are discussed. It was observed that the size of the element data decreased after the compression algorithms were applied. The effect of this situation on the communication range will be evaluated and its positive and negative effects on the link budget will be examined in this section. At this point, first of all, the definitions of some parameters should be clearly stated. The bandwidth of any signal means the lower and upper frequency range determined by the frequencies in the signal sent by the transmitter. Moreover, bandwidth means communication.It means the signal bandwidth required to carry the signal without any attenuation inside the channel. Channel capacity is called the maximum number of bits that can be transported per second in a communication channel. There are a number of factors that can weaken the signal to be carried within a communication channel. Noise can cause the signal carrying meaningful information to be mixed with unwanted signals. On the other hand, the noise factor is a parameter that should be taken into account in the calculations, since the intensity of the noise may cause the signal to be transmitted to be not received at all. Heat-induced noise arises as a result of the electrons in a material becoming mobile. As the temperature increases, the movement of the electrons will also increase. For this reason, noise generation is very likely for the electronic systems used. It is not possible to get rid of the noise factor completely, as there will be electrons in all systems and in all materials.

The scope of this study is to reduce the size of different types of telemetry data with compression algorithms. In order to evaluate the indirect effects of the reduction in data size on the RF communication distance, link budget calculations were made by considering the noise factor. Link budget calculation that can be used in wireless communication systems is made by considering the parameters given in appendix C. The necessary parameters for link budget analysis used in all wireless communication systems are shown in Table 4.5.

The link margin is obtained by adding the fade margin and atmospheric loss values and its value is 12 dBm. Receiving Bandwith can be obtained from the formula below. Link budget calculation results show the best case Signal to Noise Ratio which symbolized with SNR.

$$(DR*R_{off} / (Mod*Fec_i*Fec_o)) + Ch_{Guard} \quad (4.20)$$

$$SNR_{RX} = P_{RX} - P_n - SNR \quad (4.21)$$

Link budget calculation was made by assuming the correct ratio according to the compression ratios for data with data rates of 4 Mbps, 8 Mbps, 16 Mbps, 32 Mbps. In today's on board systems, over 9 Mbps speed is not preferred in order to minimize possible errors and losses. Therefore, the data in the frame structure used in the test set-ups corresponds to 4 Mbps. With the compression ratios obtained on that data, assumptions were made for systems with higher data rates. The results obtained are as given in the table below (Table 4.6).

Table 4. 5: Constant parameters for link budget calculation

RF Parameters	Units	RF Parameters	Units
Transmitter Power (Watt)	2 Watt	Effective Noise Temperature	288,6260713 K
Transmitter Power (dBm)	37 dBm	Boltzmann's constant	1,38E-23 J/K
RX power (Free Space Path)	-80,6 dBm	RX Noise Figure	3 dB
TX connector loss + TX cable loss + TX feed loss	1.5 dBm	Antenna Temperature	290 K
RX connector loss + RX cable loss + RX feed loss	1.5 dBm	RX Operating Temperature	290 K
TX Match Loss	0.2 dBm	Noise Power (at RX)	-102 dBm
TX antenna gain	-10 dBi	Required SNR	15 dB
RX antenna gain	-5 dBi	FEC Inner, FEC Outer	1,1
Athmosferic loss	2 dBm	Roll Off Channel Guard Modulation type	6.7 Mhz.
Fade Margin	10 dBm	Distance	1000 m

Table 4. 6 : Link budget calculation before/after compression.

Data Type	Frame with Sub Commutation	Frame with Super Commutation	Only Guidance Data	Only Video Data	Only Pressure Data	Only Vibration Data
Data Length Before Compression	1020 Byte per package (4Mbps) SNR: 10,961 dBm	1020 Byte per package (4Mbps) SNR: 10,961 dBm	100 Byte Per Package	300 Byte Per Package	806828 Byte During test	53043 Byte During Test
Data Rate After Huffman Compression	3,76 Mbps	3,73 Mbps	79 Byte	282 Byte	51440 Byte	13083 Byte
Data Rate After LZW Compression	3,04 Mbps	3,012 Mbps	64 Byte	276 Byte	38230 Byte	10504 Byte
Link Budget (SNR) for 4Mbps After Lzw	11,2653 dBm (Huffman)	12,193 dBm (LZW)	-	-	-	-
Link Budget (SNR) at 8 Mbps	7,95156 (Normal)	9,1434 (After LZW)	-	-	-	-
Link Budget (SNR) at 16 Mbps	4,9413 dBm ((Normal)	6,13313 dBm (After LZW)	-	-	-	-
Link Budget (SNR) at 32 Mbps	1,93096 dBm (Normal)	3,12283 dBm (After LZW)	-	-	-	-

5. CONLUSION AND RECOMMENDATION

In our country, design studies for various types of missiles are successfully carried out according to the needs of the defense industry, and rangefinder tests of these missiles are carried out in the test areas. The data obtained in the relevant tests are used to control and improve the design activities. In today's applications, telemetry data is transferred to the ground station without any compression process. Doing the activities in this way causes a shortage of missiles conditioned to go to high range. This shortcoming is that data with high bandwidth cannot be collected as telemetry data. Within the scope of this thesis, while designing the data collection system in the telemetry system, it is recommended to compress the telemetry data by aiming to send more data to the ground station safely with less cost. Within the scope of the study, the effects of the decrease in the data size after the compression process on the maximum range that the data can be transmitted are considered with the link budget calculation [35-37].

In this thesis study conducted with this point of view, the data in the telemetry frame structures used were produced synthetically. The synthetic data produced was collected by hardware supporting different frame formats. Huffman, LZW compression algorithms [38], which are lossless compression techniques, were applied to these data, respectively, and their effects on data sizes were evaluated. In the link budget calculations made within the scope of the study, the features that play a very active role in RF communication structures are kept constant. These features are; Receiver features, modulation type, antenna features, design features that may cause differences in the link budget calculation of the sender, fixed atmospheric features. it reveals. The results obtained support two different points of view. In tests where systems with the same telemetry frame structure will take place, the decrease in data size will cause a decrease in the required bandwidth. Thus, the biggest effect of the decrease in communication bandwidth explains that it can increase the communication distance [39].

As explained earlier, the studies carried out in the literature on the compression of telemetry data aim to gain storage space. In general, after the telemetry data radiated from the sender reaches the ground station, compression actions are performed in the archiving step. Some of the reviewed publications belong to the CCDS board established by NASA and ESA institutions. It has been observed that the CCDS organization uses lossless compression methods as the compression method and recommends the Golomb-Rice technique in publications that generally contain the techniques they use for the storage of telemetry data of spacecraft [4]. This mentioned technique is also used for efficient compression of task-command data containing images. Test conditions are a specialized parameter for the collection of mission command data containing spacecraft images. In our country, these parameters are specialized for the development of space vehicles.

Few studies have been done on the compression of telemetry data. In one study, data compression in on-board systems was investigated. In general, compression of all telemetry data is considered. It has been determined that the compressed telemetry data will decrease the bandwidth and increase the communication range [15]. In this study, apart from the compression of all telemetry data, the compression of the data in a telemetry package and its effect on the telemetry package were examined. As a result, it has been observed that analog data is compressed at a higher rate than digital data in telemetry data. Apart from that, the data collected on the hardware supporting different frame structures are placed in the data structure to be packed within certain rules. The digital data divided into small frames with the subcommutation method needs common words other than the data in order to complete the matrix structure. It has been understood that this situation causes an increase in data diversity in compression. It has been observed that the use of the supercommutation method is more beneficial in compression than the subcommutation frame structure. The implementation and costing of adding these algorithms to the data collection systems as hardware may be the subject of future studies.

Apart from the positive results of the compression algorithms, there are also factors that should be considered during the application of compression methods while designing the telemetry data collection system. It is very important to get accurate and precise results from analog sensors and digital sources in telemetry tests that are foreseen to be made. This is especially important for data whose results are analyzed live. Since no data loss is desired, Huffman and LZW methods are preferred in this study. However, at this point, when there is a problem in the communication with the ground and in case of data loss due to RF, it may cause more loss than in the case of no compression. For example, considering a data type examined within the scope of this study, this data type carries a meaningful data at every step with 8 bits. When it comes to data compression, it will cause more information loss as it no longer only affects the 8 bits it contains. These data losses will differ according to the rate of compression method used and the technique used [40]. After the compression algorithms to be applied in hardware, the loss of the data sent to the air by the transmitter and which compression method is more successful in the same number and order of packet loss are open to clarification by another study. Consequently, it should be taken into account that there may be additional compression-related losses that will be known when collecting telemetry data for a missile or an on-board data acquisition system.

Another issue to consider by the designer is the time required for the processors to complete the compression on the data. The mentioned required processing time varies depending on the technical specifications of the hardware in the system. The data collection systems used in the analysis and simulation studies carried out within the scope of this thesis are structures with 2 watts of output power, including transmitter, image converter card, encoder and rf amplifier. These structures are separated from each other due to the telemetry frame structures they support. More detailed information on test set-ups is given in Appendix-3. In addition, the implementation times for both compression algorithms were measured in MATLAB environment and it was concluded that the LZW algorithm completed the process in a shorter time. At this point, the issue that should be taken into consideration will vary depending on the execution time of the transactions, the code written and the features of the preferred hardware. In order to use the aforementioned algorithms in data collection systems, it will be necessary to encode integrated circuits with embedded software.

In parallel with this, since a much higher compression is achieved in analog data types than digital data such as guidance and digitized video data, providing separate compression at the encoder outputs of the hardware can be considered in future studies. In this context, only the analogue data in a telemetry frame structure is compressed and then placed in the frame structure by the formatter, which is open to evaluation in terms of both efficiency and cost. In this way, sending the analog data to the formatter by compressing allows more space to be made for other data to be collected in the telemetry frame structure. Considering this information, it is predicted that if the data that requires less samples is put into the frame structure after compression, it will allow the data that requires more samples to be included in the frame by sampling more.

REFERENCES

[1]**Simpson Steven**. (2016), History of Telemetry. Telemetry Inquiry, Weebly, http://telemetryinquiry.weebly.com/history.html.,

[2]**Telemetry**. 2016, Wikimedia Foundation, https://en.wikipedia.org/wiki/Telemetry., 2016.

[3]**İnger, E**. (2010). Roket ve Füze Mühendisliği. 10-120. Palme Yayıncılık. Ankara.

[4]**Hirshorn, S. R., Voss, L. D., & Bromley, L. K.** (2017). NASA systems engineering handbook.

[5]**Maluf, D. A., Tran, P. B., & Tran, D**. (2008, March). Effective data representation and compression in ground data systems. In 2008 IEEE Aerospace Conference (pp. 1-7). IEEE.

[6]**Arcangeli, J. P., Crochemore, M., Hourcastagnou, J. N., & Pin, J. E.** (1993). Compression for an effective management of telemetry data.

[7]**Horan, S.** (2018). Introduction to PCM Telemetering Systems. CRC Press.

[8]**Standard, I. R. I. G. (2004).** 200-04–IRIG serial time code formats–Sept04 timing committee telecommunications and timing group range commanders council. US Army White Sands Missile Range, NM.

[9]**Tutorial on Telemetry Testing & Data Acquisition**. (t.y.) Access: 2021, https://testworld.com/wp-content/uploads/Tutorial-Telemetry-Testing-Data-Acquisition.pdf.

[10]**Milli Frekans Planı**. 2019. Bilgi Teknolojileri ve İletişim Kurumu-Spektrum Yönetimi Dairesi Başkanlığı. Access: 01.06.2021. https://www.btk.gov.tr/uploads/undefined/mfp-01-02-2019.pdf

[11]**Christian, W., Basics, R.,** (2015). Noise, Noise Figure, Noise Temperature, https://www.radartutorial.eu/18.explanations/ex08.tr.html

[12]**RF Fundaments,** (2016). Chapter 3: Free Space Path Loss, http://wisptools.net/book/bookc3s1.php., 2016.

[13]**Türkoğlu, B., Ceylan, O., Yağcı, H. B., Paker, S., & Palamutçuoğullan, O**. (2010, April). Effects of substrate thickness and dielectric to microstrip dipol antenna parameters for 2.4 GHz wireless communication devices. In 2010 IEEE 18th Signal Processing and Communications Applications Conference (pp. 665-668). IEEE.

[14]**Blattenberger, K.,** (2016). Atmospheric Absorption / Attenuation, RF Cafe, https://www.rfcafe.com/references/electrical/atm-absorption.htm.

[15]**Yılmaz, D., & Sağlam, A.** (2017). The effects of data compression in missile telemetry systems. Journal of Aeronautics and Space Technologies, 10(2), 37-47.

[16]**Hyper Physics.** 2016. Classification of polarization, http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/polclas.html

[17]**L-3 Telemetry & RF Products,** (2015). Transmitters, http://www2.l3com.com/trf/products/airborne_transmitters.html.

[18]**Temple, K., & Selbrede, R.** (2010). Performance comparison of aeronautical telemetry in S-band and C-band. International Foundation for Telemetering.

[19]**Rice, M., & Jensen, M.** (2011). A comparison of L-band and C-band multipath propagation at Edwards AFB. AIR FORCE FLIGHT TEST CENTER EDWARDS AFB CA.

[20]**Rice, M.** (2013). The challenges of C-band missile telemetry. BRIGHAM YOUNG UNIV PROVO UT.

[21]**Antenna Introduction/ Basics.** 2016. University of Hawaii ANITA Project, http://www.phys.hawaii.edu/~anita/new/papers/militaryHandbook/antennas.pdf.

[22]**Ground Stations- Kiruna Station.** 2016. European Space Agency, http://www.esa.int/Our_Activities/Operations/Estrack/Kiruna_station., 2016.

[23]**Gray, R. M.** (1997, September). Fundamentals of data compression. In International Conference on Information, Communications, and Signal Processing, Singapore.

[24]**Britanak, V., Rao, K. R., & Yip, P. C.** (2001). The Transform and Data Compression Handbook.

[25]**Faller, N.** (1973). An adaptive system for data compression. In Record of the 7-th Asilomar Conference on Circuits, Systems and Computers (pp. 593-597).

[26]**Compression, L. D.** (2007). Report concerning space data system standards. Informational Report CCSDS, 120.

[27]**CCSDS Recommended Standard Blue Book,** (2012). Retrieved from; https://public.ccsds.org/publications/BlueBooks.aspx.

[28]**Staudinger, P., Hershey, J., Grabb, M., Joshi, N., Ross, F., & Nowak, T.** (2000, March). Lossless Compression for archiving satellite telemetry data. In 2000 IEEE Aerospace Conference. Proceedings (Cat. No. 00TH8484) (Vol. 2, pp. 299-304). IEEE.

[29]**Sayood, K.** (2002). Lossless compression handbook. Elsevier.

[30]**Huffman, D. A.** (1952). A method for the construction of minimum-redundancy codes. Proceedings of the IRE, 40(9), 1098-1101.

[31]**Leurs L.**, LZW Compression Comment, Access: 2021, https://www.prepressure.com/library/compression-algorithm/lzw.

[32]**Sedat Korkmaz.** (2003). Compression Rate Optimization in Turkish Text Compression by Using Static Huffman Algorithm, (Master dissertation). Selçuk University, Institute of Science and Technology, Konya.

[33]**Sedgewick, R., & Wayne, K.** (2011). Algorithms. Addison-wesley professional.

[34]**Ziv, J., & Lempel, A.** (1977). A universal algorithm for sequential data compression. IEEE Transactions on information theory, 23(3), 337-343.

[35]**Sağlam, A., & Yılmaz, D.** (2018, October). Increasing the Efficiency of Missile Telemetry Tests by Using Data Compression Techniques. In 2018 6th International Conference on Control Engineering & Information Technology (CEIT) (pp. 1-6). IEEE.

[36]**Couch, L.W.** (1995). Modern Communications Systems, Prentice-Hall, Inc., Englewood Cliffs, NJ.

[37]**Rice, M.** (2009). Digital communications: a discrete-time approach. Prentice Hall.

[38]**Gallager, R.** (1978). Variations on a theme by Huffman. IEEE Transactions on Information Theory, 24(6), 668-674. [39] **Thuloweit, K.** (2010). TPS adding more bandwidth. Air Force Print News Today.

[40]**Zyren, J., & Petrick, A.** (1998). Tutorial on basic link budget analysis. Application Note AN9804, Harris Semiconductor, 31.

[41]**Url** < https://www.tualcom.com.tr/en/telemetry-transmitters>, date retrieved 20.05.2021.

[42]**Url** < http://www.etep.com/products/main.php?ID=3>, date retrieved 20.05.2021.

APPENDICES

Appendix A: Huffman Compression Algorithm Matlab Code

```
%% Damla ÇOLAK, 2021
%% Huffman Encoding & Decoding For Digitalized Data
clc;
clear all;
load('input_data.mat')
N=length(input_data);
frequency=zeros(1,390);
for k=0:389
    count=0;
for i=1:N
    if(input_data(i)==k)
    count=count+1;
    end
end
frequency(k+1)=count;
end
%% Until Now; Freq. of each charachter have been counted
sym=find(frequency)-1;
%Until Now;information about each data in a package have been gotten
sym_count=frequency(sym+1);
sym_prob=sym_count/N;

%% %Until Now; Frequency & probability of symbols have been cocunted
[dict,avglen]=huffmandict(sym,sym_prob);
entropy=avglen;
entropy
enco= huffmanenco(input_data,dict);              %Encoding Data
decoded_serial_data=huffmandeco(enco,dict);      %Decoding Data
L=length(decoded_serial_data);
P=length(enco);
compression_ratio= P/L;
```

Figure A. 1 : Huffman Compression Algorithm Matlab Code.

Appendix B: LZW Algorithm Matlab Code

```
% LZW ENCODING & DECODING CODE
% DAMLA ÇOLAK
% 2021
% string to compress
[input_file, file_path] = uigetfile('*.*', 'Please select the data file which you want to compress:');
load(input_file) ;
str = input_data;

%%  pack it
[packed,table]=norm2lzw(uint8(str));

%%  unpack it
[unpacked,table]=lzw2norm(packed);

unpacked = char(unpacked);   % transfor it back to char array

isOK = strcmp(str,unpacked); % testing the correction

strvcat(table{257:end});     % show new table elements

%% Compression Ratio Calculation
RD=length(unpacked);
CD=length(packed);
Compression_ratio= CD/RD;

% Compression Ratio Calculation 2
RD=length(unpacked);
packed=typecast(packed, 'uint8');
CD=length(packed);
packed=double(packed);
Compression_ratio= CD/RD;
```

Figure B. 1 : LZW Algorithm Matlab Code.

Appendix B.1: LZW Encoding Function on Matlab

```
%% %NORM2LZW   LZW Data Compression (encoder)
function [output,table] = norm2lzw(vector) % following loop is to ensure to handle uint8 input vector
if ~isa(vector,'uint8'),
    error('input argument must be a uint8 vector')
end

vector = uint16(vector(:)');    % vector as uint16 row

table = cell(1,256);            % initializing table
for index = 1:256,
    table{index} = uint16(index-1);
end

output = vector;                % initialize output

outputindex = 1;                % main loop starting here
startindex = 1;
for index=2:length(vector),
    element = vector(index);
    substr = vector(startindex:(index-1));
    code = getcodefor([substr element],table);
    if isempty(code),
        % add it to the table
        output(outputindex) = getcodefor(substr,table);
        [table,code] = addcode(table,[substr element]);
        outputindex = outputindex+1;
        startindex = index;
    else,
        % go on looping
    end
end

substr = vector(startindex:index);
output(outputindex) = getcodefor(substr,table);
output((outputindex+1):end) = [];   % remove not used positions
```

Figure B. 2 : LZW Encoding Function on Matlab.

```
% ##############################################
function code = getcodefor(substr,table)
code = uint16([]);
if length(substr)==1,
    code = substr;
else, % this is to skip the first 256 known positions
    for index=257:length(table),
        if isequal(substr,table{index}),
            code = uint16(index-1);   % start from 0
            break
        end
    end
end

% ##############################################
function [table,code] = addcode(table,substr)
code = length(table)+1;   % start from 1
table{code} = substr;
code = uint16(code-1);    % start from 0
```

Figure B. 3 : Contiuning LZW Encoding Function on Matlab.

Appendix B.2: LZW Decoding Function on Matlab

```
%% FROM LZW APPLIED DATA TO THE NORMAL DATA
function [output,table] = lzw2norm(vector)

% ensure to handle uint8 input vector
if ~isa(vector,'uint16'),
    error('input argument must be a uint16 vector')
end
vector = vector(:)'; % vector as a row
% initialize table
table = cell(1,256);
for index = 1:256,
    table{index} = uint16(index-1);
end
% initialize output
output = uint8([]);
code = vector(1);
output(end+1) = code;
character = code;
for index=2:length(vector),
    element = vector(index);
    if (double(element)+1)>length(table),
        % addin to the table
        string = table{double(code)+1};
        string = [string character];
    else,
        string = table{double(element)+1};
    end
    output = [output string];
    character = string(1);
    [table,code] = addcode(table,[table{double(code)+1} character]);
    code = element;
end
```

Figure B. 4 : LZW Decoding Function on Matlab.

```
% ###############################################
function code = getcodefor(substr,table)
code = uint16([]);
if length(substr)==1,
    code = substr;
else, % this is to skip the first 256 known positions
    for index=257:length(table),
        if isequal(substr,table{index}),
            code = uint16(index-1);   % start from 0
            break
        end
    end
end

% ###############################################
function [table,code] = addcode(table,substr)
code = length(table)+1;   % start from 1
table{code} = substr;
code = uint16(code-1);    % start from 0
```

Figure B. 5 : Contiuning LZW Decoding Function on Matlab.

Appendix C: Parameters on Link Budget Calculation

SPECIFICATIONS OF TX & RX SYSTEMS	Variable	Units	Equation
PA Power	P_{PA}	dBm	
PA Power	Ppa	Watts	
TX Match Loss	L_{MatchT}	dB	
TX source	P_{TX}	dBm	$P_{TX} = P_{PA} - L_{MatchT}$
TX connector loss	L_{ConT1}	dB	
TX cable loss	L_{CabT}	dB	
TX feed loss	L_{ConT2}	dB	
TX power	P_T	dBm	$P_T = P_{TX}$(C&C Loss)
TX antenna gain	G_T	dBi	
Effective (Isotropic) Radiated Power	EIRP	dBm	$EIRP = P_T\, G_T$
Distance	d	m	
Free Space Loss	L_{FS}	dB	$L_{FS} = 10\log(\lambda/4\pi d)^2$
Power at RX Antenna, Free Space Path	P_{ChanFS}	dB	$P_{ChanFS} = L_{FS}\, EIRP$
RX antenna gain	G_R	dBi	
RX connector loss	L_{ConR1}	dB	
RX cable loss	L_{CabR}	dB	
RX feed loss	L_{ConR2}	dB	
RX power, Free Space Path	P_{RFS}	dBm	$P_{RFS} = P_{ChanFS}\, G_R$(C&C Loss)
Receiver	**Variable**	**Units**	**Equation**
FEC Inner	Fec_i	-	
FEC Outer	Fec_o	-	
Data Rate	DR	MHz	
Roll Off	R_{off}	-	
Channel Guard	Ch_{Guard}	MHz	
Modulation type	Mod	-	
Receive Bandwidth	BW_{RX}	MHz	$(DR*R_{off} / (Mod*Fec_i*Fec_o)) + Ch_{Guard}$
Receiver Sensitivity Calculations	**Variable**	**Units**	**Equation**
RX Noise Figure	NF	dB	
Operating Temperature	T_0	K	
Effective Noise Temperature	T_e	K	$T_e = T_0(NF - 1)$
Boltzmann's constant	k	J/K	
Receive Bandwidth	BW_{RX}	MHz	
Antenna Temperature	T_{Ant}	K	
Noise Power (at RX)	P_n	dBm	$P_n = k(T_{Ant} + T_e)BW_{RX}$
Link Margin	**Variable**	**Units**	**Equation**
Athmosferic loss		dB	
Fade Margin		dB	
Link Margin	Lm	dB	
Required SNR	**Variable**	**Units**	**Equation**
Req.SNR	SNR	dB	
CALCULATION RESULTS	**Variable**	**Units**	**Equation**
Best Case Signal to Noise Ratio - SNR	SNR_{RX}	dB	$SNR_{RX} = P_{RX} - P_n - SNR$
Worst Case Signal to Noise Ratio - SNR	SNR_{RX}	dB	$SNR_{RX} = P_{RX} - P_n - SNR - Lm$

Figure C. 1 : Parameters on Link Budget Calculation.

Appendix D: Pressure Sensor Properties Used in Test Set-up

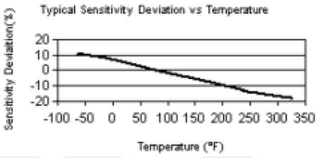
Table D. 1 : Pressure Sensor Properties Used in Test Set-up.

Description	Gage Vent Tube Temp Compensation
Full Scale Pressure (Psi)	1/2/5/200/500/2000
Sensitivity	200/100/60/1.5/0.6/0.15 mV/Psi
Resonance Frequency	55/70/85/320/500/900 kHz.
Non-Linearity	1.0 % FSO
Operating Temperature	-54 to +121 ℃
Burst Pressure	25/40/100/1000/2500/10000
Face Diameter	3.86 mm
Weight	2.3 Grams
Mounting Method	10-32 UNF-2A

Appendix E: Vibration Sensor Properties Used in Test Set-up

Model Number 356B21	TRIAXIAL ICP® ACCELEROMETER	Revision: H ECN #: 42197

Performance	ENGLISH	SI	
Sensitivity(± 10 %)	10 mV/g	1.02 mV/(m/s²)	
Measurement Range	± 500 g pk	± 4905 m/s² pk	
Frequency Range(± 5 %)(y or z axis)	2 to 10,000 Hz	2 to 10,000 Hz	
Frequency Range(± 5 %)(x axis)	2 to 7000 Hz	2 to 7000 Hz	
Resonant Frequency	≥ 55 kHz	≥ 55 kHz	
Broadband Resolution(1 to 10,000 Hz)	0.004 g rms	0.04 m/s² rms	[1]
Non-Linearity	≤ 1 %	≤ 1 %	[3]
Transverse Sensitivity	≤ 5 %	≤ 5 %	
Environmental			
Overload Limit(Shock)	± 10,000 g pk	± 98,100 m/s² pk	
Temperature Range(Operating)	-65 to +250 °F	-54 to +121 °C	[2]
Temperature Response	See Graph	See Graph	[1][2]
Electrical			
Excitation Voltage	18 to 30 VDC	18 to 30 VDC	
Constant Current Excitation	2 to 20 mA	2 to 20 mA	
Output Impedance	≤ 200 Ohm	≤ 200 Ohm	
Output Bias Voltage	7 to 12 VDC	7 to 12 VDC	
Discharge Time Constant	0.3 to 1.0 sec	0.3 to 1.0 sec	
Settling Time(within 10% of bias)	<3 sec	<3 sec	
Spectral Noise(1 Hz)	1000 μg/√Hz	9810 (μm/sec²)/√Hz	[1]
Spectral Noise(10 Hz)	300 μg/√Hz	2943 (μm/sec²)/√Hz	[1]
Spectral Noise(100 Hz)	100 μg/√Hz	981 (μm/sec²)/√Hz	[1]
Spectral Noise(1 kHz)	50 μg/√Hz	490 (μm/sec²)/√Hz	[1]
Physical			
Sensing Element	Ceramic	Ceramic	
Sensing Geometry	Shear	Shear	
Housing Material	Titanium	Titanium	
Sealing	Hermetic	Hermetic	
Size (Height x Length x Width)	0.4 in x 0.4 in x 0.4 in	10.2 mm x 10.2 mm x 10.2 mm	
Weight	0.14 oz	4 gm	[1]
Electrical Connector	8-36 4-Pin	8-36 4-Pin	
Electrical Connection Position	Side	Side	
Mounting Thread	5-40 Female	5-40 Female	



CE [4]

OPTIONAL VERSIONS

Optional versions have identical specifications and accessories as listed for the standard model except where noted below. More than one option may be used.

A - Adhesive Mount
Supplied Accessory : Model 080A109 Petro Wax (1)
Supplied Accessory : Model 080A90 Quick Bonding Gel (1)

HT - High temperature, extends normal operation temperatures

Temperature Range(Operating)	-65 to +325 °F	-54 to +163 °C

J - Ground Isolated

Frequency Range(+5 %)	7000 Hz	7000 Hz
Electrical Isolation(Base)	>10⁸ Ohm	>10⁸ Ohm
Size - Height x Length x Width	0.44 in x 0.40 in x 0.44 in	11.2 mm x 10.2 mm x 11.2 mm
Weight	0.16 oz	4.5 gm
Mounting	Adhesive	Adhesive

Supplied Accessory : Model 034K10 Cable 10FT Mini 4 Pin To (3) BNC (1)
Supplied Accessory : Model 080A109 Petro Wax (1)
Supplied Accessory : Model 080A90 Quick Bonding Gel (1)

NOTES:
[1] Typical.
[2] 250° F to 325° F data valid with HT option only.
[3] Zero-based, least-squares, straight line method.
[4] See PCB Declaration of Conformance PS023 for details.

SUPPLIED ACCESSORIES:
Model 034K10 Cable 10FT Mini 4 Pin To (3) BNC (1)
Model 080A Adhesive Mounting Base (1)
Model 080A109 Petro Wax (1)
Model 081A27 Mounting Stud (5-40 to 5-40) (1)
Model 081A90 Mounting stud, 10-32 to 5-40 (1)
Model ACS-1T NIST traceable triaxial amplitude response, 10 Hz to upper 5% frequency. (1)
Model M081A27 Metric mounting stud, 5-40 to M3 x 0.50 long (1)

Entered: AP	Engineer: JJB	Sales: WDC	Approved: JJB	Spec Number:
Date: 11/8/2013	Date: 11/8/2013	Date: 11/8/2013	Date: 11/8/2013	15127

Figure E. 1 : Vibration Sensor Properties Used in Test Set-up.

Appendix F: Data Acquisition System Properties Used in Test Set-up 1

TECHNICAL SPECIFICATIONS

Frequency Range	2.2 - 2.5 GHz
Data Rate	Up to 20 Mbps
Encoding and Modulation	PCM / FM / PSK
RF Output Power	2 W
Digital Inputs	Ethernet, RS 485, TTL
Analog Inputs	4 PT 100/TC 9 IPC 1 Pressure 4 ADC
Data Encryption (Optional)	AES 256
FEC	Reed Solomon (RS) and Convolutional, LDPC
Power Consumption	< 800 mA @ 28 V
Operating Temperature	-40 °C to +85 °C
Dimensions (cm)	7.5 x 5.5 x 2.8
Weight	120 g

Figure E. 2 : Data Acquisition Systems Properties Used in Test Set-up [41].

CURRICULUM VITAE

PHOTO

Name Surname **:Damla ÇOLAK**

EDUCATION **:University of Turkish Aeronautical Association**

- **B.Sc.** 2017, University of Turkish Aeronautical Association, Engineering Faculty, Electrical and Electronics Engineering Department
- **M.Sc.** **: -**

PROFESSIONAL EXPERIENCE AND REWARDS:

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS