SECURED HF IMAGE TRANSMISSION SYSTEM

(PENGHANTARAN IMEJ SECARA SELAMAT MENGGUNAKAN FREKUENSI TINGGI)

AHMAD ZURI B SHA'AMERI

RESEARCH VOTE NO:

74114

Jabatan Kejuruteraan Mikroelektronik dan Komputer
Fakulti Elektrik
Universiti Teknologi Malaysia

2006

ACKNOWLEDGEMENT

Thankfully, to Al-Mighty Allah SWT, I want to take this chance to acknowledge the contribution of several people who helped me to complete this project. I would like to express my appreciation to Commander (B) Wan Zulkifli Wan Hassan from Sapura Sdn. Bhd. and Mr. Wan Roz Wan Hussien from RF Communication Sdn. Bhd for their invaluable technical knowledge and advice that helped inspire many of the ideas expressed in this project.

I would like to extend my gratitude to Royal Malaysia Navy and Jabatan Laut Semenanjung Malaysia for their cooperation especially during field-testing phase of this project.

Finally, very special appreciation and gratitude to all DSP lab members Abd Rahim Mat Sidek, Abd Rahim Abdullah, Ahmad Sazali Senawi, NurulFadzilah Hasan, Fitri Dewi Jaswar, Mohd Daniel, Lim Fong Fong and DSP lab technician, Mr. Jefri for all commitment and supports to complete this project.

ABSTRACT

The HF (3 to 30 MHz) spectrum is utilized for long distance communications by the military, amateur radio, shipping and diplomatic services. Communications is no longer limited to voice and telegraphy, but now include applications such as email, text messaging, image, and telemetry. This project looks into the design and development of an image transmission system that for use in the HF radio frequency spectrum. Additional features of the system include short messaging, text file transfer, and electronic security such as authentication and confidentiality. An AES (Advanced Encryption Standard) block is cipher is used for both authentication and key distribution with key length 256 bits and 128 bits respectively. For confidentiality, stream cipher algorithm used is based on the linear feedback register (LFSR) and a nonlinear combining function. To meet the requirements of the maritime industry, further research were done to include light house telemetry and automatic vessel tracking system. The system is built around an HF data communication system: HF transceiver, modem, controller and computer. Experiments were performed for data transmission over the HF spectrum at lower power of 5 to 25 watts on the 40 meter band (7.0 to 7.1 MHz) and marine band (8.0 to 8.8 MHz) for selected links within the Peninsular Malaysia. At low power, the advantage is in increasing equipment life, minimize power supply requirements, and minimize interference to other users.

ABSTRAK

Frekuensi Tinggi (3 hingga 30 MHz) digunakan oleh tentera, radio amatur, industri perkapalan dan dalam perkhidmatan diplomatik untuk berkomunikasi jarak jauh. Kini, komunikasi jenis ini bukan sahaja terhad menggunakan suara dan telegrafi tetapi boleh juga digunakan untuk menghantar data seperti aplikasi e-mail, mesej bergambar dan juga telemetri. Projek ini bertujuan untuk merekacipta dan membangunkan sistem komunikasi yang mampu manghantar imej atau gambar menggunakan frekuensi tinggi. Selain itu, ia juga boleh digunakan untuk menghantar mesej pendek dan fail teks di samping mempunyai ciri-ciri keselamatan untuk memastikan komunikasi adalah selamat. Untuk pengesahan dan penghantaran identiti pengguna, penyahkod jenis AES digunakan manakala untuk komunikasi secara selamat, sistem menggunakan algorithma penyahkod jenis bit. Sistem ini diharap memenuhi kehendak semasa terutamanya dalam industri maritim. Untuk itu, projek ini juga memberi tumpuan untuk membangunkan sistem telemetri rumah api dan sistem pengesanan kapal secara automatik. Kesemua sistem menggunakan frekuensi tinggi sebagai medium perhubungan, maka ia memerlukan perkakasan seperti radio, modem dan komputer untuk berfungsi. Beberapa sesi ujian komunikasi telah dijalankan di beberapa bahagian di semenanjung Malaysia dengan hanya menggunakan kuasa penghantaran dalam lingkungan 5 ke 25 watt. Pada kadar ini, ia mampu menambah jangka hayat perkakasan, meminimum penggunaan kuasa dan gangguan kepada pengguna lain.

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

High frequency (HF) radio has been used as wireless communication method for decades especially for beyond line of sight communications. The high frequency spectrum refers to the band of radio frequency spectrum from 3 to 30 MHz. By using the refractive properties of the ionosphere, it is possible to use these frequencies for long distance communications by sky-wave propagation. Despite the introduction of satellite services, the use of this medium has been undergoing resurgence over the last few years (NTIA-ITS, 1998). The most important benefit is providing communication over thousands of miles, as far away as the other side of the world. The second advantage is, HF free to use because the ionosphere is not own by anyone and equipment required is with minimal infrastructure. Therefore, the cost to setup a HF communication system is much cheaper as compared to other means of communication such as satellite (Abdullah *et al.*, 2003). And the third advantage is, the HF communication is completely our national control and not compromise with other organization from other country. This will ensure the integrity and security of the communication.

The HF radio's usage has been expanded and propagation problems were overcame by new technologies in digital communication and digital signal processing (NTIA-ITS, 1998; MIL-STD-188-141B, 1999). This enhances the reliability of communication in the HF spectrum. Besides voice and telegraphy, text, fax and images can be transmitted by using HF modem (SailMail, 2004; Cruiseemail, 2004; Harris Corporation, 2002). These new technologies permit computer-to-computer communication. In communication either connection-oriented or wireless, security such as authentication and confidentiality is important due to the broadcast nature of HF communication. But unfortunately, most of the existing HF commercial systems such as Sail Mail, Cruise Mail and Winlink 2000 do not provide any features for authentication and confidentiality. Only products from Mils and Crypto AG (Mils, 2004; Crypto AG, 2004) promised that kind of security components. Others are only available as part of military communication equipment and is too costly for commercial user. Thus, there is a need for the development of a Secured HF Transmission System for commercial use which not only capable to send an image, but also text files and short message as well.

1.1 Objective

The objectives of the project are

(i) To develop a prototype of HF transmission system which capable to transmit image, text file and short message via HF frequency spectrum with security features.

(ii) Analyze a chosen set of stream cipher algorithm to access its strength and weakness.

(iii) To implement real-time HF modem by using DSP board with for low power consumption.

(iv) To develop a prototype of telemetry system using HF frequency spectrum.

1.2 Scope Of Work

(i) The prototype of system is developed by using Microsoft Visual C++ software and Windows platform as Operating System.

(ii) Block cipher AES (Advanced Encryption Standard) is included for authentication and key distribution while the stream cipher used is based on the linear feedback shift register (LFSR) for confidentiality.

(iii) The analyses on stream cipher conducted based on common key length of 64 bit keys. Due to the system developed, the security is not limited to 64 bit key but can be enhanced by increasing the key length to 128 bits or more. This is because the key length can be extended by increasing the size of the LFSR.

(iv) For development of HF modem, DQPSK is chosen as the modulation technique because of its relative simplicity of implementation and its robustness to error in phase synchronization.

(v) Sampling frequency that is used is 8000Hz and the channel bandwidth is 3 kHz. This corresponds to the typical voice bandwidth used in HF communication systems.

(vi) Even thought the project not focus on JPEG image compression, but the system prototypes is capable to use any JPEG image for transmission over HF frequency spectrum.

(vii) For telemetry, the SCADA system is developed for lighthouse telemetry and vessel tracking system.

(viii) At master station, a computer is being used in displaying information and data storage for future analysis. A Microsoft Visual C++ based

Graphical User Interface (GUI) is implemented as a computer software to display the information of the lighthouse condition and vessel position. All the information is stored in database for offline analysis.

(ix) At remote station, printed circuit board (PCB) based on PIC microcontroller is designed for remote terminal unit (RTU).

(x) The project is not includes design the HF transceiver and antenna. Therefore, both equipments are purchase directly from the open market. For the HF modems, they are purchased in order to understand the existing system works and to reverse engineering the technology involved.

(xi) The frequencies that is used during transmission is determined using third party software called ASAPS (Advanced Stand Alone Prediction System) and also based on license given by MCMC (Malaysian Communications and Multimedia Commission).

1.3 Problem Statement

Computer networks normally transfer data via ground-based communication infrastructure such as telephone lines and fiber optic cables. However, this is impossible to communicate with places where terrestrial-based links are not possible and unreachable places by land such as on a ship, or on an aircraft. Satellite can be used but studies (Abdullah *et al.*, 2003) have shown that it is too costly. Thus, HF radio becomes the alternative communication medium for data transmission. In December 2004, when the tragic tsunami disaster happened in Aceh, all the communication systems were shut down. Therefore, the help from neighboring countries is found difficult. At that time, the only communication between them and the outside world is HF communication and this unexpected situation shows the significant of HF communication.

In general, the broadcast nature of any radio communication system such as HF communication makes it vulnerable interception by an unauthorized third party. Thus, there is a need for authentication, confidentiality and integrity services. This is to ensure only the authorized users use the system and the information is not access by unauthorized third party. Due to noisy channel conditions, stream ciphers are ideal choices over block ciphers for bulk data transmission based on faster implementation speed and do not introduce error of propagation. By employing the block and stream ciphers for authentication and encryption, the system will provide a secured data transmission over the HF spectrum.

1.4 Research Methodology

The ensure the success of the project, the following steps are taken

(i) Literature and technology review of work done at the academic institutions and relevant industries.

(ii) Evaluation and development of stream cipher and block cipher algorithms for confidentiality and integrity.

(iii) Implementation of DQPSK on the targeted hardware TMS320VC5416.

(iv) Develop HF transmission system using Visual C++. The program shall be capable to control basic function for transmitting and receiving purposes.

(v) Integration of the software application, cipher system and modem as a demonstrable prototype.

(vi) Field-testing of the system is conducted to verify the performance based on the Kuala Lumpur-Skudai HF link and other designated sites.

1.5 Organization of Report

The report begins with the introduction that describes the objectives, scope and research methodology. This is followed by the literature review in Chapter 2 that gives an overview of the work done and the technology available in the open market. Chapter 3 describes the stream cipher analysis. The implementation of DQPSK HF modem and implementation of HF messenger software are described in Chapter 4 and 5. New features on lighthouse telemetry and vessel tracking system are discussed in Chapter 6. The final chapter is the conclusion and recommendation for future work.

CHAPTER 2

LITERATURE REVIEW

HF communications is alternative way for long distance communication both for commercial or military use. With the Secured HF Transmission System, data can be transmitted with authentication and confidentiality. This application consist two separate parts: HF communication and the cryptography.

In order to use this application efficiently, a basic knowledge of HF propagation is required. Thus, this chapter will describe about the science behind HF communication and its properties, followed by introduction to HF modem, cryptography and crypto analysis. By combining both technologies, many applications were developed that inspired the development of secured HF transmission system that will be also discussed in this chapter.

2.1 HF Propagation Characteristics

Wireless communication is separated into several modes, which are LF, MF, HF, VHF, UHF and microwave. In the microwave region, the wave is more directional compared to other propagation modes, which travel in a wave-like manner. In the HF region, solar ionization of the upper reaches of atmosphere causes an effect known as skywave propagation that leads to long-distance communications and intercontinental broadcasting.

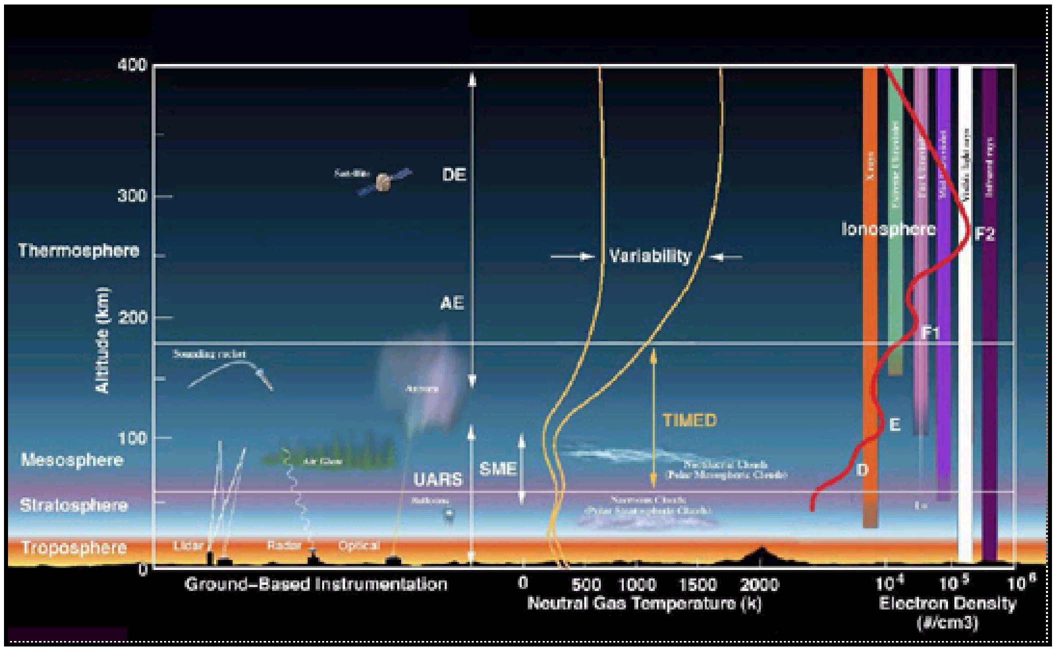


Figure 2.1: Atmosphere Layer (Australian Space Weather Agency)

Figure 2.1 shows the space that covers up to 400 kilometers high from ground level. A blanket of air, which is called atmosphere, surrounds the Earth. It reaches over 560 kilometers from the surface of the Earth (Harris Corp., 1996). The troposphere starts at the Earth’s surface and extends 8 to 14.5 kilometers high. This region, which is also known as lower atmosphere, is the densest. The stratosphere starts just above the troposphere and extends to 50 kilometers high. Stratosphere is dry and less dense compared to the troposphere. The ozone layer, which absorbs and scatters the solar ultraviolet radiation, is in this layer. Ninety-nine percent of “air” is located in the troposphere and stratosphere. The mesosphere starts just above the stratosphere and extends up to 85 kilometers high. The chemicals are in an excited state, as they absorb energy from the sun. The thermosphere starts just above the mesosphere and extends up to 600 kilometers high. Chemical reactions occur much faster here than on the surface of the Earth.

For HF communication, the ionosphere is the most important region that begins at an altitude of about 50 kilometers and extends up to approximately 300 kilometers. The ionosphere is a region of very thin atmosphere. Ionosphere is clearly a very unpredictable region. HF communication utilizes the ionosphere to enable long distance communication. During the day, there may be four regions present called D, E, F1 and F2 regions. Among these regions, only E, F1, sporadic E, and F2 refract HF waves. The conditions of the regions differ from night and day according to the solar cycle (Carr, 2001). HF propagation, as shown in Figure 2.2, is divided into three, which are

(i) ground wave propagation.
(ii) line of sight propagation or space wave.
(iii) sky wave propagation.

Ground wave propagation is the dominant mode of propagation for frequencies below 2 MHz (Couch, 1997). Here the electromagnetic tends to follow the contour of the Earth. This is the propagation mode used in amplitude modulation (AM) broadcasting. The ground wave travels in direct contact with the Earth's surface, and it suffers a severe frequency-dependent attenuation because of absorption by the ground. The losses are caused by ohmic resistive losses in conductive Earth as well as to the dielectric properties of the Earth.

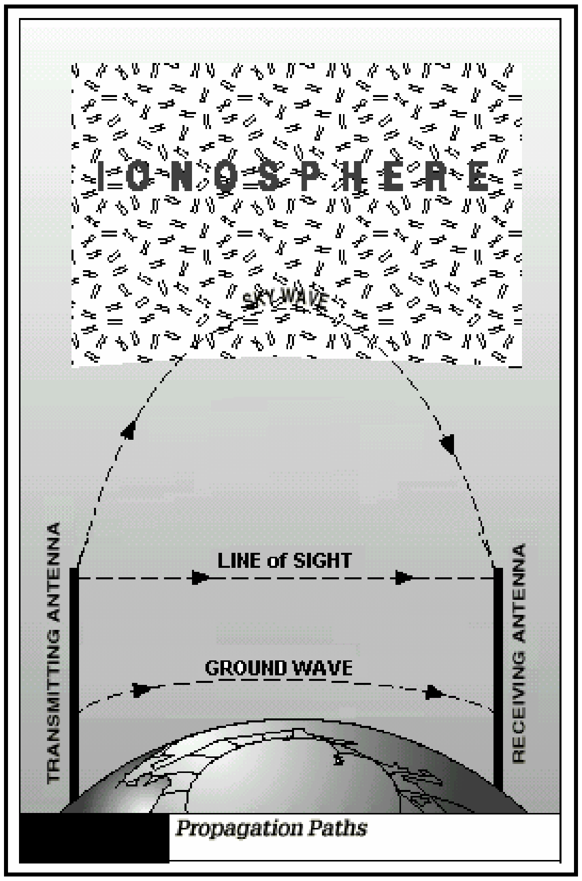


Figure 2.2: Propagation Paths

Line of sight propagation or also known as space wave is the dominant mode for frequencies above 30MHz (Couch, 1997). Here the electromagnetic wave propagates in a straight line. The disadvantage of the space wave propagation mode is for communication between terrestrial stations, the signal path has to be above the horizon, or else the Earth will block the line-of-sight path.

Skywave propagation is the dominant mode of propagation in the 3~30MHz frequency range. Here, long distance coverage is obtained by reflecting the wave at the ionosphere. Skywave propagation is caused primarily by reflection from F layer (Couch, 1997). Because of this layer, international broadcast stations in HF band can be heard from the other side of the world at almost any time during day and night.

2.2 Effects of Multipath

The advantages of HF communication arise from its relative simplicity, its ability to provide near global connectivity at low power without relay and its moderate cost. The apparent disadvantages are directly related to ionospheric variability. Fading caused by solar disturbances (Goodman, 1992) and multipath interferences leads to a reduction in reliability in HF communication.

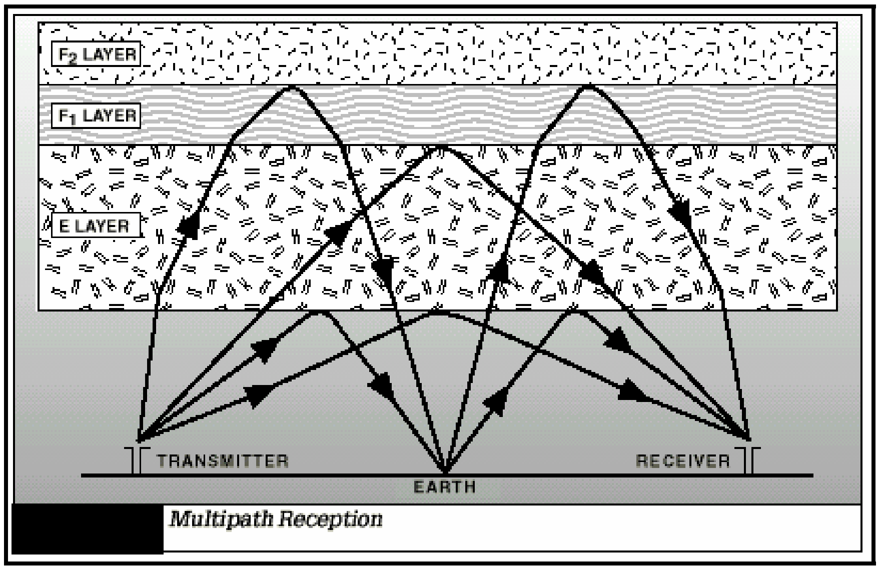


Figure 2.3: Multipath Reception

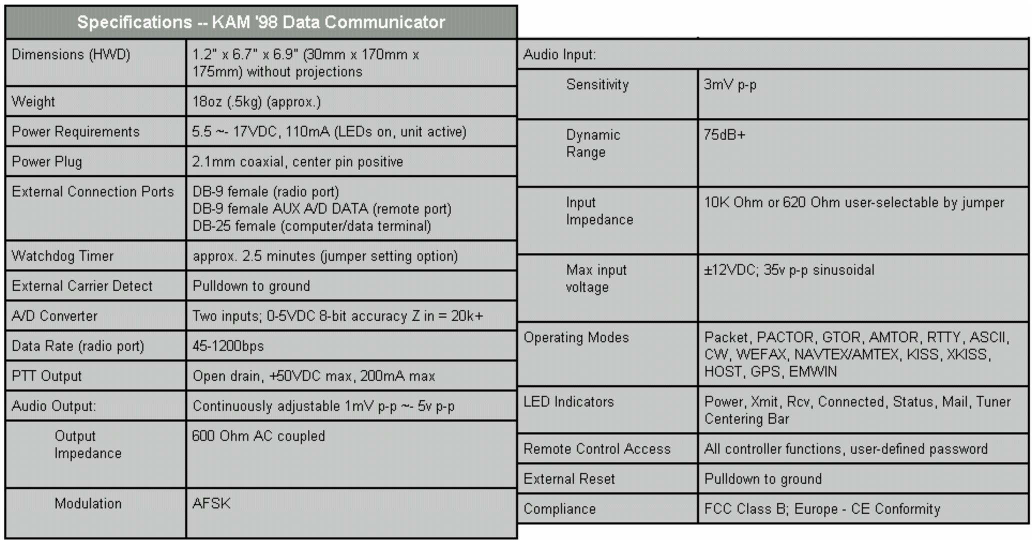
Multipath fading results from dispersion of the signal by the transmitting antenna (Goodman, 1992). A number of modes propagate have variations in phase and amplitude. These occur because of the signal which maybe be refracted by different layers of ionosphere and also because of signal hopping as shown in Figure 2.3. These waves may interfere with each other, resulting in the signal fading each other if they arrived at the receiver in different phase. This kind of fading is known as multipath fading and it leads to time selective fading and frequency selective fading, which is the main cause for baud rate limitation. If the signal is transmitted over 100 baud through skywave, a phenomena which is known as inter symbol interference (ISI) will occur. This is where adjacent symbols interfere with each other. This is caused by time delay spread, which is the main factor in symbol rate limitation of 100 baud per second (Willink et al, 1996).

Time selective fading is caused by delay due to multipath effect within one phase. This delay in phase will result in cancellation of waves or attenuation in wave amplitude. The worst case happens if the same signal from different paths arrives at the receiver at 180^0 phase different, resulting in the wave practically canceling each other. A delay in milisecond unit due to multipath, introduces a frequency selective fading to the system. Frequency selective fading will cause certain frequencies to be attenuated. This in turn will introduce time delay spread problem to the system. So in order to avoid this problem, symbol transmission rate is limited to 100 baud per second (Willink et al, 1996).

Doppler shift is caused by the vibration of electrons in the ionosphere layer (Goodman, 1992). Doppler shift will introduce a change in radio frequency. These phenomena will cause a problem if the shift in frequency is too great in which the receiver would not recognize the signal. If the receiver uses a band-pass filter to capture the signal, the frequency shift will cause the rejection of some of the received signal. In the case of coherent detection, the received frequency carrier and the reference frequency at the receiver will be totally different and this will result in the loss of a whole packet of data.

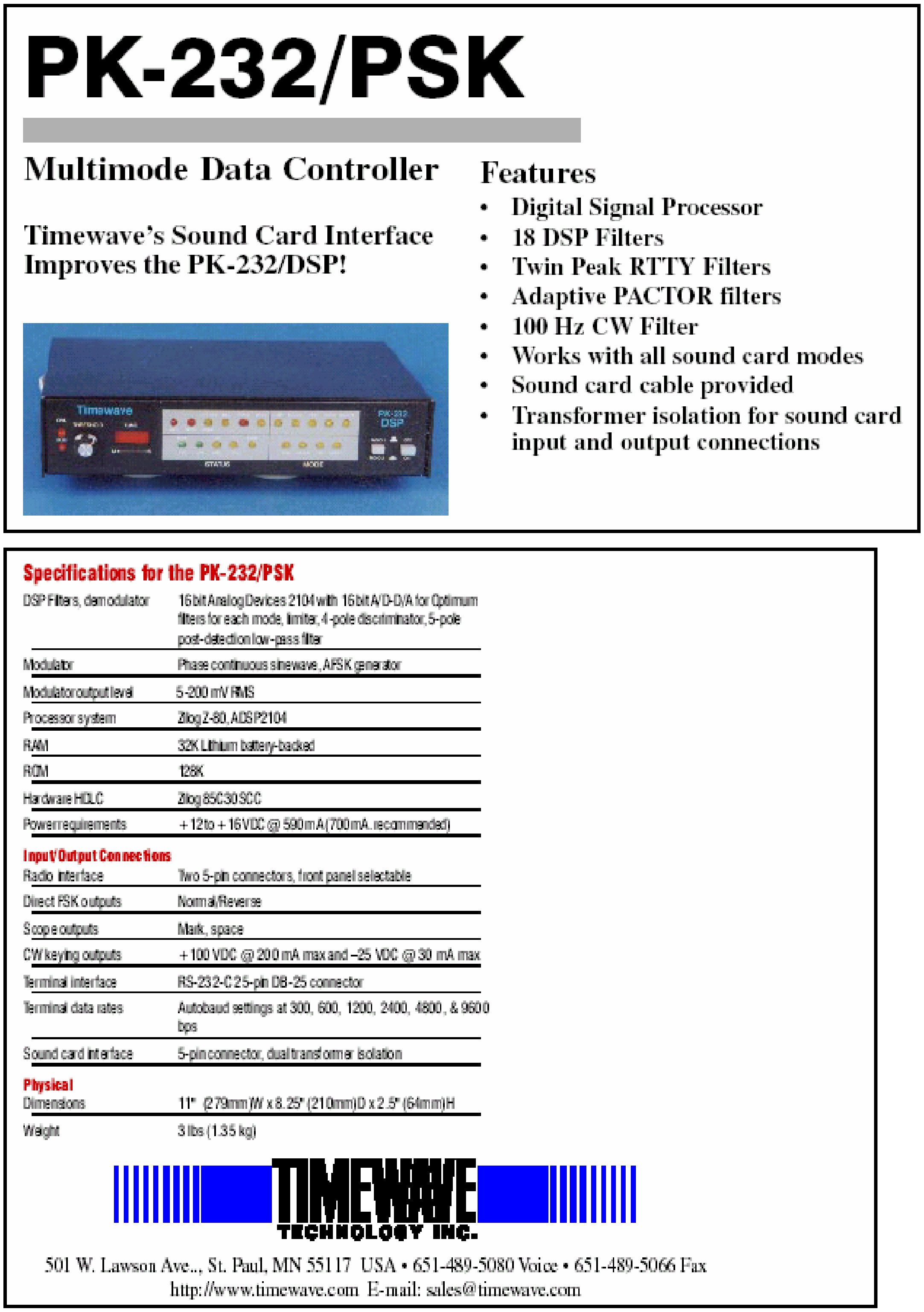
2.3 HF Modems

Commercially made HF modems are now available in the market that offers a variety of service such as HF packet radio, slow scan TV, fax service, IP over HF and robust image transmission (Harris Corp.,1996). Below are two examples of commercially made HF modem from Kantronics and Timewave Technology Inc, USA.



Specifications -- KAM '98 Data Communicator	
Dimensions (HWD)	1.2" x 6.7" x 6.9" (30mm x 170mm x 175mm) without projections
Weight	18oz (.5kg) (approx.)
Power Requirements	5.5 ~- 17VDC, 110mA (LEDs on, unit active)
Power Plug	2.1mm coaxial, center pin positive
External Connection Ports	DB-9 female (radio port) DB-9 female AUX A/D DATA (remote port) DB-25 female (computer/data terminal)
Watchdog Timer	approx. 2.5 minutes (jumper setting option)
External Carrier Detect	Pulldown to ground
A/D Converter	Two inputs; 0-5VDC 8-bit accuracy Z in = 20k+
Data Rate (radio port)	45-1200bps
PTT Output	Open drain, +50VDC max, 200mA max
Audio Output:	Continuously adjustable 1mV p-p ~- 5v p-p
Output Impedance	600 Ohm AC coupled
Modulation	AFSK
Audio Input:	
Sensitivity	3mV p-p
Dynamic Range	75dB+
Input Impedance	10K Ohm or 620 Ohm user-selectable by jumper
Max input voltage	±12VDC; 35v p-p sinusoidal
Operating Modes	Packet, PACTOR, GTOR, AMTOR, RTTY, ASCII, CW, WEFAX, NAVTEX/AMTEX, KISS, XKISS, HOST, GPS, EMWIN
LED Indicators	Power, Xmit, Rcv, Connected, Status, Mail, Tuner Centering Bar
Remote Control Access	All controller functions, user-defined password
External Reset	Pulldown to ground
Compliance	FCC Class B; Europe - CE Conformity

Figure 2.4: Kantronics HF Modem



PK-232/PSK

Multimode Data Controller

Timewave's Sound Card Interface Improves the PK-232/DSP!

Features

- Digital Signal Processor
- 18 DSP Filters
- Twin Peak RTTY Filters
- Adaptive PACTOR filters
- 100 Hz CW Filter
- Works with all sound card modes
- Sound card cable provided
- Transformer isolation for sound card input and output connections

Specifications for the PK-232/PSK

DSP Filters, demodulator	16bit Analog Devices 2104 with 16bit A/D-D/A for Optimum filters for each mode, limiter, 4-pole discriminator, 5-pole post-detection low-pass filter
Modulator	Phase continuous sinewave, AFSK generator
Modulator output level	5-200 mV RMS
Processor system	Zilog Z-80, ADSP2104
RAM	32K Lithium battery-backed
ROM	128K
Hardware HDLC	Zilog 85C30 SCC
Power requirements	+12 to +16 VDC @ 590 mA (700 mA. recommended)
Input/Output Connections	
Radio interface	Two 5-pin connectors, front panel selectable
Direct FSK outputs	Normal/Reverse
Scope outputs	Mark, space
CW keying outputs	+100 VDC @ 200 mA max and –25 VDC @ 30 mA max
Terminal interface	RS-232-C 25-pin DB-25 connector
Terminal data rates	Autobaud settings at 300, 600, 1200, 2400, 4800, & 9600 bps
Sound card interface	5-pin connector, dual transformer isolation
Physical	
Dimensions	11" (279mm)W x 8.25" (210mm)D x 2.5" (64mm)H
Weight	3 lbs (1.35 kg)

TIMEWAVE TECHNOLOGY INC.

501 W. Lawson Ave.., St. Paul, MN 55117 USA • 651-489-5080 Voice • 651-489-5066 Fax
http://www.timewave.com E-mail: sales@timewave.com

Figure 2.5: Timewave HF Modem

2.4 HF Communication Systems

Several types of data format exist in HF communication. They are classed in the standard format and non-standard format groups. Some of the most frequently used data formats for standard format group are listed as follows.

(i) RTTY (Baudot code)
(ii) AMTOR (ASCII)
(iii) PACTOR
(iv) PACTOR II
(v) PACTOR III
(vi) GLOVER
(vii) PSK31
(viii) GTOR

Radio Teletypewriter (RTTY) equipment using 5 digits BAUDOT code became available in the market in the years following World War II (Kasser, 1991). Radio amateurs experimented using that equipment for communications. RTTY communication faces a serious problem of fading and noise since error detection is not used. It is is a half duplex communication mode where a each character is transmitted as soon as it is typed.

AMTOR is a specialized form of RTTY (Kasser, 1991). The term is an acronym for Amateur Teleprinting Over Radio and is derived from the commercial SITOR system (Simplex Telex Over radio) developed primarily for Maritime use in the 1970s. In the early 1980's, Peter Martinez, G3PLX, made several minor changes to the SITOR protocol and called it AMTOR. AMTOR improves on RTTY by incorporating a simple error detection technique. AMTOR employs two forms of time diversity in ARQ (auto-repeat request) mode and FEC (forward error correction) mode. A repeat is only sent when requested in ARQ mode whereas in FEC mode each character is sent twice. In both modes, the redundancy of the code itself which sent at different times, supplies the time diversity in AMTOR (Reed, 2001). AMTOR utilizes ASCII code for transmission. ASCII (American National Standard Code II) is a coded character set used for information processing systems. ASCII uses 7 bits to represent letters, figures, symbols and control characters. ASCII has both upper and lower case letters. The system remains relatively uncomplicated but AMTOR performs well even in poor HF conditions. While there can still be many errors in AMTOR data, the error detection helps a lot and the result is quite tolerable for normal text mode conversations because of the high redundancy in plain language text. AMTOR is a half duplex communications mode with some of the attributes of a full duplex mode.

PACTOR was designed in 1991 in Germany to overcome the disadvantages of AMTOR and Packet Radio (Reed, 2001). It improves on the error detection technique, by employing the CRC-16 or cyclic redundancy check. PACTOR is a cheap and reliable means of fast, robust and error-free data transfer over HF. PACTOR format uses not only the complete ASCII character set, but any given binary information which could be transferred over HF, even in very poor propagation conditions. Initially Frequency Shift Keying (FSK) was chosen as a modulation method. PACTOR employs packet structure, which contains 20 characters of data for 200-baud transmission or 8 characters of data for 100 baud.

PACTOR II uses m-ary PSK as it modulation method and employes 2 sub-carriers, transmitting about 800 bits per second at 100 baud (Reed, 2001). It utilizes Huffman and Markov compression method and viterbi decoding to further increase the data transfer rate. Error control used for PACTOR II is a soft decision ½ code rate convolutional code with the constraint length of 9.

The only significant difference between PACTOR III and PACTOR II is PACTOR III is an m-ary modulation method where it uses up 18 sub-carriers while PACTOR-II uses only two sub-carriers (Reed, 2001). Carrier separations are 120 Hz and the modulation methods are DBPSK or DQPSK at 100 baud.

CLOVER uses a four-tone multi-level modulation system that includes a combination of frequency, phase and amplitude-shift modulation (Reed, 2001). CLOVER uses a very low base data rate 31.25 symbols per second to counter the multipath propagation distortion that commonly occurs on HF radio signals. Modulation technique, which is used, is BPSK or QPSK. 4 carriers are used in CLOVER with 125Hz carrier spacing within 500Hz bandwidth. Clover uses Reed-Solomon error correction codes to correct a moderate number of errors but it can also switch to ARQ whenever the conditions are very bad and number of error exceeds the capacity of Reed-Solomon error corrector.

PSK31 stands for phase shift keying, which is the method used for modulation (Reed, 2001). The precise bit rate for PSK31 is 31.25. PSK31 is designed based on RTTY mode of operation. The RTTY code shuffles various combinations of five bits to represent each character. For example, the letter A is expressed as 00011. For a new code called *Varicode* that combines the best of RTTY and Morse was designed. In Varicode, shorter codes are allocated to the letters that appeared most often in standard English text. The idea was to send the least number of bits possible during a given transmission. For example E is a very popular letter on the English alphabet hit parade, so it gets a Varicode of 11. Z sees relatively little use, so its Varicode becomes 111010101.

G-TOR is a completely new hybrid – ARQ HF digital communications system for commercial and amateur services. Golay error correction coding forms the basis for G-TOR (short for Golay - TOR), G-TOR is the innovation of KANTRONICS (Reed, 2001), introduced in 1994. Key features of G-TOR are extended Golay forward error correction coding, full-frame interleaving, link-quality-based baud rate (300, 200, and 100), 2.4 second hybrid-ARQ cycle and use of standard FSK tone pairs (mark and space). Format of G-TOR operation is proprietary.

Several of the non-standard formats are listed as follows (Scalsky, Chace, 1997):

(i) **ARQ6-90/98** - 6-character-block simplex ARQ used by French and Italian Diplomatic services, typically 200 bd. ARQ-6/90 and ARQ-6/98 differ in their inter data block timing.

(ii) **IRA-ARQ** - Duplex ARQ with IRA (ITA-5), used by Czech/Slovak Diplomatic stations, typically 171.42, 200.2, or 300.3 bd.

(iii) **PICCOLO** - Originally developed in 1957 in Great Britain at the Diplomatic Wireless Service or as it is known today the Communication Engineering Department of the British Foreign and Commonwealth Office (FCO).

(iv) **COQUELET** - COQUELET Mk I is an asynchronous 13 tone ITA2 system used by French (possibly abandoned) and Belgian military police. COQUELET Mk II is a synchronous 8 tone ITA2 system used by Algerian Diplomatic and Customs.

Other than the standard format and non-standard formats listed above, there are two governing bodies that sets the standard for HF communication. STANAG 5066 is a standard protocol that covers the NATO countries while FED-STD-1052 is a standard by U.S. Government to ensure the minimum level of interoperability among HF modems.

The STANAG 5066 is a NATO Standardization agreement: Profile for HF Radio Data Communications (Trinder, Gillespie, 2001). It is an open standard defining the requirements for building interoperable HF data communication system. STANAG 5066 was completed prior to the standardization of high data rate waveform capable of data rates of 9.6kbps and higher. In addition for ARQ protocol, the standard includes a mechanism for adapting the data rate in accordance with the prevailing channel conditions. STANAG 5066 NATO Standardization agreement targets a very high data transfer rate for military use HF communication system.

FED-STD-1052 is a standard by U.S. Government which contains technical standard for minimum interface and performance standards pertinent to modems which operate in HF radio equipment (FED-STD-1052; 1994). The general standard is the HF modems shall be capable of modulating and demodulating serial data into/from an FSK waveform. The minimum acceptable performance is 75 bps using the FSK and PSK single-tone waveforms. Modems with 150, 300, 600, 1200, 2400, all coded and 4800 bps uncoded, should have the capability to adapt to channel condition. This standard states that FEC encoder shall be used for data rates up to an including 2400 bps. It proposes the use of ½ code rate for the FEC coding scheme.

2.5 Recent Development in HF Digital Modulation Techniques

Continuous research is conducted in finding the best modulation method to be used in HF. Among the types that are frequently investigated is the m-ary modulation method which is capable in transferring high data rate. The best method to implement error control is also explored where a faster decoding method could reduce the overall time needed for processing. The effect of different computational platform is compared to find the trade-off between the speed and power consumption (Jorgenson et al, 2001).

(Cook, 1993) employs a 16-DQPSK signaling tones at a 75 baud QPSK modems placed in adjacent channels. The low symbol rates of the tones were chosen to combat the time delay spread introduced by HF channels, typically in the range of a few milliseconds. (Nilsson, Timothy, 1997) explored the potential of m-ary or OFDM for military HF communication. The proposed system uses a differential binary PSK (DBPSK) modulation method on each carrier. The number of carriers used in this system is 1024 over a bandwidth of 125 kHz and the symbol duration is

8.2ms. The modem proposed by Nilsson is capable of operating until 1.22Mbps. (Cook et al, 1994) conducted a work on designing a high speed m-ary HF modem. The modem used 16 tone formats and the modulation method is 8PSK. This modem could operate for 3.6kbps. (Clark et al, 1993) implemented multi frequency shift keying (MFSK) in his paper. Maximum number of tones transmitted in his modem over 2 kHz of bandwidth is 32 tones. Data format used in his approach is the PICCOLO format. Reed Solomon (RS) code is used as an error correction coding.

(Brakemier, 1988) proposed a system using 4 PSK as modulation method and RS code for forward error correction (FEC). Bandwidth used for his modem is about 2-3 kHz and the transmission rate is 2.4kbps. Brakemier concluded in his work that one of the requirements for HF modem is having a nearly constant envelope of transmitted signal helps to overcome the disturbing effect introduced by HF radio channels. This conclusion led to the development of single tone HF modem.

The m-ary HF modem was developed by Racal Research (Hoult, 2000). This modem used a 56 tones orthogonal frequency division multiplexing (OFDM), and each modulated with 256-QAM constellation. This modem was designed to operate at 16kbps in a 3 kHz bandwidth channel. The studies on multi channel modulation on HF communication were done by (Jorgenson et al, 2000). In his approach 8 separate channels (8 modems on adjacent bandwidth) were used to achieve 64kbps. Each channel transmits 8kbps over bandwidth of 3 kHz. 32 QAM was used in his approach as his modulation method. The total of bandwidth used for 8 channels is 24 kHz. In (Kotlowski et al, 2000) paper to answer NATO's demand for higher data transfer rate, he proposed a 128 QAM in a 3 kHz bandwidth that can transfer up to 14.4kbps.

(Boyarinov, 2000) investigated the speed of extended Golay Code soft decoding in his paper. Several methods exist for Golay code decoding which are; algebraic decoding algorithm, bounded-distance decoding algorithm and trellis decoding algorithm. However, these algorithms are not suitable for applications in software as they are complex for implementation and introduce a large decoding delay. Boyarinov introduced decoding algorithm, based on Turyn construction, which is capable in correcting all triple and fewer errors. This decoder still requires an extensive computation since it requires at least 80 operations to calculate the initial syndromes to determine there are no errors present. (Cook, 1993) did a study to find the best error-control options for HF modems. He investigated six error control coding schemes and he concluded that Trellis coded modulation (TCM) is the most suitable for an m-ary (16 sub-carrier) 2.4kbps HF modem.

Considerable work is done to investigate the appropriate platform of HF modem. Converting the computer to be the HF software modem may not be the correct solution in some cases. (Jorgenson, 2001) proved that a PC that runs on processors before Pentium III ® processor may not be capable in handling the real-time calculation for the signal processing. Jorgenson compared the interrupt latencies and thread latencies between a PC running on NT OS ® and Linux OS and Jorgenson concluded that PC running on Linux OS performs better. A comparison between PC software modem and modem implemented on DSP board are also compared. DSP processors are at an advantage where its power consumption is low compared to multi purpose processor such as Pentium. Power consumption for DSP processor such as Texas Instrument TMS320VC5416 DSP boards at full operation is only 100 mWatt (TMS320VC5416 Technical Reference), whereas Pentium drained about 10 to 100 Watt for it to be fully operational (Blonstein, Katorgi, 2003). Relative to advance DSPs, general purpose processors like Pentium are high in power consumption. However, DSPs have an obvious disadvantage compared to PC software modem. The programmers are faced with a very limited internal memory during modem implementation on DSP boards.

2.6 Cryptography

Cryptography is the science of information security (Nichols and Lekkas, 2002). It is the technology that encodes information so that only accessible by authorized parties. In the modern computer world, cryptography is commonly associated with encryption and decryption where encryption refers to scramble ordinary data called plaintext into cipher text and decryption means the vice versa. According to the Federal Standard 1037C: Glossary of Telecommunications Terms, cryptography is defined as "The principles, means and methods for rendering plain information unintelligible and for restoring encrypted information to intelligible form" (Federal Standard 1037C, 2002). It is closely related to the disciplines of cryptography and cryptanalysis.

There are 4 major objectives of modern cryptography:

(i) **Confidentiality:** ensures only authorized parties can access the information. The standard mechanism for enabling confidentiality is encryption.

(ii) **Authentication:** ensures both sender and recipient can confirm each other's identity. There are many authentication mechanism exist, for example presenting user ID and password, using smart card, digital signatures, biometric authentication and challenges and response authentication.

(iii) **Integrity:** ensures no altering can be made to information without being detected. The alterations include but not limit to change, delete and create. Message digests are the primary mechanism for ensuring data integrity.

(iv) **Non-repudiation:** ensures neither the sender nor the recipient can deny his intentions in the transmission of the information. Digital signatures are the basic non-repudiation enabling mechanism.

Procedures and protocols that meet some or all of the above criteria are known as cryptosystems or cipher system. These systems are not only refer to mathematical procedures and computer programs, in fact, it includes the regulation of human behavior such as choosing hard-to-guess password, frequently change of passwords, logging off unused systems and not discuss sensitive procedures with outsiders.

Now, cryptography is a very important field especially in communication and banking system. It is also a crucial factor to success in war or business as well. Due to this significant, there are many parties who attempt to design new cipher system in order to improve an existing system. They are not only creating better cipher systems that tends to be more difficult to be hacked but they are also trying to hack the existing cipher systems in order to discover the weaknesses and further strengthen it.

Referring to Federal Standard 1037C, the cryptology is "the science that deals with hidden, disguised or encrypted communications. It embraces communications security and communication intelligence" (Federal Standard 1037C, 2002). It is the science of mathematics, such as number of theory and the application of formulas and algorithms that underpin cryptography and cryptanalysis.

Cryptanalysis refers to the study of cipher systems, either the algorithms and procedures or the cipher-text, with the sole objective to find weaknesses in them that will permit retrieval of the plaintext from the cipher-text, without necessarily knowing the key or the algorithms. This is known as breaking the cipher systems. It includes the weakening strategy that find a property or fault in the design or implementation of the cipher that reduces the number of keys required to facilitate others attack such as a brute force attack.

There are numerous techniques for performing cryptanalysis, depending on the access to the plaintext, cipher text, or other aspects of the cipher systems (Stallings, 2003). These include:

(i) Cipher-text-only analysis
(ii) Adaptive chosen-plaintext analysis
(iii) hosen-cipher text analysis
(iv) Meet-in-the-middle attack

(v) Timing or differential power analysis
(vi) Slide attack cryptanalysis
(vii) Differential cryptanalysis
(viii) Linear cryptanalysis

Besides these electronics programmable methods, there are some other unorthodox techniques such as convincing individuals to reveal password or keys, developing Trojan horse programs to steal secret key or tricking a victim into using a weakened cipher systems.

2.7 Cipher Systems

Cipher system is the system that encrypts and decrypts data. Generally, there are two kinds of cipher systems, which are symmetric and asymmetric. The symmetric or the secret key cipher system uses the same key in encryption and decryption. Asymmetric or the public key cipher systems uses one key to encrypt and the other corresponding key to decrypt. Usually, a cipher system comprises 5 elements: the plaintext, cipher text, key, encryption and decryption functions (Nichols and Lekkas, 2002).

2.7.1 Symmetric Cipher Systems

Symmetric Cipher systems use the same key for encryption and decryption. It is often referred to as secret-key cipher systems or conventional cipher systems (Lail, 2002). Generally, the symmetric cipher systems are algorithms that use the underlying transposition and substitution operation, to ensure that cipher-text can only be decrypted by the corresponding secret key.

The core security factor for symmetric cipher systems is the encryption algorithm. It must be powerful enough so that it is impossible to decrypt a message based on the cipher-text alone. Secondly, the security depends on the secrecy of the key, and not the algorithm. Thus we are not required to keep algorithm secret.

Symmetric cipher systems have a few common disadvantages (Kotsakis, 2004). First, it is impossible for the sender of the message to prove to his partner that he has sent a particular message. Secondly, the keys have to be communicated on a channel whose cryptanalytic security is much higher than the security of the channel used for normal transmission. With a large number of partners wanting secure communication, the number of two-way channels and thus the number of keys becomes quite large. This is because for a network with N parties, when each wanting to exchange messages safely with everyone, total of N*(N-1)/2 keys are required (Stallings, 2003). For example, in the network of 10 persons, total of 45 keys are required and kept on each party. However, these disadvantages can be overcome by using suitable authentication and key distribution technique.

On the other side, as comparatively to asymmetric cipher systems, symmetric cipher systems can process data faster. Thus a lot of applications in the market today use an asymmetric system to exchange secret keys at initial stage, and then use a symmetric system to transport data (Kotsakis, 2004).

There are two types of symmetric algorithms, which are stream ciphers and block ciphers. Examples of symmetric cipher systems are Data Encryption Standard (DES) (Stallings, 2003), Advanced Encryption Standard (AES) (NIST, 2001), Blowfish, Twofish, IDEA, CAST, SEAL and RC4. Among these, RC4 (Schneier, 1996) and SEAL (Menezes *et al.*, 1996) are the stream ciphers and the rest are block ciphers.

2.7.1.1 Block Cipher

A block cipher is a method of encrypting text in which a cryptographic key and algorithm are applied to a fixed length block of data at once rather than to one bit at a time (Pawliw, 2001). The fixed length is called the block size. A block cipher effectively provides a permutation of the set of all possible messages as different plaintext blocks are mapped uniquely to different cipher-text blocks. The permutation effected during any particular encryption is the function of the secret key. Block cipher utilize both diffusion and confusion criteria. Diffusion means every block or character of the cryptogram is dependent on each other. Every single bit is dependency, which causes an error in block size. The cryptogram generated by block cipher also random and unpredictable which is called confusion. By make use these criteria, the block cipher has high resistant in security.

There are three basic important behaviors of block ciphers (Pawliw, 2001):

(i) Knowing both the plaintext block and the key, it must be easy to calculate the cipher-text block
(ii) Knowing both the cipher-text block and the key, it must be easy to calculate the plaintext block
(iii) Knowing both plaintext block and the cipher-text block, it must be as difficult as possible to find the key

There are a lot of cryptanalysis theories and practices relevant to block ciphers that have been published such as differential cryptanalysis, linear cryptanalysis (Schneier, 1996), slide attack cryptanalysis and algebraic cryptanalysis (Menezes *et al.*, 1996). For a modern proposal for a block cipher to be taken seriously, there must be a good reason to believe it is strongly resistant to all these.

Examples of popular block ciphers include AES and DES. AES is the replacement of the DES certificate by National Institute of Standards and

Technology (NIST). Another block ciphers that have been published are Twofish, Serpent, RC6, RC5, Safer, IDEA, Blowfish (Stallings, 2003), and GOST (Schneier, 1996).

2.7.1.2 Stream Cipher

Stream ciphers encrypt input data one bit (sometimes one byte) at a time (Beker and Piper, 1982). They are also called state ciphers, as the encryption of a bit is dependent on the current state. The encryption and decryption process of stream ciphers normally involves the exclusive-OR (XOR) operation of the plaintext with the keystream to produce the ciphertext. Keystream generally consist of a pseudorandom bit pattern, such as the output of a pseudorandom number generator (PRNG). Key or password is then used to generate a seed for the PRNG in order to generate same keystream in encryption and decryption.

Generally, stream ciphers can be designed to be exceptionally faster to execute in hardware than block ciphers. Another important feature is a single bit of cipher text error results in a single bit of plaintext error, which is very useful when the transmission error rate is high. In order to provide high security, a stream cipher needs all these characteristics (Beker and Piper, 1982)

(i) A cryptogram must have random characteristics
(ii) A keystream must have high linear complexity

Examples of stream ciphers are RC4, Shrinking, Improve Geffe, SEAL (Menezes *et al.*, 1996), SNOW (Ekdahl and Johansson, 2001) and SOBER (Rose, 2000).

2.7.2 Comparison between block and stream cipher system

Even though both block and stream ciphers need same secret key to encrypt and decrypt, but obviously the processing is different. Block cipher encrypts the plaintext by blocking, usually 64 bits or 128 bits respectively depends on algorithms but stream cipher encrypts the plaintext bit by bit. Block cipher utilizes both diffusion and confusion and is not for stream cipher, which only had confusion criteria. Because of that, block cipher suitable to be used in key management, authentication and encryption while stream cipher only for encryption (Schneier, 1996).

Actually, the choice between using block cipher or stream cipher is greatly affected by its application. The usage of block cipher implies error propagation. Thus, block ciphers can only be used when error propagation is either an advantage or, at least, not a handicap (Tuan Sabri, 1995). The example where the block cipher often used for encryption is in banking system and Internet service (Lail, 2002).

However, in any communication over a noisy channel such as high frequency medium, an introduction of extra errors because of encryption is unacceptable. For block cipher, an introduction of error in transmission causes propagation error. Even though there is an error correction to handle error in transmission, but it is still not guarantee. Due to no propagation error produce, a stream cipher is better choice rather than a block cipher.

2.7.3 Asymmetric Cipher systems

The asymmetric or the public key cipher system uses one key to encrypt and other corresponding key to decrypt. It was found and published by Whitfield Diffie and Martin Hellman (Diffie and Hellman, 1976), although the National Security Agency (NSA) claims to have discovered it some years earlier. This system makes use of various intractable mathematics problems, that are normally easy to calculate from one way, but theoretically almost impossible to compute the original value from the results, which is the other way. These problems include discrete logarithm problem, the integer factorization problem and elliptic curve discrete logarithm problem. Asymmetric cipher systems allow public keys to be simply distributed to the public. Data that is encrypted using the published public key can only be decrypted using the secure private key kept secretly by individuals. The computation of one key from the other key is infeasible. Some examples of asymmetric cipher systems are Digital Signature Standard (DSS), RSA, El-Gamal and Diffie-Hellman (DH) (Stallings, 2003).

2.8 Advanced Encryption Standard (AES)

On December 6th 2001, the Secretary of Commerce, United State (US) officially approved FIPS 197, which specifies that all sensitive, unclassified documents will use Rijndael as the Advanced Encryption Standard (AES). AES in fact is the result of the NIST effort to find a more robust replacement for DES and to a lesser degree Triple DES (Stallings, 2003). In January 1997, NIST has initiated a call for symmetric cipher algorithm that uses 128-bit block size, supporting key sizes of 128, 192 and 256 bits as a minimum. The algorithm was required to be royalty-free for use worldwide and offered security of a sufficient level to protect data for the next 20 to 30 years. It was to be easy to implement in various types of hardware and software, offer good defenses against various attack techniques.

The entire selection process was fully open to public scrutiny and comment; it had being decided that full visibility would ensure the best possible analysis of the designs. In August 1999, NIST selected five algorithms for more extensive analysis, which were: MARS from IBM research, RC6 by RSA Security, Rijndael by two Belgian Cryptographers, Joan Deamen and Vincent Rijment, Serpent by Ross Andersen, Eli Biham and Lars Knudsen, and Twofish submitted by researchers including Counterpane's respected cryptographer, Bruce Schneier. The end result was that on October 2, 2000, NIST announced that Rijnadael had been selected as the proposed standard.

Rijndael was initially developed to support variable block length and key length, and they can be extended very easily to multiples of 32 bits. The design of Rijndael was strongly influenced by the design of the block cipher square.

The new AES cipher (NIST, 2001) is fast in both software and hardware, relatively easy to implement and requires little memory. As the new block cipher standard it is currently being deployed on a large scale. AES has 10 rounds for 128-bit keys, 12 rounds 192-bit keys and 14 rounds for 256-bit keys. It is very fast, almost approaching the speed of existing hashing algorithm, nonetheless faster than DES and Triple DES.

2.9 Authentication, Key Distribution and Confidentiality

Authentication is a basic security services, without it most other communication security services become meaningless. This mechanism will enable both parties to verify the authenticity of message or user as well. The authentication can be grouped into three classes, as follows:

- **(i)** **Message encryption:** The cipher text of the entire message serves as its authenticator
- **(ii)** **Message authentication code (MAC):** A public function of the message and a secret key that produces a fixed-length value that serves as the authenticator.
- **(iii)** **Hash function:** A public function that maps the message of any length into fixed-length hash value, which serves as the authenticator

One of the popular methodologies for authentication, which is used in many applications, is challenge and response authentication (Menezes *et al.*, 1996). In general, this method can be implemented either using symmetric or public key cipher system as long they provide an authenticity as well. Symmetric is best for encrypting data, while public key is best for key management (Schneier, 1996). Secured HF Transmission System is an example of communication system where the users coming from specific parties. Therefore, the user network is not complex as ordinary network-based station. So, the block cipher is chosen due to fewer burdens of key management, faster encryption time and less complex of implementation. Figure 2.6 shows the diagram of challenge and response authentication using block cipher Advanced Encryption Standard (AES) with 256 bits.

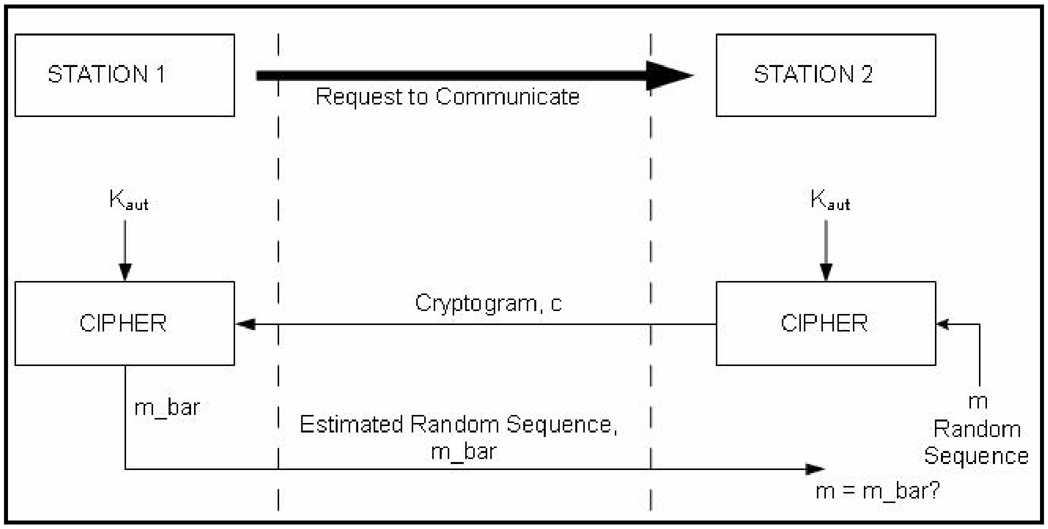


Figure 2.6: Challenge and Response Authentication

From the diagram, firstly Station 1 requests Station 2 to start communication. After receiving the request, Station 2 will generate random message, *m* and by using authentication key, K_{aut} that message will encrypt to cryptogram, *c*. That is cryptogram, will be sent to Station 1. At the other side, Station 1 receives the cryptogram and decrypts that message by using same authentication key, K_{aut}. The decipher message, *m_bar* will be returned to Station 2. Station 2 will compare whether *m_bar* is equal or not with random message, *m*. If the message is equal, authentication is successful and both stations can start to communicate confidentially. Otherwise the communication will be discarded.

Usually, an authentication works together with key distribution in order to provide authenticity and confidentiality. Key distribution required to protect the session key from access by third party. Therefore, the strength of any cryptographic system rests with the key distribution technique, a term that refers to the means of delivering key to two parties who wish to exchange data, without allowing others to see the key (Stallings, 2003). For two parties A and B, key distribution can be achieved in number of ways, as follows:

(i) A can select a session key and physically deliver it to B.

(ii) A third party can select the session key and physically deliver it to A and B.

(iii) If A and B have master key, one party can transmit a session key to the other, encrypted using master key. This also called decentralized key distribution.

(iv) If A and B each has an encrypted connection to a third party C, C can deliver a session key on the encrypted links to A and B. This method is called centralized key distribution.

Due to Secured HF Transmission System where both stations are far away and using end-to-end encryption, manual delivery of session key is awkward. Here session key will change rapidly depending on the number of stations involve and communication had occurred. Therefore, session key supplied should be dynamically, and the solution of this is using decentralized key distribution technique.

Because the trusted third party is not involve directly in communication, both parties need master key which is consist authentication key and session key distribution key. The master key management is handled or programmed by trusted third party (Mils, 2004). By using master key, session key is distributes using block cipher AES 128 bits. The rest of the communication than occurs confidentially using a proprietary stream cipher. The security of Secured HF Transmission System was provided based on symmetric cipher system which need both parties have same secret key. In practice, GSM communication also uses symmetric cipher system where A3 block cipher used for authentication and A5 stream cipher for confidentiality (Quirke, 2004).

2.10 Examples of application for HF transmission system

HF e-mail systems such as Sail Mail (SailMail, 2004), and Cruise email (Cruiseemail, 2004) are capable for data transmission via HF medium and now available in the market. Both commercial systems also support the messaging system but unfortunately they do not have features for authenticity and confidentiality. They are needed because the HF medium is free and low cost of infrastructure setup compare with satellite system. By using the advances in High Frequency radio, these systems can be sent and received in the most remote areas. Besides, the communications is easy and transparent to the user because the users have complete controls of the radio and modem.

EasyTransfer is another system developed by SCS PC Software that allowed the communication via HF medium (Pactor, 2004). EasyTransfer (for Win98 and above) is a program developed for binary file transfers between two computers and it is using PACTOR coding for data transmission. The graphical user interface is similar to some well-known FTP clients, which are used for file transfers via the Internet. In addition to the file transfer, EasyTransfer has a chat mode to exchange hand typed messages. With that, EasyTransfer is the ideal tool to exchange digital information over unlimited distances through HF medium.

The Winlink 2000 (WL2K) radio-email digital network system is the software that is capable to extend with the amateur radio to provide data transmission over HF medium (Winlink, 2000). It was developed by Winlink Development Team to assist the mobile or remotely located user, and to provide emergency email capabilities to community agencies. Because of this, WL2K supports a clean simple interface to the Internet SMTP e-mail system. Using own B2F format, any message sent or received may include multiple recipients and multiple binary attachments. The radio user's email address, however, must be known to the system as a radio user or the message will be rejected. This simple Internet interface protocol has an added benefit in case of an emergency where local services are interrupted and the system can use by non-Amateur groups as an alternative to normal SMTP email. Connecting to any one of the WL2K publicly used PMBOs (Participating Network Stations) via HF (radio) or the specialized non-public PMBOs, can immediately and automatically connect a local amateur station to the Internet for emergency traffic. Using MS Outlook or MS Outlook Express, the Paclink mini-email server can replace a network of computers (behind a router) as a transparent substitute for normal SMTP mail (Winlink, 2000). WL2K uses no external source for sending or receiving Internet email. It is a stand-alone function, which interacts directly with the internet rather than through any external Internet service provider.

Communication through HF medium whether using email or messaging system is still not perfect without having security features. It is important to make the communication with authentication, confidential and integrity. Primarily, security to the military is to avoid their enemy from getting the secret information. Second entities that need this feature in their system are anyone that involved in business. This is because they need to protect their asset or secret information from their business competitor. Some of the messaging systems that had security features are System 700 that is produced by Mils Electronic (Mils, 2004), HC-6830 by Crypto AG (Crypto AG, 2004) and HF Email from Reids Radiodata (Reidsradiodata, 2004).

The Mils Electronic System 700 is not the only one to support messaging system but also others in communication like GSM, E-mail, HF radio and Telex. The M730 Cipher Machine handles the cipher function of this system. This is a Windows application for processing messages at a station of the System 700 network. Everything about encrypting and decrypting of messages, sending and receiving of ciphered messages and the administration of these messages happened here. A proprietary stream cipher algorithm encrypts and decrypts the messages. M730 also provides an authentication algorithm to provide authentication functions.

The Crypto AG HC-6830 is a secure, state-of-the- art, fully ruggedized field communication station. It combines local security with secure communication via telephone or radio modem at the tactical and strategic levels. Special attention has also been paid to HF communication by integrating a very compact HF radio modem into the HC-6830. Due to its versatile design, it may be used for stationary, portable, vehicular, air-borne, ship borne and man packs applications. The unit provides secure message handling primarily for army, air force, navy, and military intelligence organizations and also non-military users such as police forces, international field organizations and diplomatic. As the HC-6830 is fully modular, the system may be upgraded at any time to accommodate future applications.

The HF Email produced by Reids Radiodata is distinguishing from the other commercial product. Unlike Sail Mail and Cruise email, this HF Email supported with the compression and security service to make the data transmission faster and secure (Reidsradiodata, 2004). This Reids Radio Data HF Email service gives us our own email address such as *rahim@reidsradiodata.com.au* so anyone anywhere in the world can send an email to us, all we need to do is connect to the email server and our email will automatically be downloaded to computer.

Finally, the HF Messenger™ (Soyer, 2001) created by Rockwell-Collins, France is advanced HF data communication software. It implements the NATO STANAG 5066 standard and uses Q9600 modem device implementing the MIL-STD-188-110B waveform and equipped with ALE capability. Besides, this system also provides stream cipher algorithm to ensure the transmission occurred secure. The main objective of this system is to permit personal computers to exchange text, files, facsimiles, images and pictures at data rates equivalent to current satellite radios over a HF medium. This system also provides wireless transmission between several HF users for broadcasting, multicasting or point-to-point with services in LAN operating environment. The main application offered by this system is HF e-mail for ground, tactical airborne and maritime.

2.11 Telemetry

SCADA is an acronym for Supervisory Control and Data Acquisition. As the name indicates, it is not a full control system but more focuses on the supervisory level or in other words telemetry or remote monitoring. One of the advantages of implementing the SCADA system is it has databases system that allows information collection, sharing and offline analysis. SCADA system is used in industrial and engineering applications to monitor and control distributed station remotely from a master location. Therefore, SCADA system usually covers a large geographical area.

A SCADA system consists of three main components, which are the field data interface devices or a Remote Telemetry/Terminal Unit (RTU), the communication medium, and human-machine interface or Graphical User Interface (GUI). A SCADA system gathers information at remote stations, transmit back the information to master station through a communication medium and display the information in organized fashion and store information in database to allow future analysis.

2.11.1 Tanjung Tuan Lighthouse VHF Telemetry

Lighthouse telemetry is an example of SCADA system. A visit to Tanjung Tuan Lighthouse, Port Dickson was conducted to understand a SCADA system in practical application. Tanjung Tuan Lighhouse has been equipped with electric distribution line. A generator set is used as back up power source. Main light is the ac lamp that will only transmit white light when supplied with rated current. Motor is used to rotate pedestal in a fixed velocity to provide a flashing fog signal. Photo sensor is used to turn on the light system when low visibility. Figure 2.7 shows the lighthouse system block diagram.

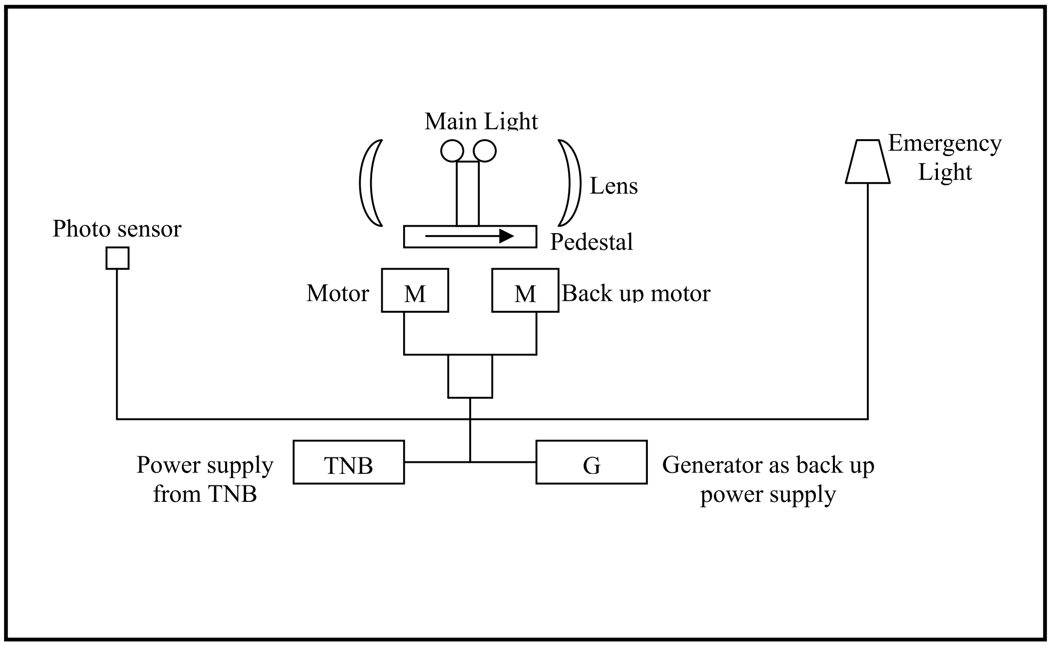


Figure 2.7 Lighthouse system block diagram

The lighthouse VHF telemetry is carried out by RF Comm. Sdn. Bhd. using a VHF transceiver, model Motorola GM300 and a Kantronics Modem. The purpose of this lighthouse telemetry is to obtain a remote picture of the condition at the lighthouse. The VHF telemetry system transmits the following information from lighthouse to headquarter:

(i) Power supply
(ii) Generator
(iii) Motor
(iv) Main light
(v) Standby light
(vi) Emergency light
(vii) Back up batteries

From SCADA system, any problem at the lighthouse can be trace and further action can be made immediately.

2.12 Conclusion

HF communication is important as an alternative for long distance communication due to low cost equipment setup and being completely under national control. With the present technology in digital signal processing, advance communication and adaptive radio technology, digital information is not only possible to be transmitted over HF radio but also more reliable and error free transmission. Security features such as authentication and confidentiality will ensure that only the authorized parties communicate with confidence not to unauthorized third parties. By understanding the existing system in market and technology behind it, the proposed system will develop to achieve the objective to exchange an image over HF radio.

CHAPTER 3

STREAM CIPHER ANALYSIS

The broadcast nature radio of communications such as in the HF (High Frequency) spectrum exposes the transmitted information to unauthorized third parties. Employing cipher system ensures confidentiality. For bulk transmission of data, stream ciphers are ideal choices over block ciphers due to the faster implementation speed and do not introduce error propagation. Thus, this chapter will describe the theory of stream cipher algorithm, which contains linear feedback shift register (LFSR) and nonlinear combining function. By using a common key length and worst-case conditions, the strength of several stream cipher algorithms are evaluated based on statistical tests, correlation attack, linear complexity profile and nonstandard test. The best algorithm is the one that exceeds all of the tests.

3.1 Stream Cipher

The stream cipher (Beker and Piper, 1982) is a symmetric cipher that is described in Figure 3.1. Unlike the block cipher, the stream cipher enciphers the plaintext one bit at a time and only utilizes the confusion characteristics not diffusion of the cipher system. This is because each character of the cryptogram is independent of each other. The main component of the stream cipher is the keystream generator that is shown in Figure 3.2. Various types of stream ciphers can be generated based on the choice of the combining function and the linear feedback shift registers (LFSR).

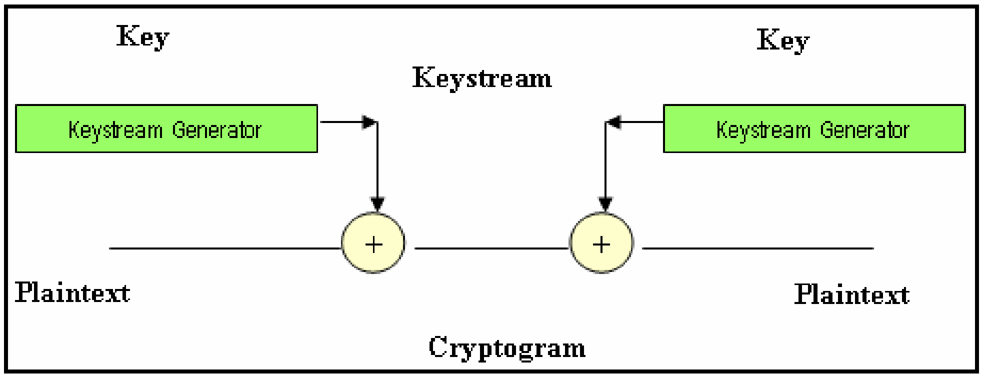


Figure 3.1: Block Diagram of stream cipher.

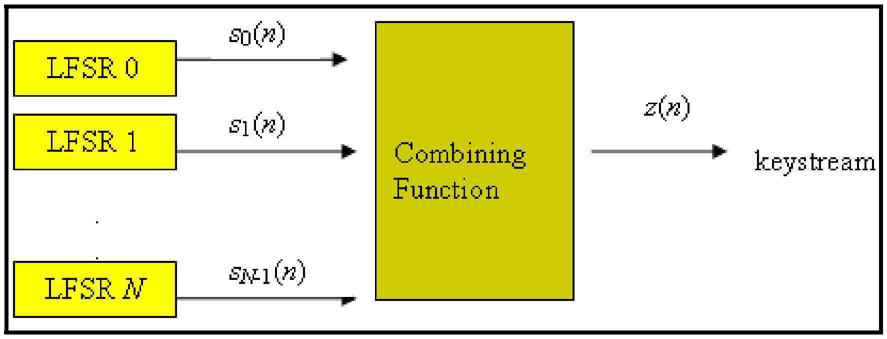


Figure 3.2: Block diagram of keystream generator

Each of the linear feedback shift registers (LFSR) that form the keystream generators are shown in Figure 3.3. The combining function can be any logic functions either linear or nonlinear combination depending on algorithm.

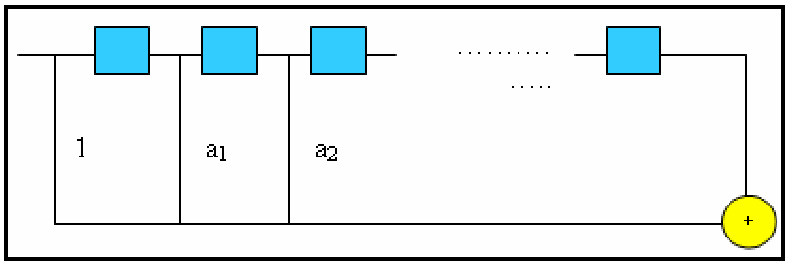
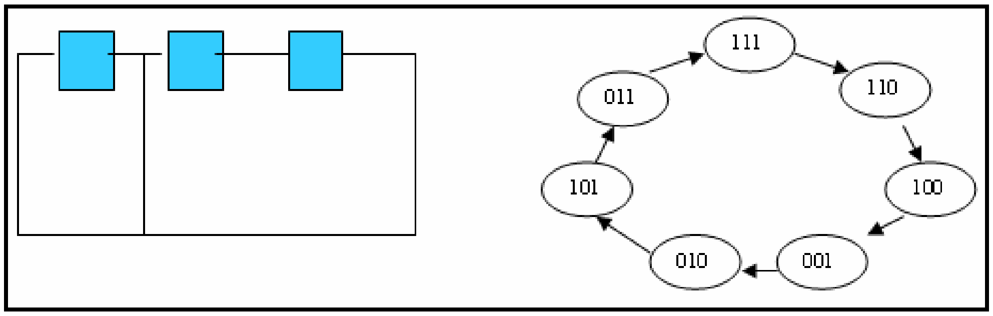


Figure 3.3: A general case *N*-length linear feedback shift register (LFSR).

3.1.1 Linear Feedback Shift Register (LFSR)

The LFSR is a finite state machine that is described by a sequence of states and it output is the pseudorandom sequence. An example of a 3-stage LFSR and its state diagram are shown in Figure 3.4.



(a) (b)

Figure 3.4: (a) 3-Stage LFSR. (b) State Diagram of 3-stage LFSR.

If the initial condition is chosen as $(111)_2$, the resulting sequence is

$$s(n)=[11100101110010111 0010\ldots\ldots] \tag{3.1}$$

In this example, the number of states is 7 or equal to 2^3-1. Except for the initial condition $(000)_2$, any state can be chosen as the initial condition, and the resulting sequence has a period of 7.

The output of a N_c stage LFSR is defined by a recursion relationship

$$s(n) = \sum_{l=1}^{N_c} c(i).s(n-i) = c(1).s(n-1) \oplus c(2).s(n-2) \oplus ...... \oplus c(N_c).s(n-N_c) \tag{3.2}$$

where $c(i)$ represents the feedback coefficients, the operation $\oplus$ represents a modulo 2 addition or exclusive-or operation, and the operation '.' represents an AND function.

The coefficients of the LFSR can be defined by $f(x)$ polynomial over GF(2). For the N_c LFSR defined in Equation (3.2), the $f(x)$ polynomial over GF(2) that described the coefficients is

$$f(x) = 1 + \sum_{i=1}^{N_c} c(i).x^i = 1 + c(1).x^1 + c(2).x^2 + ...+ c(N_c).x^{N_c} \tag{3.3}$$

The polynomial is irreducible if it is divisible by 1 and by itself. If $f(x)$ and $g(x)$ are two polynomials over GF(2), they are irreducible if GCD($f(x)$,$g(x)$)=1. Examples of reducible and irreducible polynomials are

$$f(x) = 1 + x^1 + x^2 + x^3 = (1+x)(1+x^2) \qquad \text{(reducible)} \tag{3.4}$$

$$f(x) = 1 + x^2 + x^3 \qquad \text{(irreducible)} \tag{3.5}$$

An irreducible polynomial of order N_c over GF(2) such that $f(0) \neq 0$, it has an exponent e if $f(x)/(1+x^e)$. The polynomial is primitive if its exponent is 2^{Nc}-1. A primitive polynomial of order N_c ensures that the resulting sequence repeats itself at every 2^{Nc}-1 regardless of the choice of the initial condition except for zero value. Table 3.1 shows example of primitive polynomial from order 2 to 8. Further examples are found in (Press and Teukolsky, 1992; Menezes *et al.*, 1996).

Table 3.1: Examples of primitive polynomial from order 2 to 8.

Degree	Polynomial
2	$1+x+x^2$
3	$1+x+x^3$
4	$1+x+x^4$
5	$1+x^2+x^5$
6	$1+x^5+x^6$
7	$1+x^3+x^7$
8	$1+x^2+x^3+x^4+x^8$

If *f*(*x*) is a primitive polynomial over GF(2), then the generation function is

$$g(x) = \frac{\phi(x)}{f(x)(1+x^p)} = (s(0)+s(1)x+s(2)x^2+......+s(p)x^{p-1})(1+x^p+x^{2p}+.......) \qquad (3.6)$$

where $s(n)$ represents the generated sequence, $\phi(x)$ is the polynomial that defines the initial conditions, and p is the period of the resulting random sequence.

3.1.2 Worst Case Condition

A cipher system is secured as long as the attacker does not know the algorithm, the keys and equivalent plaintext and cryptogram. The algorithm is compromised if any one of these factors is known. This leads to the worst-case cryptographic conditions (Beker and Piper, 1982) that are

(i) The algorithm can completely be described.

(ii) A considerable amount of cryptogram is known

(iii) There is certain amount of cryptogram and its equivalent plaintext available.

For the first condition, the only security that can be provided by algorithm is in the key length. Attack based on an exhaustive keysearch of all the possible keys should not be possible within a reasonable time. Given the present computing technology, a 64-bit key is no longer considered safe compared to a 128-bit key. That is why a double or triple DES (Data Encryption Standard) block cipher is considered more secured compared to the basic DES algorithm. If a cryptogram is random, condition two is not valid since it is not possible to derive the plaintext from the cryptogram based on the statistics. Condition three is as the result of the known plaintext attack where it is possible to derive the keystream from the cryptogram and its equivalent plaintext. The strength of the keystream can be tested based on the correlation attack and the linear complexity profile. An algorithm that can be proven of its strength under the worst-case cryptographic condition is considered ideal. A good stream cipher system must have all these criteria (Beker and Piper, 1985):

(i) The mathematical equations describing the algorithms operation are so complex that, for all practical purposes, it is not possible to solve those using analytical methods and cost or time required to recover the message or key is too great.

(ii) Keystream should have a long period. If registers used have size N1, N2,…..Nr, the period is usually bounded by $(2^{N1}-1)(2^{N2}-1)\ldots(2^{Nr}-1)$.

(iii) The keystream should have good statistical properties that passed all the statistical test

(iv) The keystream should have a large LCP that any attempt to find an equivalent LFSR to reconstruct the entire keystream is infeasible.

(v) The keystream should be correlation immune

3.2 Keystream Generators

There are many different pseudorandom sequence generators applied to stream ciphering. The analysis focuses to stream ciphers based on structure of LFSR as discuss in previous section, which is a bit oriented keystream. The LFSR permits in simple way to obtain sequences of very high periods and furthermore with excellent statistics properties. This section describes stream cipher based on LFSR and nonlinear combining function.

3.2.1 Linear Generator

A set of *M* LFSR's are combined such that the output sequence is

$$z(n) = s_0(n) \oplus s_1(n) \oplus s_2(n) \oplus \ldots\ldots.. \oplus s_{M-1}(n) \tag{3.7}$$

where $s_0(n)$, $s_1(n)$ ……..$S_{M\text{-}1}(n)$ represents the outputs of LFSR 0 to *M*-1 (Beker and Piper, 1982). If *M* is chosen 3, then Equation (3.7) becomes

$$z(n) = s_0(n) \oplus s_1(n) \oplus s_2(n) \tag{3.8}$$

The LFSR used are defined by polynomials over GF(2) as shown

$$f(x) = 1 + x + x^2 + x^5 + x^{19} \tag{3.9}$$

$$f(x) = 1 + x^5 + x^{23} \tag{3.10}$$

$$f(x) = 1 + x^2 + x^{29} \tag{3.11}$$

3.2.2 Improved Geffe Generator

This keystream generator is based on a nonlinear combining function with three LFSRs (Menezes *et al.*, 1996). The output of the generator is

$$z(n) = s_0(n).s_1(n) \oplus s_0(n).s_2(n) \oplus s_1(n).s_2(n) \tag{3.12}$$

where $s_0(n)$, $s_1(n)$ and $s_2(n)$ are the output of the LFSR 0 to 2. The LFSR's used that is defined by polynomials as in Equation (3.9)-(3.11) in GF(2).

3.2.3 Summation Registers Generator

Unlike the Improved Geffe generator, this keystream has an internal memory in the combining function (Menezes *et al.*, 1996). The summation register is

$$< z(n), c_{out}(n) >= \sum (s_0(n), s_1(n), c_{in}(n)) \tag{3.13}$$

where $s_0(n)$ and $s_1(n)$ are the output of LFSR 0 and 1, $c_{in}(n)$ is the carry-in, $c_{out}(n)$ is the carryout and z(n) is the arithmetic sum of the input. Its equivalent Boolean equations are

$$z_0(n) = s_0(n) \oplus s_1(n) \oplus c_{in}(n) \tag{3.14}$$

$$c_{out}(n) = s_0(n).s_1(n) \oplus s_0(n).c_{in}(n) \oplus s_1(n).c_{in}(n) \tag{3.15}$$

Possible output for the generator can be chosen as

$$z(n)=z_0(n) \text{ if } c_{in}(n)=c_{out}(n-1) \tag{3.16}$$

$$z(n)=c_{out}(n) \text{ if } c_{in}(n)=z_0(n-1) \tag{3.17}$$

The configurations based on Equation (3.16) and (3.17) are known as summation register (z_0 output) and summation register (c_{out} output) respectively. The polynomials used in GF(2) are

$$f(x)=1+x^2+x^{29} \tag{3.19}$$

$$f(x)=1+x^3+x^{41} \tag{3.20}$$

Like linear generator, summation register can also be expandable depending on numbers of LFSR used. Previous description is based 2 LFSR $s_0(n)$ and $s_1(n)$ respectively. For 3 LFSR nonlinear combinations, Boolean equations are

$$z_o(n)=s_0(n)\oplus s_1(n)\oplus s_2(n)\oplus c_{in}(n) \tag{3.21}$$

$$c_{out}(n)=s_0(n)s_1(n)\oplus s_0(n)s_2(n)\oplus s_0(n)c_{in}(n)\oplus s_1(n)s_2(n)\oplus s_1(n)c_{in}(n)\oplus s_2(n)c_{in}(n) \tag{3.22}$$

where $s_0(n)$, $s_1(n)$ and $s_2(n)$ are the output of the LFSR 0 to 2. The LFSR's used that is defined by polynomials as in Equation (3.9)-(3.11) in GF(2).

3.2.4 Multiplexing Generator

This cipher uses a standard digital electronic component called multiplexer (Beker and Piper, 1982). A multiplexer has many inputs but only one output. The set of inputs (often termed select lines) uses the state of LFSR 0, R_0 to provide an address for the multiplexer. The output of multiplexer is then merely the member of LFSR 1, R_1 specified by the address. Figure 3.5 shows the example of nonlinear combination for multiplexing generator. Polynomial used to provide R_0 and R_1 respectively defined in Equation (3.19) and (3.20) in GF(2).

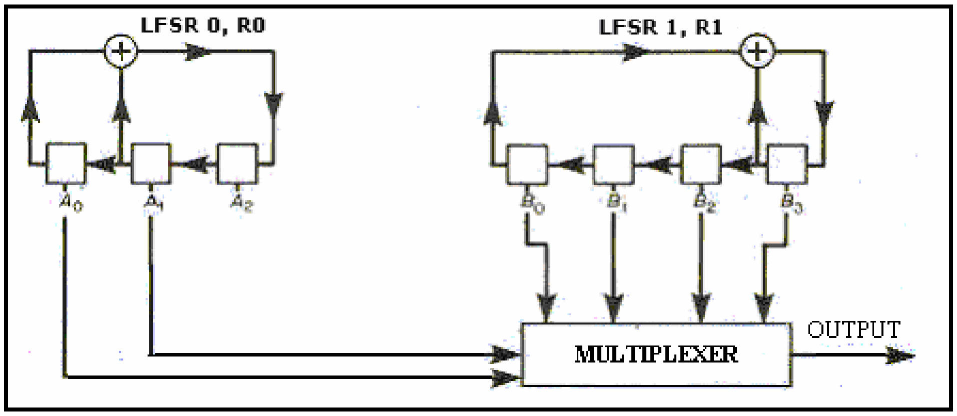


Figure 3.5: A 4 to 1 Multiplexing Generator

3.2.5 Shrinking Generator

Shrinking generator is a relatively new keystream generator that promises candidate for high-speed encryption applications (Schneier, 1996). This cipher uses 2 LFSR's for nonlinear combination that LFSR 0, R_0 is used to select a portion of the output sequence of a second LFSR 1, R_1. The keystream produced from the output sequence of R_1 as shown in Figure 3.6

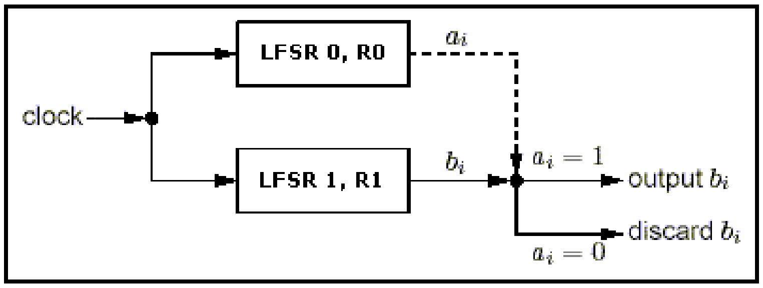


Figure 3.6: The Shrinking generator

Instead of using LFSR R_0 to select sequences of LFSR R_1, modifying the condition of selector is another method to implement this cipher. This modify cipher is called XOR-shrinking register as shown in Figure 3.7. The generator was modified by the researcher to increase the complexity of producing the keystream.

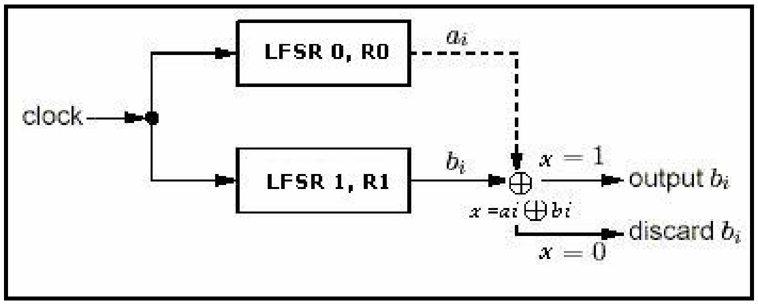


Figure 3.7: The XOR-Shrinking generator

Both shrinking and XOR-shrinking uses polynomials in Equation (3.19) and (3.20) in GF(2) for LFSR R_0 and R_1.

There is another type of shrinking cipher called self-shrinking generator (Schneier, 1996). This cipher only uses single LFSR. A pair of bits from LFSR was taken and if the first bit in the pair is 1, the output of the generator is the second bit. But if not, the pair will discard and same process occurs for next clock. The polynomials used in GF(2) is

$$f(x) = 1 + x^2 + x^3 + x^{64} \tag{3.23}$$

3.2.6 Variable-Memory Binary Generator (Memory Generator)

Variable-Memory Binary Generator also called memory generator needs three LFSRs, R_0, R_1, R_2 respectively and a memory to implement. (Golic and Mihaljevic, 1990). First, the output of R_1 is read out of the memory location addressed by the read address becomes a keystream sequences. Second, the output bit of R_0 is written into the memory location addressed by the write address R_2. Non-linear combinations for this cipher more like substitutions as shown in Figure 3.8.

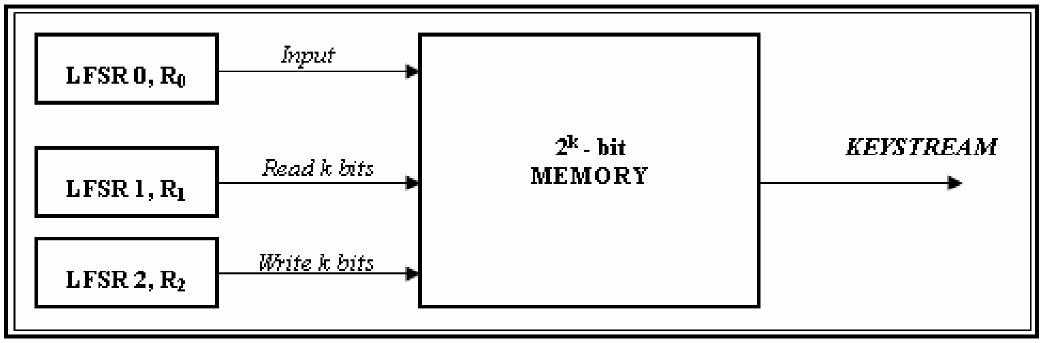


Figure 3.8: The Variable-Memory Binary generator

For analysis purpose, two types of memory are used, that are 16 and 64 addresses. Polynomials involved for all LFSRs are defined in Equation (3.9)-(3.11) in GF(2).

3.2.7 W7 Generator

The last generator that will be used in the research is the W7 generator. Actually, this generator designed to produce a keystream in byte oriented for more suitable in software implementation. However, the generator still uses LFSR as a basic structure, which combines 3 LFSR as shown in Figure 3.9. Therefore 8 basic structures in parallel are needed to supply each byte of keystream. Due to its fundamental, the research will analyze the basic structure that produces keystream in bit oriented. Either the strength or weakness of this structure will influence the whole of W7 generator.

The W7 cipher does not use the output bit directly from LFSR. Instead, it uses a nonlinear filtering function that is a combination of several bits in the LFSR (Thomas and Anthony, 2002). The Figure 3.9 below shows the combination of each state of LFSR in W7 generator.

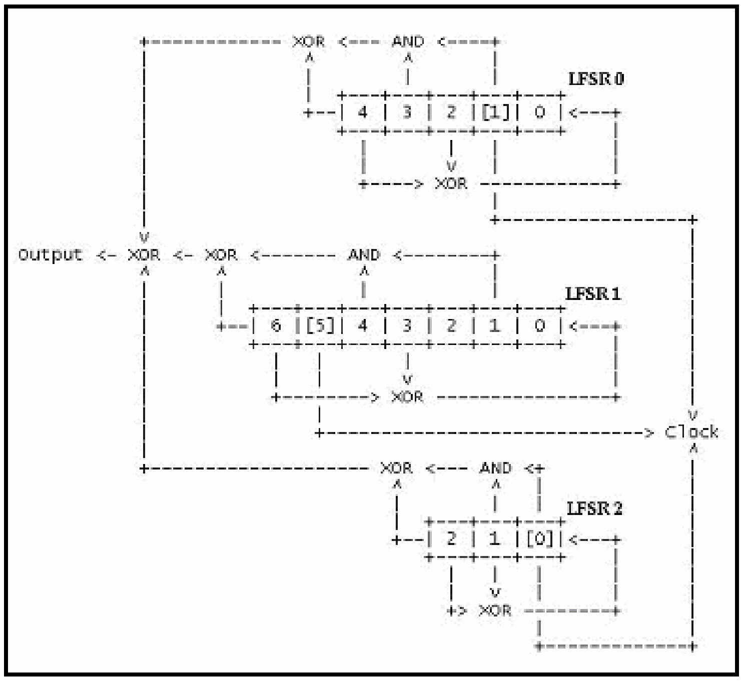


Figure 3.9: The W7 Generator

The output of each correspond LFSR is the exclusive-OR of two quantities which are the LFSR output and the output of logical-AND. For example, in Figure 3.7, the output of LFSR 0 is the result of exclusive-OR between bit 4 and logical AND of bits 3 and 1. Finally, the random keystream produced from the exclusive OR of the output of 3 LFSRs

$$z(n) = s_0(n) \oplus s_1(n) \oplus s_2(n) \tag{3.24}$$

where $s_0(n)$, $s_1(n)$ and $s_2(n)$ are the output of the LFSR 0 to 2. In addition, the 3 LFSRs together also determine when each shift register is clocked. One bit in each register is designated as the clock tap for that register which represented by "[]" in Figure 3.9. At each clock cycle, the majority value for those three taps determines which LFSR actually advance. Only those LFSR whose clock taps agree with the majority will advance. The LFSR's used that is defined by polynomials as in Equation (3.9)-(3.11) in GF(2).

3.3 Tests for Keystream Generator

There are several tests that can be used to quantify the strength of stream ciphers. Standard tests that are independent of the algorithm are statistical tests, correlation attack and linear complexity profile. Nonstandard test specific to the algorithm based on the guess-and-determine attack is also used.

3.3.1 Statistical Tests

A binary sequence is said to be random if there is no obvious relationship between the individual bits of the sequence. Since the sequence generated by the LFSR is periodic with a period *p*, then it is not considered a true random sequence but is referred as a pseudorandom sequence or a pn (pseudonoise) sequence. For this class of sequences, the randomness postulates by Golomb (Golomb, 1967) is applicable. If the period *p* is large, it is of interest to evaluate the randomness of the sequence within an observation interval that is referred as the local randomness. The statistical tests are derived from hypothesis testing and the standard statistical tables utilized are found in (Johnson, 1992). A set of statistical tests applicable is frequency test, serial test, poker test, autocorrelation test and runs test (Beker and Piper, 1982).

3.3.1.1 Frequency Test

The test check for the distribution of 1's and 0's present in a binary sequence. If N is the observed sequence length, the numbers of 1's N_1 and 0's N_0 present should be equally distributed at $N/2$. The calculated chi-square value is

$$\chi^2 = \frac{(N_1 - N_0)^2}{N} \tag{3.25}$$

From the statistical tables, the chi-square value for 5% significant level is 3.84. Accept the sequence if the computed chi-square value is less than the tabulated value.

3.3.1.2 Serial Test

This test is used to check the transition characteristics of the sequence that is '00','01','10', and '11'. For N length sequence, the number of transitions N_{00}, N_{01}, N_{10}, and N_{11} should be equal at $N/4$. The calculated chi-square value is

$$\chi^2 = \frac{4}{N-1}\sum_{i=0}^{1}\sum_{j=0}^{1}\left(N_{ij}\right)^2 - \frac{2}{N}\sum_{i=0}^{1}N_i^2 + 1 \qquad (3.26)$$

For 5% significant level, the tabulated chi-square value is 5.99. A sequence that has calculated chi-square values less than this value is acceptable.

3.3.1.3 Poker Test

N length sequence is segmented into blocks of M bits and the total number of segments is N/M. Within each segment, the integer value can vary from 0 to $m=2^M-1$. The objective of this test is to count the frequency of occurrence of each M length segment. If the frequencies of occurrence are $f_0, f_1, f_2, \ldots\ldots f_{m-1}$ then f_0 is the frequency of occurrence for a segment with an integer value of zero. Ideally, all the frequency of occurrences should be equal. If the mean of the frequency of occurrence is

$$F = \sum_{i=0}^{2^M-1} f_i \qquad (3.27)$$

then the chi-square value is

$$\chi^2 = \frac{2^M}{F}\sum_{i=0}^{2^M-1} f_i^2 - F \qquad (3.28)$$

For a significant value of 5%, the calculated chi-square value is compared with the table for a degree of freedom of 2^M-1. The sequence is accepted if the computed chi-square value is less than the table value. For analysis purpose, M is equal to 4 bits and the degree of freedom is 2^4-1 as well. Thus, the calculated chi-square value is 25 for a chosen significance value of 5 percent.

3.3.1.4 Autocorrelation Test

The autocorrelation function measures the similarity between the elements of a binary sequence. It is defined as

$$R_{ss}(m) = \sum_{n=0}^{N-m-1} s(n)s(n-m) \qquad 0 \le m \le N-1 \tag{3.29}$$

where m is the number of shifts and N is the number of bits in the sequence.

For a random sequence, the autocorrelation function $R_{ss}(m)$ is approximately Gaussian with mean of 0.5(N-m) and variance 0.25(N-m) that is obtained from the z tables. If a 5 percent significant level is chosen, the sequence is rejected if calculated z value is

$$\left| \frac{R_{ss}(m) - 0.5(N-m)}{0.5\sqrt{N-m}} \right| > 1.96 \tag{3.30}$$

The number of shifts chosen for analysis is 19 and it is desired to count the number of shifts where the calculated z value is within the significant value of 5 percent. Ideally, the desired number is 19/19.

3.3.1.5 Runs Test

The sequence is divided into contiguous stream of 1's that is referred as blocks and contiguous stream of 0's that is referred as gaps. If r_{0i} is the number of gaps of length i, then half of the gaps will have length 1 bit, a quarter with length 2 bits, and an eighth with length 3 bits. If r_{1i} is the number of blocks of length i, then the distribution of blocks is similar to the number of gaps.

3.3.2 Correlation Attack

A pseudorandom sequence $z(n)$ is generated by a combination of N LFSR where $s_0(n)$, $s_1(n)$ ….. $s_N(n)$ and p_0, p_1 ….. p_N are their input sequences and periods respectively in Figure 3.2. There is a possibility that any one of the input sequences will leak into the output $z(n)$. A sequence is said to be N-th order correlation immuned if it is not possible to correlate any combination of m input sequence to the output (Siegenthaler, 1984).

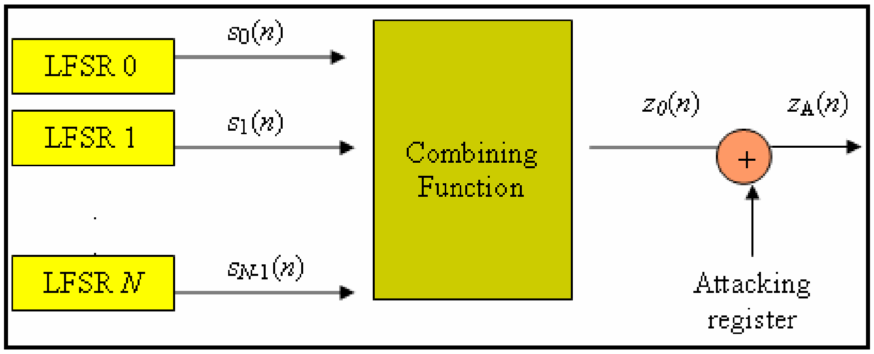


Figure 3.10: Methodology for performing correlation attack on a keystream generator

For a pseudorandom sequence that is proven statistically random, it is desired to find a sequence from an external register that is correlated to this sequence. The following block diagram in Figure 3.10 explains how this is done. The setting of the attacking register to anyone of the input register will result in the resulting sequence $z_0(n)$ to be nonrandom. The randomness of $z_A(n)$ is quantified by performing a statistical test such as frequency test on the sequence.

3.3.3 Linear Complexity Profile

If N length sequence is

$$s(n)=[\ s(0)\ s(1)\ s(2)\ \ldots\ldots\ s(N)] \tag{3.31}$$

then the linear complexity of the sequence, denoted by $L(N)$, is the length of the shortest LFSR that will generate the first N terms of $s(n)$. The properties of the linear complexity for random sequence $s(n)$ and $r(n)$ are

(i) For any $N \geq 1$, the linear complexity of a sequence $s(n)$ satisfies $0 \leq L(N) \leq \mathrm{N}$.

(ii) $L(N)=0$ if and only if $s(n)$ a zero sequence of length N.

(iii) $L(N)=N$ if and only if $s(n)=[0,0,0,0\ \ldots\ 1]$.

(iv) If $s(n)$ is periodic with period N, then $L(N) \leq N$.

(v) If the linear complexity of $s(n)$ and $r(n)$ are $L(N)$ and $L(M)$ respectively, the linear complexity of a sequence

$$\mathrm{z}(n)=s(n)+r(n) \tag{3.32}$$

Its relation to $L(N)$ and $L(M)$ is

$$L(P) \leq L(N)+L(M) \tag{3.33}$$

If $s(n)$ sequence is defined as in sequence (3.31), then the linear complexity profile L_N of the sequence up to N is

$$L_1, L_2, \ldots\ldots L_N \tag{3.34}$$

Ideally, the linear complexity profile of a random sequence will increase linearly with the n. If the linear complexity approaches a constant value L, the resulting L-th length LFSR can be used to regenerate the random sequence. For this analysis, Berlekamp-Massey algorithms used as Linear Complexity Profile test and details of the algorithm can be found in (Massey, 1969). Analysis was done based on 10,000 bits sequences that provided by each keystream generator.

3.3.4 Guess and Determine (GD) Attack

Guess and Determine (GD) is a nonstandard and effective method in analyzing stream ciphers. By considering the worst-case condition, this attack will exploit the relationships between internal values (such as the recurrence relationship in a shift register) and the relationship used to construct the keystream values from the internal values (Hawkes and Rose, 2002). A GD attack guesses some internal values and then exploits the relationships to determine other internal values. The cipher is broken when a complete internal state has been determined from the guessed values. However, this attack limits on generators that uses more than one LFSR and their nonlinear functions is not complex where register value and keystream that is produced correlates either forward or backward processes.

From the study, Self-shrinking is uses only one LFSR and for XOR-Shrinking, W7 and both Memory Generators, their nonlinear combination are complex. Therefore, these ciphers are immune on GD attacks. The following are the summary of GD attacks that performed on stream ciphers during the study. The example of full processes on this attack can be found in Appendix A.

3.3.4.1 Multiplexing Generator

First, consider all these following assumptions:

(i) LFSR 0 become a selector and polynomial of LFSR 0 is GF(2^3):

(ii) $f(x) = 1 + x^2 + x^3$

(iii) LFSR 1 as input and polynomial of LFSR 1 is GF(2^4) : $f(x) = 1 + x^3 + x^4$

(iv) Amount of keystream is known. For example: *K(n) = 1,1,1,0,0,0,0,1*

(v) Complete knowledge of algorithm. In this case, the algorithm is using 4 to 1 multiplexer and X^3 and X^2 states as selectors.

Table 3.2: Truth table for both LFSRs

X^3	X^2	X^1
1	1	1
1	1	0
1	0	0
0	0	1
0	1	0
1	0	1
0	1	1
1	1	1

a) LFSR 0

X^4	X^3	X^2	X^1
1			
1			
	1		
			0
		0	
	0		
		0	
1			

b) LFSR 1

Then, guess the initial condition of LFSR 0. In this case, total guessing equal to 2^3. For each trial, the attackers will have the selector value of multiplexer and from this value; the binary bit for each state of LFSR 1 will be determined. To make it easy, build a truth table of LFSR 0 and LFSR 1 as shown in Table 3.2. Then, put the keystream bit by bit to each state of LFSR 1 depending on the selector value.

Table 3.2 shows that every row of truth table filled with the keystream. Finally, fill in the truth table for LFSR 1. From the truth table of LFSR 1, another secret or private key will appear and the algorithm not secure anymore. As a conclusion, the real strength of this algorithm depends on LFSR 0 and in this case, instead of 2^7 the real strength of Multiplexer Generator is 2^3. With reference to common key 64 bit, the strength of Multiplexing Generator is 2^{29} not 2^{64} as claimed.

3.3.4.2 Linear Generator

Linear Generator is built from linear combination of 3 LFSRs as discussed in previous section. In order to perform GD attack on this cipher, the attackers need to guess the initial condition at least for 2 LFSRs. Then, with some amount of keystream, reverse the process to determine the other initial condition of LFSR 2. Table 3.3 shows the example of the initial conditions required before reversing the process. Usually, the attackers will guess 2 smallest LFSRs to reduce number of trials. After GD attack, the real strength of Linear Generator reduces to 2^{42}.

Table 3.3: The value of LFSR 2 can be determined by reverse the linear process.

LFSR 0	1	1	1	0	0	1	0
LFSR 1	1	1	0	0	0	1	0
LFSR 2							
Keystream K(n)	1	0	1	0	1	1	1

3.3.4.3 Improved Geffe

Improved Geffe Generator is more complicated compared with linear generator. Beside linear function, it also had nonlinear combination, which is a logical-AND functions. However, it is still not immune from GD attacks. Unlike linear generator that attackers will guess 2 smallest LFSR, this time they need to guess the small and the larger LFSR together. Then, with some amount of keystream, the nonlinear combination could be reverse to determine the other initial condition of LFSR 1. Table 3.4 shows the example of the initial conditions and keystream that are required before reversing the process. Although it is not immune against GD attacks but this generator is better compare to linear generator with the real strength is 2^{48}.

Table 3.4: The value of LFSR 1 can be determined by reverse the generator process.

LFSR 0	1	1	0	0	0	1	0
LFSR 1							
LFSR 2	1	1	1	0	1	1	0
Keystream *K(n)*	1	1	1	0	1	1	0

3.3.4.4 Summation Registers

Summation 2 Registers generator consist 2 LFSRs that is combine each other to generate keystream. It also had an internal memory that gives an effect to the keystream generated. The attackers need to guess each one of the LFSR initial conditions and also the initial value of an internal memory as well. However, it is not require guessing the initial value of internal memory because it is not considered as a key. Under worst-case conditions, the security that algorithm had is a secret key. Thus, it can be assumed that the attacker has complete knowledge of algorithm including the initial value of an internal memory. Assume that initial value is “0”. Now, guess one of the LFSR and usually the attackers will guess the smaller LFSR. As describe in previous subsection, the smaller LFSR is LFSR 0.

From the known initial condition of LFSR 0, internal memory and some keystreams, the attackers can guess the output sequence of LFSR 2 by reversing the algorithm process. The initial value for each component is shown in Table 3.5.

Table 3.5: The values of LFSR 1 and internal memory can be fulfilling by reverse the algorithm process

LFSR 0		1	1	1	0	0	1	0
LFSR 1								
Int. Mem. S(n)	0							
Keystream,K(n)		1	1	1	0	0	0	1

.

By guessing the initial condition of LFSR 0, the attackers recovered another initial condition of LFSR 1 that is a part of secret key. From the analysis, the real strength of this algorithm depends on the smaller LFSR used. In this case, the smaller LFSR used is LFSR 0. By referring to the described algorithm in previous section, instead of 2^{64} the real strength of this algorithm is 2^{29}.

Summation 3 Registers is another type of generator in summation register family. The difference between this algorithm and previous one is the number of register or LFSR used. This algorithm needs three LFSRs to combine them to generate keystream as described before. The method to break this algorithm is similar to previous but this time the attackers need to guess more than 1 LFSR. In order to minimize the number of trials, the attackers will guess 2 smallest LFSR as shown in Table 3.6.

Table 3.6: The value of LFSR 2 and internal memory can be fulfilling by reverse the algorithm process.

LFSR 0		1	1	1	0	0	1	0
LFSR 1		1	1	0	0	1	0	1
LFSR 2								
Int. Mem S(n)	0							
Keystream K(n)		1	1	1	0	0	0	1

From the GD attacks, the real strength of algorithm is 2^{42}. Although it is not as good as claimed, 2^{64} but this algorithm is better than the previous.

3.3.4.5 Shrinking

Shrinking Generator needs 2 LFSRs in order to generate sequence of keystream, which are LFSR 0, and LFSR 1 respectively. The output of LFSR 0 will determine whether output of LFSR 1 become a keystream or not. This condition increases the LCP linearly with sequence but at the same time it reduces the number of keystream-produced compare with actual sequence of LFSR 1.

To verify the real strength of algorithm, attackers have to guess each one of this LFSR. Different LFSR chosen will cause different reverse process and also different number of trials as well. Usually, LFSR 0 uses smaller polynomial compare with LFSR 1. Because of that, attackers will guess the LFSR 0 and from the known keystream, backward process performed in order to get the initial condition of LFSR 1. Table 3.7 shows the example of initial condition required before making reverse processes.

Table 3.7: By doing the reverse process of algorithm, all initial conditions of LFSR 1 can be determined.

LFSR 0	1	1	0	0	1	0	1
LFSR 1							
Keystream K(n)	1	1	1	0	0	0	1

From the guess and determine attack, the number of trials or complexity to break this algorithms is 2^{29} not 2^{64} anymore.

3.4 Register Setup and Initial Condition

Keystream generator should provide a randomness of sequence for any initial condition in order to make it usable in implementation because in practical, the initial condition produced randomly. To verify whether this characteristic provides by keystream generator or not, 1000 initial conditions were chosen randomly for each polynomial. For the Linear, Improved Geffe, Summation 3 Registers and both Memory Generators, their example of 20 random initial conditions for LFSR 0, LFSR 1 and LFSR 2 respectively are described in Table 3.8 to Table 3.10.

Table 3.8: The initial value for polynomial f(x)=1 + x + x^2 + x^5 + x^{19}

Bil	Initial Condition
1	1111111111111111111
2	1000000000000000000
3	1010101010101010101
4	1100110011001100110
5	0000111100001111000
6	1110010000000000000
7	0011110001110011010
8	1111111111111111111
9	1000100110101011110
10	1111111011011100101
11	1111111111111111110
12	0111111111111111111
13	0101010101010101010
14	0011001100110011001
15	1111000011110000111
16	0001101111111111111
17	1100001110001100101
18	1111111111111111100
19	0111011001010100001
20	0000000100100011010

Table 3.9: The initial value for polynomial $f(x)=1+x^5+x^{23}$

Bil	Initial Conditions
1	11111111111111111111111
2	11111111111111111111111
3	01101101101101101101101
4	10111011101110111011101
5	11111111110000000000111
6	11001100110011001100110
7	11111000001111000011100
8	11100011100011100011100
9	00000001001000110100010
10	10101010101010101010101
11	00110011001100110011001
12	00000111110000111100011
13	00011100011100011100011
14	11111110110111001011101
15	01010101010101010101010
16	11111111111111111111000
17	11111111111111111110000
18	10010010010010010010010
19	01000100010001000100010
20	00000000001111111111000

Table 3.10: The initial value for polynomial $f(x)=1+x^2+x^{29}$

Bil	Initial Conditions
1	11111111111111111111111111111
2	10000100001000010000100001000
3	11100111001110011100111001110
4	00100000000000000000100000001
5	10011110100111101001111010011
6	10110011100011110000111110000
7	11111111110000000000011111111
8	01001100011100001111000001111
9	01111000100110101011110011011
10	10110011100011110000111110000
11	11111111111111111111111100000
12	01111011110111101111011110111
13	00011000110001100011000110001
14	11011111111111111111000000001
15	01100001011000010110000101100
16	01001100011100001111000001111
17	00000000000111111111100000000
18	10110011100011110000111110000
19	10000111011001010100001100100
20	01001100011100001111000001111

The example random initial conditions for both LFSR that is used for the Summation 2 Registers, Multiplexing, Shrinking and XOR-Shrinking generator are shown in Table 3.11 and Table 3.12. And finally, for Self-shrinking generator, its random initial conditions are described in Table 3.13.

Table 3.11: The initial value for polynomial $f(x) = 1 + x^2 + x^{29}$

Bil	Initial Conditions
1	11111111111111111111111111111
2	10101010101010101010101010101
3	10011001100110011001100110011
4	11100100000001010011100101110
5	00100011010001010110011110001
6	11100011100011100011100011100
7	00000000000000000000000000001
8	10000000000000000000011101100
9	11110000111100001111000011110
10	10110011100011110000111100001
11	11111111111111111111111000000
12	01010101010101010101010101010
13	01100110011001100110011001100
14	00011011111110101100011010001
15	11011100101110101001100001110
16	00011100011100011100011100011
17	11111111111111111111111111110
18	01111111111111111111100010011
19	00001111000011110000111100001
20	01001100011100001111000011110

Table 3.12: The initial value for polynomial $f(x) = 1 + x^3 + x^{41}$

Bil	Initial Conditions
1	11111111111111111111111111111111111111111
2	11101100111011001110110011101100111011001
3	01001100011100001111000001111100000011111
4	00000000000000000000111111111111111111111
5	10011010101111001101111011110000000100100
6	00000001001000110100010101100111100010011
7	00000000000000000000100110011001100110011
8	10101010101010101010100000000001111111111
9	00110011001100110011001100110011001100110
10	01001100011100001111000001111100000011111
11	10110011100011110000111110000011111100000
12	11001100110011001100110011001100110011001
13	01010101010101010101011111111110000000000
14	11111111111111111111011001100110011001100
15	11111110110111001011101010011000011101100
16	11111111111111111111111111111111110000000
17	00010011000100110001001100010011000100110
18	10110011100011110000111110000011111100000
19	11111111111111111111000000000000000000000
20	01100101010000110010000100001111111011011

Table 3.13: The initial value for polynomial $f(x) = 1 + x^2 + x^3 + x^{64}$

Bil	Initial Conditions
1	1111111111111111111111111111111111111111111111111111111111111111
2	1110110011101100111011001110110011101100111011001110110011101100
3	0100110001110000111100000111110000001111110000000111111100000000
4	0000000000000000000000000000000011111111111111111111111111111111
5	1001101010111100110111101111000000010010010011010101111001101111
6	0000000000000000010010001101000101011001111000100111001000110100
7	0000000000000000000000000000001001100110011001100110011001100110
8	1010101010101010101010101010101010101010100000000000001111111111
9	0011001100110011001100110011001100110011001100110011001100110011
10	0100110001110000111100000111110000001111101001100011100000100110
11	1111111111111111111101101110010111010100110000111011000011101100
12	1111111111111111111111111111110110011001100110011001100110011001
13	0101010101010101010101010111111111111111111110000000000000000000
14	1100110011001100110011001100110011001100111111111111111100000000
15	1011001110001111000011111000001111110000001111110000001111110000
16	1111111111111111111111111111111110000000111111111111111111110000
17	0001001100010011000100110001001100010011011101100111011001110110
18	1011001110001111000011111000001111110000001010101010101010101010
19	1111111111111111111100000000000000000000011111111111111111111000
20	0110010101000011001000010000111111101101101100110001110110110011

For all keystream generators, the simulation program was written in C++ language and by using small LFSR, the program is checked step-by-step process to verify the output at every stage in the algorithm. The verification of the generator can be found in Appendix A. Then, the keystream for each generator was analyzed to determine their statistical properties, correlation immunity and complexity.

The statistical test programs were checked by testing a number of large sequences that are well known to have good statistical properties confirming that they will pass the entire test. For correlation attack, the program was checked by XOR a sequence N length of LFSR with the output of external register using the same initial state and coefficient. The result from the frequency test should be equal to N. Finally for linear complexity profile, the program was checked by finding the linear complexity of a number of sequences from known linear feedback shift register.

The entire simulation program must working properly to ensure the results obtained from the analysis are accurate in order to determine the good stream cipher system.

3.5 Analysis Results

The analyses were performed using standard test such as statistical tests, correlation attack and linear complexity profile and also nonstandard test that is the guess-and-determine attack. The following are the results for each test that were made.

3.5.1 Statistical Test

The statistical test consists of 5 series of test and each series were performed with 1000 different initial conditions that were selected randomly as described in previous section. This is to determine the number of keys that will produce a statistically random sequence. In practice, session keys will generate randomly and not selected by any parties (Stallings, 2003). A good generator will present a good statistical characteristic in whatever key used. The summary of statistical test results is shown in Table 3.14.

Table 3.14: Results of statistical test for each generator

Bil	Generator	Frequency Test	Serial Test	Poker Test	Autocorrelation Test	Runs Test
1	Linear	830/1000	941/1000	1000/1000	18522/19000	920/1000
2	Geffe	956/1000	818/1000	732/1000	17962/19000	800/1000
3	Sum 2 reg. (z_0 output)	986/1000	975/1000	979/1000	18002/19000	863/1000
4	Sum 2 reg. (C_{out} output)	689/1000	760/1000	728/1000	18231/19000	981/1000
5	Sum 3 reg. (z_0 output)	1000/1000	984/1000	1000/1000	16748/19000	915/1000
6	Sum 3 reg (C_{out} output)	0/1000	0/1000	0/1000	1000/19000	691/1000
7	Multiplexing	963/1000	0/1000	0/1000	15562/19000	865/1000
8	Shrinking	992/1000	739/1000	981/1000	17316/19000	933/1000
9	XOR-Shrinking	987/1000	992/1000	663/1000	17726/19000	961/1000
10	**Self-Shrinking**	**998/1000**	**989/1000**	**993/1000**	**18578/19000**	**974/1000**
11	Memory Gen.(16Add)	842/1000	0/1000	0/1000	2082/19000	579/1000
12	Memory Gen.(64Add)	882/1000	636/1000	994/1000	12360/19000	937/1000
13	**W7**	**988/1000**	**994/1000**	**971/1000**	**18359/19000**	**969/1000**

Table 3.14 presents the number of keys that passed for each statistical test. Based on 95% significant level, a good generator should passes at least 950 over 1000 initial conditions or keys. This is true for only 2 generators and they are Self-

Shrinking and W7 generator. Thus, the probability of choosing a set of keys that generate a statistically random sequence is higher for these generators as compared to the Linear, Gaffe, Multiplexing, both Summation Registers (Z_0 and c_{out} output), XOR-shrinking, and both Memory (16 and 64 addresses) generator. Even though Self-Shrinking has good statistical properties but on average, the sequence length of LFSR to produce same amount of keystream with W7 is double. This is because the characteristic of Self-Shrinking itself that need 2 bits or more to produce 1 bit of keystream. Therefore, the processing time to produce keystream also increases.

For memory generators, the size of memory obviously influences their randomness. A large memory size will present a better keystream compare with smaller memory due to statistical characteristics. From the table, both Summation 2 and 3 registers (Z_0 output) give a good statistical result as compared to both Summation 2 and 3 registers (C_{out} output). Summation 3 register present (Z_0 output) present a better statistical characteristic as compared to Summation 2 registers (Z_0 output). From this observation, the number of register used in this generator influences their randomness.

The XOR-Shrinking generator, which modified by researcher also present better statistical results compared with the original Shrinking generator. However, it still not passed for 95% significant level.

3.5.2 Correlation Attack

This standard test is to examine the strength of each generator in terms of register correlation as explained in previous section. The test was conducted for each initial condition that was used in statistical tests. But the numbers of attack between generators are different because it depends on numbers of LFSR that was used inside the generator. The frequency test is performed to check the output of correlation attacks in order to verify the sequence of LFSR used into combining function leaks into keystream or not. The summary of correlation attacks is shown in Table 3.15. The strength of generators is presented as correlation immunity, which is the numbers of attacks that passes the frequency test.

Table 3.15: Result for Correlation Attacks

Bil	Keystream Generator	Correlation Immunity
1	**Linear generator**	**56 out of 60 were immune**
2	Improved Geffe	0 out of 60 were immune
3	Summation 2 registers (z_0 output)	25 out of 40 were immune
4	Summation 2 registers (C_{out} output)	3 out of 40 were immune
5	**Summation 3 registers (z_0 output)**	**54 out of 60 were immune**
6	Summation 3 registers (C_{out} output)	5 out of 60 were immune
7	Multiplexing	19 out of 40 were immune
8	**Shrinking**	**38 out of 40 were immune**
9	**XOR-Shrinking**	**38 out of 40 were immune**
10	**Self-Shrinking**	**19 out of 20 were immune**
11	Memory Generator (16 Addresses)	33 out of 60 were immune
12	**Memory Generator (64 Addresses)**	**50 out of 60 were immune**
13	**W7 Generator**	**58 out of 60 were immune**

From observation, Linear generator, Summations 3 Registers (Z_0 output), Shrinking, XOR-shrinking, Self-shrinking, Memory generators (64 addresses) and W7 generator present good performance where 80% of attacks were immune. For Multiplexing, Memory Registers (16 addresses) and Summation 2 Registers (Z_0 output), half of the possible attacks were successful. Others generators were absolutely not immune and can be easily broken by this attack. Notice that the strength of generator will reduce to 2^N trials with, N as the length of LFSR that leaks into keystream. With reference to Table 3.14, both self-shrinking and W7 generator that pass the statistical test are immune on correlation attack as shown in Table 3.15.

3.5.3 Linear Complexity Profile (LCP)

Linear Complexity Profile (LCP) is another standard test for measurement of strength, and one of the popular methods is Berlekamp Massey algorithm. Ideally, the linear complexity profile increases linearly with the sequence length. If the linear complexity becomes a constant with the increasing of sequence length, the maximum linear complexity profile is the equivalent length estimated coefficient of LFSR that can generate the sequence, and for analysis purpose, 10,000 bits keystream for each generator used. Ideally, the LCP for each generator should be half of sequence length, which is 5000. Below is the result of LCP for each generator.

Table 3.16: Result for Linear Complexity Profile test

Bil	Keystream Generator	Linear Complexity Profile (Maximum)
1	Linear generator	71
2	Improved Geffe	1665
3	Summation 2 registers (z_0 output)	**5000**
4	Summation 2 registers (C_{out} output)	2378
5	Summation 3 registers (z_0 output)	**5000**
6	Summation 3 registers (C_{out} output)	2556
7	Multiplexing	**5000**
8	Shrinking	**5000**
9	XOR-Shrinking	**5000**
10	Self-Shrinking	**5000**
11	Memory Generator (16 Addresses)	**5000**
12	Memory Generator (64 Addresses)	**5000**
13	W7	**5000**

From Table 3.16, Linear generator, Improved Geffe and Summations Register (c_{out} output) is not secure against LCP attack. Others are immune that have large LCP, which increase linearly with sequence length until 5000. Which means that, 10,000 bit keystream is not enough to find their equivalent LFSR. From the LCP test, a relation between LCP and key length can be derived but limited for certain generators such as linear generator and summation 2 registers (c_{out} output). Their relations are as follows:

(i) Linear generator: $L_{max} = N_0+N_1+N_2$ = 19+23+29 = 71

(ii) Summation 2 registers (c_{out} output): $L_{max} = 2N_0N_1$ = 2(29)(41) = 2378

The summary of strength for each generator based on standard test is shown in Table 3.17. From the table, only two generators succeeded all statistical tests and immune for strength test. They are Self-Shrinking and W7 generator.

Table 3.17: Summary of strength based on standard test

Bil	**Generator**	**Freq. Test**	**Serial Test**	**Poker Test**	**Auto. Test**	**Runs Test**	**Corr. Attacks**	**LCP (Max)**
1	Linear	✖	✖	√	√	✖	√	✖
2	Geffe	√	✖	✖	✖	✖	✖	✖
3	Sum 2 reg. (z_0 output)	√	√	√	✖	✖	✖	√
4	Sum 2 reg. (C_{out} output)	✖	✖	✖	√	√	✖	✖
5	Sum 3 reg. (z_0 output)	√	√	√	✖	✖	√	√
6	Sum 3 reg (C_{out} output)	✖	✖	✖	✖	✖	✖	✖
7	Multiplexing	√	✖	✖	✖	✖	✖	√
8	Shrinking	√	✖	√	✖	✖	√	√
9	XOR-Shrinking	√	√	✖	✖	√	√	√
10	Self-Shrinking	√	√	√	√	√	√	√
11	Memory Gen.(16Add)	✖	✖	✖	✖	✖	✖	√
12	Memory Gen.(64Add)	✖	✖	√	✖	✖	√	√
13	W7	√	√	√	√	√	√	√

Indicator:

√ - Pass ✖ - Fail

3.5.4 Guess-and-Determine (GD) Attack

A Guess-and-Determine attack is called nonstandard test because this attack performs depends on generator. Different generators will produce different GD attacks. Because the key length is fixed 64 bits, so the best result for this attack is 2^{64}. Summary of GD attack is shown in Table 3.18.

Table 3.18: Result for Guess and Determine (GD) attack

Bil	Keystream Generator	Number of trials after GD attacks
1	Linear generator	2^{42}
2	Improved Geffe	2^{48}
3	Summation 2 registers (z_0 output)	2^{29}
4	Summation 2 registers (C_{out} output)	2^{29}
5	Summation 3 registers (z_0 output)	2^{42}
6	Summation 3 registers (C_{out} output)	2^{42}
7	Multiplexing	2^{29}
8	Shrinking	2^{29}
9	**XOR-Shrinking**	$\mathbf{2^{64}}$
10	**Self-Shrinking**	$\mathbf{2^{64}}$
11	**Memory Generator (16 Addresses)**	$\mathbf{2^{64}}$
12	**Memory Generator (64 Addresses)**	$\mathbf{2^{64}}$
13	**W7 Generator**	$\mathbf{2^{64}}$

Table 3.18 presents the results of Guess and Determine (GD) attack. There are 5 generators that were immune on this attack where their strength after the attack is 2^{64} same as they claimed. They are XOR-shrinking, Self-shrinking, both of Memory generators and W7 generator. While, for others the strength of generators were reduced to 2^{29}, 2^{42} and 2^{48} respectively.

Both generators that succeeded standard tests are immune of GD attacks. They are really robust and satisfy the properties of good stream cipher as mentioned in previous section. But, it does not mean that they are unbreakable. They could be break with another nonstandard or mathematical attack, which not consists in this study.

3.5.5 Discussion

After the analyses of 13 keystream generators, there are 2 cipher systems that pass all tests. They are Self-Shrinking andW7 stream ciphers. Due to the performance of computer technology at present in term of speed and memory space, both cipher system can be implemented easily on Secured HF Transmission System but only W7 generator is adopted. Based on the performance, this cipher system will guarantee the digital information that exchange through radio communication, which is confidential. For other cipher systems, analysis shows that they have some strength and weaknesses. However, it does not mean that they are useless because they are still applicable for implementation depending on application and information to protect.

Basically, the encryption purpose correlates with cover time. Cover time is defined as the length of time the encryption algorithm can protect plaintext when subjected to an attack (Nichols, 2002). The cover time should also consider the expected security value of the information and the existing computer technology that is presently available. Usually, longer cover time requires stronger encryption algorithm.

The time, T to crack the algorithms is

$$T = 2^L/R \tag{3.35}$$

where L is the key length and R is the processing rate expressed as key per second (Nichols, 2002). With current computer processing which is capable to process 100 million keys per second, the 128 bit key length is preferred because it would take 10^{20} years to search all possible keys. Due to Secured HF Transmission System, if the information is top secret, then the key should be increase to 128 bits key. Expanding the polynomial of W7 cipher system can do this but the structure of algorithm is still the same.

3.5 Conclusion

The stream cipher is a type of cipher system where the process of enciphering and deciphering is performed one bit at a type. This type of cipher is useful in noisy channel conditions such as in radio communication environment and bulk data transmission. Comparisons in performance are made for several stream ciphers based on the statistical test, correlation attack, linear complexity profile and guess-determine attacks. From analyses, a cipher system which succeeds all the tests is chosen to adopt in Secured HF Image Transmission System. It is the W7 cipher system.

CHAPTER 4

IMPLEMENTATION OF DQPSK HF MODEM

In digital communication, modulation and demodulation are important aspect to make communication possible. They are compromise with the type of channel propagation. As mention in Chapter 2, HF propagation is unpredictable and varying by time. Therefore the suitable method or technique for both modulation and demodulation are needed to increase the reliability and throughput during data transmission.

4.1 Differential Quadrature Phase Shift Keying (DQPSK) Theory

DQPSK is a derivation of Differential Phase Shift Keying (DPSK) where the two main characteristics of DQPSK and DPSK are the same; information is encoded in the phase transition and previous signal is used as the reference signal. The advantage of DQPSK is that it is more spectrums efficient, which make its transmission rate to be double compared to DPSK. DQPSK data transfer rate is twice the transfer rates of DPSK. In DQPSK, a symbol represents 2 bits of data, and this is achieved by encoding the data in the constellation as illustrated in Figure 4.1. The constellations of symbols are arranged in the Gray code pattern as shown in Table 4.1, so that the difference of every adjacent symbol is only one bit.

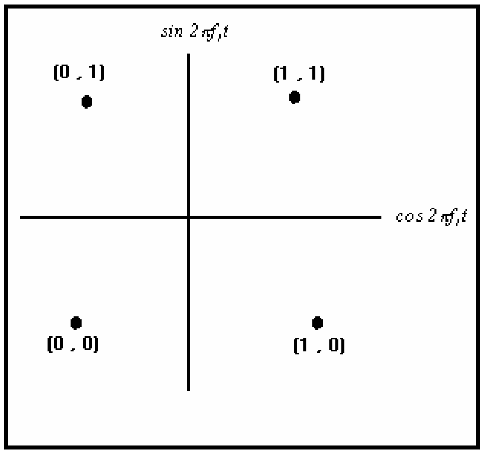
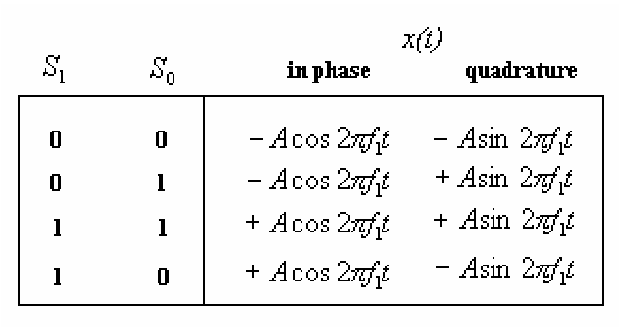


Figure 4.1: QPSK Constellation Diagram

Table 4.1: Arrangement of QPSK Symbols



		$x(t)$	
S_1	S_0	**in phase**	**quadrature**
0	0	$-A\cos 2\pi f_1 t$	$-A\sin 2\pi f_1 t$
0	1	$-A\cos 2\pi f_1 t$	$+A\sin 2\pi f_1 t$
1	1	$+A\cos 2\pi f_1 t$	$+A\sin 2\pi f_1 t$
1	0	$+A\cos 2\pi f_1 t$	$-A\sin 2\pi f_1 t$

4.1.1 Generation of DQPSK Signal

In differential encoding, the data are encoded in the phase transitions. The information is contained in the transition from ϕ_{k-1} to ϕ_k . Sequence encoded at the transmitter are represented as

$$a_k = a_{k-1}.s_k \oplus \overline{a_{k-1}}.\overline{s_k} \qquad (1)$$

where s_k is the true sequence and a_k is the encoded sequence. Generation of DQPSK signal for a given sequence 10011101 is shown in Table 4.2. Odd placing numbers is taken as the true sequence s_k and the differential encoding is produced by placing the initial condition as 1 in the encoder a_k. This process is repeated for the even placing numbers and both of the generated bits are grouped in one symbol.

Table 4.2: Generation of DQPSK Signal

sequence, s_k		1	0	0	1	1	1	0	1
encoder, a_k	1	1	0	1	1	1	1	0	0
Signal Transmitted									
ϕ	0	0	π	0	0	0	0	π	π
$\cos 2\pi f_1 t$	✓	✓		✓	✓	✓	✓		
$-\cos 2\pi f_1 t$			✓					✓	✓

4.1.2 Demodulation of DQPSK Signal

Structure of DQPSK receiver is shown in Figure 4.2. From practical point of view, this structure can only work if perfect synchronization is achieved, where no sample delay occurs in the start bit detection. If the detection is delayed by even one sample, the signal would be corrupted because the correlation part will correlate the incoming signal with cosine waveform and sine waveform, thus the result of the correlation is not accurate. The correlation procedure needs to be precise to 1 sample value. Differential modulation method does not actually need the perfect phase synchronization method, but the correlation part requires the perfect synchronization with the incoming signal.

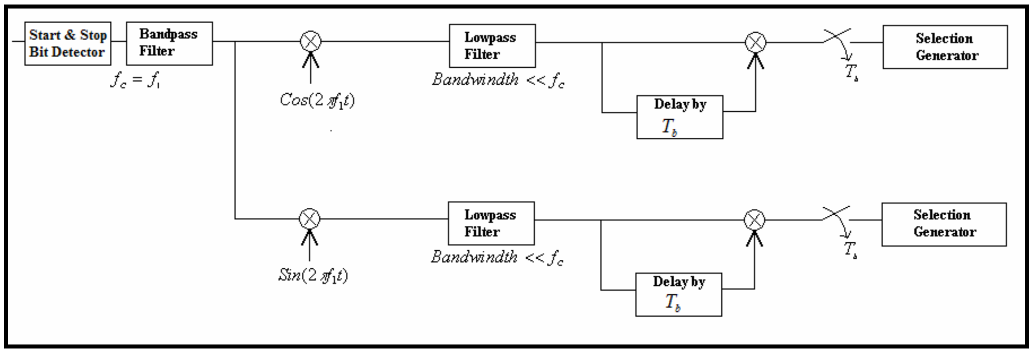
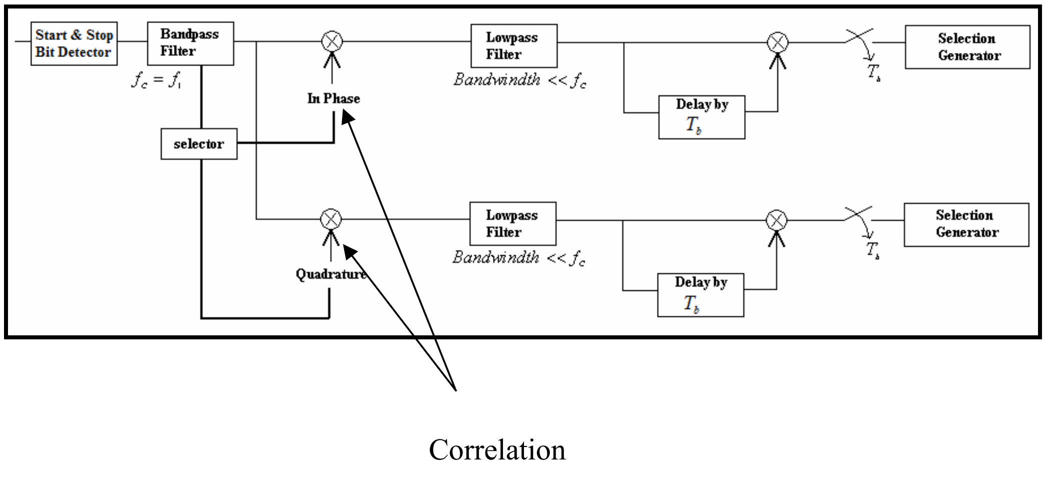


Figure 4.2: Block Diagram of DQPSK Receiver

To actually implement DQPSK and really make it work, certain modification had to be made on the DQPSK receiver structure. The real solution is to make the correlation part to be perfectly synchronized with the incoming signal.



Correlation

Figure 4.3: Modified DQPSK Receiver Structure

To achieve the perfect synchronization with the incoming signal, the selector needs to retrieve the reference signal from the incoming signal itself as shown in Figure 4.3. This is done on the assumption that the start bit detector is not efficient. The selector taps the incoming signal that has been filtered and adjust the waveform to get the in-phase and quadrature components. Since in this case, the phase difference between 2000Hz cosine component and 2000Hz sine component is only 2 samples, the selector only needs to shift 2 samples to the left to get the quadrature waveform. This process ensures that the first branch is perfectly in the same phase with the incoming signal and the second branch differs by 90 or 270 degrees with the incoming signal.

4.1.3 DQPSK Theoretical BER

Theoretical BER for DQPSK is derived from DPSK theoretical BER shown in Equation (4.2). The union bound theory is also applicable for DQPSK as illustrated in Figure 4.4 where errors are more likely to occur in the adjacent symbols.

$$P_e = \frac{1}{2}\exp\left(-\frac{A^2}{2N_P}\right) \qquad (4.2)$$

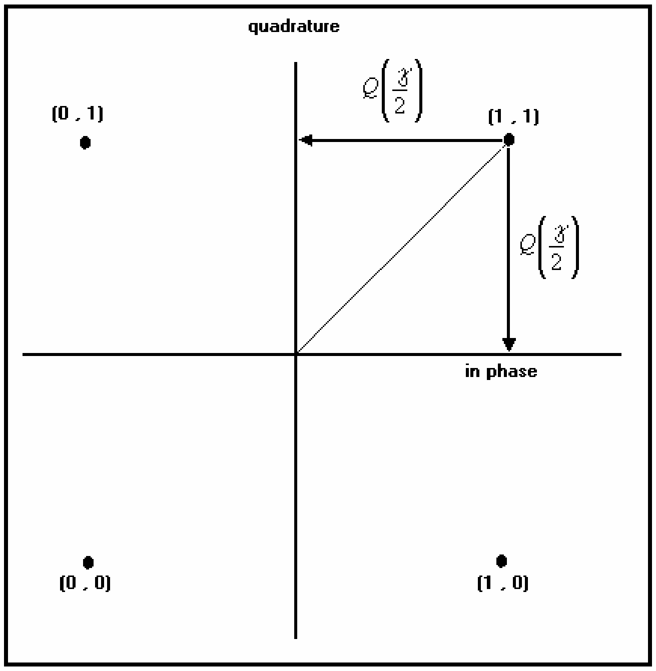

quadrature
(0 , 1)
(1 , 1)
$Q\left(\frac{\gamma}{2}\right)$
$Q\left(\frac{\gamma}{2}\right)$
in phase
(0 , 0)
(1 , 0)

Figure 4.4: Union Bound Border

BER for DQPSK is the sum of error probability P_e as shown in Equation (4.3) where $P_{e11}, P_{e10}, P_{e01}$ and P_{e00} are also the conditional error probabilities for each symbol and $P(s=11), P(s=10), P(s=01)$ and $P(s=00)$ are the probabilities of occurrence or priori probabilities for each symbol that is equal to ¼. For example, P_{e11} is the probability of getting *s=01* or *s=10* if actual data transmitted is *s=11*. If *s=11* is transmitted, error P_{e11} occur if *s=01* or *s=10* is decoded at the receiver. P_{e11} is the sum of the distance at the two borders

$$P_e = P_{e11}P(s=11) + P_{e10}P(s=10) + P_{e01}P(s=01) + P_{e00}(s=00) \tag{4.3}$$

$$\begin{aligned} P_{e11} &= \frac{1}{2}\exp\left(-\frac{A^2}{2N_P}\right) + \frac{1}{2}\exp\left(-\frac{A^2}{2N_P}\right) \\ &= \exp\left(-\frac{A^2}{2N_P}\right) \end{aligned} \tag{4.4}$$

$$N_P = 2N_0 r_b = 2N_0 / T_b \tag{4.5}$$

where the relation of N_P is shown in Equation (4.5), r_b is the bit-rate, T_b is the bit-duration and N_0 is power of the additive white noise. Since signal per direction is DPSK and conditional error probability $P_{e11} = P_{e10} = P_{e01} = P_{e00}$ then BER for DQPSK is calculated as

$$\begin{aligned} P_e &= \frac{1}{4}\times\left(\exp\left(-\frac{A^2}{2N_P}\right)\right)+\frac{1}{4}\times\left(\exp\left(-\frac{A^2}{2N_P}\right)\right)+\frac{1}{4}\times\left(\exp\left(-\frac{A^2}{2N_P}\right)\right) \\ &\quad +\frac{1}{4}\times\left(\exp\left(-\frac{A^2}{2N_P}\right)\right) \\ &= \exp\left(-\frac{A^2}{2N_P}\right) \end{aligned} \tag{4.6}$$

BER for DQPSK is the sum of probability of occurrence for each symbol

$$\text{BER for DQPSK, } P_e = \exp\left(-\frac{A^2}{2N_P}\right) \tag{4.7}$$

Table 4.3 is summarized of BER for several modulation techniques. It shows that BER for DQPSK is double the BER of DPSK.

Table 4.3: Theoretical BER for Various Method of Modulation

BER for **PSK** BER = $Q\left(\sqrt{\frac{A^2T_b}{2N_0}}\right)$	BER for **DPSK** BER = $\frac{1}{2}\exp\left(-\frac{A^2T_b}{4N_0}\right)$
BER for **QPSK** BER = $2Q\left(\sqrt{\frac{A^2T_b}{2N_0}}\right)$	BER for **DQPSK** BER = $\exp\left(-\frac{A^2T_b}{4N_0}\right)$

4.2 Theoretical and Simulation Result

Figure 4.6 shows the result of theoretical BER on various modulation methods in the presence of additive white Gaussian noise. It shows that the performance of DPSK and DQPSK are very close, but DQPSK has more advantage from DPSK in terms of spectrum efficiency where its transmission rate is twice than DPSK. The more complex modulation method D8PSK and D16PSK can encode 3 bits per symbol and 4 bit per symbol respectively, but they require an even higher SNR to get the same performance as DQPSK. Non-coherent FSK is much easier to implement but from the performance wise, non-coherent FSK lies between D8PSK and D16PSK as shown in the graph. More detail explanation on modulation, demodulation and simulation of FSK, D8PSK and D16PSK can be referred from (Norhashimah, 2004).

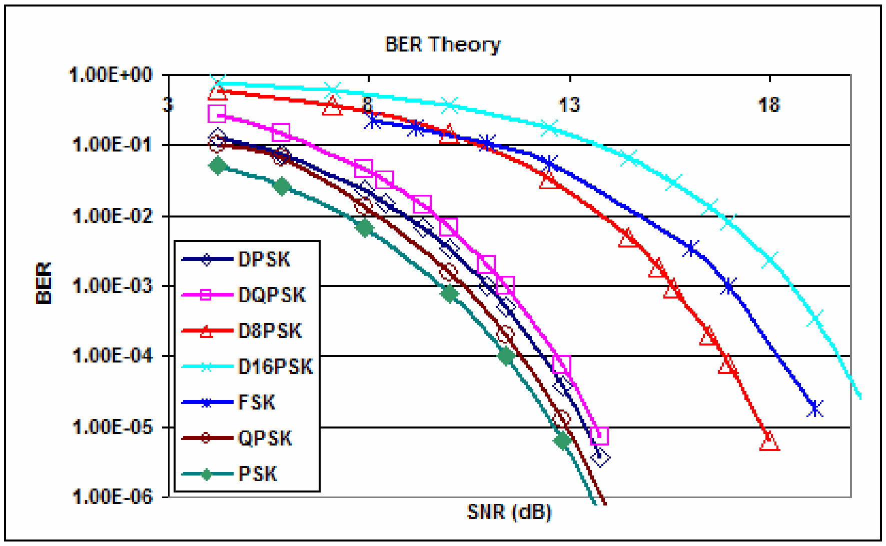


Figure 4.6: Theoretical BER Result

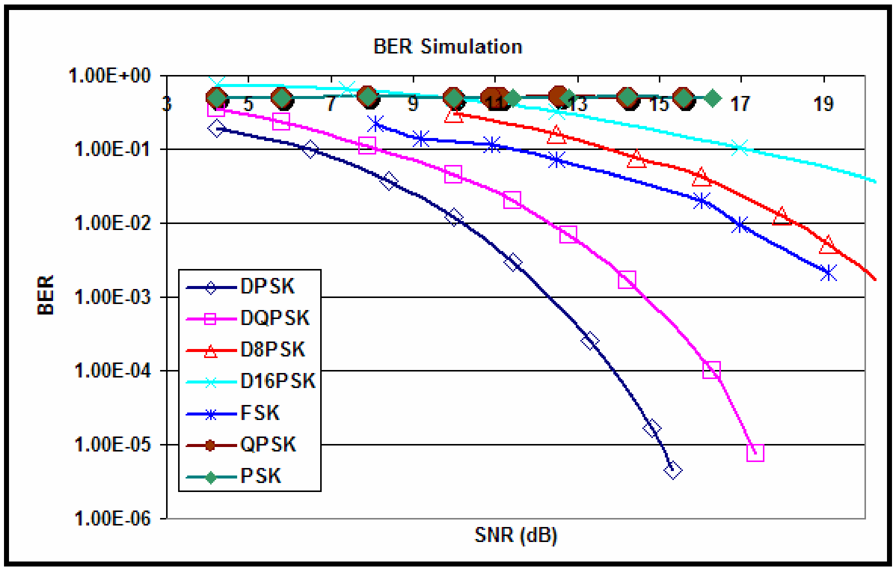


Figure 4.7: Simulation BER Result

Figure 4.7 illustrates the result of BER from simulation. Random sample delay is introduced in the detection to simulate the real condition in synchronization. This simulation study did not take into account the effect caused by multipath fading and Doppler effect. Here we can see that, without perfect synchronization PSK and QPSK are the worst in terms of BER. The graph shows that to get the same performance at BER10^{-2}, the difference between DQPSK and DPSK is only 3dB. D8PSK and D16PSK require a higher SNR to get the same performance at BER of10^{-2}. DQPSK is chosen as the modulation method best option in terms of performance, spectrum efficiency and complexity.

4.3 Linear Phase FIR Filter

The FIR (Finite Impulse Response) filter which has an impulse response sequence $h(0)$,$h(1)$,… , $h(N\text{-}1)$ has N coefficients and is said to be an N th order filter. The transfer function for this filter is:

$$H(z) = h(0) + h(1)z^{-1} + \ldots + h(N-1)z^{-(N-1)} \tag{4.8}$$

The output of the system shown in Figure 4.8 is described by the equation

$$y(n) = \sum_{k=0}^{N-1} h(k)s(n-k) \tag{4.9}$$

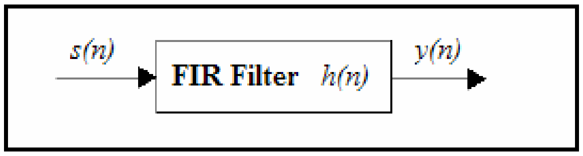


Figure 4.8: Description of a FIR Filter

The signal flow graph for the filter given by Equation (4.9) is shown in Figure 4.9. This structure is called a direct form of a FIR filter (Oppenheim, 1999).

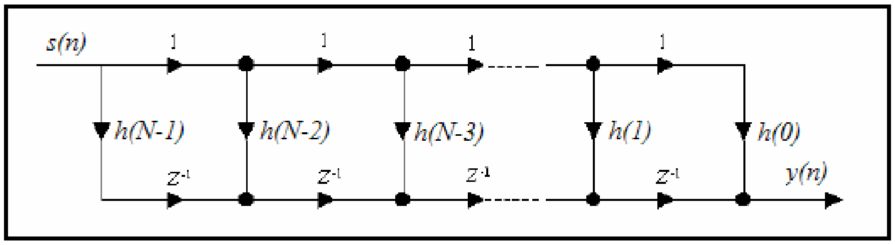


Figure 4.9: First Direct Form of a Transversal Filter

When the impulse response of a FIR filter satisfies *h*(*n*) = *h*(*N*-1-*n*), the filter is a symmetrical FIR filter and has a linear phase response. This symmetry allows the symmetric coefficients to be added together before they are multiplied by the coefficients. Taking advantage of the symmetry lowers the number of multipliers from *N* to *N*/2 if *N* is even and from *N* to (*N*+1)/2 for *N* odd.

4.4 Error Control

The signal containing information may not be interpreted correctly at the receiver due to the distortion and interference in the channel between the transmitter and receiver. An effective communication system will incorporate an error control method to minimize the probability of making errors while simultaneously maintaining the system complexity (Sklar, 2001). In general, error control can be classed into:-

(i) Auto repeat request (ARQ)
(ii) Forward error correction (FEC)

In ARQ method, the receiver sends acknowledgement to the transmitter regarding the status of the received packet. If the received packet is free of error, the receiver sends an acknowledgement that tells the transmitter to send the next packet of data. Even if one error occurs in a packet, the receiver sends an acknowledgement to request the same packet of data. This type of error control does not repair the error on its own but it depends on the transmitter to resend the same packet of data whenever error occurs. The most common and frequently used error detection technique is the cyclic redundancy check (CRC). Four most favored versions of CRC are CRC-12, CRC-16, CRC-CCITT and CRC-32. CRC-12 uses 12th order of pattern polynomial, CRC-16 and CRC-CCITT use 16th order pattern polynomial and CRC-32 utilizes 32nd order of pattern polynomial (Stalings, 2000). The longer the polynomial pattern, the more error it can detect.

FEC is more complicated than ARQ because not only it has to decide whether there is an error, it also need to determine where the error is, in order to correct the error. This means that FEC is capable of correcting error on itself, but only to a certain limitation of number of errors. The more complicated the error control coding is the more error it can detect and repair. Error control techniques for FEC are classed as block coding and convolutional coding. The main difference between block coding and convolutional coding is that the calculation process for block coding is done in the fixed length of data in a block whereas for convolutional coding, the calculation is done bit by bit. Some of the well-known block codes are Hamming codes, BCH codes, Reed-Solomon codes and Golay codes. Golay code is chosen to handle the error correction part for this system. Golay code is a ½ code rate and it is capable in correcting all triple errors or less. Hamming codes can only correct one error. BCH codes and Reed-Solomon codes are not ½ code rate coding but they can correct triple error.

Both ARQ and FEC are implemented using binary cyclic code method which is explained in detail in section 4.4.1.

4.4.1 Binary Cyclic Code

Binary cyclic codes are an important subclass of linear block codes. The codes are easily implemented with feedback shift registers and the syndrome calculation is easily accomplished using similar feedback shift registers. The cyclic nature of the code can be expressed in polynomial form. In order to clearly understand the process, the method should be viewed as a long division in the Galois field (GF (2)) or polynomial form. If we have a binary sequence $m = [1100 \quad 0001 \quad 1111]$, the polynomial representation in the GF (2) is

$$m(x) = x^{11} + x^{10} + x^4 + x^3 + x^2 + x + 1 \qquad (4.10)$$

The polynomial is shifted 12 bits to the left to calculate the checksum for extended Golay code application. Left shift operation is denoted as multiplication with x^{12} as shown below:

$$m'(x) = x^{12}m(x) \tag{4.11}$$

Referring to Equation (4.10), the 12 bits left shift operation produces Equation (4.12) where the power of every polynomial increases.

$$m'(x) = x^{23} + x^{22} + x^{16} + x^{15} + x^{14} + x^{13} + x^{12} \tag{4.12}$$

Various types of error control method exist and each utilizes a completely different pattern polynomial. This example is based on the implementation of extended Golay code. The polynomial in Equation (4.12) is then divided with a *p*=[1010 1110 0011] pattern sequence that has a polynomial representation

$$p(x) = x^{11} + x^{9} + x^{7} + x^{6} + x^{5} + x + 1 \tag{4.13}$$

The remainder *r(x)* or checksum is calculated by dividing the sequence *m'(x)* with its pattern polynomial *p(x)* as shown in the following equation

$$\frac{m'(x)}{p(x)} = u(x) \text{ with remainder } r(x)$$
$$r(x) = m'(x) \bmod p(x) \tag{4.14}$$

where *u(x)* is the result of the long division. Actual long division operation is illustrated in Figure 4.10.

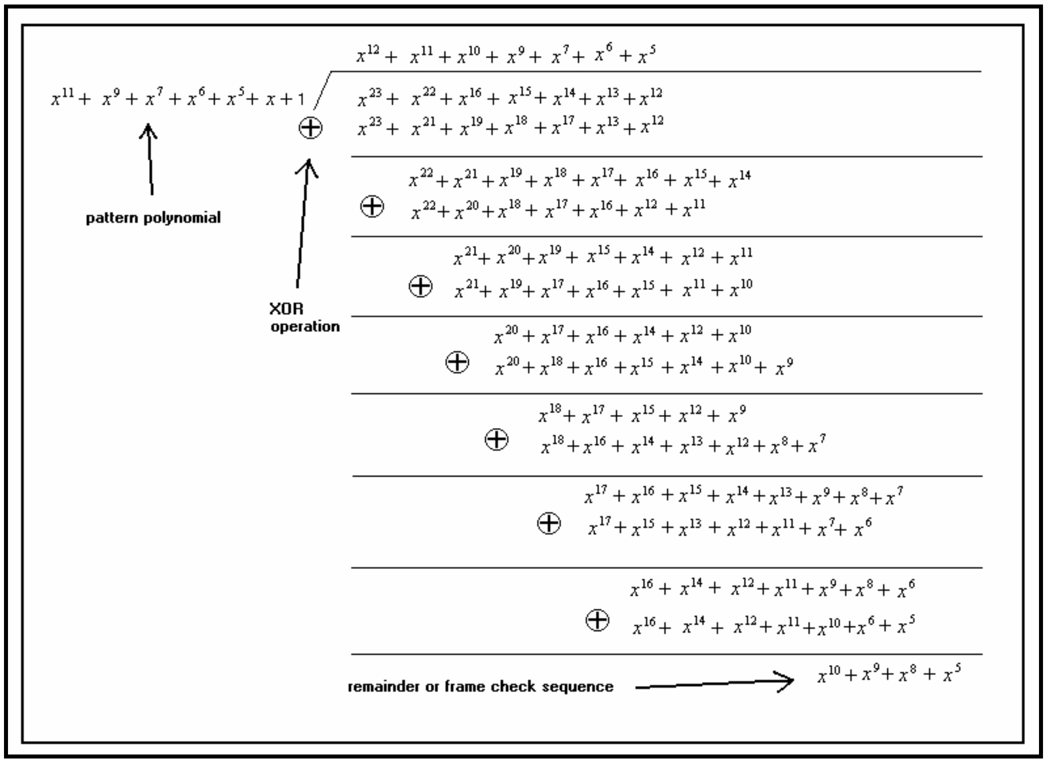

$x^{12}+x^{11}+x^{10}+x^{9}+x^{7}+x^{6}+x^{5}$
$x^{11}+x^{9}+x^{7}+x^{6}+x^{5}+x+1$
$x^{23}+x^{22}+x^{16}+x^{15}+x^{14}+x^{13}+x^{12}$
$\oplus$
$x^{23}+x^{21}+x^{19}+x^{18}+x^{17}+x^{13}+x^{12}$
pattern polynomial
XOR operation
$x^{22}+x^{21}+x^{19}+x^{18}+x^{17}+x^{16}+x^{15}+x^{14}$
$\oplus$
$x^{22}+x^{20}+x^{18}+x^{17}+x^{16}+x^{12}+x^{11}$
$x^{21}+x^{20}+x^{19}+x^{15}+x^{14}+x^{12}+x^{11}$
$\oplus$
$x^{21}+x^{19}+x^{17}+x^{16}+x^{15}+x^{11}+x^{10}$
$x^{20}+x^{17}+x^{16}+x^{14}+x^{12}+x^{10}$
$\oplus$
$x^{20}+x^{18}+x^{16}+x^{15}+x^{14}+x^{10}+x^{9}$
$x^{18}+x^{17}+x^{15}+x^{12}+x^{9}$
$\oplus$
$x^{18}+x^{16}+x^{14}+x^{13}+x^{12}+x^{8}+x^{7}$
$x^{17}+x^{16}+x^{15}+x^{14}+x^{13}+x^{9}+x^{8}+x^{7}$
$\oplus$
$x^{17}+x^{15}+x^{13}+x^{12}+x^{11}+x^{7}+x^{6}$
$x^{16}+x^{14}+x^{12}+x^{11}+x^{9}+x^{8}+x^{6}$
$\oplus$
$x^{16}+x^{14}+x^{12}+x^{11}+x^{10}+x^{6}+x^{5}$
remainder or frame check sequence
$x^{10}+x^{9}+x^{8}+x^{5}$

Figure 4.10: Long Division Operation in Galois Field (2)

The shifted polynomial is as follows

$$t(x) = m'(x)+r(x) \tag{4.15}$$

where the final message is

$$t(x) = x^{23}+x^{22}+x^{16}+x^{15}+x^{14}+x^{13}+x^{12}+x^{10}+x^{9}+x^{8}+x^{5} \tag{4.16}$$

The similar operation in binary is represented in Figure 4.11. This operation implements binary addition without carry, which is an exclusive-OR operation.

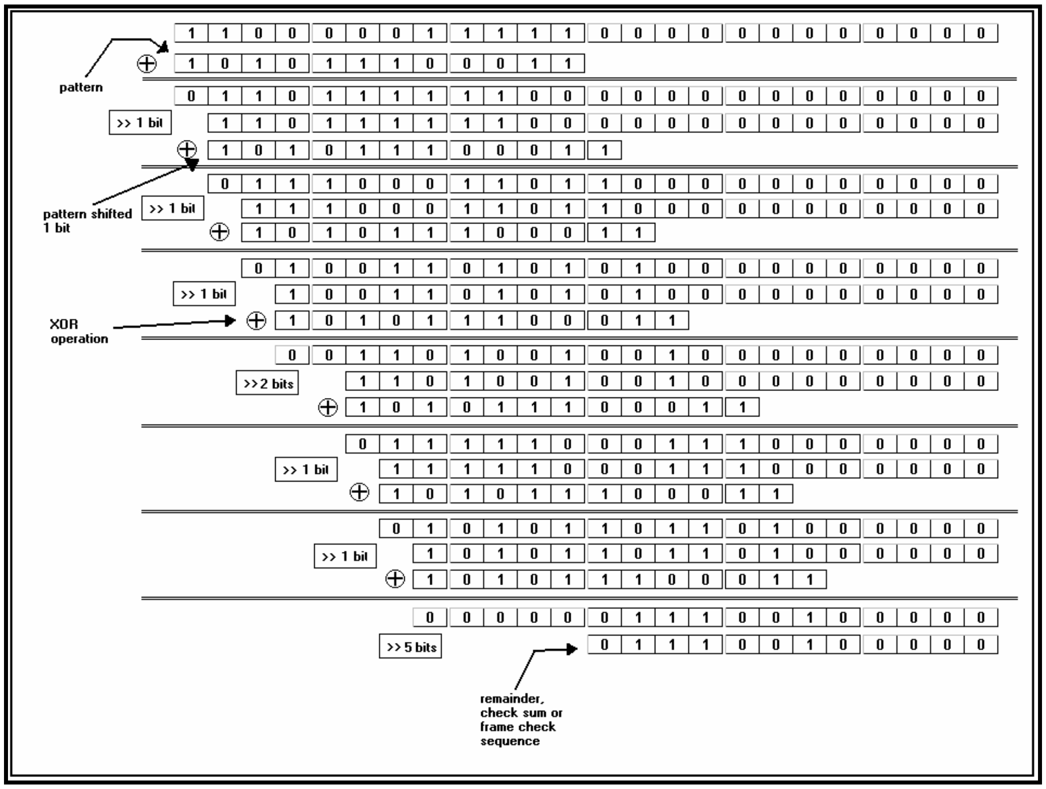


Figure 4.11: Actual Binary Operation

The operation above utilizes the shift register and the value of MSB (most significant bit) is checked after every XOR operation. If the MSB is 0 than the remainder bits are copied down. If the MSB is 1, then the binary sequence is XORed with the shifted pattern. The operation is continued until 12 bits remainder is obtained. The next step is attaching the remainder or checksum at the back of original binary sequence as follows

$$t = [1100 \quad 0001 \quad 1111 \quad 0111 \quad 0010 \quad 0000] \tag{4.17}$$

The sequence obtained from Equation (4.17) is the actual data to be transmitted. At the receiver end, the received sequence is then divided with the same pattern polynomial *p(x)* shown in Equation (4.13). If the remainder is zero, then the received sequence is the same as the transmitted sequence and no error occurred. If the remainder is not zero, the remainder is then used as the error syndrome to locate where the errors are.

4.4.2 Cyclic Redundancy Check

Cyclic redundancy check (CRC) is one of the most common, and one of the most powerful error detecting codes. The operation of CRC is similar to the example in previous section except that a different pattern polynomial is used and the receiver does not check the syndrome to locate the error position. CRC only tells whether or not an error has occurred. If an error is detected the receiver will post a request to the transmitter to retransmit the same packet. Pattern polynomials *p(x)* for the most common use CRC methods are listed in the table as follows:

Table 4.4: CRC Pattern Polynomial

CRC-12	$= X^{12} + X^{11} + X^{3} + X + 1$
CRC-16	$= X^{16} + X^{15} + X^{2} + 1$
CRC-CCITT	$= X^{16} + X^{12} + X^{5} + 1$
CRC-32	$= X^{32} + X^{26} + X^{23} + X^{22} + X^{16} + X^{12} + X^{11} + X^{10} + X^{8} + X^{7} + X^{5} + X^{4} + X^{2} + X + 1$

An error will only be undetectable if the received sequence is divisible by *p(x)*. Error will be detected in the following cases (Stalings, 2000)

(i) All single-bit errors
(ii) All double-bit errors, as long as *p(x)* has at least three 1s
(iii)Any odd number of errors, as long as *p(x)* contains a factor of (X+1)

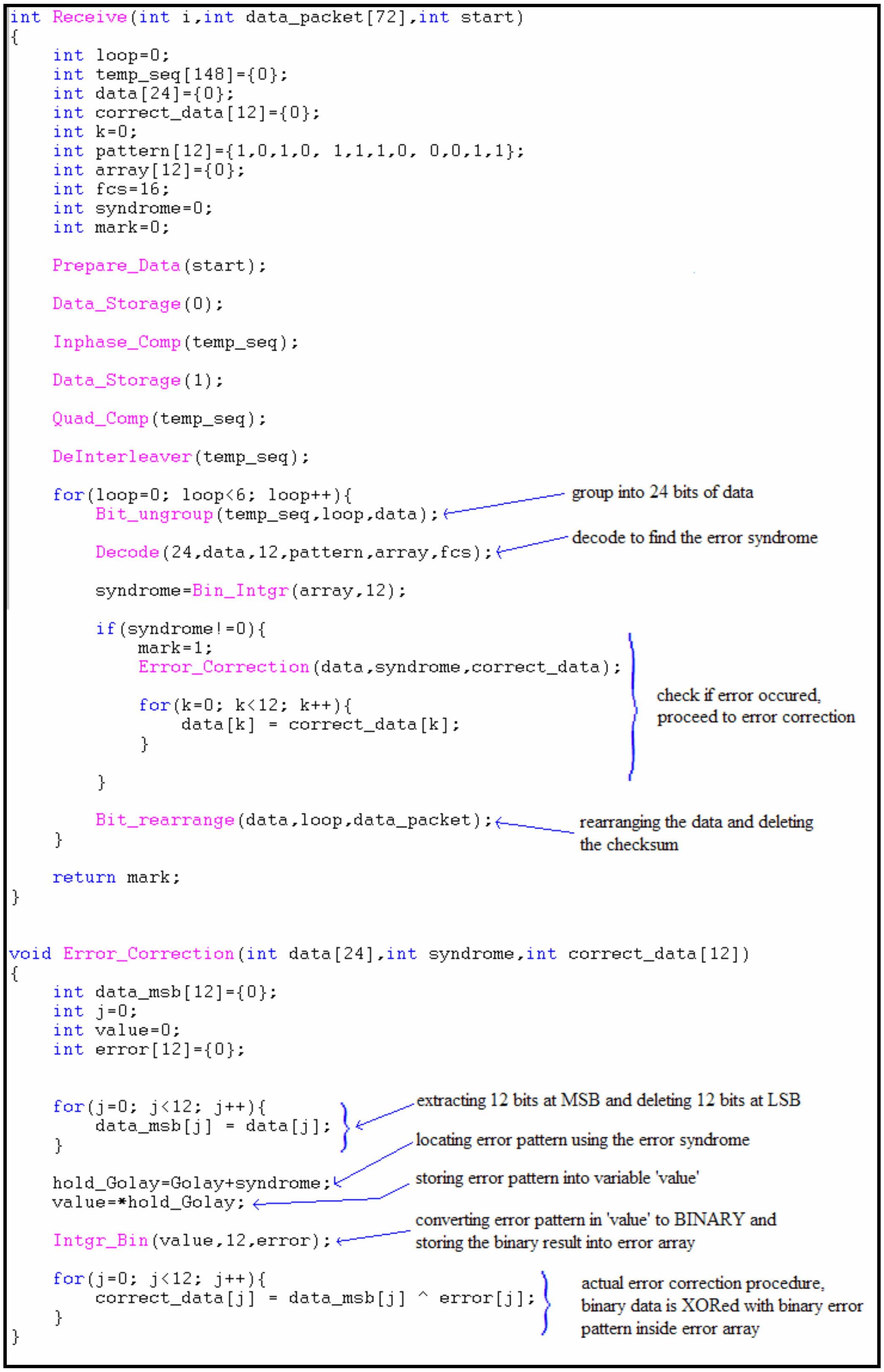
(iv) Any burst error for which the length of the burst is less than the length of the pattern polynomial; that is, less than or equal to the length of the frame check sequence or check sum

4.4.3 Extended Golay Code

One of the more useful block codes is the binary (24, 12) extended Golay code, which is formed by adding an overall bit to the *perfect* (23, 12) code, known as the Golay code (Sklar, 2001). This added bit increases the minimum distance $d_{\min}$ from 7 to 8 and produces a rate 1/2 code, which is easier to implement than the 12/23 original Golay code. Minimum distance for the extended Golay code, $d_{\min} = 8$, where the code is guaranteed to correct all triple errors.

Total error pattern possibilities for 12 bits of data plus 12 bits of checksum are 2046. A look-up table is implemented since the size of memory needs to be allocated for the look-up table is quite small. Error syndrome for Golay code is stored in external memory on board DSK board starting from address 0xF000 until 0xFFFF.

A snippet of error correcting code is inserted in Figure 4.12 to show how the error correction is performed at the receiver. Before proceeding to the error control part, the received bit is divided to 6 groups of 24 bits of data. Each group of 24 bits is then decoded to calculate the syndrome. Error occurs in the packet if the syndrome is not equal to zero. As shown in the code in Figure 4.12, error correction is only executed if error occurred in the packet. Error pattern is located by referring to the error syndrome, where the error syndrome acts as a binary pointer to point to the exact location inside the memory.



```
int Receive(int i,int data_packet[72],int start)
{
    int loop=0;
    int temp_seq[148]={0};
    int data[24]={0};
    int correct_data[12]={0};
    int k=0;
    int pattern[12]={1,0,1,0, 1,1,1,0, 0,0,1,1};
    int array[12]={0};
    int fcs=16;
    int syndrome=0;
    int mark=0;

    Prepare_Data(start);

    Data_Storage(0);

    Inphase_Comp(temp_seq);

    Data_Storage(1);

    Quad_Comp(temp_seq);

    DeInterleaver(temp_seq);

    for(loop=0; loop<6; loop++){
        Bit_ungroup(temp_seq,loop,data);

        Decode(24,data,12,pattern,array,fcs);

        syndrome=Bin_Intgr(array,12);

        if(syndrome!=0){
            mark=1;
            Error_Correction(data,syndrome,correct_data);

            for(k=0; k<12; k++){
                data[k] = correct_data[k];
            }

        }

        Bit_rearrange(data,loop,data_packet);
    }

    return mark;
}

void Error_Correction(int data[24],int syndrome,int correct_data[12])
{
    int data_msb[12]={0};
    int j=0;
    int value=0;
    int error[12]={0};


    for(j=0; j<12; j++){
        data_msb[j] = data[j];
    }

    hold_Golay=Golay+syndrome;
    value=*hold_Golay;

    Intgr_Bin(value,12,error);

    for(j=0; j<12; j++){
        correct_data[j] = data_msb[j] ^ error[j];
    }
}
```

group into 24 bits of data

decode to find the error syndrome

check if error occured, proceed to error correction

rearranging the data and deleting the checksum

extracting 12 bits at MSB and deleting 12 bits at LSB

locating error pattern using the error syndrome

storing error pattern into variable 'value'

converting error pattern in 'value' to BINARY and storing the binary result into error array

actual error correction procedure, binary data is XORed with binary error pattern inside error array

Figure 4.12: Error Correction Procedure

4.4.4 Interleaving

Extended Golay code is capable in correcting all triple errors in a block of 24 bits. Error may occur anywhere in the packet of 144 bits, which are actually 6 groups of 24 bits of data. Since error tends to appear in burst, there is a tendency of some of the group containing more errors while the other groups may contain none at all. Interleaving is done to distribute the errors evenly throughout the whole packet. The process is shown in Figure 4.13.

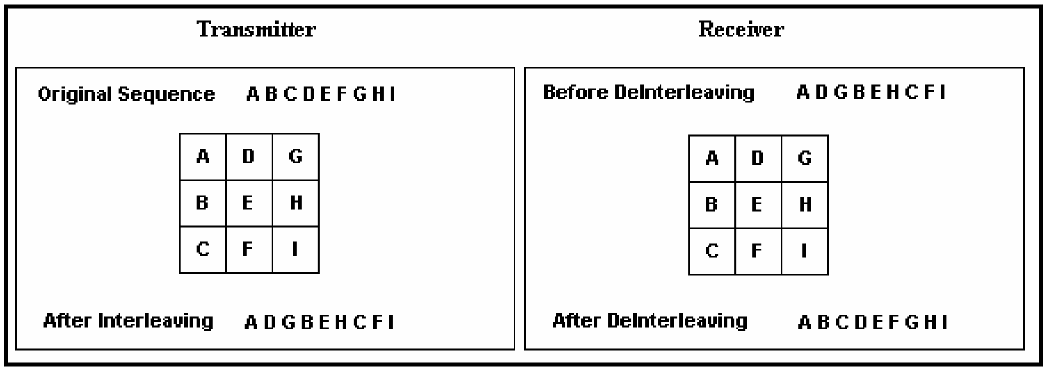

Transmitter
Receiver
Original Sequence A B C D E F G H I
A D G
B E H
C F I
After Interleaving A D G B E H C F I
Before DeInterleaving A D G B E H C F I
A D G
B E H
C F I
After DeInterleaving A B C D E F G H I

Figure 4.13: Interleaver and Deinterleaver Block

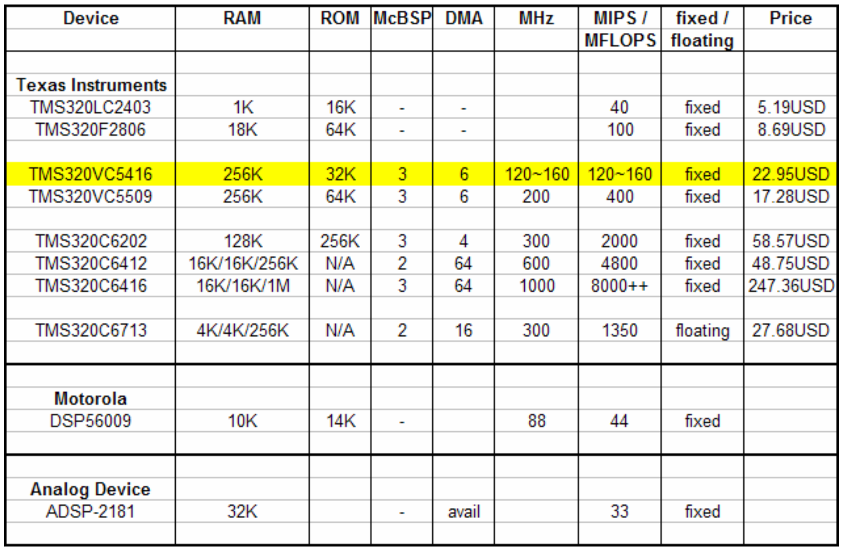
The actual process employs 144 bits of data but the example shown here only deal with 9 bits of data to simplify the explanation. Figure 4.13 shows that at the transmitter, the original sequence is placed systematically from top to bottom in a square box. The interleaved sequence is obtained by reading from left to right. De-interleaving process is actually the reverse process of the interleaving process done earlier. This is the process, which is executed at the receiver side to actually spread the errors as far as possible in a packet if any error occurred. Here the received data is placed from left to right, then to get the original data the sequence is read from top to bottom.

The interleaving process ensures that errors are located randomly inside the full length of the packet. For example, if the transmitted sequence is *A D G B E H C F I*, but during the transmission errors are introduced to the 4th, 5th and 6th bit, the received sequence is *A D G* x_1 x_2 x_3 *C F I*. De-interleaving produces *A* x_1 *C D* x_2 *F G* x_3 *I*. If the sequence used is 144-bit length, the result of de-interleaving will be more obvious.

4.5 Platform Overview

Texas Instruments produces a wide range of dsp processors in the market. The ranges include C2000 family, C5000 family and C6000 family. The latest processors in C2000 family are TMS320C24x and TMS 320C28x fixed-point dsp processors. C5000 family consists of TMS320C54x and TMS320C55x fixed-point dsp processors. C6000 family are consists of fixed-point TMS320C62x and floating-point TMS320C67x dsp processors. C2000 family is designed for low performance, where these processors are best use for control application. One of the application where these dsp processor is used is in motor control for air conditioning system. C5000 family is targeted for a high efficiency and low power application. These processors are best used for handheld portable devices or wireless communication devices which operate on limited power supply such as batteries. The last family which is C6000 family is the highest performance dsp processor in the market but the disadvantage is, it requires a constant power supply which makes it unsuitable for handheld device (Texas Instruments, DSP Selection Guide). C6000 family processors are used in High Definition TV (HDTV) where high speed processing of image is required. C6000 family can reach up to 1 GHz clock speed. Table below displays the characteristics of the processors from each family.

Table 4.5: Comparison of Various Types of DSP Processors



Device	RAM	ROM	McBSP	DMA	MHz	MIPS / MFLOPS	fixed / floating	Price
Texas Instruments								
TMS320LC2403	1K	16K	-	-		40	fixed	5.19USD
TMS320F2806	18K	64K	-	-		100	fixed	8.69USD
TMS320VC5416	256K	32K	3	6	120~160	120~160	fixed	22.95USD
TMS320VC5509	256K	64K	3	6	200	400	fixed	17.28USD
TMS320C6202	128K	256K	3	4	300	2000	fixed	58.57USD
TMS320C6412	16K/16K/256K	N/A	2	64	600	4800	fixed	48.75USD
TMS320C6416	16K/16K/1M	N/A	3	64	1000	8000++	fixed	247.36USD
TMS320C6713	4K/4K/256K	N/A	2	16	300	1350	floating	27.68USD
Motorola								
DSP56009	10K	14K	-		88	44	fixed	
Analog Device								
ADSP-2181	32K		-	avail		33	fixed	

Based on the characteristics that are shown in Table 4.5, it is clear that Texas Instruments DSP C5000 family processor is the suitable choice for implementation purposes. In addition, company like Motorola also using the C5000 family DSP processor for their product. The two best choices are TMS320VC5509 and TMS320VC5416 but during the initial stage of the project, TMS320VC5509 was not available yet to the market. Therefore, TMS320VC5416 is chosen because of the size of RAM and ROM is larger compared to DSP processors from different makers. Number of MIPS is also high that can also ensure a very effective implementation. This project is targeted to be a stand alone system which means that C6000 family DSP processors are not suitable, eventhough they are faster and more powerful compared to C5000 family.

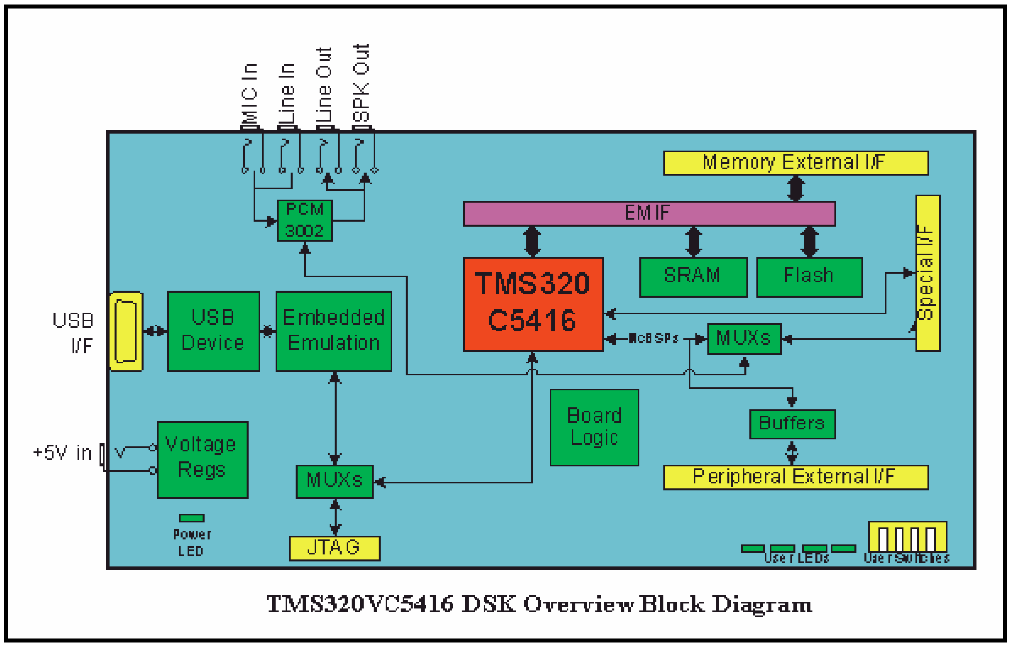


Figure 4.14: TMS320VC5416 DSK Overview Block Diagram (TMS320VC5416 Tech. Ref. 2002)

4.6 Synchronization

Digital communication requires some sort of synchronization in order for the receiver to recognize the incoming signal. Coherent detection requires perfect phase synchronization whereas for non-coherent detection phase synchronization is not critical. The most widely used synchronization method for coherent detection is frequency and phase synchronization or also known as phase-locked loop (PLL). Symbol synchronization and frame synchronization are less complicated than the first method. A system using non-coherent detection may use either symbol synchronization or frame synchronization as its synchronization method where accurate phase lock is not required.

Frequency and phase synchronization or PLL has three basic components which are a phase detector, a loop filter and a voltage-controlled oscillator (VCO) (Sklar, 2001). The phase detector measures the phase difference between incoming signal and local oscillator. The loop filter controls the variations in the phase difference between incoming signal and local oscillator. And the last component, VCO is responsible in producing the carrier replica.

Symbol synchronization is classed into two types (Sklar, 2001); non-data-aided (NDA) and data-aided (DA). The similarity between symbol synchronization and phase synchronization is that both methods incorporate the process of producing a replica of a portion the transmitted signal. Symbol synchronization method generates a square wave at each symbol transition, whereas phase synchronization needs to replicate an accurate replica of the carrier.

Frame synchronization is the simplest method of detection. This type of synchronization is required when the information is organized in blocks (Sklar, 2001). Similar to symbol synchronization, frame synchronization is required to generate a square wave at the frame rate. Systems using non-coherent detection method employ symbol synchronization or frame synchronization depending on the organization of the information.

One of the major hurdles during implementation is the synchronization problem. In the case of coherent PSK demodulation, the receiver is assumed to be able to generate the reference signals where its phase is identical to the incoming signal transmitted from the transmitter. These reference signals are compared with the incoming signals in order to get back the signal, which is modulated, onto the carrier.

In this project, the need to generate the reference signal is eliminated since the type of modulation is non-coherent. The complexity of the receiver is reduced since the circuitry to obtain the exact phase synchronization is not required. Phase synchronization is not a critical issue in non-coherent type of modulation. In non-coherent demodulation, envelope demodulation is employed and there is no need for precise tracking of the phase and frequency of the carrier at the receiver.

Even though phase synchronization is not a critical issue in non-coherent demodulation, the process of detecting the start of the frame is still important. The synchronization has to be performed effectively so that the data is not lost due to some of the data being discarded at the beginning of the packet. This may happen if the synchronization is not perfect. The detector may not be able to detect whether or not the signal which is passing through the detector, contains data. Normally, the detector can only detect whether the signal contains data after a certain amount of signal has passed through the detector and some calculations have been done. A good detector only requires a small amount of signal in order for it to be able to decide whether a signal contains data. The synchronization method used for this project is an adaptation of frame synchronization as explained earlier in previous section.

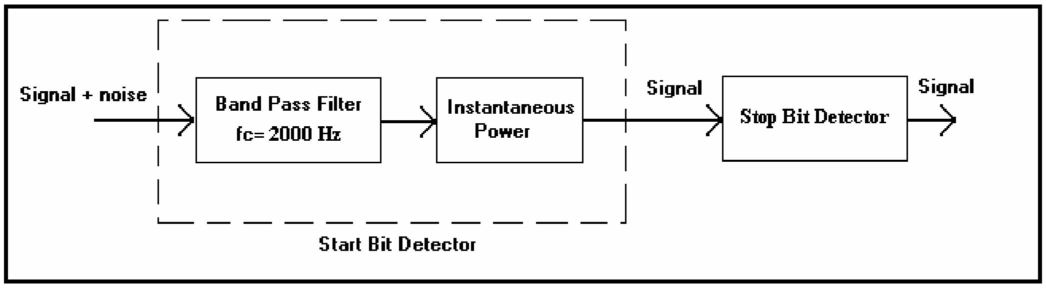


Figure 4.15: Start and Stop Bit Detector

Shown above is the block diagram for the start and stop bit detector. At the first stage, signal and noise will pass through the band pass filter. Filtering for frequency 2000 Hz is done and the sample is squared and summed. Once the start bit is detected, the exact location of the stop bit is determined. This method of detection ensures the perfect knowledge of the exact location where the data starts. Flow chart for start and stop bit detection is shown in the Figure 4.16.

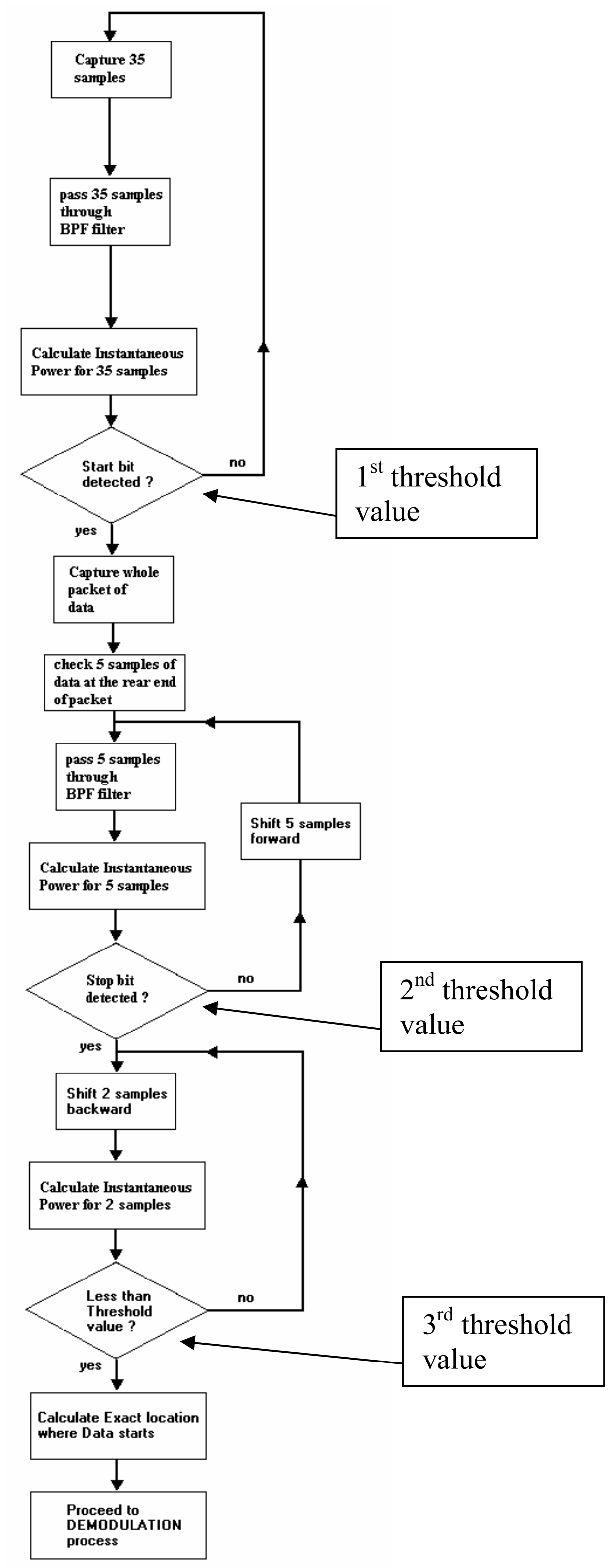

Capture 35 samples
pass 35 samples through BPF filter
Calculate Instantaneous Power for 35 samples
Start bit detected ?
no
yes
1st threshold value
Capture whole packet of data
check 5 samples of data at the rear end of packet
pass 5 samples through BPF filter
Shift 5 samples forward
Calculate Instantaneous Power for 5 samples
Stop bit detected ?
no
yes
2nd threshold value
Shift 2 samples backward
Calculate Instantaneous Power for 2 samples
Less than Threshold value ?
no
yes
3rd threshold value
Calculate Exact location where Data starts
Proceed to DEMODULATION process

Figure 4.16: Start bit and Stop bit detection Flowchart

Although phase synchronization is not as critical in DQPSK compared to QPSK, delay in samples due to poor method of detection will introduce error. In order to overcome this problem, the sample duration of the start bit is increased to 400 samples and sample duration of stop bit is increased to 120 samples. The method is done in such a way that after the start bit is detected, the exact location of the stop bit is located by using two methods of calculation. First stop bit calculation calculates the instantaneous power of 5 samples starting from the supposedly end of packet location. The total of instantaneous power is compared whether it is larger than a fixed threshold value. If this condition is fulfilled, second type of stop bit calculation is executed. If the condition is not fulfilled, the starting point of the samples is shifted 5 samples backward and the process is repeated.

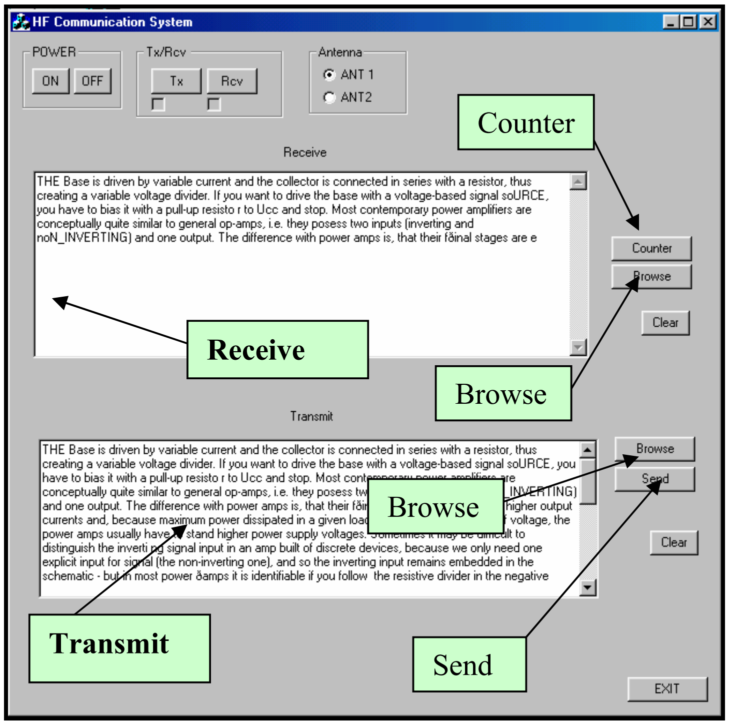
The second type of stop bit calculation is the backup of the first, in case the result of first calculation failed to locate the exact location of stop bit. Sample location calculated previously is shifted 4 samples forward and the value instantaneous power for the next subsequence 2 samples is calculated. The value of instantaneous power is then compared with another fixed threshold value. Three threshold values are used in this project for the purpose of detecting the start bit and the stop bit. These threshold values are acquired from the experiment when the SNR is at 16 dB.

4.7 Modulation and Demodulation

Digital modulation is a process where digital data are converted to waveform that suits the characteristics of the channel. It involves the process of translating information to radio form, before letting it travel in radio wave. The process starts from extracting files from the host computer and sending 9 characters each time to the target DSK board. The 9 characters contain 72 bits of data which are divided into 6 groups. Each of the group which consists of 12 bits of data is then encoded with the

Golay code pattern to get the check sum. The 12 bits of check sum is attached at the back of each group. This process is repeated for the remaining groups of data.

A graphical user interface is built on the host computer using Microsoft Visual C++® as shown in Figure 4.17. Users only need to browse to the text file that needs to be transmitted, regardless of the size of the file. Visual C++ at the Host sends 9 characters each time to the VC5416 board or known as Target from now on. The Target handles most of the process. It reads the 9 characters sent from the Host and converts it to the binary representation.



Receive:

THE Base is driven by variable current and the collector is connected in series with a resistor, thus creating a variable voltage divider. If you want to drive the base with a voltage-based signal soURCE, you have to bias it with a pull-up resisto r to Ucc and stop. Most contemporary power amplifiers are conceptually quite similar to general op-amps, i.e. they posess two inputs (inverting and noN_INVERTING) and one output. The difference with power amps is, that their fåinal stages are e

Transmit:

THE Base is driven by variable current and the collector is connected in series with a resistor, thus creating a variable voltage divider. If you want to drive the base with a voltage-based signal soURCE, you have to bias it with a pull-up resisto r to Ucc and stop. Most cont[illegible]re conceptually quite similar to general op-amps, i.e. they posess tw[illegible]INVERTING) and one output. The difference with power amps is, that their fåi[illegible]higher output currents and, because maximum power dissipated in a given loa[illegible]f voltage, the power amps usually have [illegible] stand higher power supply voltages. [illegible]lt to distinguish the inverti ng signal input in an amp built of discrete devices, because we only need one explicit input for signal (the non-inverting one), and so the inverting input remains embedded in the schematic - but in most power åamps it is identifiable if you follow the resistive divider in the negative

Figure 4.17: Visual C Graphical User Interface

The combined 6 groups of data with check sum are then interleaved to ensure that errors if occurred are separated as far as possible in the packet. Total 144 bits are interleaved as explained in previous section. The bits are then differentially encoded and then modulated, before they are combined with the additional start bit and stop bit prepared earlier. This step increases the length of the packet duration and this increase length of start and stop bits are important to ensure the correct detection of data packet. The completed data packet is then transmitted through radio.

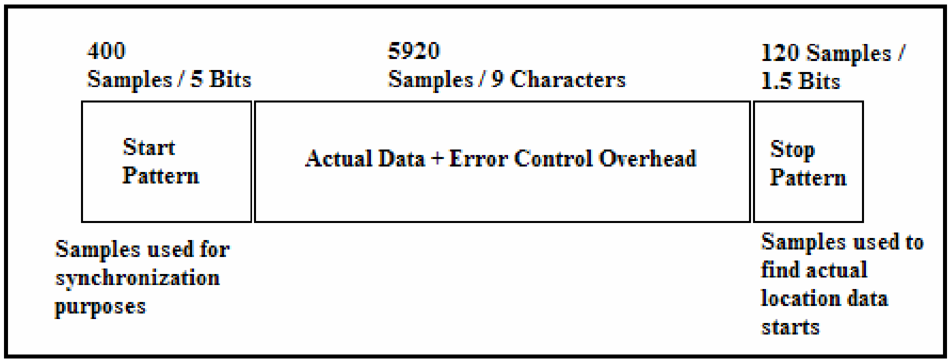

400
Samples / 5 Bits
5920
Samples / 9 Characters
120 Samples / 1.5 Bits
Start Pattern
Actual Data + Error Control Overhead
Stop Pattern
Samples used for synchronization purposes
Samples used to find actual location data starts

Figure 4.18: DQPSK Packet Structure

DQPSK packet structure implemented is illustrated in Figure 4.18. The packet is made of 9 characters or 72 bits of data and another 72 bits of check sum for the FEC overhead. As explained earlier, the length of the actual data is only 0.740 seconds or 5920 samples, but in order to increase the signal detection efficiency, 400 samples are added at the front of the packet and another 120 samples are added at the back of the packet. These additional samples are comprised of single harmonic 2000Hz cosine waveform which is used as in-phase reference signal and quadrature reference signal at the receiver. These additional samples do not affect the overall processing time because these samples are not used in the actual demodulation process. The total length of the packet is 6440 samples or 0.805 seconds. Packet cycle is fixed at 6 seconds to allow for processing time at both transmit and receiver.

The receiver side captures 35 samples of data and the captured data are processed to detect the start bit. This process is repeated until start pattern is detected. The whole packet of data is captured once the start pattern is detected. Stop pattern detection is then and from this stop pattern information, the exact sample where the data starts can be calculated. Data is shifted, to get the actual data, according to the number of samples calculated from above. The whole length of the data packet is then passed through a band pass filter with lower cut off frequency 1900Hz and higher cut off frequency 2100Hz. The band pass filter is designed to be a 35 filter length FIR filter. Only frequency component of 2000Hz will pass through while other frequency ranges is attenuated. The flowchart of modulation and demodulation process is illustrated in Figure 4.19.

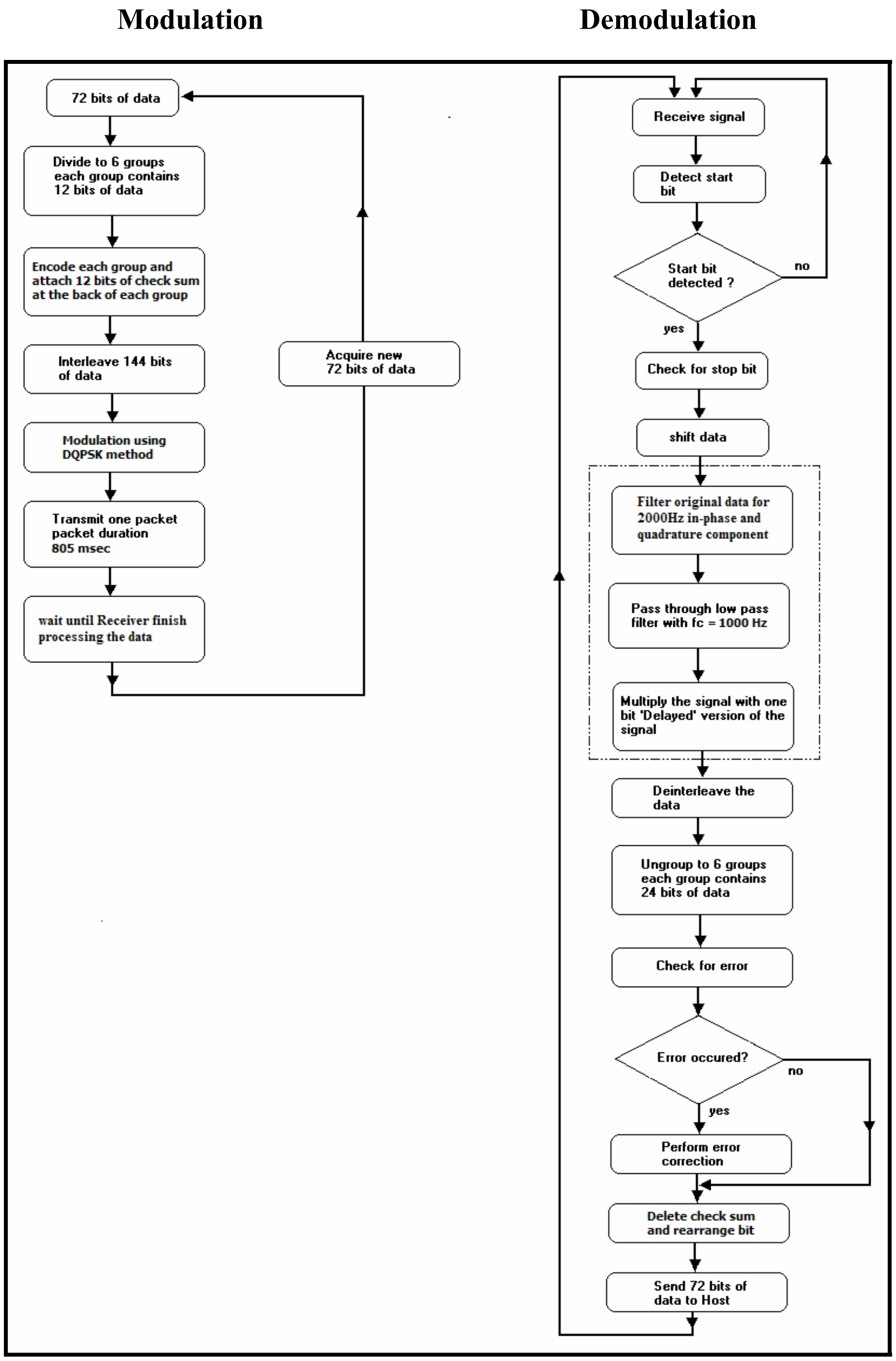

Modulation
Demodulation
72 bits of data
Divide to 6 groups each group contains 12 bits of data
Encode each group and attach 12 bits of check sum at the back of each group
Interleave 144 bits of data
Modulation using DQPSK method
Transmit one packet packet duration 805 msec
wait until Receiver finish processing the data
Acquire new 72 bits of data
Receive signal
Detect start bit
Start bit detected ?
no
yes
Check for stop bit
shift data
Filter original data for 2000Hz in-phase and quadrature component
Pass through low pass filter with fc = 1000 Hz
Multiply the signal with one bit 'Delayed' version of the signal
Deinterleave the data
Ungroup to 6 groups each group contains 24 bits of data
Check for error
Error occured?
no
yes
Perform error correction
Delete check sum and rearrange bit
Send 72 bits of data to Host

Figure 4.19: Modulation and Demodulation

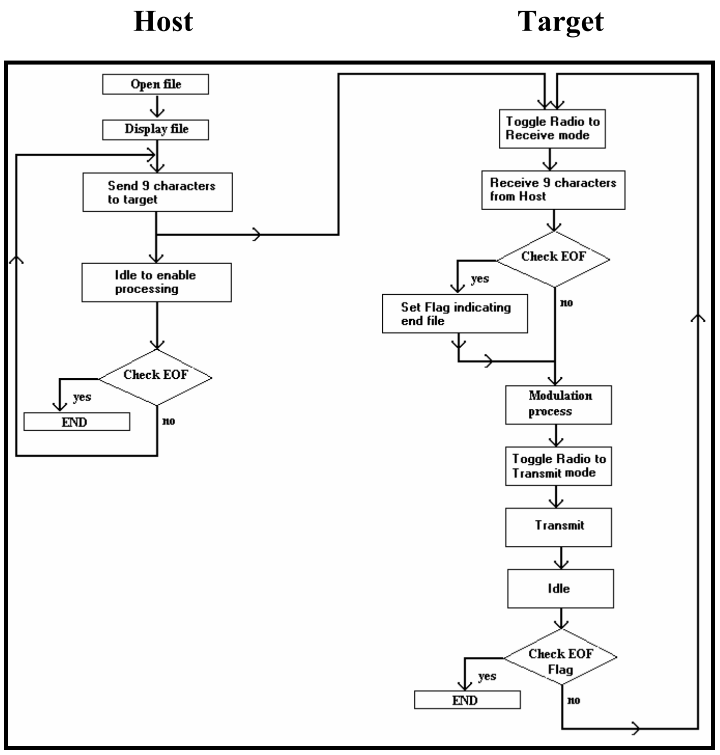

Host
Target
Open file
Display file
Send 9 characters to target
Idle to enable processing
Check EOF
yes
END
no
Toggle Radio to Receive mode
Receive 9 characters from Host
Check EOF
yes
Set Flag indicating end file
no
Modulation process
Toggle Radio to Transmit mode
Transmit
Idle
Check EOF Flag
yes
END
no

Figure 4.20: Transmitter Side Operation Flowchart

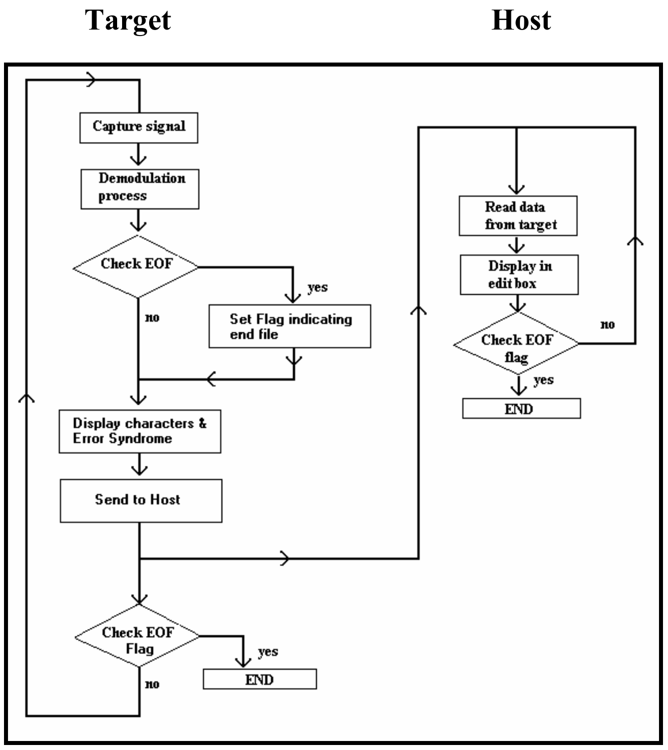


Figure 4.21: Receiver Side Operation Flowchart

Figure 4.20 and Figure 4.21 explain the processes that occur in both transmitter and receiver side respectively. Here we can see that the host and target operate independently. The host only handles the process of extracting file or storing the received file, the target handles all the extensive computation.

4.8 Selection of Field-test Sites

HF is most suitable for long distance, where in this case the distance between the transmitter and receiver station are separated for more than 100 kilometers. This assumption is done to exclude the line of sight signal components from reaching the receiver. The prototype HF DQPSK modem was tested between DSP Lab in UTM Skudai and Kuala Jasin Camping Site in Taman Negara Endau, Baling which is in Kedah and also Chemor which is in Perak. Endau Rompin was chosen based on these reasons; no other means of communications, located in a remote place and far from Skudai to ensure no ground wave communication, thick forest with a lot of ceiling coverage that prohibit satellite communication and blocked by mountain range on all sides to ensure no line of sight communication or VHF signal can pass through. Baling and Chemor were chosen because the distance is greater and there isn’t any mobile phone coverage to the Baling test site and Chemor is situated in the lowlands.

4.9 Test Equipments Setup

Test setup is as shown in Figure 4.22. A Transmitter side is placed in Skudai, where the main function is to transmit known file. The difference between the transmitter side and the receiver side is that the transmitter side utilizes the TMS320VC5416 DSK board to generate the transmit signal, whereas the receiver side records the signal for analysis. Figure 4.23 shows the connection between TMS320VC5416 DSK board and the transceiver.

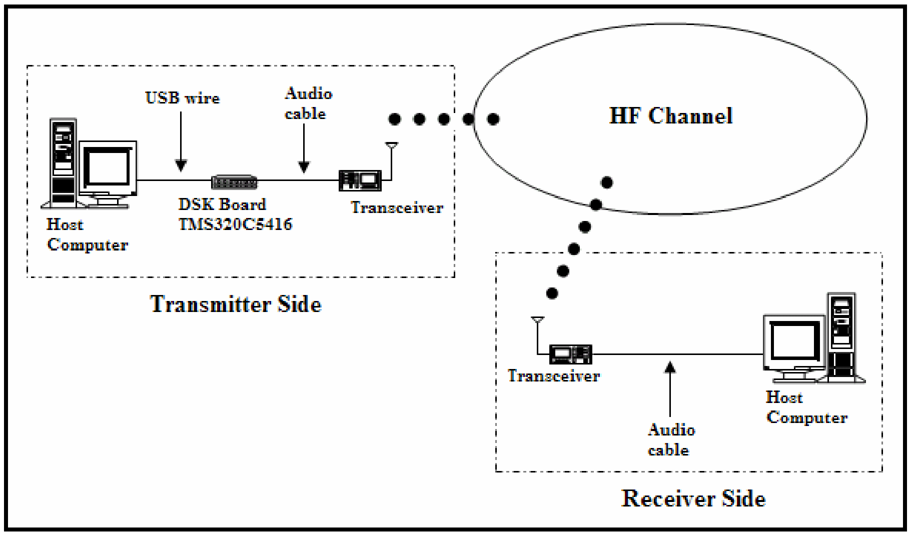


Figure 4.22: Test Setup

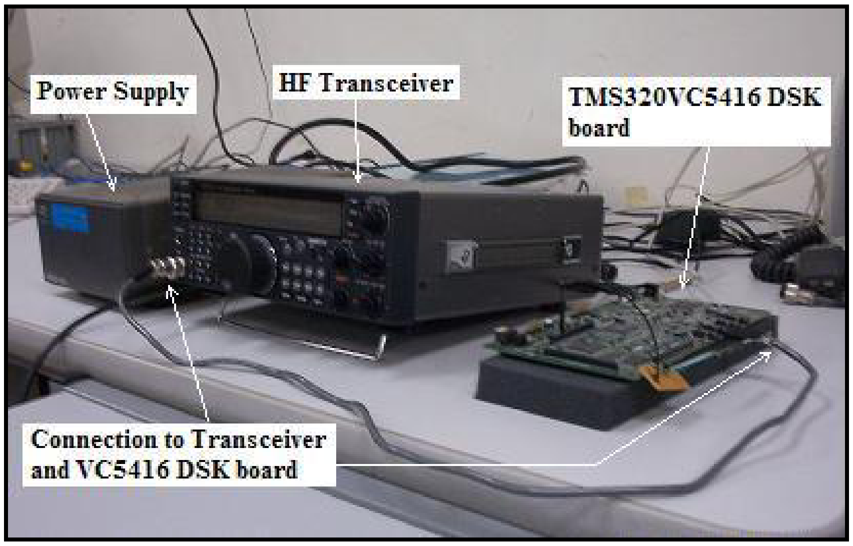
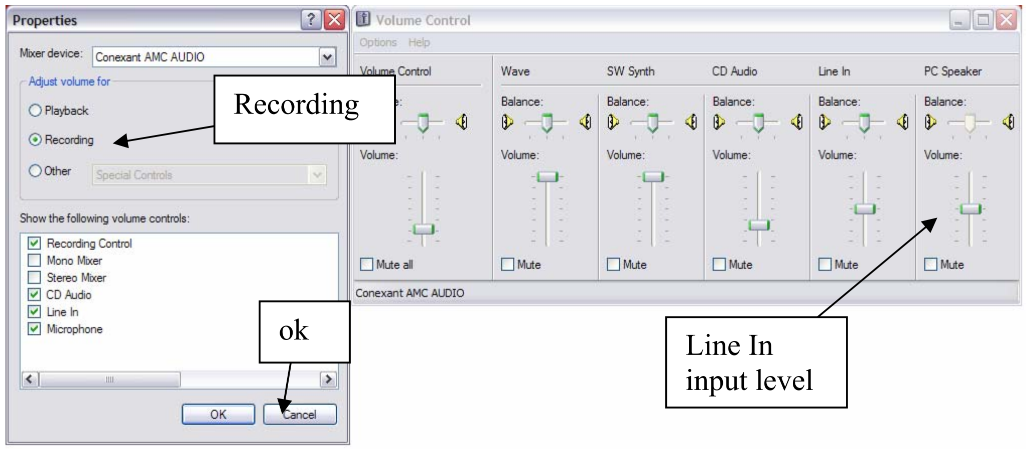


Figure 4.23: TMS320VC5416 DSK Board and Transceiver Connection

4.9.1 Computer Setup

The receiver side requires a simple connection from the radio to the line input of the sound card in the computer. The received signal is recorded in the computer using the common sound recorder program in the computer. Certain initial settings need to be done before proceeding with the actual recording of the received signal. These settings are essential in order to get the correct signal, with the correct sampling frequency and unclipped signal.

Figure 4.24 illustrates the properties of the sound card. We need to select Recording before a signal can actually be recorded. After pressing the OK button, we need to reduce the Line In level to control the magnitude of the received signal, in order to record without clipping the signal. A clipped recorded signal will produce a different result since it changes the frequency component of the received signal.


Properties

Mixer device: Conexant AMC AUDIO

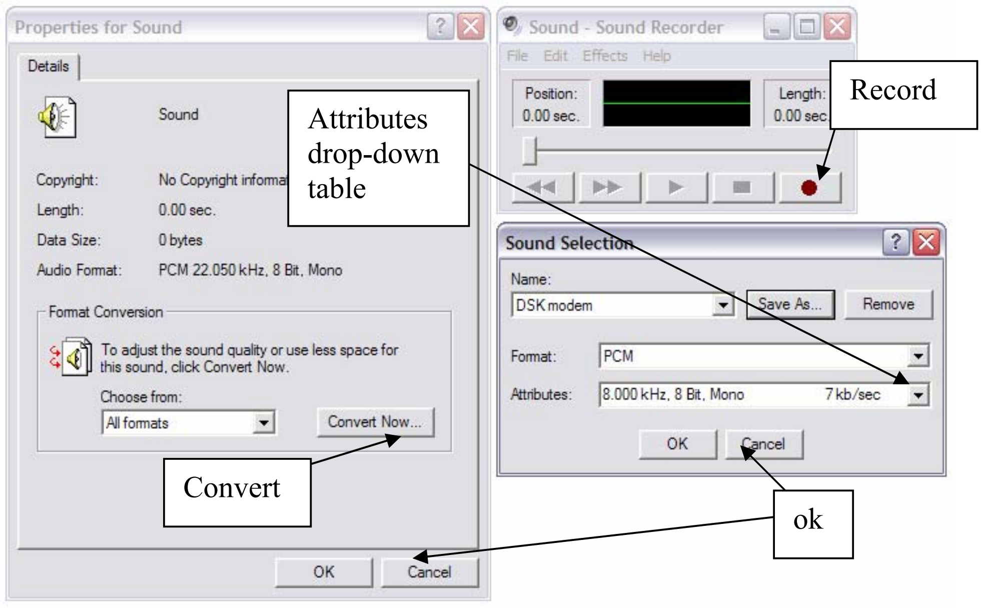
Adjust volume for

○ Playback
[✓ ◉ Recording]
○ Other Special Controls

Show the following volume controls:

- [✓] Recording Control
- [ ] Mono Mixer
- [ ] Stereo Mixer
- [✓] CD Audio
- [✓] Line In
- [✓] Microphone

Figure 4.24: Sound Card Properties



Sound

Copyright: No Copyright informa

Length: 0.00 sec.

Data Size: 0 bytes

Audio Format: PCM 22.050 kHz, 8 Bit, Mono

To adjust the sound quality or use less space for this sound, click Convert Now.

Choose from: All formats

Position: 0.00 sec.

Length: 0.00 sec.

Name: DSK modem

Format: PCM

Attributes: 8.000 kHz, 8 Bit, Mono 7 kb/sec

Figure 4.25: Sound Recorder Properties

Properties for the sound recorder are illustrated in Figure 4.25. The transmitter is programmed to produce signal using sampling frequency sampling of 8000 Hz and in order to record the correct information, the properties of the sound recorder has to be adjusted to the proper settings. By pressing the convert button, we can configure the sound recorder parameter to 8000Hz frequency sampling, 8 bit input and mono from the drop-down table at the attributes.

4.9.2 Transceiver setup

Hardware setup for the transmitter side is as shown in Figure 4.23. The receiver only utilizes the common sound recorder program already installed inside the computer. The reliability of the dipole antenna needed to be checked before transmission could be conducted. Chapter 5 explained in detail the method to check the ratio of forward/reverse power for a dipole antenna. Squelch level in the receiver radio is adjusted until the threshold level is just above the noise level. This step is done to ensure only the true signal is received at the receiver. The next crucial step is to set the mode to LSB+FSK in the receiver radio. By setting this particular mode, we are utilizing the built-in bandpass filter inside the Kenwood HF transceiver to reduce noise. The bandwidth of this built-in bandpass filter is 300Hz. The final step is to connect the stereo cable from the receiver radio to sound card Line In to record the received signal.

4.10 Results

Data transmission testing was conducted in the morning and evening to monitor the effect of various time during the day. The received signal power and the SNR can be measured using spectrum analyzer. Only DPSK signal was transmitted during the Endau Rompin field-testing. The frequency used is 7.1MHz. The BER result and its SNR are listed in Table 4.5. The method to calculate the theoretical uncoded BER from the measured SNR is explained in Appendix B.

The actual transmit power was 10Watt and signal transmitted during this field-testing was only DPSK because the proper way to synchronize the incoming signal for DQPSK was not yet solved. DPSK does not require the strict synchronization as DQPSK since it does not need to perform any correlation process. Night-time shows a drop in SNR compared with day-time transmission. Day-time transmission is at 17dB and the uncoded BER is around 0.03. Compared with simulation result in Figure 4.7 and theoretical BER in Table 4.5, it is clear that BER during field-testing are far worse. This is expected since the theory and simulation result did not take into account the effect introduced by multipath fading and Doppler effect.

Table 4.5: Endau Rompin Field-testing BER and SNR

Time of Test	Theoretical BER	Simulation BER	Actual BER	SNR (dB)
20 April **10:00**	1.903e -15	2.78e-08	0.037	18.2219
20 April **13:10**	5.446e-13	3.83e-07	0.035	17.4108
20 April **21:15**	8.358e - 4	0.0023	0.091	11.0680
21 April **11:28**	2.1183e-13	4.52e-07	0.033	17.5572
21 April **15:10**	2.375e-13	3.23e-07	0.035	17.5397
21 April **21:20**	1.228e-3	0.0119	0.097	10.7898

Field-testing in Baling was conducted after the problem in synchronization had been solved. The solution was explained in detail in previous section where the in-phase component and quadrature component is recovered from the incoming signal itself. Even if the detection is delayed by certain samples, the received signal would not be corrupted since the in-phase correlator and quadrature correlator will shift accordingly.

Table 4.6: Example of Error Syndrome and Number of Errors per Packet

Characters	Syndrome (in Hexadecimal)						Number of Errors
ABCDEFGHI	0xC76	0x000	0x001	0xF2A	0x5C7	0xF2A	7
ABCDEFGHI	0x5C6	0x5C7	0x000	0x5C7	0x000	0x000	5
ABCDEFGHI	0x000	0x000	0x336	0xA62	0x000	0xD2A	4
ABCDEFGHI	0x000	0xB78	0x336	0xA62	0x000	0xD2A	5
ABCDEFGHI	0xB8C	0x7C9	0x000	0x262	0xD2A	0x2B8	10
ABCDEFGHI	0x000	0x7C9	0x000	0xAE2	0x000	0x000	4
ABCDEFGHI	0xF2A	0xF2A	0x000	0x000	0x000	0xB92	6
ABCDEFGHI	0x000	0xB8E	0xB8E	0x000	0x000	0x000	4
ABCDEFGHI	0xB8C	0x000	0xC5A	0x0F2	0x172	0x238	13
ABCDEFGHI	0x000	0x000	0x000	0x000	0x000	0xF92	1

Table 4.6 shows the example of error syndrome and number of errors per packet. This example listed the errors and its syndrome for 10 packets of data. The packets which contained the same 9 characters 'ABCDEFGHI' were sent continuously and their number of errors were totaled to get the overall number of errors. All of the errors were corrected in this example. Total of bits transmitted are 1440 and total number of errors are 59, which resulted in uncoded BER of 0.04 for this example.

Table 4.7: Baling Field-testing BER and SNR

Time of Test	**Theoretical BER**	**Simulation BER**	**Actual BER**	**SNR (dB)**
18 August **10:00**	7.16e-12	2.01e-05	0.041	17.1033
18 August **15:10**	3.144e-10	7.32e-05	0.046	16.4108

Minimum of 100 packets were sent to get the average of uncoded BER for the field test. Result of uncoded BER and SNR for Baling filed-testing are listed in Table 4.7. Testing was conducted on August, 18th 2004, once in the morning and once in the evening. The field-testing was conducted to test the performance of the prototype DQPSK modem and not to find the characteristics of the channel. The method to calculate the theoretical uncoded BER from the measured SNR is explained in Appendix B.

Chemor field-testing result is listed in Table 4.8. The method of the test was the same with the test done in Baling, where the same packet of characters was sent continuously. Minimum 100 packets were sent for every session. This was done to get the average uncoded BER for that particular session. Carrier frequency used in the morning test session was 6.65 MHz and the transmit power was set at 10 Watt. The transmit power for the test in the evening session and night session were set at 15 Watt. Carrier frequency used in the evening was 7.08 MHz while at night was 6.65 MHz.

Table 4.8: Chemor Field-testing BER and SNR

Time of Test	**Theoretical BER**	**Simulation BER**	**Actual BER**	**SNR (dB)**
6 November **9:00**	7.31e-12	2.23e-05	0.041	17.0213
6 November **14:00**	3.205e-10	7.51e-05	0.037	16.4037
6 November **21:00**	8.098e-12	2.08e-05	0.043	17.0824
8 November **9:00**	9.321e-15	2.01-e07	0.038	18.1032
8 November **14:10**	1.687e-10	4.21e-05	0.035	16.5326
8 November **21:00**	1.339e-12	7.52e-06	0.042	17.3781

From these test it is clear that the actual uncoded BER is at 10^{-2} if the SNR of the channel could be maintained at 16~17dB. If the selection of the frequency is inappropriate, transmitting at a higher power will not be able to increase the SNR at the receiver. Most of the signal will be transmitted to a farther distance or the receiving station will be located in the skip zone if the selection is inappropriate. The selection of frequency was based on prediction software and given licensed by MCMC which will explain detail in Chapter 5. It is found that the frequency used in the morning may not be usable in the afternoon and at night.

This prototype HF modem is guaranteed to be able to correct errors if the BER is at10^{-2}. Extended Golay code is capable in correcting 3 errors in a packet of 24 bits. This prototype DQPSK HF modem utilizes 6 packets of 24 bits as the data format, where the maximum number of errors which it can correct is 18 errors and if the numbers of errors in the 24 bits packet are not more than 3 errors. A serious problem that is discovered in these tests is that numbers of errors do not increase but the whole packet is lost instead. These may be due to the packet being corrupted or the receiver failing to even detect the incoming signal. The start and stop bit detection explained in detail in previous section is designed to detect signal at SNR 16dB. It may not be functioning properly if the SNR is lower or if the front end of the packet itself is corrupted. Examples of corrupted packets are shown in the Appendix B.

4.11 Conclusion

The results show the comparison of BER and SNR between theoretical, simulation and experimental. It is found that the prototype is designed to operate at SNR 16dB. Due to propagation in HF, the prototype found difficulties to fulfill the objective to transmit secured image over HF radio. However, the research found the significant in term of modulation technique, channel propagation and error control which believed could be used to develop stand alone and high speed HF modem in future.

CHAPTER 5

SYSTEM REQUIREMENTS AND IMPLEMENTATION OF SECURED HF MESSENGER

Besides an HF modem, another important part in secured HF transmission system is the application software that executes in a computer. The software will handle the process of digital information and security before converted to analog signal by HF modem. Due to the problem of development DQPSK HF modem using TMS320C5416, the commercialized stand alone modems were purchased. The application software is needed to control every function of HF modem to ensure image transmission is possible over HF radio.

5.1 System Components

Basically, the system needs two stations, which are connected to each other via HF medium. Each station needs a computer, HF modem, transceiver and antenna to allow them to communicate as shown in Figure 5.1. Usually, the communication occurs between based station and mobile station. The antenna used could be wide band or narrow band as long as it supports the compatible range of frequencies for both stations. This antenna is connected to the transceiver using coaxial cable. Then, the transceiver is connected to HF modem. For this project, Kenwood Ts-570D is used as transceiver while KAM'98 as HF modem. Detail specification of these components can be found in Appendix C.

Instead of all equipments, another important part is Secured HF Messenger software, which is installed in the computer. The application is capable to control HF modem through computer serial port. By using this application, both stations can exchange their digital information such as JPEG image , text file, winzip file and short message confidentially.

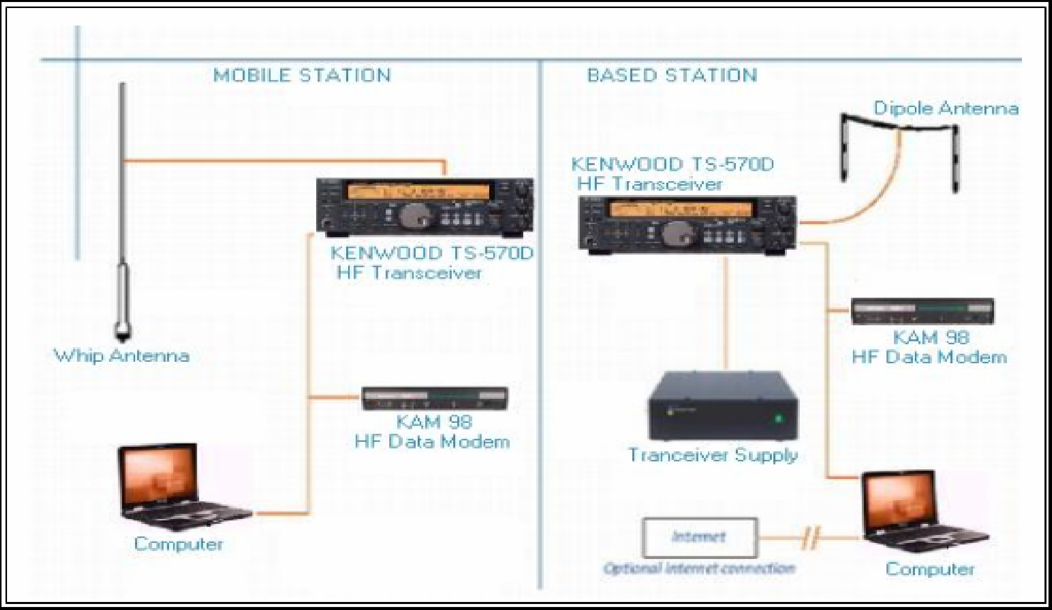
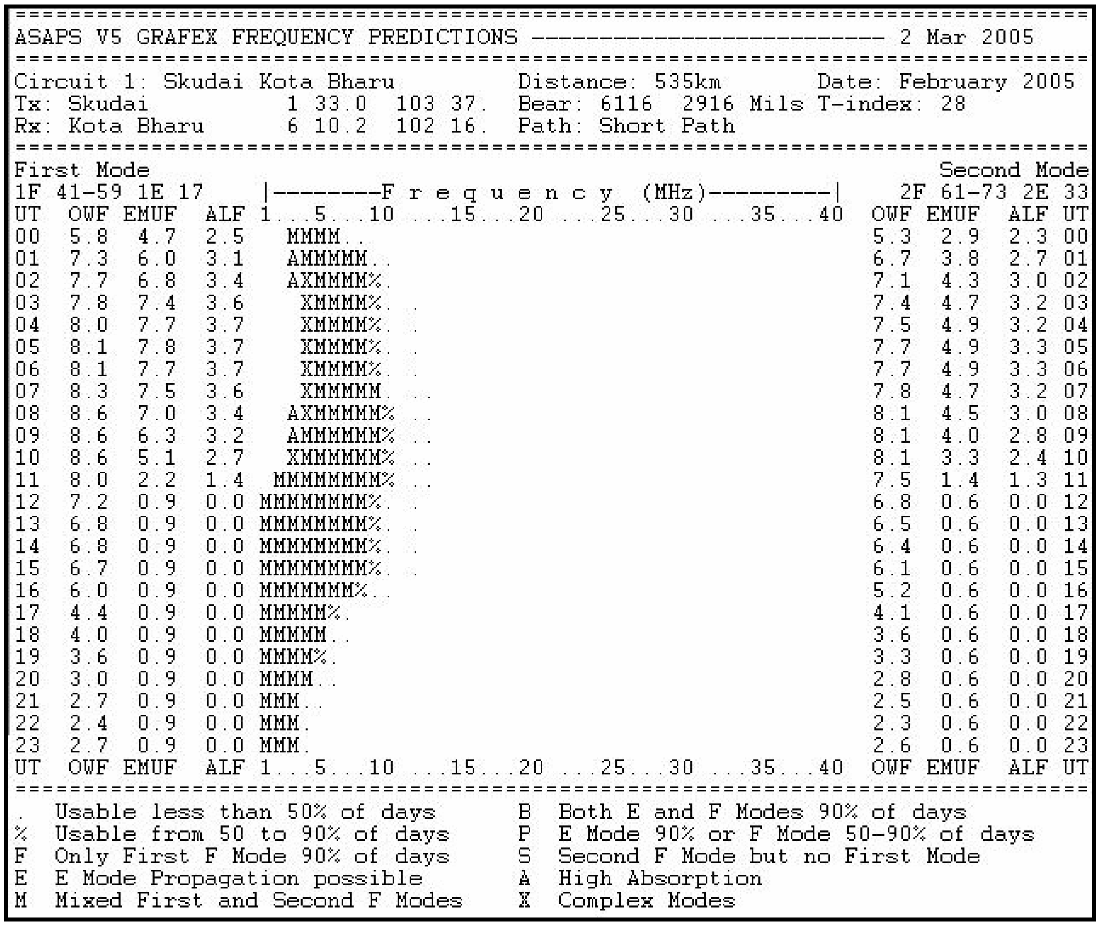


Figure 5.1: System structure for both Stations

5.1.1 Operating Frequency

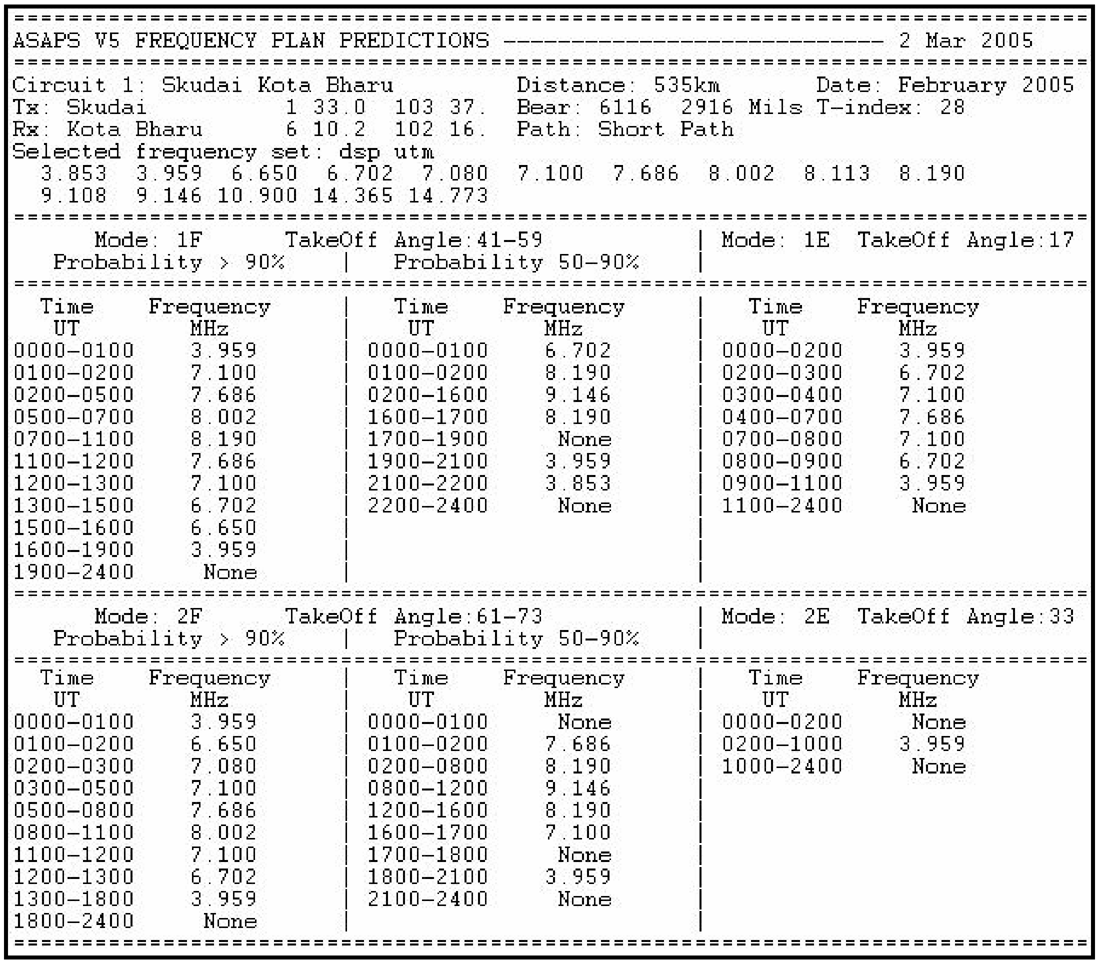
As known that HF propagation always changes by a lot of factors. So, a chosen of operating frequency is very crucial to enhance the quality of transmission. For this project, the frequencies used are referred to experimental license that has been given by Malaysian Communication and Multimedia Communication (MCMC). There are 15 usable frequencies and details of the license shows in Appendix C.

Due to HF propagation, selected suitable frequency is crucial for optimizing data transmission. Therefore, a prediction needed to find which frequency is suitable to use at certain time. Here, third party software which is Advanced Stand Alone Prediction System (ASAPS) is used to predict the Optimum Working Frequency (OWF) as shown in Figure 5.2. Based on OWF, the best usable frequency is chosen for testing purposes as shown in Figure 5.3. Besides predict OWF, the software is also capable to predict the field strength based on antenna and power chosen. So, both stations can determine whether they need to increase the transmission power or not during the communication. Figure 5.4 presents the prediction of Signal to Noise Ratio (SNR) based on 25 Watt power transmit and half wavelength horizontal dipole antenna (half-wave height).



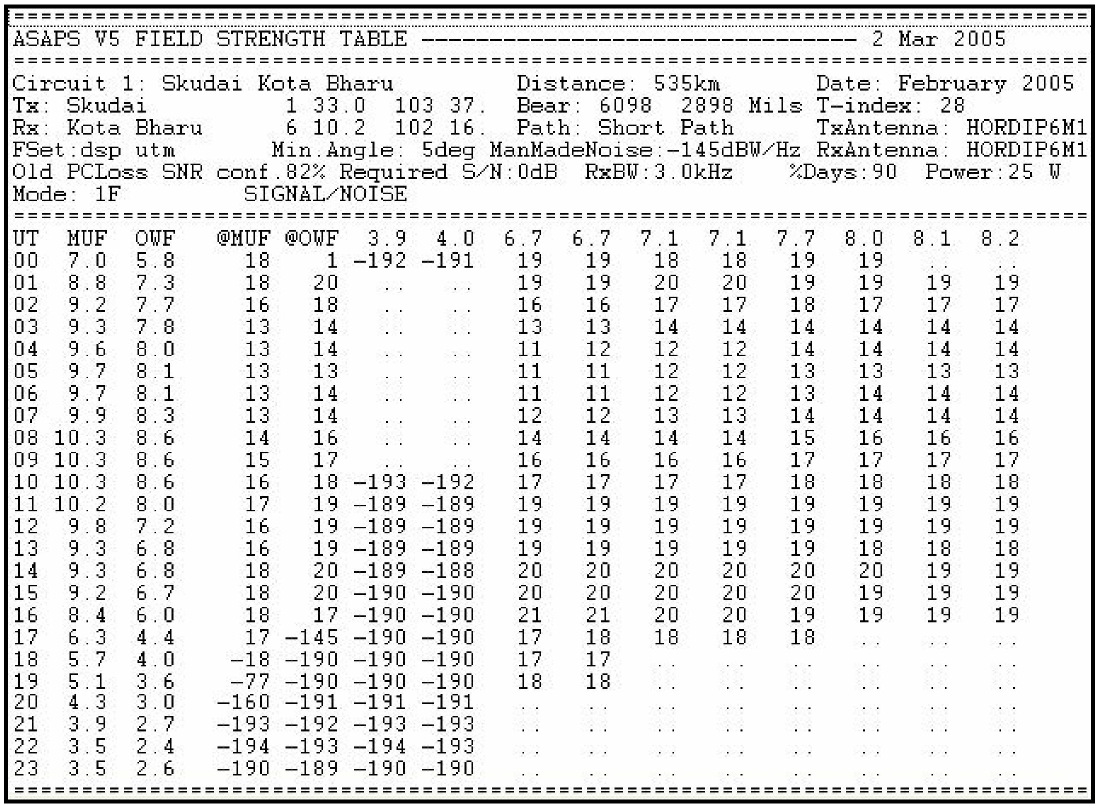
```
===============================================================================
ASAPS V5 GRAFEX FREQUENCY PREDICTIONS -------------------------- 2 Mar 2005
===============================================================================
Circuit 1: Skudai Kota Bharu         Distance: 535km       Date: February 2005
Tx: Skudai          1 33.0  103 37.  Bear: 6116  2916 Mils T-index: 28
Rx: Kota Bharu      6 10.2  102 16.  Path: Short Path
===============================================================================
First Mode                                                          Second Mode
1F 41-59 1E 17    |--------F r e q u e n c y  (MHz)---------|    2F 61-73 2E 33
UT  OWF EMUF  ALF 1...5...10 ...15...20 ...25...30 ...35...40  OWF EMUF  ALF UT
00  5.8  4.7  2.5   MMMM..                                     5.3  2.9  2.3 00
01  7.3  6.0  3.1   AMMMMM..                                   6.7  3.8  2.7 01
02  7.7  6.8  3.4   AXMMMM%.                                   7.1  4.3  3.0 02
03  7.8  7.4  3.6    XMMMM%. .                                 7.4  4.7  3.2 03
04  8.0  7.7  3.7    XMMMM%. .                                 7.5  4.9  3.2 04
05  8.1  7.8  3.7    XMMMM%. .                                 7.7  4.9  3.3 05
06  8.1  7.7  3.7    XMMMM%. .                                 7.7  4.9  3.3 06
07  8.3  7.5  3.6    XMMMMM. ..                                7.8  4.7  3.2 07
08  8.6  7.0  3.4   AXMMMMM% ..                                8.1  4.5  3.0 08
09  8.6  6.3  3.2   AMMMMMM% ..                                8.1  4.0  2.8 09
10  8.6  5.1  2.7   XMMMMMM% ..                                8.1  3.3  2.4 10
11  8.0  2.2  1.4  MMMMMMMM% ..                                7.5  1.4  1.3 11
12  7.2  0.9  0.0 MMMMMMMM%. .                                 6.8  0.6  0.0 12
13  6.8  0.9  0.0 MMMMMMMM%. .                                 6.5  0.6  0.0 13
14  6.8  0.9  0.0 MMMMMMMM%. .                                 6.4  0.6  0.0 14
15  6.7  0.9  0.0 MMMMMMMM%. .                                 6.1  0.6  0.0 15
16  6.0  0.9  0.0 MMMMMMM%..                                   5.2  0.6  0.0 16
17  4.4  0.9  0.0 MMMMM%.                                      4.1  0.6  0.0 17
18  4.0  0.9  0.0 MMMMM..                                      3.6  0.6  0.0 18
19  3.6  0.9  0.0 MMMM%.                                       3.3  0.6  0.0 19
20  3.0  0.9  0.0 MMMM..                                       2.8  0.6  0.0 20
21  2.7  0.9  0.0 MMM..                                        2.5  0.6  0.0 21
22  2.4  0.9  0.0 MMM.                                         2.3  0.6  0.0 22
23  2.7  0.9  0.0 MMM.                                         2.6  0.6  0.0 23
UT  OWF EMUF  ALF 1...5...10 ...15...20 ...25...30 ...35...40  OWF EMUF  ALF UT
===============================================================================
.  Usable less than 50% of days      B  Both E and F Modes 90% of days
%  Usable from 50 to 90% of days     P  E Mode 90% or F Mode 50-90% of days
F  Only First F Mode 90% of days     S  Second F Mode but no First Mode
E  E Mode Propagation possible       A  High Absorption
M  Mixed First and Second F Modes    X  Complex Modes
```

Figure 5.2: Prediction result shows the OWF for F and E layer



```
================================================================================
ASAPS V5 FREQUENCY PLAN PREDICTIONS ---------------------------- 2 Mar 2005
================================================================================
Circuit 1: Skudai Kota Bharu         Distance: 535km       Date: February 2005
Tx: Skudai          1 33.0  103 37.  Bear: 6116  2916 Mils T-index: 28
Rx: Kota Bharu      6 10.2  102 16.  Path: Short Path
Selected frequency set: dsp utm
  3.853  3.959  6.650  6.702  7.080  7.100  7.686  8.002  8.113  8.190
  9.108  9.146 10.900 14.365 14.773
================================================================================
      Mode: 1F      TakeOff Angle:41-59          | Mode: 1E  TakeOff Angle:17
   Probability > 90%    |   Probability 50-90%   |
================================================================================
  Time    Frequency     |  Time    Frequency     |  Time    Frequency
   UT        MHz        |   UT        MHz        |   UT        MHz
0000-0100    3.959      | 0000-0100    6.702     | 0000-0200    3.959
0100-0200    7.100      | 0100-0200    8.190     | 0200-0300    6.702
0200-0500    7.686      | 0200-1600    9.146     | 0300-0400    7.100
0500-0700    8.002      | 1600-1700    8.190     | 0400-0700    7.686
0700-1100    8.190      | 1700-1900     None     | 0700-0800    7.100
1100-1200    7.686      | 1900-2100    3.959     | 0800-0900    6.702
1200-1300    7.100      | 2100-2200    3.853     | 0900-1100    3.959
1300-1500    6.702      | 2200-2400     None     | 1100-2400     None
1500-1600    6.650      |                        |
1600-1900    3.959      |                        |
1900-2400     None      |                        |
================================================================================
      Mode: 2F      TakeOff Angle:61-73          | Mode: 2E  TakeOff Angle:33
   Probability > 90%    |   Probability 50-90%   |
================================================================================
  Time    Frequency     |  Time    Frequency     |  Time    Frequency
   UT        MHz        |   UT        MHz        |   UT        MHz
0000-0100    3.959      | 0000-0100     None     | 0000-0200     None
0100-0200    6.650      | 0100-0200    7.686     | 0200-1000    3.959
0200-0300    7.080      | 0200-0800    8.190     | 1000-2400     None
0300-0500    7.100      | 0800-1200    9.146     |
0500-0800    7.686      | 1200-1600    8.190     |
0800-1100    8.002      | 1600-1700    7.100     |
1100-1200    7.100      | 1700-1800     None     |
1200-1300    6.702      | 1800-2100    3.959     |
1300-1800    3.959      | 2100-2400     None     |
1800-2400     None      |                        |
================================================================================
```

Figure 5.3: The usable frequencies based on OWF



```
===============================================================================
ASAPS V5 FIELD STRENGTH TABLE --------------------------------- 2 Mar 2005
===============================================================================
Circuit 1: Skudai Kota Bharu        Distance: 535km        Date: February 2005
Tx: Skudai           1 33.0  103 37.  Bear: 6098  2898 Mils T-index: 28
Rx: Kota Bharu       6 10.2  102 16.  Path: Short Path      TxAntenna: HORDIP6M1
FSet:dsp utm       Min.Angle: 5deg ManMadeNoise:-145dBW/Hz RxAntenna: HORDIP6M1
Old PCLoss SNR conf.82% Required S/N:0dB  RxBW:3.0kHz     %Days:90  Power:25 W
Mode: 1F          SIGNAL/NOISE
===============================================================================
UT   MUF  OWF    @MUF @OWF  3.9  4.0  6.7  6.7  7.1  7.1  7.7  8.0  8.1  8.2
00   7.0  5.8      18    1 -192 -191   19   19   18   18   19   19   ..   ..
01   8.8  7.3      18   20   ..   ..   19   19   20   20   19   19   19   19
02   9.2  7.7      16   18   ..   ..   16   16   17   17   18   17   17   17
03   9.3  7.8      13   14   ..   ..   13   13   14   14   14   14   14   14
04   9.6  8.0      13   14   ..   ..   11   12   12   12   14   14   14   14
05   9.7  8.1      13   13   ..   ..   11   11   12   12   13   13   13   13
06   9.7  8.1      13   14   ..   ..   11   11   12   12   13   14   14   14
07   9.9  8.3      13   14   ..   ..   12   12   13   13   14   14   14   14
08  10.3  8.6      14   16   ..   ..   14   14   14   14   15   16   16   16
09  10.3  8.6      15   17   ..   ..   16   16   16   16   17   17   17   17
10  10.3  8.6      16   18 -193 -192   17   17   17   17   18   18   18   18
11  10.2  8.0      17   19 -189 -189   19   19   19   19   19   19   19   19
12   9.8  7.2      16   19 -189 -189   19   19   19   19   19   19   19   19
13   9.3  6.8      16   19 -189 -189   19   19   19   19   19   18   18   18
14   9.3  6.8      18   20 -189 -188   20   20   20   20   20   20   19   19
15   9.2  6.7      18   20 -190 -190   20   20   20   20   20   19   19   19
16   8.4  6.0      18   17 -190 -190   21   21   20   20   19   19   19   19
17   6.3  4.4      17 -145 -190 -190   17   18   18   18   18   ..   ..   ..
18   5.7  4.0     -18 -190 -190 -190   17   17   ..   ..   ..   ..   ..   ..
19   5.1  3.6     -77 -190 -190 -190   18   18   ..   ..   ..   ..   ..   ..
20   4.3  3.0    -160 -191 -191 -191   ..   ..   ..   ..   ..   ..   ..   ..
21   3.9  2.7    -193 -192 -193 -193   ..   ..   ..   ..   ..   ..   ..   ..
22   3.5  2.4    -194 -193 -194 -193   ..   ..   ..   ..   ..   ..   ..   ..
23   3.5  2.6    -190 -189 -190 -190   ..   ..   ..   ..   ..   ..   ..   ..
===============================================================================
```

Figure 5.4: The SNR prediction based on 25Watt power transmit and half wavelength horizontal dipole antenna (half-wave height).

5.2 Antenna

Antenna is a transducer that converts electrical alternating current oscillations at a radio frequency to an electromagnetic wave of the same frequency. Fundamentally, the electric and magnetic field radiated from an antenna form the electromagnetic field and this field is responsible for the transmission and reception of electromagnetic energy through free space (Carr, 2001). Various types of antenna exist nowadays, and each type of antenna produces different types of electromagnetic radiation. The type of antenna chosen depends heavily on the purpose of the application, whether it is mainly for receiving or whether the orientation of the (receiving and transmitting) station is critical. For this project, narrow band horizontal dipole antenna was used due to lower power transmission, low cost built and radiation pattern.

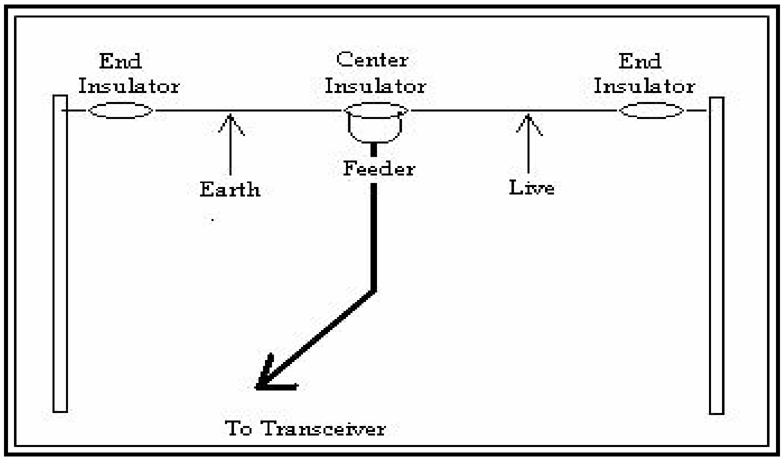


Figure 5.5: Dipole Antenna

The dipole or direction antenna in Figure 5.5 allows for a very low power transmission. A low power transmission will prolong the life of the equipment used. The length of dipole antenna that used in this project is a half-wavelength which also claimed as most practical antenna for communication purpose (Mohamad Kamal, 2005). An approximation for a free space half-wavelength as explained in (Carr, 2001) is

$$L = \frac{468}{F_{Mhz}} ft \tag{5.1}$$

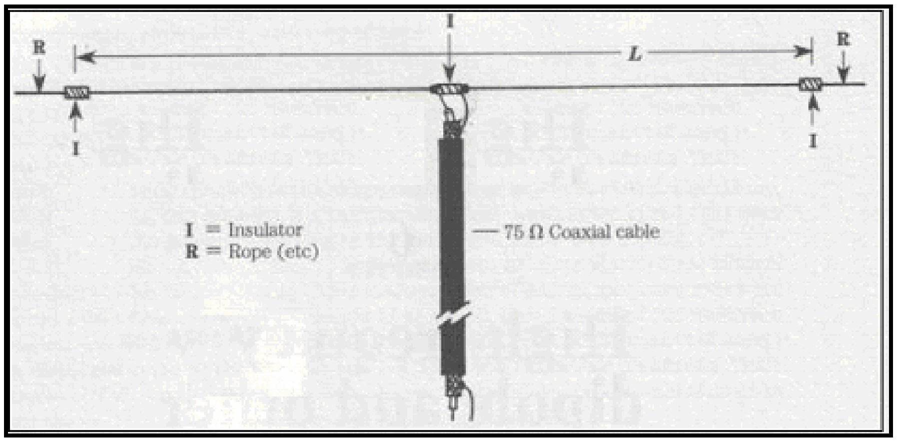


Figure 5.6: Example of half-wavelength dipole antenna

By using Equation (5.1), a 6 MHz horizontal dipole is constructed as shown in Figure 5.6. For effective forward transmit power from the transmitter to the antenna, the transceiver should be placed close to the antenna so that the feeder line is stretched as short as possible.

After an antenna is designed, the next crucial step is the installation of the antenna. The height of the antenna from the ground is important in order to get the correct radiation pattern. Different kind of pattern radiates when the antenna is fixed at different height. The height could be one, half or quarter wavelength. In this project, half-wave length height from the ground is chosen and its vertical radiation is shown in Figure 5.7.

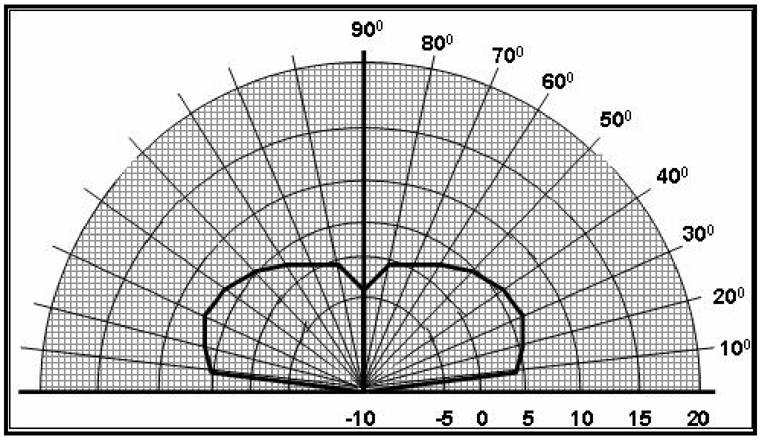


Figure 5.7: Antenna radiation pattern for half-wave length dipole (half-wave height)

An antenna might not be able to transmit full power during transmission because the impedance is not matched. Impedance matching process is essential to ensure that full power is transferred from the radio to the antenna. It is important to avoid the signal from losing during transmission. This process is easily done with Kenwood transceiver since it already has a built in antenna tuner and the process can be performed by merely a push of a button. The location of built-in antenna tuner button is shown in Figure 5.10.

One important equipment (besides the multimeter to check the continuity) used in antenna installation is the transmit power wattmeter as shown in Figure 5.8. The equipment can be used to check the forward-transmit power, which is from the radio to the antenna and the reverse-transmit power, which is from the antenna to the radio. If in any case the reverse-transmit power is larger than forward-transmit power in the frequency band of antenna designed, we will straightaway know that the antenna is faulty. No signal will be transmitted even if we transmit at high power. Figure 5.9 shows the antenna characteristic based on standing wave ratio (SWR) for 6 MHz horizontal dipole antennas. SWR is the term used to explain the ratio of the effective forward power and reflected on the transmission line (Carr, 2001).

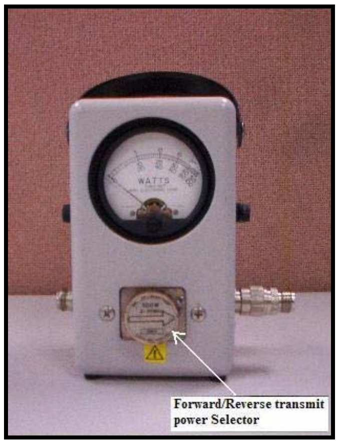


Figure 5.8: Power Wattmeter

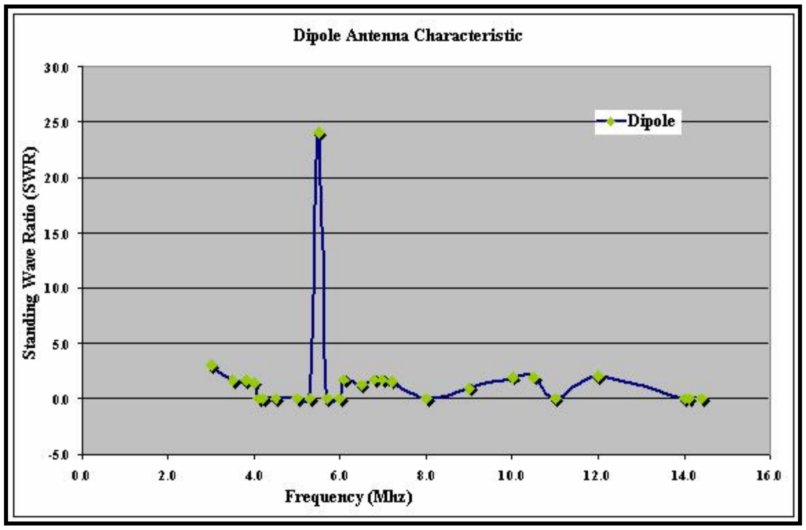


Figure 5.9: Dipole Antenna Characteristics

5.3 Transceiver

Kenwood TS-570D (Kenwood Corp, 1998) transceiver is used in this project for monitoring and field-testing purposes. This transceiver includes a 16-bit DSP unit to process audio frequencies. By taking maximum advantage of DSP technology, the transceiver provides enhance reduction capabilities and improves the quality of audio when transmitting. Some of this transceiver features are:

(i) Provides high performance receive filters
(ii) Enhances the Beat cancel and Noise Reduction tools
(iii) Allows total customization of transmitted audio through the use of functions such as the Transmit Equalizer
(iv) Enables Automatic Zero-beating for CW operation

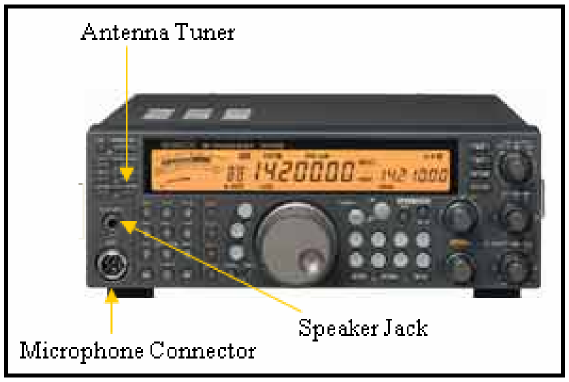


Figure 5.10: Kenwood HF Transceiver TS-570D

Figure 5.10 shows the HF transceiver front connection utilizes the Mic. 9-pin connector, which comprises the PTT pin, receive pin and transmit pin. After each transmission, the transceiver needs to be toggled back to the Receive mode to eliminate the AC hum from interfering with the channel. Besides using Mic 9-pin connector, the transceiver also can be controlled by sending the command through RS-232C COM connector. For this project, the transceiver controlled by HF modem (KAM '98) and the connection between them will be discussed in next section.

5.4 HF Modem

KAM'98 Multi-Mode Terminal Node Controller (TNC) (Kantronics Co, 1998) as shown in Figure 5.11 is a modem for digital data transmission. The KAM'98 can be used either for HF or VHF communication. Beside ASCII mode, this modem provides PACTOR, AMTOR and GTOR modes of operation. Some properties of KAM'98 modem are listed below:

(i) Packet modes: users can communicate with the full range of TOR modes either linked or unlinked.

(ii) Non-packet modes: users can communicate using RTTY, CW, or ASCII protocols.

(iii) More speeds of communication. For HF TOR modes, transmission can be done at 100, 200 and 300 baud (bps).

(iv) Software control capability: this modem supported with RS232 connector which enable to be controlled using terminal communication programs such as Kantronics' DOS-based Pacterm 2.0, Kantronics' Pacterm '98, or by using Terminal Programs that included inside Windows 95/98/NT (HyperTerminal).

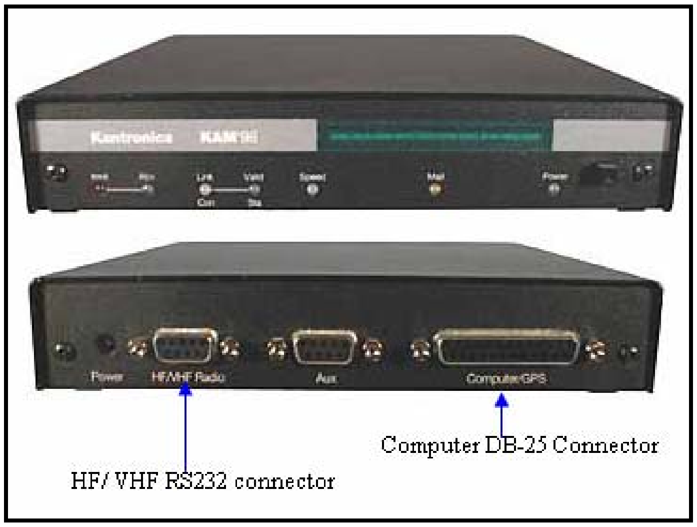
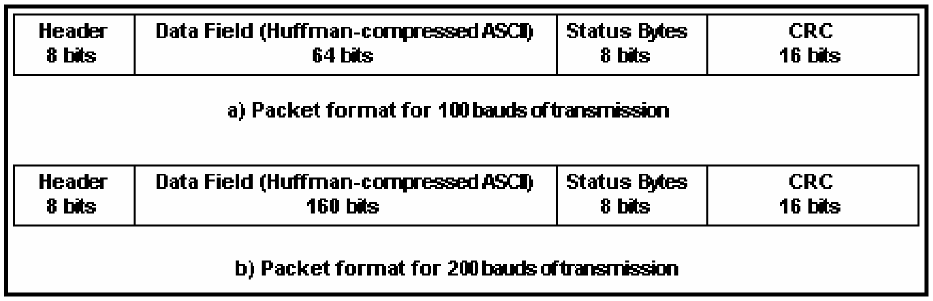


Figure 5.11: HF Modem KAM '98

Although there are many choices of mode supported by KAM ’98 but for this project PACTOR and GTOR mode are preferred. This is because both modes are easy to use, more speed and provide error control correction, which is to ensure the data transmission is error free. PACTOR mode is using Automatic Repeat Request (ARQ) with CRC (Cyclic Redundancy Check) method to handle an error in order to improve reception. It uses standard AFSK (Amplitude Frequency Shift Keying) tone pairs (mark and space) (Kantronics Co, 1998).

PACTOR packets are either 96 bits long sent at 100 bauds or 192 bits long sent at 200 bauds, with the data rate dependent on conditions. Each packet consists of a Header byte, Data Field, Status byte, followed by the CRC byte given twice. The Header byte consists of the 8-bit pattern for 55 hexadecimal and is used for synchronization, Memory ARQ and listen mode. The Data field contains 64 bits if sent at 100 bauds or 160 bits if sent at 200 bauds. Its format is normally Huffman-compressed ASCII, with conventional 8-bit ASCII as the alternative. The Status byte provides the packet count data format (whether standard 8-bit ASCII or Huffman-compressed ASCII), and break-in request, for a total 8 bits. The CRC calculation is based on the ITU-T polynomial $X^{16}+X^{12}+X^{5}+1$. The CRC byte calculated for the whole packet starting with the data field, without header, and consists of 16 bits. Figure 5.12 shows the packet format for both 100 and 200 bauds.



Header 8 bits	Data Field (Huffman-compressed ASCII) 64 bits	Status Bytes 8 bits	CRC 16 bits

a) Packet format for 100 bauds of transmission

Header 8 bits	Data Field (Huffman-compressed ASCII) 160 bits	Status Bytes 8 bits	CRC 16 bits

b) Packet format for 200 bauds of transmission

Figure 5.12: Packet formats for both 100 and 200 bauds of transmission

PACTOR normally uses ASCII characters that have been compressed with a Huffman algorithm. Huffman-compressed ASCII table can be found in Appendix C.

This Huffman compression reduces the average character length for improved efficiency. The length of individual characters varies from 2 to 15 bits, with the most frequently used characters being the shortest. This result in an average character length of 4 to 5 bits for English text, instead of the 8 bits required for normal ASCII.

PACTOR is a synchronous transmission system with packet duration of 0.96 second, Control Signal duration of 0.12 second and an idle time of 0.17 second for a total cycle time of 1.25 seconds. Detail of link initialization and transmission procedure between terminals can be found in (ARRL, 2001).

Like PACTOR, GTOR also operates using standard AFSK but it is using hybrid Forward Error Correction (FEC) and ARQ (Kantronics Co, 1998) for error correction. By using extended Golay forward error correction coding and full-frame interleaving, this mode can transmit information up to 300 baud. Therefore, GTOR performance is more powerful in transmission up to 3 times fasters compare the PACTOR (Johston. 1999). However, the transmission speed will reduce to 200 and 100 baud depends on HF propagation.

KAM'98 operation will control by the Secured HF Messenger application that is installed inside the computer. Thus, suitable connection cable between computer and KAM'98 required and its will be described in next section.

5.4.1 System Integration

In order to integrate all system components together, some installations are needed. It is essential to ensure the components communicate each other properly and this can optimize the system performance.

5.4.2 Assembling Computer (DB-9) and KAM'98 (DB-25) connectors

The connection cable between computer and KAM'98 required enabling Secured HF Messenger application controls KAM'98 for transmission purposes. Mostly computers have a standard serial (COM) port RS-232C either DB-9 or DB-25. Since, the KAM'98 has female DB-25 connector, a male DB-25 connector needed to connect to the KAM'98's female port. The pins connection between both connectors is shown in Table 5.1.

Table 5.1: Pin connections between DB-9 and DB-25 connectors.

9-Pin Connector (Computer)	25-Pin Connector (KAM'98)
Pin 1 DCD	Pin 8 DCD
Pin 2 RD	Pin 3 RD
Pin 3 TD	Pin 2 TD
Pin 4 DTR	Pin 20 DTR
Pin 5 GND	Pin 7 GND
Pin 6 DSR	Pin 6 DSR
Pin 7 RTS	Pin 4 RTS
Pin 8 CTS	Pin 5 CTS
Pin 9 RI	Pin 22 RI

5.4.3 Assembling KAM '98 and Kenwood TS-570D transceiver connectors

To integrate between Kenwood TS-570D and KAM'98 to become as part of the system, a suitable cable had assembled to ensure both equipments connected and communicate as well. In this particular case, we need DB-9 male and 8-pin Mic. female connectors. Both connectors are wired as shown in Figure 5.13 below.

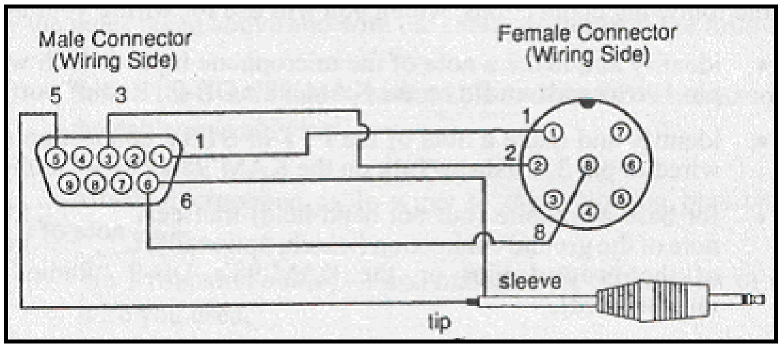


Figure 5.13: Wiring between DB-9 pin (KAM'98) and 8-pin Mic (Kenwood Transceiver)

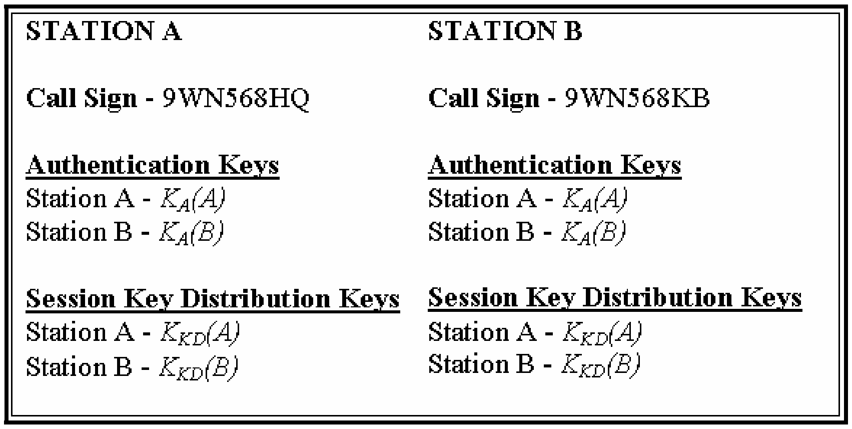
Make sure all wiring between KAM'98 and transceiver's microphone and speaker jack followed these connections:

(i) Identify the microphone input connection, pin 1 and wired to pin 1 of KAM'98's DB-9.
(ii) Identify the PTT or STBY connection, pin 2 and wired to pin 3 of KAM'98's DB-9.
(iii)Identify ground connection, pin 8 and wired to pin 6, one of the ground pins on the KAM'98's DB-9.
(iv)Identify an external speaker plug and wired to pin 5 of KAM'98's DB-9.
(v) Identify sleeve external speaker plug and wired to pin 6, one of the ground pins on the KAM'98's DB-9.

5.5 Security Features

The security features present in the Secured HF Messenger application are authentication, key distribution and confidentiality. They will be activated once a link is established between two communicating parties. A trusted third party is required to manage the authentication key and session key distribution key for each site. However, it is not involved directly to both communicating parties during actual authentication and key distribution. The key structure is shown in Figure 5.14 and stored in floppy disk. For real implementation the key should be stored in a tamper proof storage media. The challenge and response authentication methodology (Menezes, 1996) is adopted and the cipher algorithm used is 256 bit key AES (Advanced Encryption Standard) (NIST, 2001). Figure 5.15 shows procedure for performing authentication. Here, the application provides double authentications where both stations need to validate their identity before they continue the communication.

Next, session keys are randomly generated and exchange between both sites as shown in Figure 5.16. The session keys are encrypted using the session key encryption key and the cipher system used is the 128 bit key AES. Once completed, both sites can exchange information using the proprietary stream cipher algorithm.



STATION A	**STATION B**
Call Sign - 9WN568HQ	**Call Sign** - 9WN568KB
<u>Authentication Keys</u>	**<u>Authentication Keys</u>**
Station A - $K_A(A)$	Station A - $K_A(A)$
Station B - $K_A(B)$	Station B - $K_A(B)$
<u>Session Key Distribution Keys</u>	**<u>Session Key Distribution Keys</u>**
Station A - $K_{KD}(A)$	Station A - $K_{KD}(A)$
Station B - $K_{KD}(B)$	Station B - $K_{KD}(B)$

Figure 5.14: Key structure for the secured data communication system.

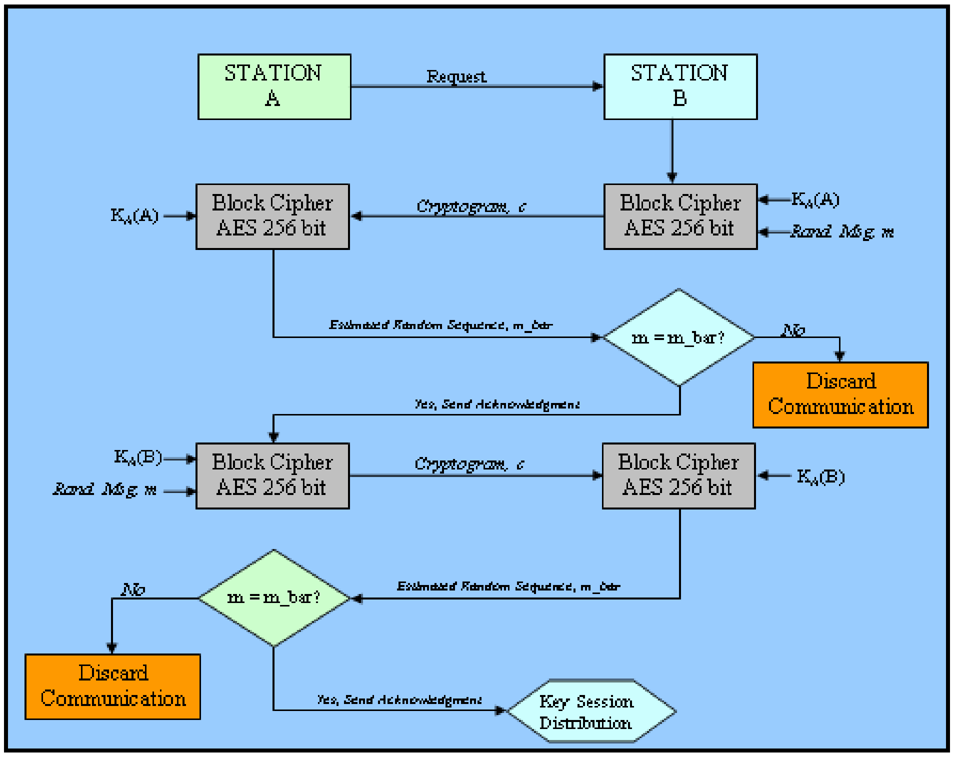


Figure 5.15: Challenge and respond authentication.

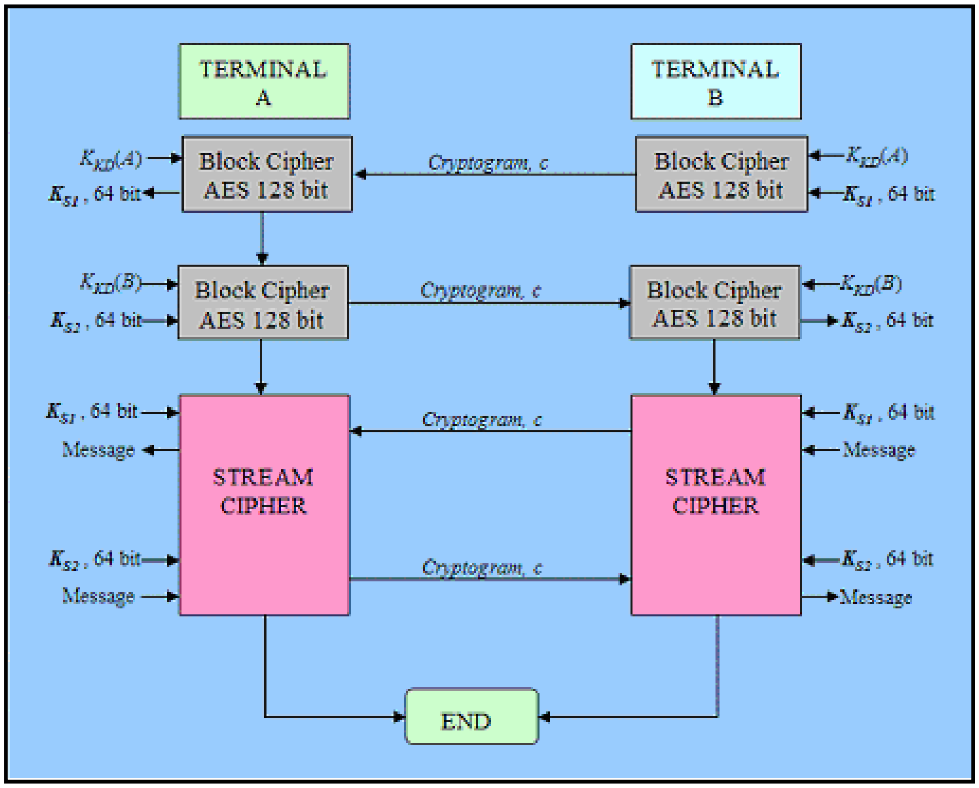


Figure 5.16: Session key generation and distribution.

Based on Figure 5.15 and 5.16, the first step that application does is to ensure the communication is between valid users. If not, the communication is hopeless. For that purpose, the application uses AES 256 bits because it provides the highest security among the cipher system inside the system. Session key distribution is necessary to ensure that no one, friend or foe, is able to steal session key and therefore compromise the communication. It is handled using AES 128 bits. And finally, W7 stream cipher with 64 bits is used for confidentiality. Everything done by the application is to ensure both parties are valid and to maintain the integrity during the communication. This methodology was implemented on System 700, which produced by Mils Electronic (Mils, 2004).

5.6 Radix 64 Encoding

Radix-64 encoding also called Base64 encoding is a process to create a data represents protocol that would allow binary data to be encapsulated within another document (Stallings, 2003). The encoding has the following relevant characteristics:

(i) The character set consist of 65 printable characters, one of which is used for padding. With 2^6 or 64 available characters, each character can be used to represent 6 bits of input.

(ii) No control characters are included in the set. Thus, a message encoded in radix 64 can traverse any systems that scan the data stream for control characters.

(iii) The hyphen character ("-") is not used. This character has significance in the RFC 822 format and should therefore be avoided.

Table 5.2: Radix 64 Encoding

6-Bit Value	Character encoding	6-Bit Value	Character encoding	6-Bit Value	Character encoding	6-Bit Value	Character encoding
0	A	16	Q	32	G	48	w
1	B	17	R	33	H	49	x
2	C	18	S	34	I	50	y
3	D	19	T	35	J	51	z
4	E	20	U	36	K	52	0
5	F	21	V	37	L	53	1
6	G	22	W	38	M	54	2
7	H	23	X	39	N	55	3
8	I	24	Y	40	O	56	4
9	J	25	Z	41	P	57	5
10	K	26	A	42	Q	58	6
11	L	27	B	43	R	59	7
12	M	28	C	44	S	60	8
13	N	29	D	45	t	61	9
14	O	30	E	46	u	62	+
15	P	31	F	47	v	63	/
						(pad)	=

Table 5.2 shows the mapping of 6 bit input values to character. The character set consists of the alphanumeric character plus “+” and “/”. The “=” character is used as the padding character. Figure 5.17 illustrates the simple mapping scheme. Binary input is processed in block of 3 octets or 24 bits. Each set of 6 bits in the 24 bit block is mapped into a character. In the figure, the characters are shown encoded as 8 bit quantities. In this typical case, each 24 bit input is expanded to 32 bits of output. Figure 5.18 shows the example of radix 64 encoding.

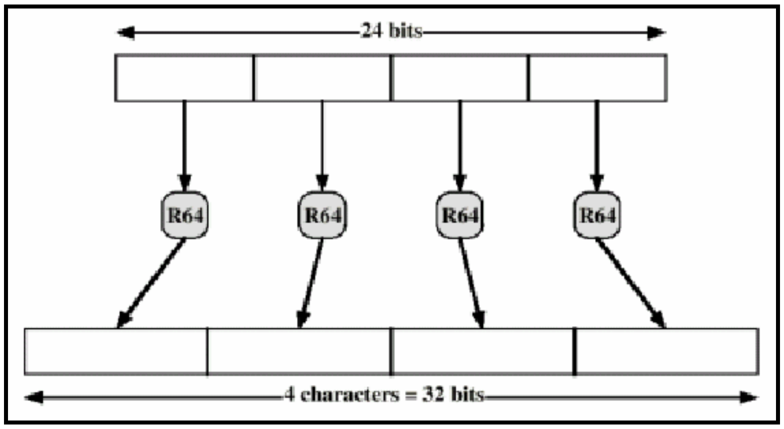
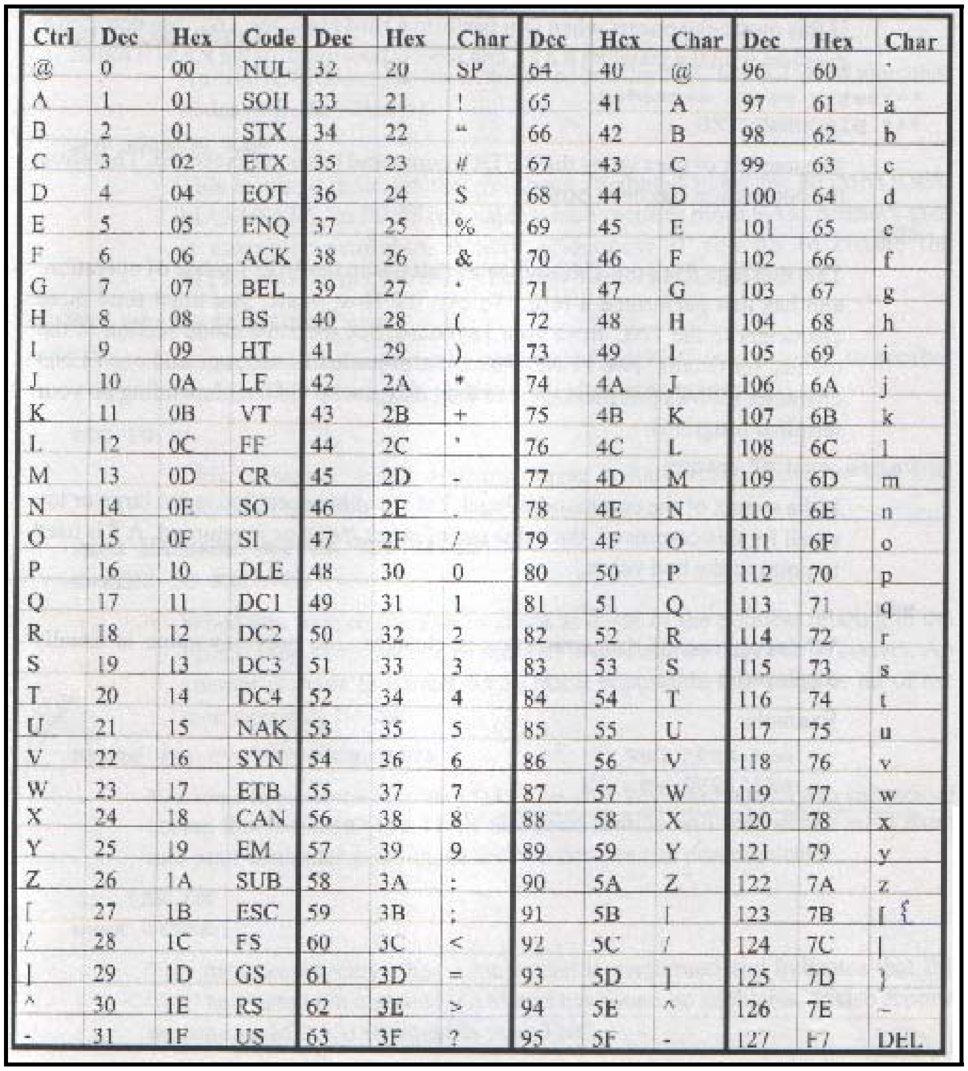


Figure 5.17: Printable Encoding of Binary Data into Radix-64 Format

Input Data	
Binary representation	0010 0011 0101 1100 1001 0001
Hexadecimal representation	235c91
Radix-64 Encoding of Input Data	
Character representation	I1yR
ASCII code (8 bit, zero parity)	0100 1001 0011 0001 0111 1001 0101 0010
Hexadecimal representation	49317952

Figure 5.18: Example of Radix-64 encoding

To implement Secured HF Messenger application, this method needed to avoid KAM '98 HF modem from scanning data stream of control characters during transmitting encrypted information. This is because KAM '98 does not transmit control characters. However, a modification was made to this encoding format. After splitting binary data to 6 bits each, it will plus with 40_{10} offset and kept as 8 bit quantities. No mapping is required. Now, the printable encoding of data is not followed Radix 64 format as well, and the character used is represented from 40_{10} to 103_{10} as shown in Figure 5.19. It is also showing the control characters that are represented from 0_{10} to 32_{10}. Obviously the reason to plus 40_{10} is to avoid using a control character, which effected the transmission, and at receiver all data stream will minus 40_{10} before decrypt processing made. By implementing this method, the application does not need radix 64-lookup tables anymore.



Ctrl	Dec	Hex	Code	Dec	Hex	Char	Dec	Hex	Char	Dec	Hex	Char
@	0	00	NUL	32	20	SP	64	40	@	96	60	`
A	1	01	SOH	33	21	!	65	41	A	97	61	a
B	2	01	STX	34	22	"	66	42	B	98	62	b
C	3	02	ETX	35	23	#	67	43	C	99	63	c
D	4	04	EOT	36	24	S	68	44	D	100	64	d
E	5	05	ENQ	37	25	%	69	45	E	101	65	e
F	6	06	ACK	38	26	&	70	46	F	102	66	f
G	7	07	BEL	39	27	'	71	47	G	103	67	g
H	8	08	BS	40	28	(	72	48	H	104	68	h
I	9	09	HT	41	29	)	73	49	I	105	69	i
J	10	0A	LF	42	2A	*	74	4A	J	106	6A	j
K	11	0B	VT	43	2B	+	75	4B	K	107	6B	k
L	12	0C	FF	44	2C	,	76	4C	L	108	6C	l
M	13	0D	CR	45	2D	-	77	4D	M	109	6D	m
N	14	0E	SO	46	2E	.	78	4E	N	110	6E	n
O	15	0F	SI	47	2F	/	79	4F	O	111	6F	o
P	16	10	DLE	48	30	0	80	50	P	112	70	p
Q	17	11	DC1	49	31	1	81	51	Q	113	71	q
R	18	12	DC2	50	32	2	82	52	R	114	72	r
S	19	13	DC3	51	33	3	83	53	S	115	73	s
T	20	14	DC4	52	34	4	84	54	T	116	74	t
U	21	15	NAK	53	35	5	85	55	U	117	75	u
V	22	16	SYN	54	36	6	86	56	V	118	76	v
W	23	17	ETB	55	37	7	87	57	W	119	77	w
X	24	18	CAN	56	38	8	88	58	X	120	78	x
Y	25	19	EM	57	39	9	89	59	Y	121	79	y
Z	26	1A	SUB	58	3A	:	90	5A	Z	122	7A	z
[	27	1B	ESC	59	3B	;	91	5B	[	123	7B	[{
/	28	1C	FS	60	3C	<	92	5C	/	124	7C	|
]	29	1D	GS	61	3D	=	93	5D	]	125	7D	}
^	30	1E	RS	62	3E	>	94	5E	^	126	7E	~
-	31	1F	US	63	3F	?	95	5F	-	127	F7	DEL

Figure 5.19: ASCII chart

5.7 Software Design and Implementation

Secured HF Messenger is a software application that is developed using Microsoft Visual C++. Microsoft Visual C++ is the most productive tools for creating high performance application and also contains Microsoft Foundation Classes (MFC) that offers developer the ability to create robust application that resides on the Secured HF Messenger. Another purpose of using this software is because of its capability to execute in various types of Operating System (OS) that is currently available such as Windows 95/98/NT, Windows ME/XP and also Windows 2000.

5.7.1 The Visual C++ Development Environment

The Visual C++ consist MFC which can be used to develop Graphic User Interface (GUI) to provide user-friendly application and uses C++ language with some additional function compare Turbo C++. Therefore, most of the functions inside Secured HF Messaging System were designed using C++ language. Figure 5.20 shows the development environment of Visual C++.

5.7.1.1 The Workspace

The workspace allows us to view the parts of application in three ways:

(i) Class Views to navigate and manipulate the source code on C++ class level
(ii) Resource View to find and edit each of the various resources in application, including dialog window designs, icons and menus.
(iii)File View to view and navigate all the files that make up in your application

5.7.1.2 The Output Pane

The Output Pane is the place to all compiler progress statement, warning and error messages. It reopens itself when Visual C++ has any message that need to display for us.

5.7.1.3 The Editor Area

This is the area where we perform all the editing when using Visual C++. Everything that has been designed in an application will display here, including source code.

5.7.1.4 Menu Bar

It consist standard toolbars such as opening and saving files, copying, pasting, and a variety of other command. The WizardBar toolbars enables us to perform a number of Class Wizard actions without opening the Class Wizard. Finally, the Build minibar provides with the build and run commands used to test the application.

5.7.1.5 Control Palette

It consist several standard control such as static text, edit box, command button, check box slider, progress bars and so on. Used for graphic user interface design.

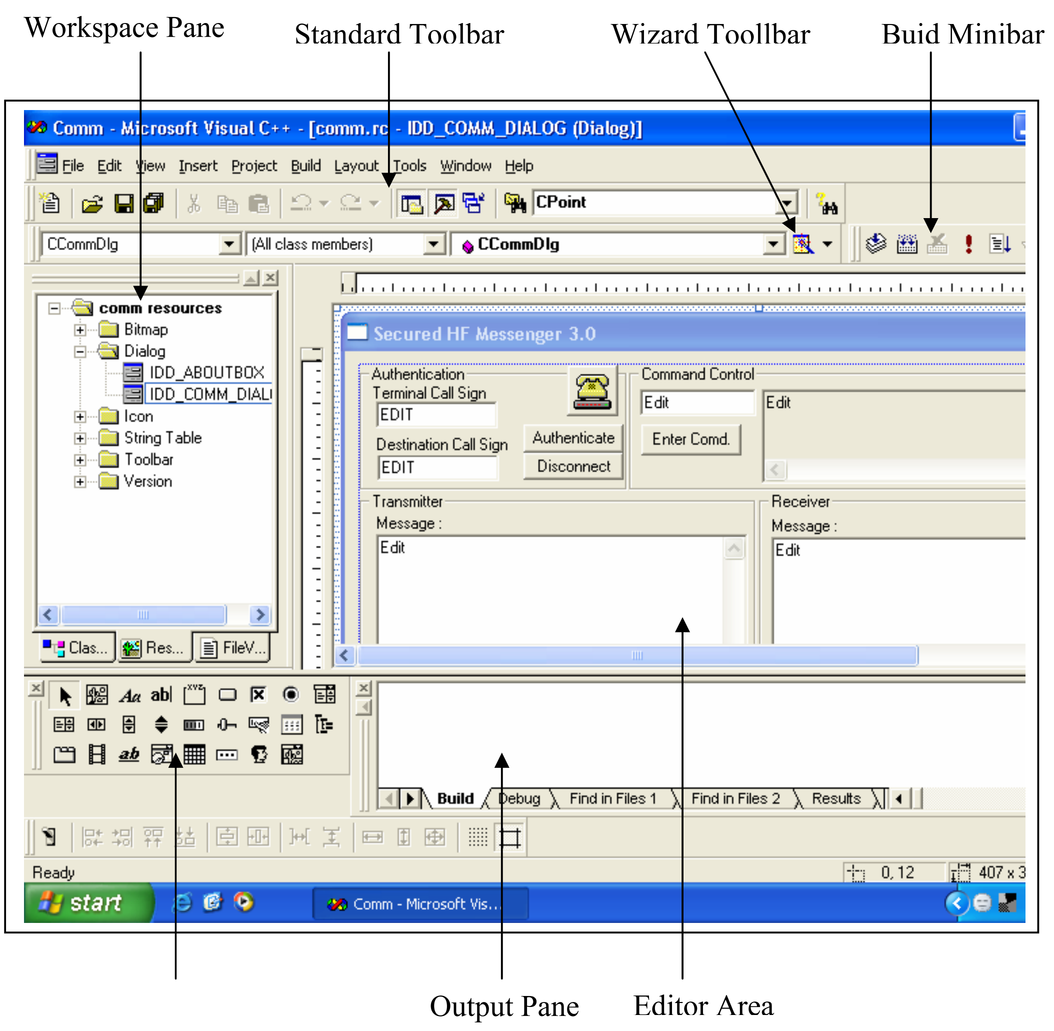


Figure 5.20: The Visual C++ development environment

5.7.2 System Architecture

Basically, Secured HF Messenger consist three level of stage of software design, which is Graphic User Interface, Internal Function and Serial Communication. Figure 5.21 presents the architecture of system design.

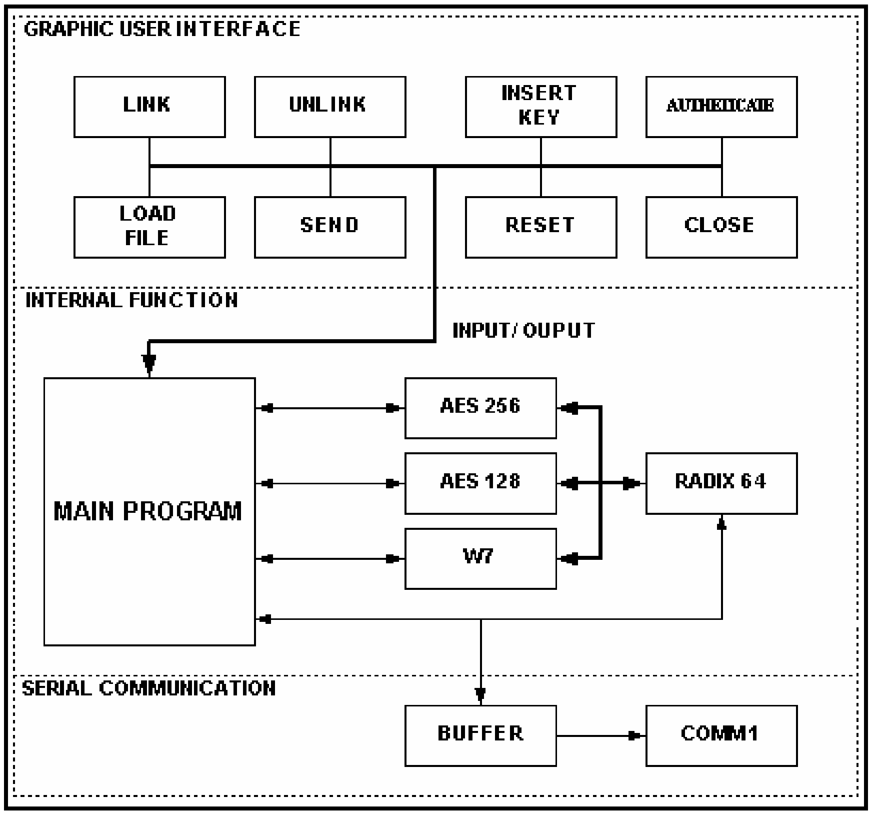


Figure 5.21: The Architecture of Secured HF Messenger

Graphic User Interface (GUI) is the interface between the user and the application. The user gives the commands to application by inserting the input or presses the button and the processing part is handled by Internal Function. It consist Main Program, Security Features and Radix 64 encoder. Main Program controls every action of the application such as authentication, key distribution, encryption, load file, sending the messages and so on. The last part is the serial communication, which responsible to transfer data from the application to equipment that is HF modem. All the digital information transfers to HF modem through Communication Port 1 which existing on computer.

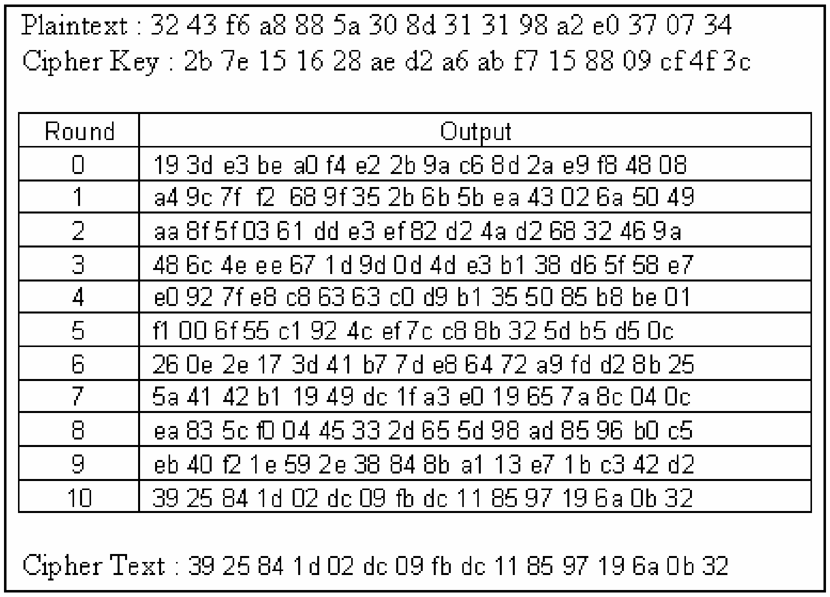
5.7.3 Software Implementation

The most important part in the application is security features used for authentication, key distribution and encryption. Therefore, this subsection will discuss the implementation of AES block cipher for 256 and 128 bits, W7 stream cipher, Radix 64 encoder and also serial communication. All the programming for each function was done using C++ language.

5.7.3.1 AES 128 bits

AES process the plaintext or input with block size of 128-bits. The description of AES 128 block cipher can be found in (NIST, 2001). Before encrypting or decrypting, the system must generate the key schedule. It is happen every time user inserts the secret key. Figure 5.22(a) and 5.22(b) is a flowchart of AES 128 encryption and decryption respectively. Detail of programming on key expansion, encryption and decryption can be found in Appendix D.

Table 5.3: The result for each round of AES 128 bits encryption (NIST, 2001)



Plaintext : 32 43 f6 a8 88 5a 30 8d 31 31 98 a2 e0 37 07 34

Cipher Key : 2b 7e 15 16 28 ae d2 a6 ab f7 15 88 09 cf 4f 3c

Round	Output
0	19 3d e3 be a0 f4 e2 2b 9a c6 8d 2a e9 f8 48 08
1	a4 9c 7f f2 68 9f 35 2b 6b 5b ea 43 02 6a 50 49
2	aa 8f 5f 03 61 dd e3 ef 82 d2 4a d2 68 32 46 9a
3	48 6c 4e ee 67 1d 9d 0d 4d e3 b1 38 d6 5f 58 e7
4	e0 92 7f e8 c8 63 63 c0 d9 b1 35 50 85 b8 be 01
5	f1 00 6f 55 c1 92 4c ef 7c c8 8b 32 5d b5 d5 0c
6	26 0e 2e 17 3d 41 b7 7d e8 64 72 a9 fd d2 8b 25
7	5a 41 42 b1 19 49 dc 1f a3 e0 19 65 7a 8c 04 0c
8	ea 83 5c f0 04 45 33 2d 65 5d 98 ad 85 96 b0 c5
9	eb 40 f2 1e 59 2e 38 84 8b a1 13 e7 1b c3 42 d2
10	39 25 84 1d 02 dc 09 fb dc 11 85 97 19 6a 0b 32

Cipher Text : 39 25 84 1d 02 dc 09 fb dc 11 85 97 19 6a 0b 32

The AES 128 bit is used in session key distribution, which only consist 64 bits. Therefore, the others 64 bits in block are 0. Due to it purpose, only a block of plaintext used, therefore the cipher is implement using electronic codebook (ECB) mode. By using the plaintext and key that given by (NIST, 2001), the state of transformation is checked step by step to verify the software running correctly. Table 5.3 presents the example of plaintext, cipher key and results for each round.

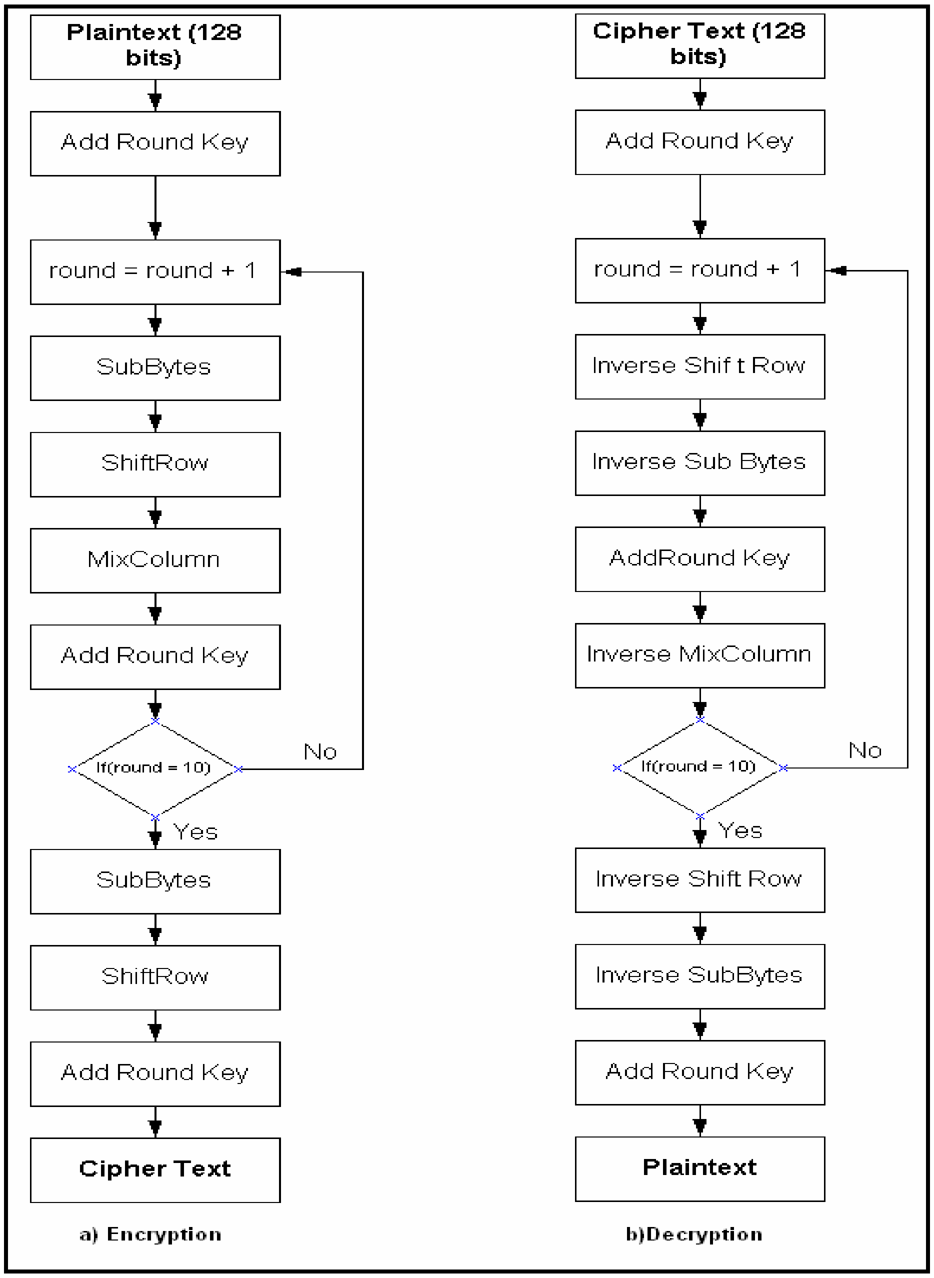


Figure 5.22: Flowchart of encryption and decryption for AES-128

5.7.3.2 AES 256 bits

The differences between AES 256 and the previous are the key length and number of round during encryption and decryption. Instead of using 128 bits key length and 10 rounds, this cipher uses 256 bits key length and number of rounds is 14. Therefore, the flowcharts of encrypt and decrypt is same with AES 128 bits except the number of rounds. Detail of this cipher can be found in Appendix D. Practically this cipher is more secured and suitable of it purpose to authenticate the user.

5.7.3.3 W7 Stream Cipher

After authentication and session key distribution, the application generates 10,000 bits of keystream using W7 generator and saves in memory. In practice, long messages are not transmitted to avoid Possibility of Intercept (POI) and on average, data format for military standard is around 4000 bits (ACP 127(G), 1988). The Main Program provides the confidentiality by XOR the plaintext from user with keystream. The description of W7 generator was discussed in Chapter 2 and Figure 5.23 shows the flowchart of W7 implementation. Detail of W7 implementation in C++ language can be found in Appendix D.

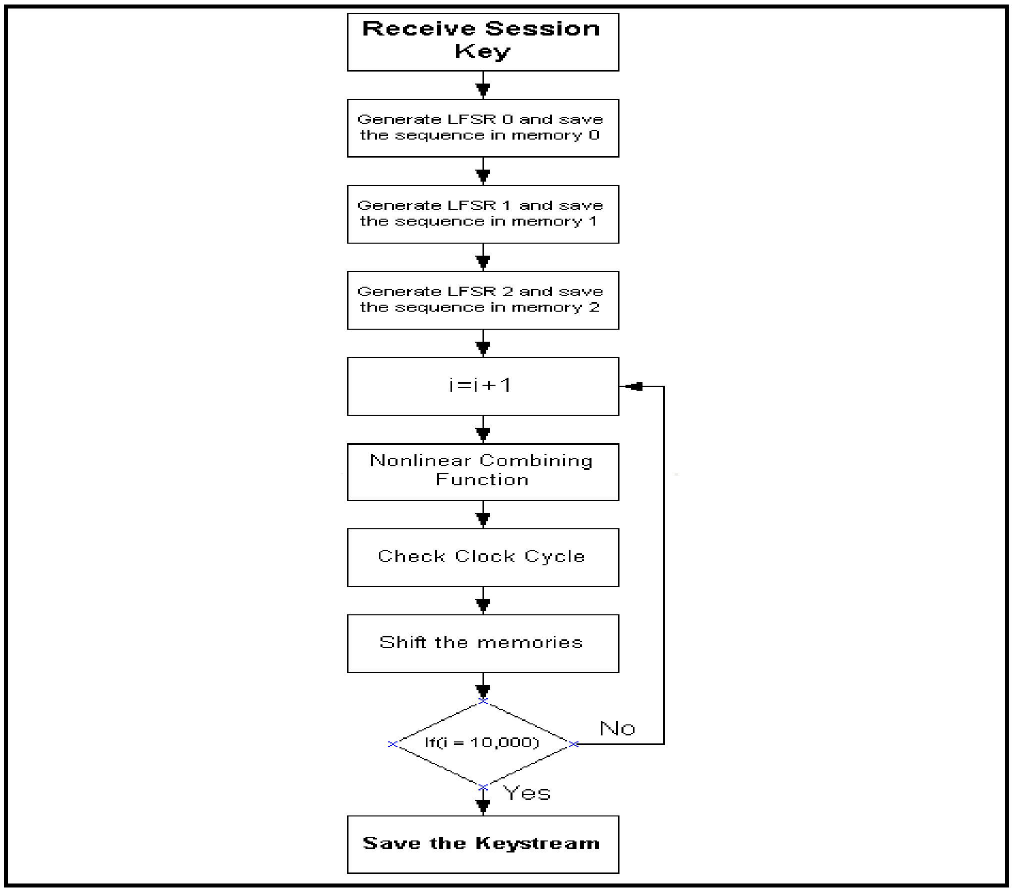

Receive Session Key
Generate LFSR 0 and save the sequence in memory 0
Generate LFSR 1 and save the sequence in memory 1
Generate LFSR 2 and save the sequence in memory 2
i=i+1
Nonlinear Combining Function
Check Clock Cycle
Shift the memories
If(i = 10,000)
No
Yes
Save the Keystream

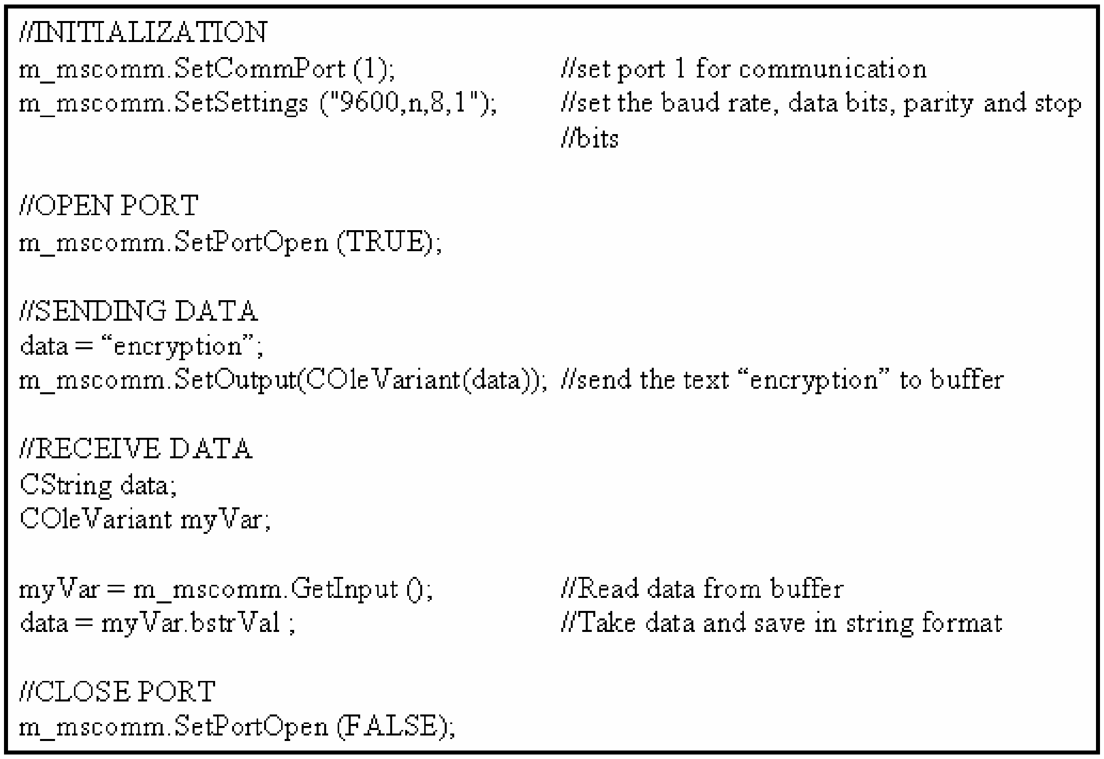
Figure 5.23: Flowchart of W7 generator

5.7.3.4 Radix 64 Encoder and Decoder

After encryption process, every bytes of digital information must be encoded with Radix 64 format before transferring to HF modem via serial communication. The reverse process occurs at the receiver before decrypting the cryptogram. The description of Radix 64 was explained in previous section. Detail of Radix 64 encoder and decoder can be found in Appendix D**.** The function is checked whether perform properly of not by encode 3 bytes of data as shown in Figure 5.18. The result must be the same with the expected.

5.7.3.5 Serial Communication.

Another important part is serial communication. The application must capable to control this feature so it can manipulate the HF modem for transmission and reception purposes. Basically, to control the serial communication, we need five important functions which is initialization, open port, sending data, receive data and close port. The following code shows the function that is used to create a handle:

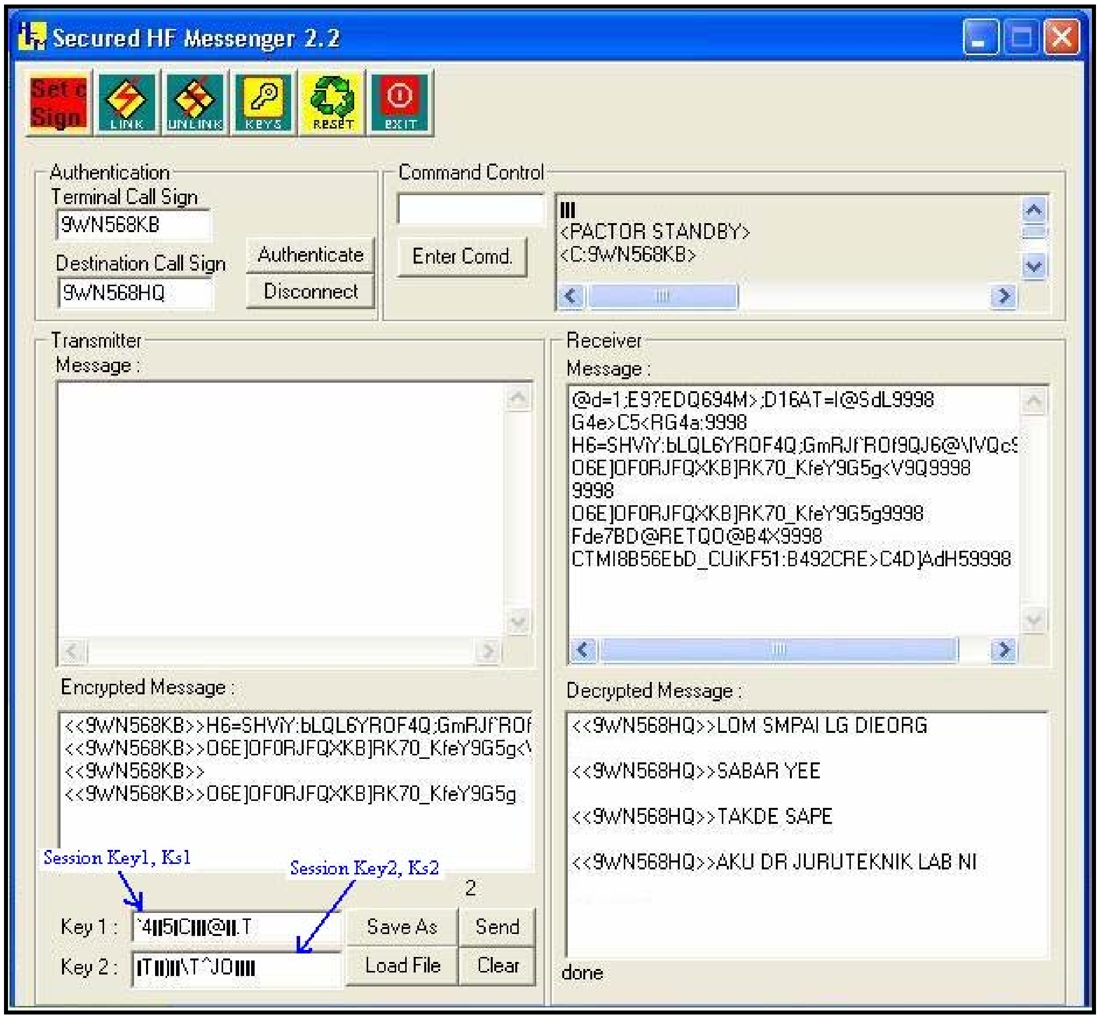


```
//INITIALIZATION
m_mscomm.SetCommPort (1);                //set port 1 for communication
m_mscomm.SetSettings ("9600,n,8,1");      //set the baud rate, data bits, parity and stop
                                          //bits

//OPEN PORT
m_mscomm.SetPortOpen (TRUE);

//SENDING DATA
data = "encryption";
m_mscomm.SetOutput(COleVariant(data)); //send the text "encryption" to buffer

//RECEIVE DATA
CString data;
COleVariant myVar;

myVar = m_mscomm.GetInput ();            //Read data from buffer
data = myVar.bstrVal ;                   //Take data and save in string format

//CLOSE PORT
m_mscomm.SetPortOpen (FALSE);
```

Figure 5.24: Basic configuration for serial communication

5.7.3.6 Graphic User Interface (GUI) of Secured HF Messenger Application

Secured HF Messenger with Graphic User Interface (GUI) in Figure 5.25 is the final result of implementation. The application is capable of controlling the HF modem (KAM'98) via serial communication, RS-232C to enable data transmission through HF spectrum. The application was designed to handle digital information transmissions such as short message, text file, image file and also winzip file. Winzip file prefers user to send data in the compression mode and this can speed up HF transmission. By adopting cipher algorithms, the system will provide a practically secure data transmission over HF spectrum.



Authentication
Terminal Call Sign: 9WN568KB
Destination Call Sign: 9WN568HQ

Command Control

```
<PACTOR STANDBY>
<C:9WN568KB>
```

Transmitter
Message :

Encrypted Message :

```
<<9WN568KB>>H6=SHViY:bLQL6YROF4Q;GmRJf`ROf
<<9WN568KB>>O6E]OF0RJFQXKB]RK70_KfeY9G5g<\
<<9WN568KB>>
<<9WN568KB>>O6E]OF0RJFQXKB]RK70_KfeY9G5g
```

Key 1 : `4II5ICIII@II.T
Key 2 : ITII)II\T^JOIIII

2

Receiver
Message :

```
@d=1;E9?EDQ694M>;D16AT=I@SdL9998
G4e>C5<RG4a:9998
H6=SHViY:bLQL6YROF4Q;GmRJf`ROf9QJ6@\IVQcS
O6E]OF0RJFQXKB]RK70_KfeY9G5g<V9Q9998
9998
O6E]OF0RJFQXKB]RK70_KfeY9G5g9998
Fde7BD@RETQO@B4X9998
CTMI8B56EbD_CUiKF51:B492CRE>C4D]AdH59998
```

Decrypted Message :

```
<<9WN568HQ>>LOM SMPAI LG DIEORG

<<9WN568HQ>>SABAR YEE

<<9WN568HQ>>TAKDE SAPE

<<9WN568HQ>>AKU DR JURUTEKNIK LAB NI
```

done

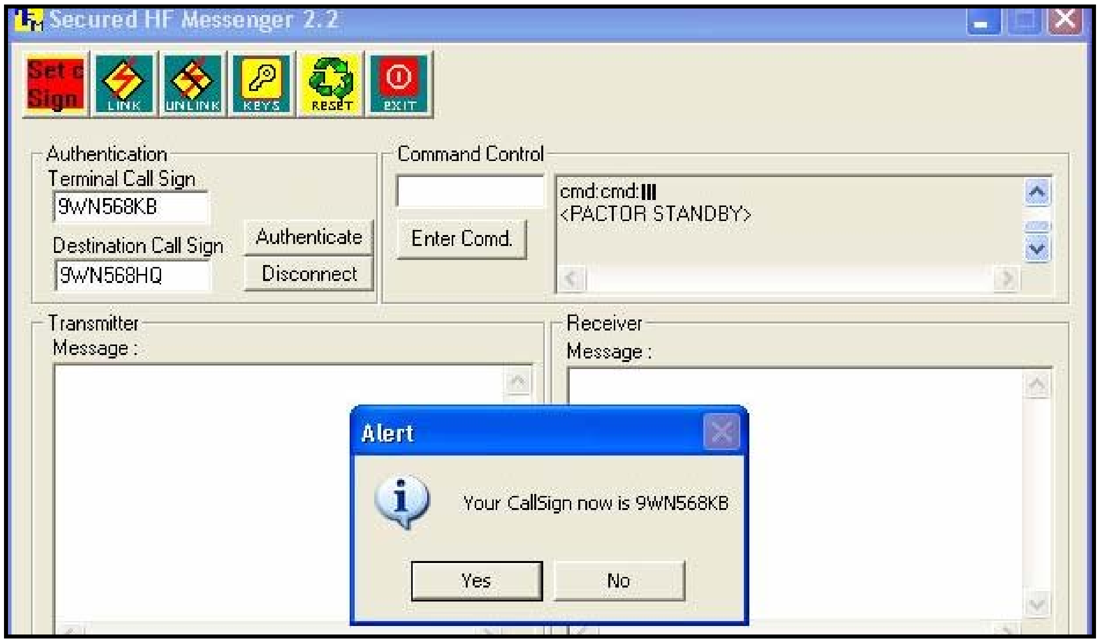
Figure 5.25: Graphic User Interface (GUI) for Secured HF Messenger

5.8 System Operation

These are procedures required to be followed by users to allow them to communicate with each other:

(i) First, install and run Secured HF Messenger application. Make sure to turn on the modem first before running the application.

(ii) Insert the call sign for both Stations and click Set C. Sign toolbar button to verify both stations call sign. Message Box as shown in Figure 5.26 will appear for confirmation. Next, insert the secret key. This can be done by clicking the Key button. Get the key in the floppy disk as shown in Figure 5.27.

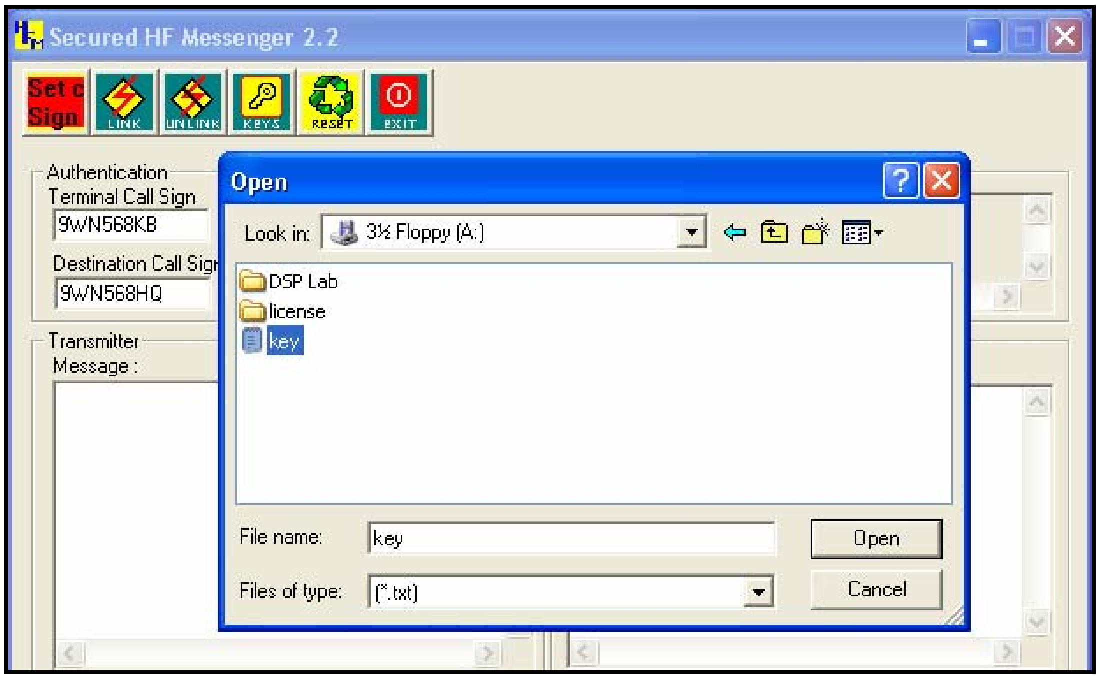


Terminal Call Sign: 9WN568KB
Destination Call Sign: 9WN568HQ

```
cmd:cmd:
<PACTOR STANDBY>
```

Your CallSign now is 9WN568KB

Figure 5.26: Message Box for Call Sign verification.



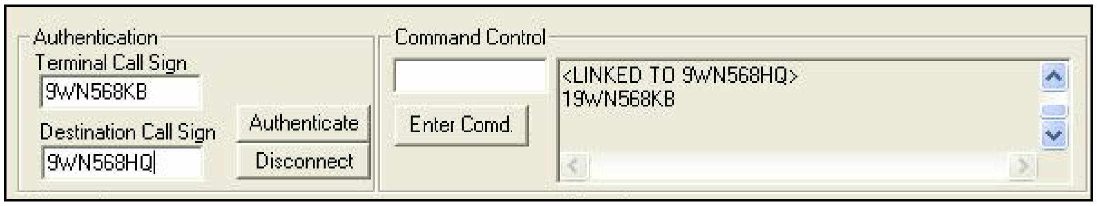
Authentication
Terminal Call Sign
9WN568KB
Destination Call Sign
9WN568HQ
Transmitter
Message :

DSP Lab
license
key

File name: key
Files of type: (*.txt)

Figure 5.27: User can insert the secret key by clicking the Insert Key button.

(iii) Then, click link button to order KAM '98 HF modem to establish the link between stations. After the link is established, the message "LINKED TO 9WN568HQ" will appear at command column as shown in Figure 5.28.



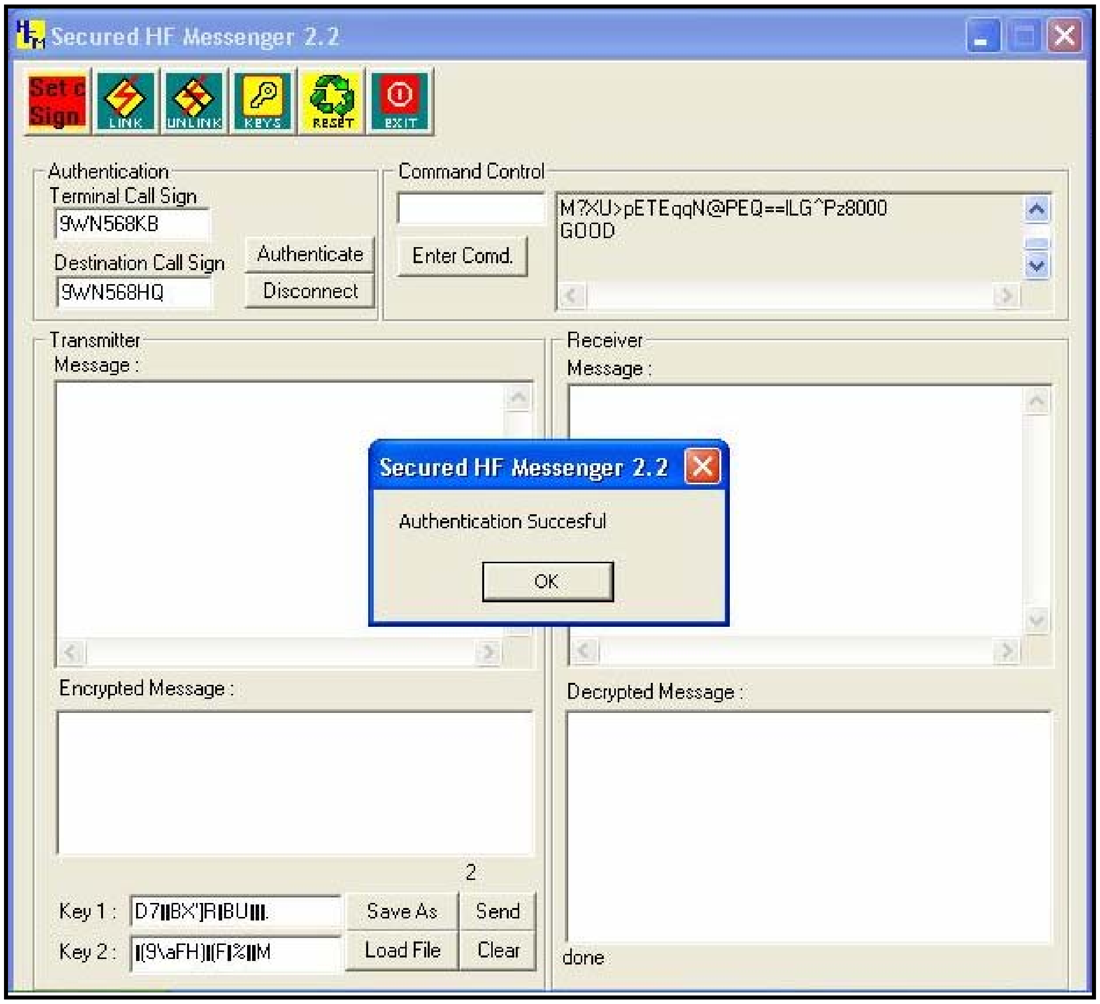
Authentication
Terminal Call Sign
9WN568KB
Destination Call Sign
9WN568HQ

Command Control

```
<LINKED TO 9WN568HQ>
19WN568KB
```

Figure 5.28: Linked message will appear in command control column when the link is established.

(iv) Next, click authenticate button to verify the user identity either valid party or not. If the authentication successful, the Message Box *"Authentication Successful"* will appear. Figure 5.29 shows the authentication result and the information inside Key 1 and Key 2 columns are the session keys.



Terminal Call Sign: 9WN568KB

Destination Call Sign: 9WN568HQ

```
M?XU>pETEqqN@PEQ==ILG^Pz8000
GOOD
```

Secured HF Messenger 2.2

Authentication Succesful

2

Key 1 : D7‖BX']R|BU|||.

Key 2 : |[9\aFH)|[F|%||M

done

Figure 5.29: Message Box of authentication result will appear either its success or failed.

(v) After all four steps done successful, then both users can start communicates each other by typing the message at transmitter column and the message will send after clicking Send button.

(vi) Beside short message, user also can transmit another document such as Text File, Image (JPEG) and WinZip File. All these documents need to load first before sending to another user. This can be done with click the Load File button.

(vii) When the communication finish, user has to click Disconnect button and followed Unlink Button to close the communication. These actions will break the link and return the application as a beginning

5.9 Experimental Setup

A series of field-testing were conducted since April 2004 from UTM Skudai to various sites in Malaysia. Before both terminals start to communicate, each terminal has to setup their stations as shown in Figure 5.1. After that, Secured HF Messenger application is installed into computer. Then the procedure in section 5.10 is followed to operate the system. During the transmission, the HF digital modes used are PACTOR and GTOR with the transmit power ranging from 5 to 50 watts. The experiments conducted consist of JPEG image, text file and short messages.

As known that HF propagation always changes by a lot of factors. It varies daily, monthly or even a year as described in Chapter 2. So, a chosen frequency is very critical to enhance the quality of transmission. For field-testing, the frequencies used are referred to experimental license that has been given by MCMC (Malaysian Communication and Multimedia Communication). The performance of system observe based on UTM Skudai to Endau Rompin, UTM Skudai to Kuala Lumpur, UTM Skudai to Chemor and UTM Skudai to Kota Bharu.

5.9.1 UTM Skudai to Endau Rompin

Taman Negara Endau Rompin managed by Johor National Parks Corporation, encompasses some 49,000 ha of virgin lowland tropical rainforest. There are no less than 230 species of birds, 179 species of butterflies and all the great Malaysian mammals such as the tiger, the elephant, the tapir and the Sumatran rhinoceros, as well as a host of other animals. Traveling time from UTM Skudai to the national park by road is 5 hours. The straight-line distance is 120 km.

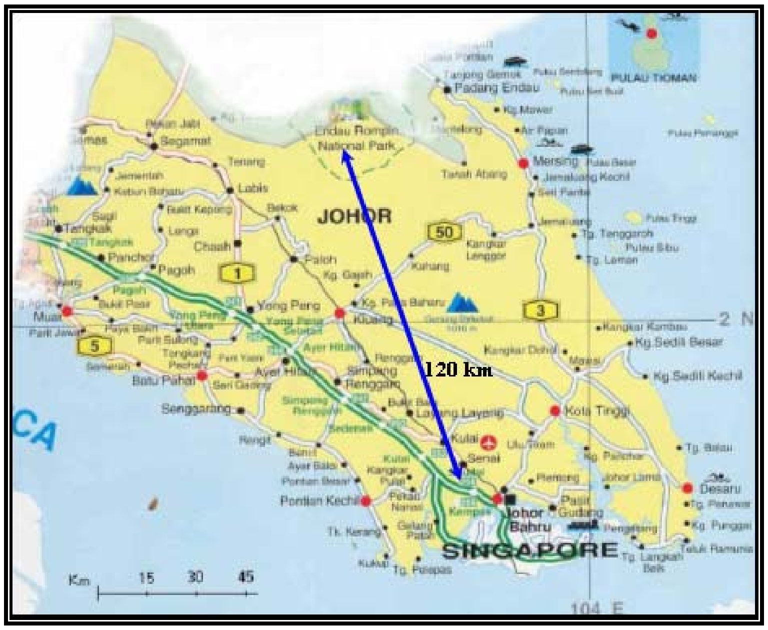


Figure 5.30: Map of Johor Darul Ta'zim showing the location of UTM Skudai and Taman Negara Endau Rompin

Before any communication is done, all equipments are needed to setup, as discussed in previous chapter. The most important part is antenna installation and for testing purpose 6 MHz half-wavelength dipole was made. The installation of antenna and equipments layout is shown in Figure 5.31 and 5.32.

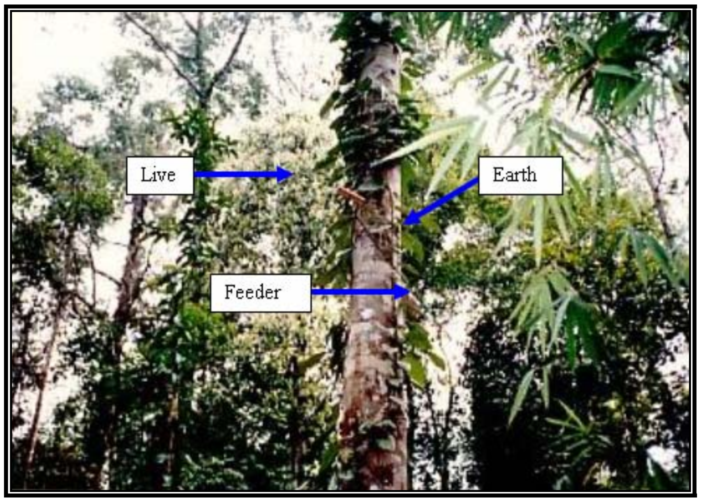


Figure 5.31: The center of the dipole antenna.

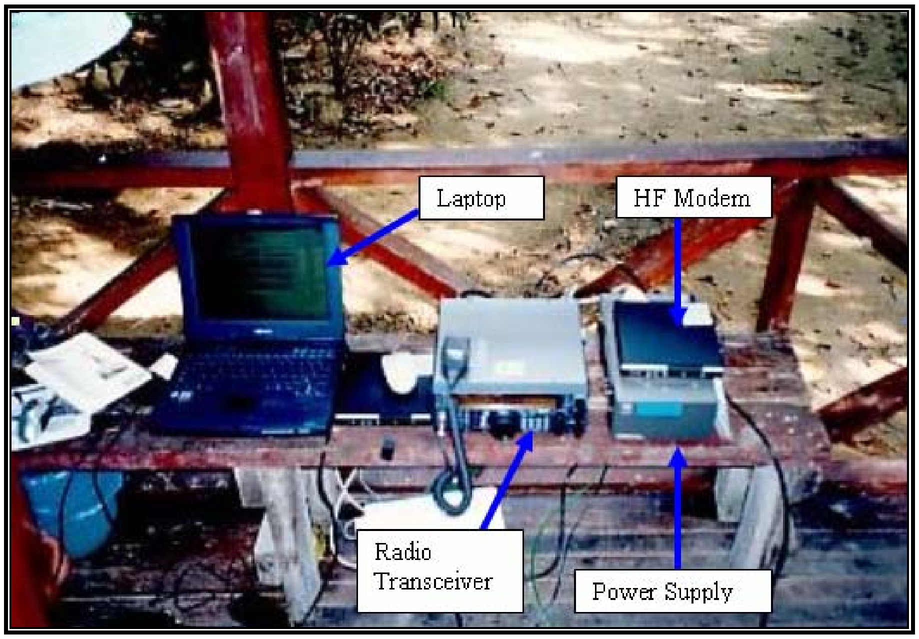


Figure 5.32: The layout of the equipment

The transmission results are shown in Table 5.4 and Table 5.5. Examples of text file and JPEG image can be found in Appendix C.

Table 5.4: Summary of text file transmission between UTM Skudai and Endau Rompin

Date	Time	Frequency (MHz)	File Size (Kbytes)	Transmit Power (Watt)	Baud Rate	Mode	Transmission Time
19thApril 2004	2310	7.08	4	10	200	PACTOR	25 min 50 sec
	2350	7.08	4	10	300	GTOR	3 min 41 sec
20th April 2004	1115	7.08	4	10	300	GTOR	1 min 57 sec
	1710	7.08	4	10	200	PACTOR	4 min 15 sec
	1722	7.08	4	10	300	GTOR	1 min 34 sec
	2102	7.08	4	10	200	PACTOR	14 min 46 sec
21st April 2004	0905	7.08	4	10	200	PACTOR	5 min 22 sec
	0940	7.08	4	10	300	GTOR	1 min 24 sec
	1325	7.08	4	50	200	PACTOR	4 min 14 sec
	1335	7.08	4	50	300	GTOR	2 min 31 sec
	1340	7.08	4	10	200	GTOR	5 min 36 sec
	1705	7.08	4	10	200	PACTOR	4 min 26 sec
	1712	7.08	4	10	300	GTOR	1 min 42 sec

Table 5.5: Summary of image transmission between UTM Skudai and Endau Rompin

Date	Time	Frequency (MHz)	Image Size (Kbytes)	Transmit Power (Watt)	Baud Rate	Mode	Transmission Time
20th April 2004	0905	7.08	10	10	200	PACTOR	22 min 50 sec
	0940	7.08	10	10	200	PACTOR	22 min 36 sec
	1040	7.08	5	10	200	PACTOR	12 min 0 sec
	1140	7.08	10	10	300	GTOR	13 min 41 sec
	1335	7.08	14	50	300	GTOR	17 min 37 sec s
	1540	7.08	9	50	300	GTOR	13 min 40 sec
	1735	7.08	9	10	300	GTOR	17 min 44 sec
21st April 2004	0915	7.08	6	10	200	PACTOR	14 min 21 sec
	1045	7.08	6	50	300	GTOR	9 min 42 sec
	1725	7.08	6	10	200	PACTOR	15 min 37 sec

From the results, the usable frequency at that time is only 7.08 MHz while other frequencies are not propagating successfully. During the transmission, the effect of diurnal variability in frequency band has no significant affect to the reliability. No errors were presented during messaging and text file transfer for both digital modes. The transmitted image was also decoded at the receiver correctly with no distortion observed. Based on the experimental results, PACTOR is more robust as compared to GTOR. If it is possible to use GTOR, the transmission time is three times faster over PACTOR as shown in Table 5.4.

5.9.2 UTM Skudai to Kuala Lumpur

The site in Kuala Lumpur that became another station for field-testing is RF Communication (M) Sdn. Bhd. It is founded in August 1986 and located at Jalan Ipoh. RF Communication (M) Sdn. Bhd. has played an increasingly active role in the development of tomorrow's standards in radio frequency communication. Traveling time from UTM, Skudai to RF Communication (M) Sdn. Bhd. is about 4 hours. The line of sight between UTM, Skudai and RF Communication (M) Sdn. Bhd. is about 275 km.

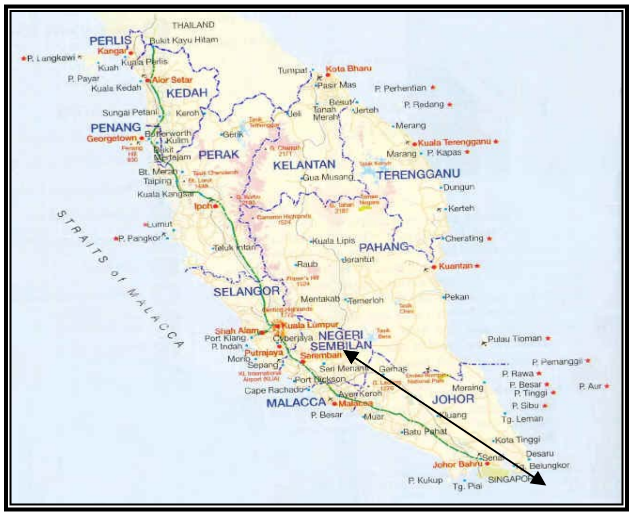


Figure 5.33: Map of Peninsular of Malaysia

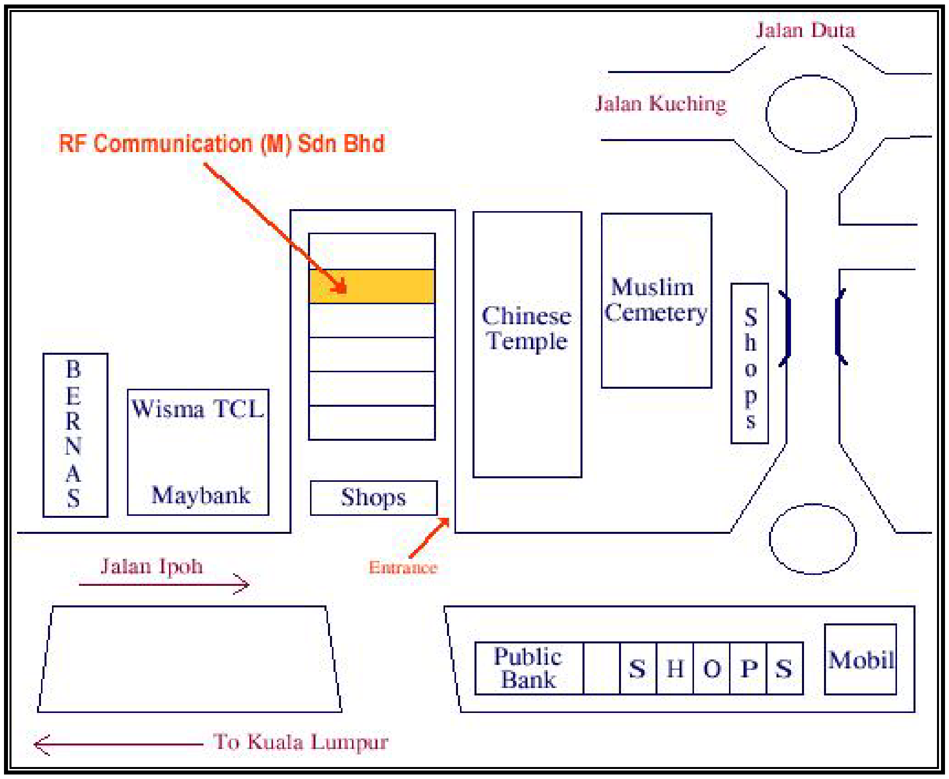


Figure 5.34: The detail map showing the location of RF Communication (M) Sdn. Bhd.

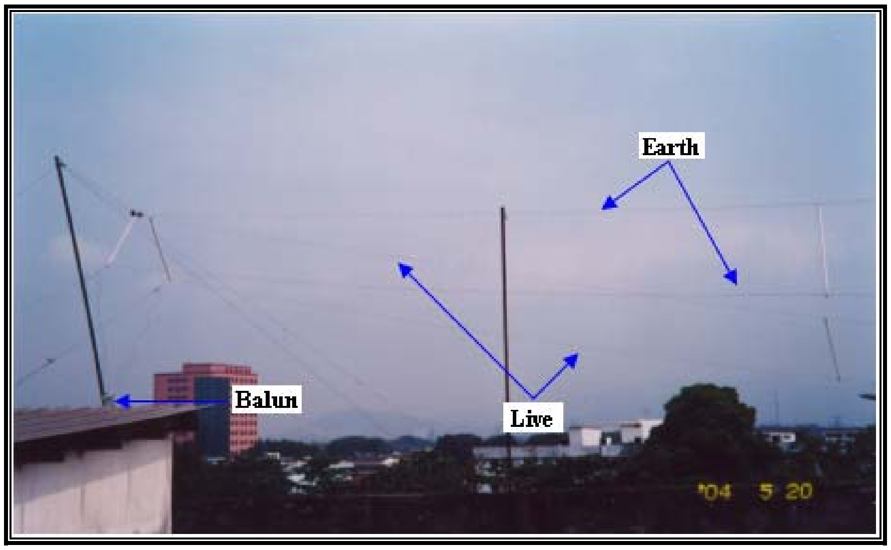


Figure 5.35: The installation of The Barker & Williamson Model AC2-22 Broadband Folded Dipole Antenna

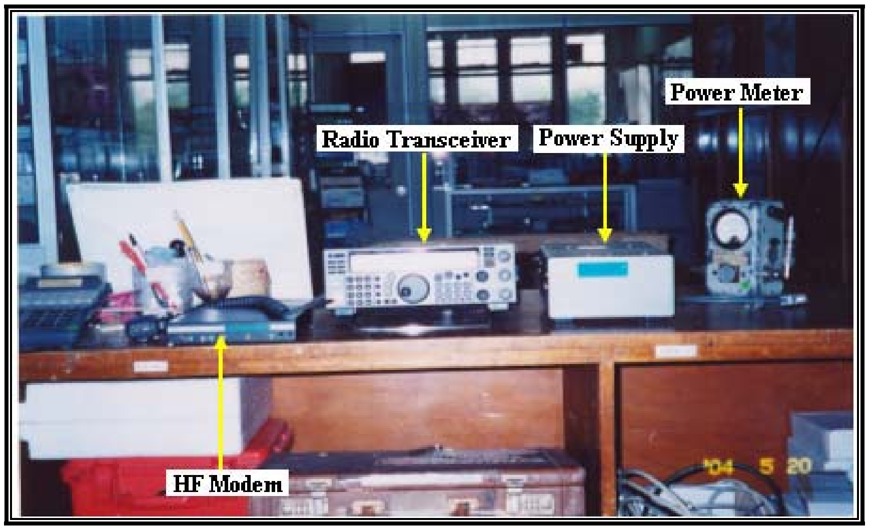


Figure 5.36: The arrangement equipments

Here, the antenna used is The Barker & Williamson Model AC2-22 Broadband Folded Dipole, which already exists on the roof of RF Communication (M) Sdn. Bhd. as shown in Figure 5.35. After completing equipment setup, the testing is performed starting with short messages, text file and JPEG image. Table 5.6 and 5.7 show the results of transmission.

Table 5.6: Summary of text file transmission between UTM Skudai and Kuala Lumpur

Date	Time	Frequency (MHz)	File Size (Kbytes)	Transmit Power (Watt)	Baud Rate	Mode	Transmission Time
20th May 2004	1609	7.08	4	25	200	PACTOR	6 min 41 sec
21st May 2004	0916	7.08	4	10	200	PACTOR	6 min 35 sec
	1510	7.08	4	10	100	PACTOR	14 min 53 sec
24th May 2004	1100	7.08	4	50	200	PACTOR	11 min 51 sec
	1128	7.08	4	50	100	GTOR	6 min 12 sec
26th May 2004	0925	7.08	4	10	200	PACTOR	7 min 10 sec
	1012	7.08	4	25	300	GTOR	4 min 27 sec
	1025	7.10	4	25	200	PACTOR	11 min 19 sec
28th May 2004	1500	7.08	4	50	200	PACTOR	9 min 38 sec
29th May 2004	0920	7.08	4	25	200	PACTOR	7 min 3 sec
31st May 2004	0900	7.08	4	25	200	PACTOR	7 min 8 sec
	1048	7.08	4	10	200	PACTOR	8 min 24 sec

Table 5.7: Summary of image file transmission between UTM Skudai and Kuala Lumpur

Date	Time	Frequency (MHz)	Image Size (kbytes)	Transmit Power (Watt)	Baud Rate	Mode	Transmission Time
18th May 2004	1550	7.08	3k	25	200	PACTOR	10 min 12 sec
26th May 2004	0925	7.08	3k	10	200	PACTOR	10 min 47 sec
28th May 2004	1620	7.08	3k	100	200	PACTOR	23 min 11 sec
	1700	7.08	3k	100	200	PACTOR	18 min 27 sec
29th May 2004	0920	7.08	3k	25	200	PACTOR	7 min 3 sec
	0935	7.08	10k	25	200	PACTOR	55 min 43 sec
31st May 2004	0915	7.08	3k	10	100	PACTOR	27 min 51 sec
1st June 2004	0906	7.08	12k	10	200	PACTOR	30 min 13 sec
	1114	7.01	12k	15	200	PACTOR	32 min 42 sec
2nd June 2004	0856	7.01	12k	10	200	PACTOR	25 min 42 sec

5.9.3 UTM Skudai to Chemor

Next designated site was chosen for testing purpose is Chemor. The line of sight between UTM Skudai and Chemor is 450 km as shown in Figure 5.37.

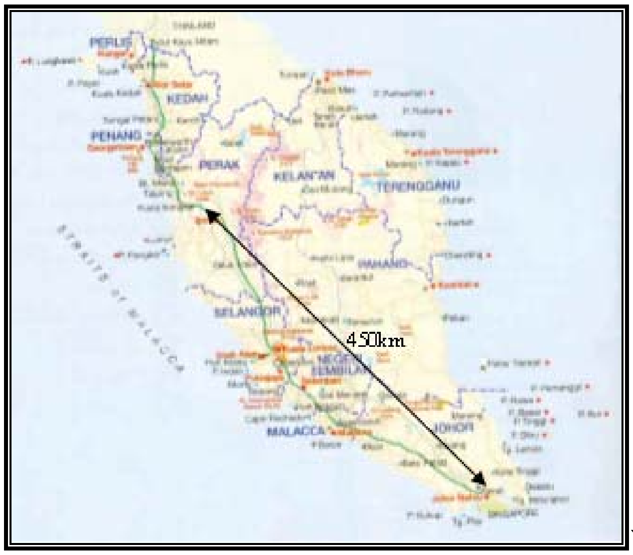


Figure 5.37: Map shows the location between UTM Skudai and Chemor

As usual the testing starts with antenna installations and followed by other equipments setup as shown in Figure 5.38 and Figure 5.39. Both previous field tests prove that HF communication is reliable and could be an alternative of communication especially for remote places. The tests also are conducted for JPEG image, short message and text file transfer. The different between this testing and previous are this is the first time of field test that uses secured mode. Therefore, the purpose of this testing is to determine the effect of encrypted and non-encrypted (plaintext) data during the transmission and also efficiency of authentication in term of time consumption. Here, some variables like frequency is used, packet mode (PACTOR), power and size of data become a constant value. Although both transmission cannot be made in parallel but the gap between those transmissions is very close and can be assumed as using a same ionosphere conditions. Both results were shown in Table 5.8 and 5.9.

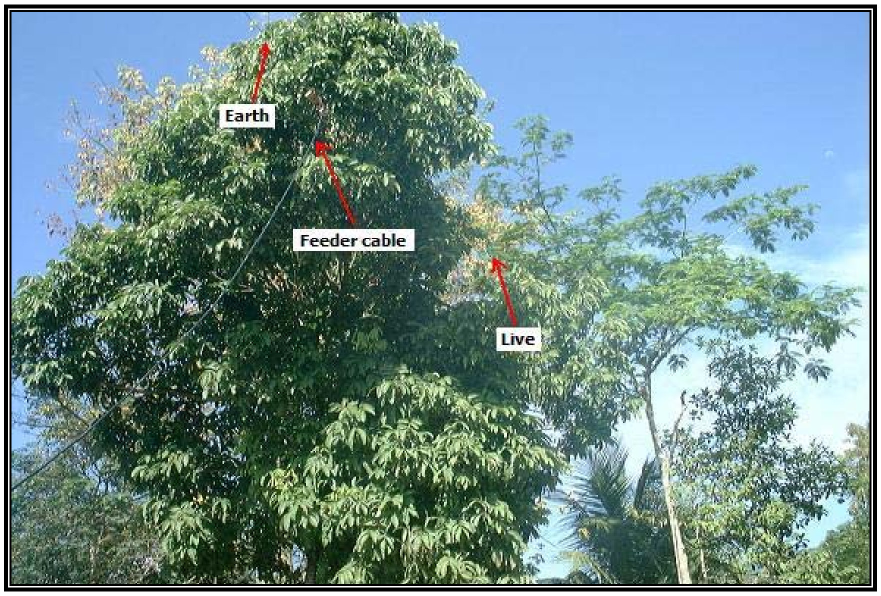


Figure 5.38: The center of the dipole antenna.

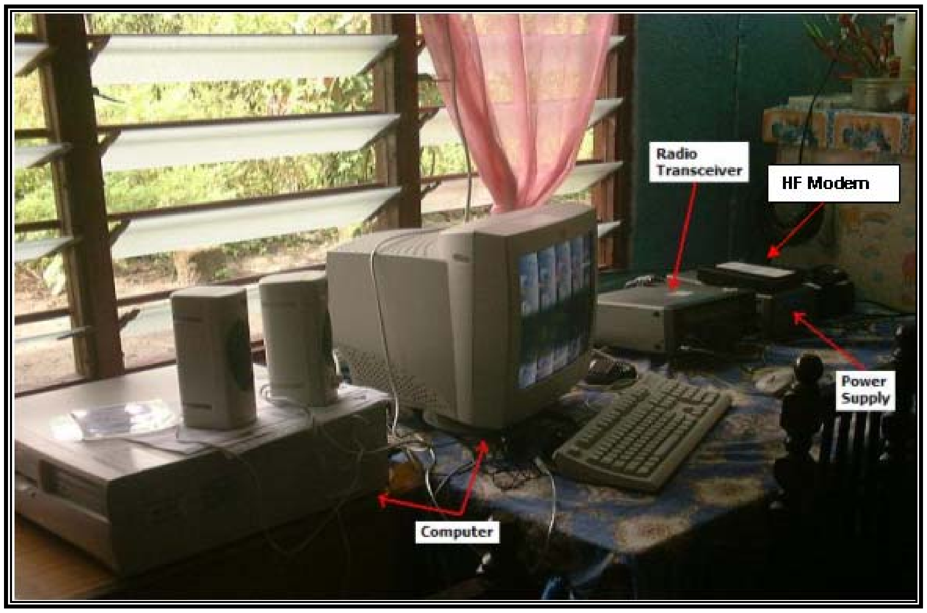


Figure 5.39: The layout of the equipments

Table 5.8: Transmission result for non-encrypted data (plain text)

Date	Time	Frequency (MHz)	File Size (Kbytes)	Transmit Power (Watt)	Baud Rate	Transmission Time
19th Oct 2004	0939	7.08	6	10	200	8 mins 50 secs
20th Oct 2004	1242	6.65	6	10	100	10 mins 45 secs
21st Oct 2004	1609	7.08	3	10	200	3 mins 10 secs
22nd Oct 2004	1018	6.65	6	10	100	12 mins
29th Oct 2004	1556	7.08	3	10	200	4 mins 30 secs

Table 5.9: Transmission results for authentication and encrypted data.

Date	Time	Frequency (MHz)	Image Size (Kbytes)	Transmit Power (Watt)	Baud Rate	Authentication Time	Transmission Time
19th Oct 2004	0950	7.08	6	10	200	35 Second	11 mins 10 secs
20th Oct 2004	1305	6.65	6	10	100	42 Second	14 mins 21 secs
21st Oct 2004	1614	7.08	3	10	100	50 second	6 mins 15 secs
22nd Oct 2004	1032	6.65	6	10	100	52 second	15 mins 49 secs
29th Oct 2004	1602	7.08	3	10	200	37 second	6 mins

On the average, time taken for authentication is 43 seconds and time taken for encrypted file transfer is longer as compared to plaintext by 1.5 times. For authentication, the delay is not due to the algorithm implementation and the computing platform but the nature of the propagation medium that limits the data transmission rate. The encrypted file is encoded using the radix 64 format prior to transmission that results in file size increase by about 1.5 times as compared to plaintext file. This is to ensure that the encrypted characters do not correspond to an equivalent control character in the ASCII code. For 6 Kbytes file, the average encrypted and plaintext file transfer time is about 10 minutes and 13 minutes respectively.

5.9.4 UTM Skudai to Kota Bharu

The final site of field-testing series was conducted between UTM Skudai and Kota Bharu. The line of sight between both places is approximately 535 km as shown in Figure 5.40.

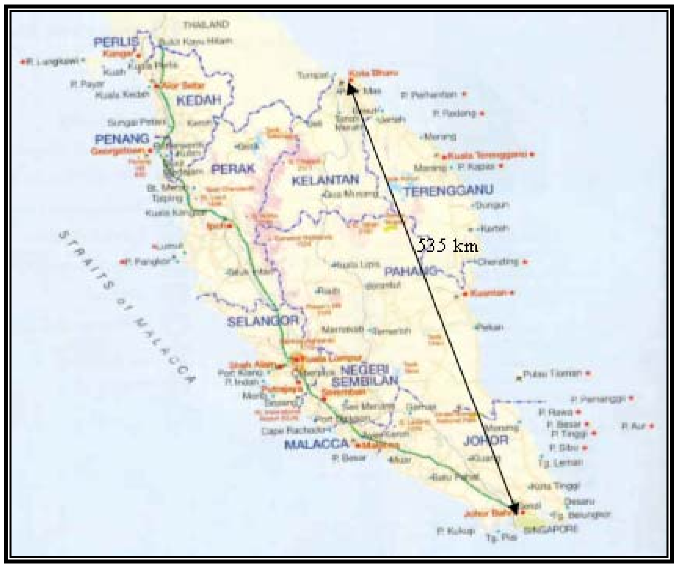


Figure 5.40: Map of location between UTM Skudai and Kota Bharu

Before any transmission made, all equipments including antenna were installed as shown in Figure 5.41 and Figure 5.42. This field-testing uses secured mode application and the constant variables used are the same as previous field test. The performance of encrypted and plaintext transmission is shown in Table 5.10 and 5.11.

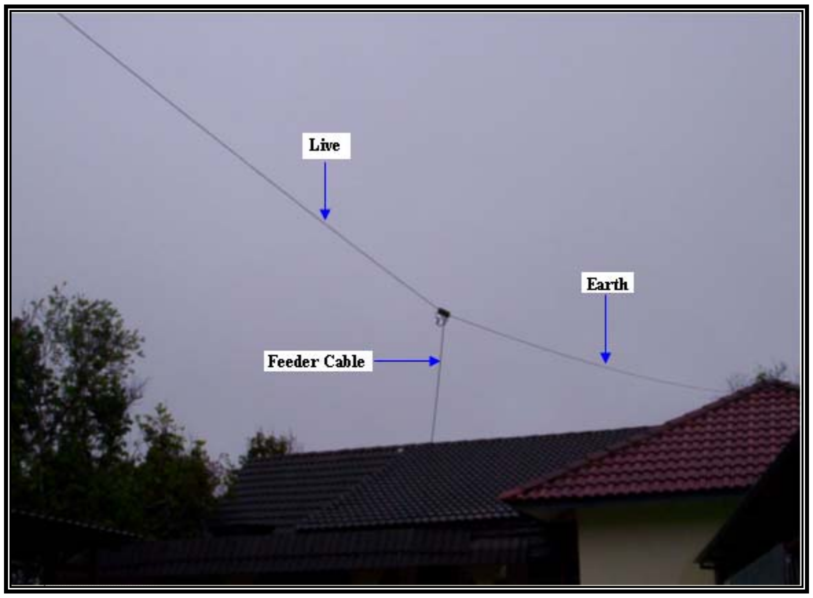


Figure 5.41: Installation of dipole antenna

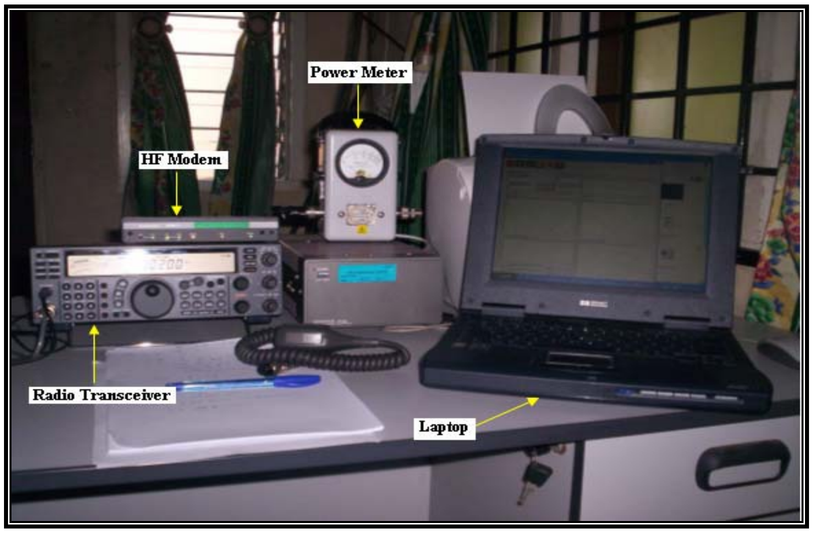


Figure 5.42: The arrangement of equipments

Table 5.10: Transmission result for non-encrypted data (plain text)

Date	Time	Frequency (MHz)	File Size (Kbytes)	Transmit Power (Watt)	Baud Rate	Transmission Time
14th March 2005	1044	7.080	4	10	200	4 min 43 sec
15th March 2005	1305	8.002	6	10	200	6 min 45 sec
17th March 2005	1421	8.002	4	10	200	4 min 36 sec
21ndMarch 2005	1230	9.146	6	10	200	7 min 20 sec
22th March 2005	1545	8.19	6	10	200	7 min 17 sec

Table 5.11: Transmission results for authentication and encrypted data.

Date	Time	Frequency (MHz)	Image Size (Kbytes)	Transmit Power (Watt)	Baud Rate	Authentication Time	Transmission Time
14th March 2005	1049	7.080	4	10	200	40 Second	6 min 45 sec
15th March 2005	1312	8.002	6	10	200	42 second	9 min
17th March 2005	1430	8.002	4	10	200	50 second	7 min 9 sec
21ndMarch 2005	1238	9.146	6	10	200	60 second	10 min 30 sec
22th March 2005	1555	8.19	6	10	200	52 second	11 min 3 sec

From the result, the frequencies used during this testing are higher compared to previous testing. This is because of equinoxes (March and September) phenomena where the frequencies around this period are higher from ordinary months. Table 5.11 shows the average time taken for authentication is 48 seconds. Although the transmit power is 10 Watt, but the transmission still occur at 200 baud. This shows the importance of selecting the suitable frequency in order to optimize the transmission over HF spectrum. For all transmission, the average encrypted and plaintext file transfer time is about 9 minutes and 6 minutes respectively.

5.10 Conclusion

Although several equipment were purchased, but the system is classified as low cost system structure because it only used commercial equipments such as computer, HF modem (KAM’98), HF radio (Kenwood) and antenna. With a little setup and installation, all equipments were integrated to become a system. Based on field-testing, Secured HF Messenger is user-friendly and by following a few steps as mentioned, users can use this application to exchange their digital information over HF confidentially.

CHAPTER 6

LONG RANGE HF TELEMETRY SYSTEM

Malaysia is a maritime nation where much of its wealth in natural resources and assets lie within the 200 nautical mile economic exclusive zone (EEZ). Example of natural resources and assets includes oil and gas fields, fishing areas, shipping lanes, ports, and ships. From international perspective, the Straits of Malacca is an important waterway for international trade between Europe and the Far East with a traffic flow of 1000 vessels a day. Thus, it is important for maritime organizations such as Jabatan Laut Semenanjung Malaysia to ensure maximum reliability of their navigation aids assets such as light houses and beacons.

For fleet operators, monitoring of movement of ships is important to ensure that product deliveries and services are on schedule with safety on passage. Any deviation from route and emergencies should be alerted on time to the fleet operators as well to the appropriate maritime organizations for further actions. Both applications can be best served using long range telemetry systems (Barr, 2004): light house telemetry system and vessel tracking system.

6.1 Implementation of Lighthouse Telemetry

Figure 6.1 shows the diagram of light house telemetry system. For light house application, the basic components at the light house consist of voltage and current sensors, light sensors, remote terminal unit (RTU), and HF modem and transceiver. The basic system at the master station consists of an HF transceiver, HF modem and personal computer with internet connectivity. With the system in place, the marine organization will be able to monitor the condition of the light house at all times without permanent technical staff at the light house. They are only required in the event of equipment failure.

By using existing equipments, RTU and software application (GUI) for master station are developed.

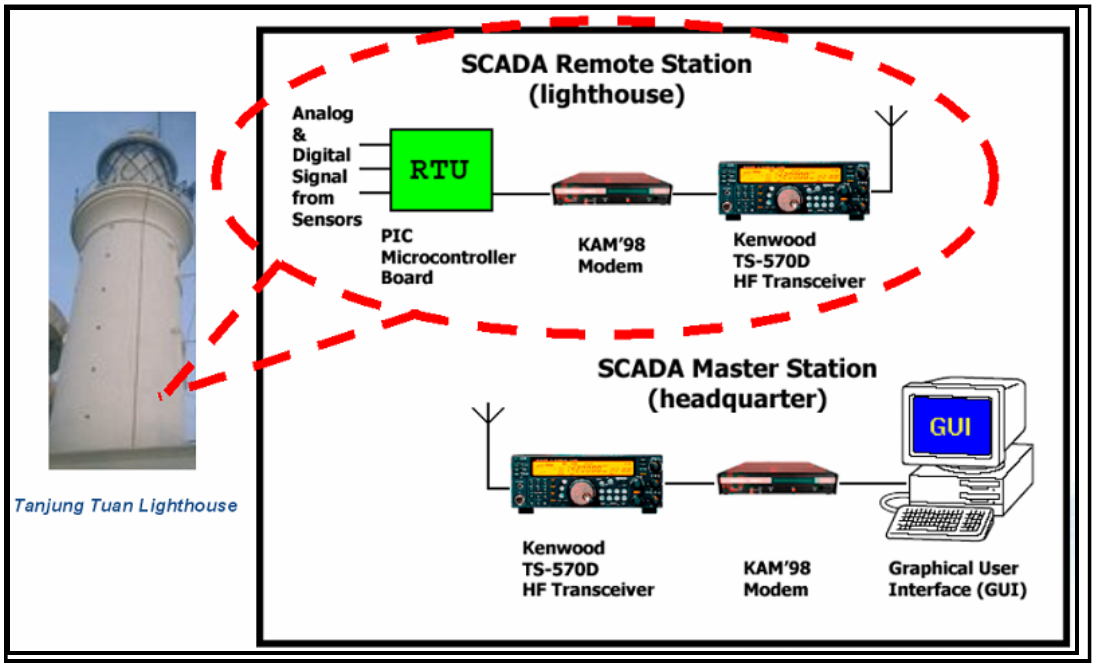

SCADA Remote Station
(lighthouse)
Analog & Digital Signal from Sensors
RTU
PIC Microcontroller Board
KAM'98 Modem
Kenwood TS-570D HF Transceiver
SCADA Master Station
(headquarter)
GUI
Kenwood TS-570D HF Transceiver
KAM'98 Modem
Graphical User Interface (GUI)
Tanjung Tuan Lighthouse

Figure 6.1: Overall SCADA system diagram

6.1.1 Hardware Design

Hardware design is needed to develop the Remote Terminal Unit (RTU), which consists of a power supply unit and also a PIC16F877A microcontroller based RTU circuit. The power supply unit is capable of supplying +5V, +12V and –12V to the RTU. PIC16F877A is a RISC microcontroller produced by *Microchip Technology Inc*. It can operate at a maximum clock input of 20MHz with 8k words of Flash Program Memory, 368 bytes of Data Memory (RAM) and 256 bytes of EEPROM Data Memory. It has operating voltage range of 2.2V to 5.5V. It also has 5 I/O ports (Port A, B, C, D and E) and some useful features includes Analog-To-Digital Converter, Universal Synchronous Asynchronous Receiver Transmitter (USART/SCI) and Timer/Counter.

6.1.1.1 RTU Circuit Board

The RTU microcontroller circuit consists of three main parts, which are the PIC16F877A microcontroller basic circuit, analog voltage level shifting circuit and TTL voltage level to RS-232 voltage level conversion circuit. The PIC16F877A microcontroller basic circuit is very important in providing an input clock signal to the microcontroller. A 20M Hz crystal oscillator has been used as an input clock device. Besides, two switches have been included into the circuit, which are the reset switch, and the interrupt input switch. Two digital inputs have been connected to digital input port, RC0 and RC1. Figure 6.2 shows the PIC16F877A microcontroller basic circuit for RTU.

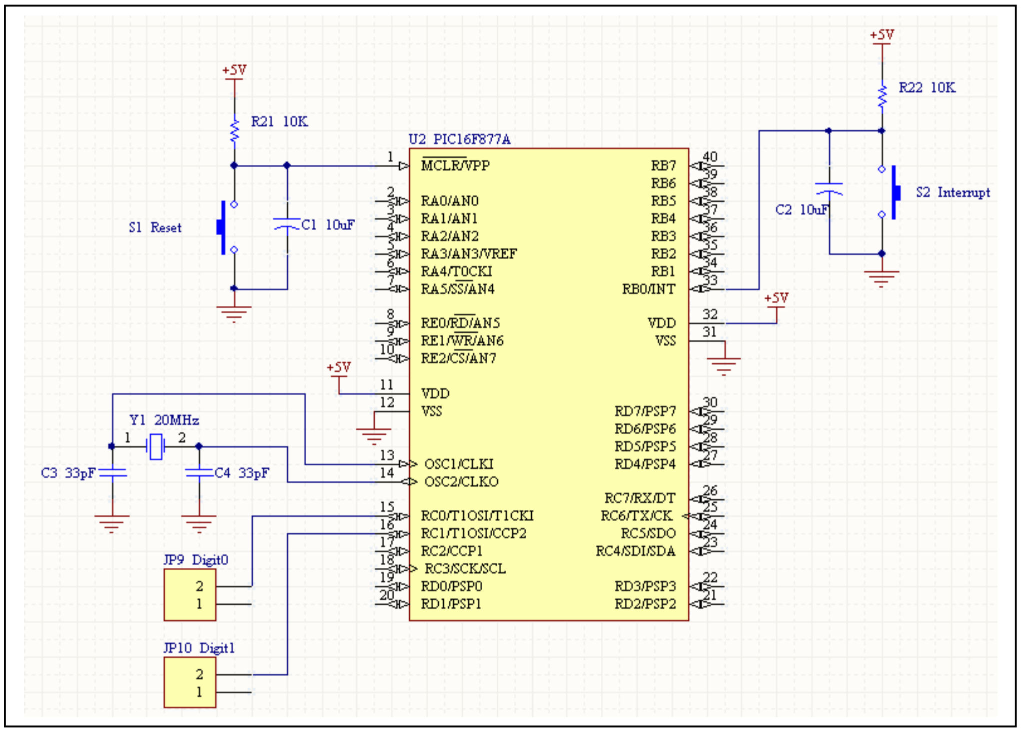


Figure 6.2: PIC16F877A microcontroller basic circuit for RTU

The built-in Analog-To-Digital Converter of PIC16F877A is only capable of handling input voltage range from 0V to +5V. For this project, the RTU needs to acquire ac input signal, which may have negative voltage level. Therefore, an op-amp circuit has been designed with the purposes of input voltage shifting and scaling, which has the voltage range of –5V to +5V.

Two analog input ports have been designed for ac analog input and dc analog input. Two op-amps used for each analog input port. First op-amp is an inverting summing amplifier and second op-amp is an inverter. Both op-amps are designed to connect cascaded.

Equation for inverting summing amplifier output (first op-amp):

$$V_{01} = -0.5\ (V_{in} + 5) \tag{6.1}$$

where V_{in} is analog input voltage (V).

Equation for inverter output (second op-amp):

$$V_{02} = -V_{01} \quad (6.2)$$

where V_{01} is output voltage of inverting summing amplifier (V).Figure 6.3 shows the analog voltage level shifting and scaling circuit.

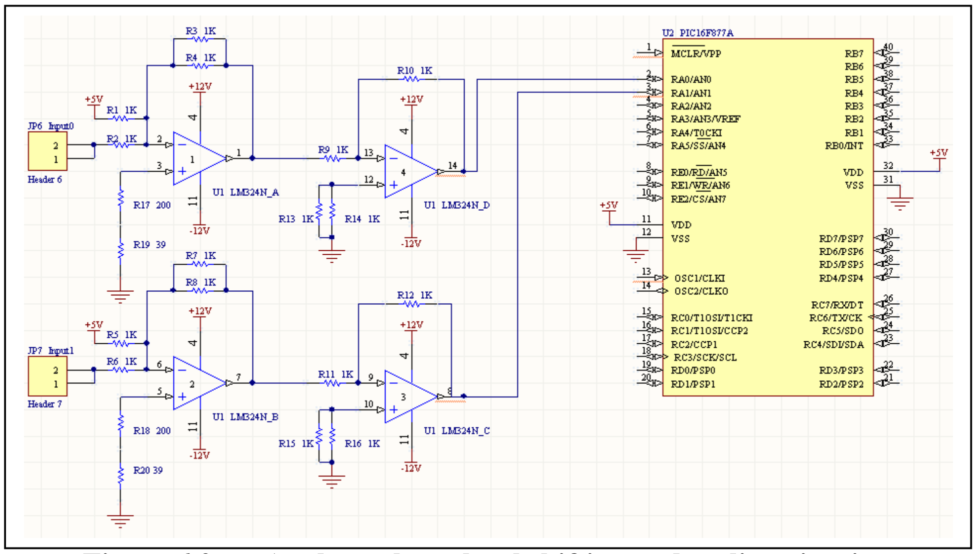


Figure 6.3: Analog voltage level shifting and scaling circuit

PIC16F877A microcontroller is using the TTL voltage level standard (0V as logic ‘0’ and +5V as logic ‘1’) but the HF modem is using serial communication RS-232 standard (+12V as logic ‘0’ and -12V as logic ‘1’) as mentioned in previous chapter. In order to allow the communication between the PIC16F877A microcontroller and the *Kantronics* modem, an interface circuit has been developed.

The interface circuit consists of a MAX232 Integrated Circuit (IC) chip with some 1uF capacitors. Four pins are connected, which are the Transmit (TX) connected to RC6, Receive (RD) connected to RC7, Request-To-Send (RTS) connected to RB1 and Clear-To-Send (CTS) connected to RB2. Transmit (TX) and Receive (RD) pin are actually the data pins. Request-To-Send (RTS) and Clear-To-Send (CTS) are the control pins. Figure 6.4 shows the RS-232 interface circuit.

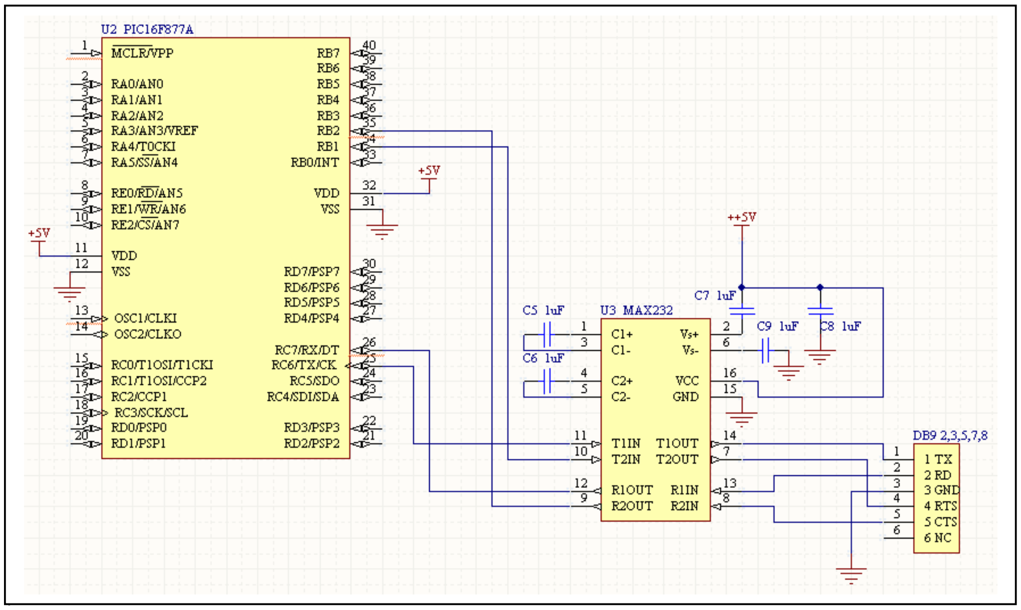


Figure 6.4: RS-232 interface circuit

6.1.1.2 Power Supply Design

Power supply is a device that converts power from a characteristic to another to meet specified requirement. There are two types of power supply, which are linear regulator and switch mode power supply. Linear power supply has been chosen for this project since it is a most simple type, easy to implement and small in size power supply. Power supply circuit has been designed for supplying +12V, -12V and +5V to the RTU circuit. It is a very important part because improper design of the power supply circuit may affect the stability and reliability of the RTU.

A +12V and –12V voltage regulator circuit has been developed using 7812 voltage regulator IC and 7912 voltage regulator IC. It is designed for supplying power to the analog voltage level shifting and scaling circuit (LM324N op-amp IC). Some capacitors are used as filter to reduce ripple of the output voltage. Figure 6.5 shows the +12V and –12V power supply circuit.

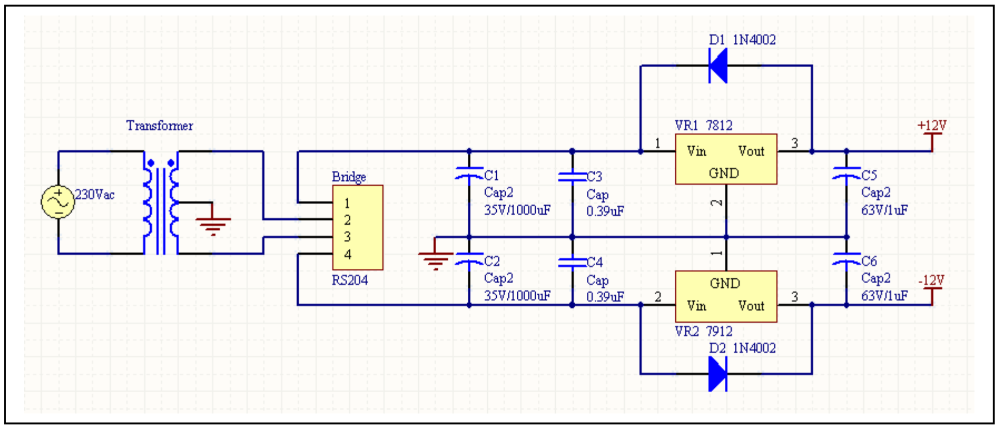


Figure 6.5: +12V and –12V power supply circuit

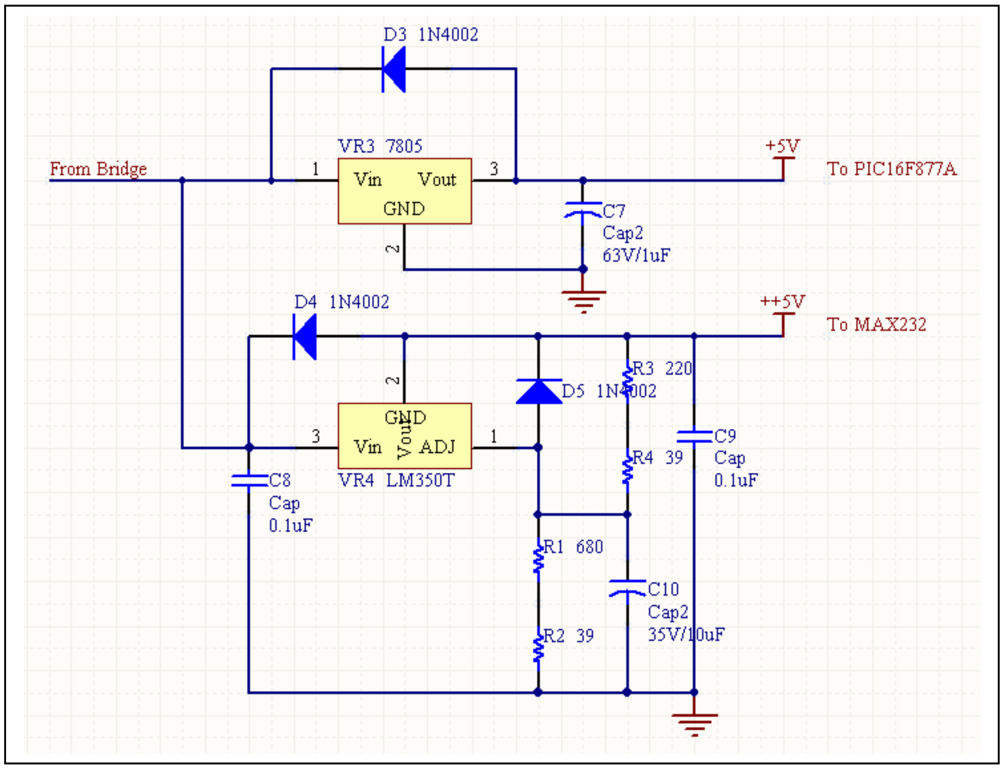


Figure 6.6: +5V power supply circuit

Initially, a +5V voltage regulator circuit was designed for the PIC16F877A and also the MAX232 using the 7805 voltage regulator IC. Anyway, the 7805 IC is only capable of provide 1.5A maximum current and was facing an overheat problem although it had been added with heat sink. Another IC voltage regulator, which is the LM350T, is used for supplying power to MAX232 IC since it is a higher power consumption device. It is capable of provide up to 3A maximum current. Therefore, LM350T is designed for MAX232 and 7805 is designed for other 5V devices. Figure 6.6 shows the +5V power supply circuit.

6.1.2 Programming

The PIC16F877A microcontroller based RTU must be programmed in order to functions as a control unit to acquire data, process data and then transmits the data to HF communication network using serial communication (RS-232). The RTU is programmed using C language. A compiler is needed to convert the high level language (C language) to assembly language. Therefore, MPLAB IDE is used as a development environment and PICC Lite is used as C compiler.

6.1.2.1 Initialization

Input and Output (I/O) peripheral of the PIC16F877A must be assigned as input port or output port at the beginning of the program. The USART, Analog-To-Digital Converter and interrupt features must be configured too. Figure 6.7 shows the program fragment for initialization and setting of PIC16F877A.

```
….

TMR1ON=0;              //off timer

TRISA=0xFF;            //PortA all input: RA0 ac input, RA1 dc input
TRISB=0x05;            //RB1 RTS_Out, RB2 CTS_In, RB0 Interrupt input
TRISC=0x83;            //RC7 input RX, RC0 & RC1 digit input, others output
TRISD=0x00;            //PortD all output

SPBRG=129;             //BAUD=9600, SPBRG=20M/(16*9600)-1=129.208= 129
BRGH=1;                //Set High Baud Rate
TXSTA=0B00100100;      //Set TXEN, BRGH and SYNC, 8bits asynchronous mode
RCSTA=0B10010000;      //Set SPEN, enable COM port, 8bits continuous receive mode
OPTION=0b00000000;
ADCON1=0b00000100;     //AN0 AN1 analog input, AN3 unused, others digital input
INTF=0;
TMR1IF=0;
TMR1IE=1;              //Enable timer interrupt
RCIE=1;                //Enable receive interrupt
PEIE=1;                //Enable peripheral interrupt
INTE=1;
GIE=1;                 //Enable global interrupt
RTS_Out=0;

…
```

Figure 6.7: Initialization and setting of PIC16F877A

6.1.2.2 Timer

A timer (Timer1 Module) is initiated to set a fixed sampling rate at 1.6k Hz (sampling interval 625us) with 32 data samples. The Timer interrupt the PIC every 625us (1.6k Hz) to start the ADC conversion. Figure 6.8 shows the program fragment of the Timer setting.

```
….

TMR1IE=1;                        //Enable Timer Interrupt
INTCON=0b11010000;               //Enable other Interrupts
TMR1L=0xCB;                      //1.6kHz sampling rate so that n=32
TMR1H=0xF3;
T1CON=0b00000001;                //prescale=1:1
State=S_ADC;

…
```

Figure 6.8: Timer setting

6.1.2.3 Analog to Digital Converter

Steps to initiate the conversion of Analog-To-Digital Converter (ADC) must be followed carefully to ensure an accurate and reliable output conversion of ADC. Figure 6.9 shows the program fragment of the ADC initialization.

```
….

Delay20us();                         //Delay 20us for acquisition time

ADGO=1;                              //Start conversion
while (ADGO)
        continue;                    //Wait for conversion to complete
RawData[SampleCount]=ADRESH;         //Read Result

Delay3_2us();                        //Delay 3.2us before next conversion

…
```

Figure 4.9: ADC initialization

6.1.2.4 RMS Calculation for AC Signal

RMS value for ac signal (in digital form) is calculated to reduce the size of the data sent to SCADA master through HF transmission. A program has been written to select the peak value of the ac data from 32 data samples. The peak value will only be divided at the SCADA master GUI to reduce program complexity and increase program efficiency since the PIC16F877A microcontroller does not have multiplier and divider. Figure 6.10 shows the program fragment of RMS calculation for ac signal.

```
….

//Change all the negative value to positive

for (SampleCount=0;SampleCount<32;SampleCount++)
{
        if (RawData[SampleCount]<127)
        {
                RawData[SampleCount]=(127-RawData[SampleCount])+128;
        }
}


//Select a biggest (peak) value

for (SampleCount=1;SampleCount<32;SampleCount++)
{
        if (RawData[SampleCount]>RawData[0])
        {
                RawData[0]=RawData[SampleCount];
        }
}

…
```

Figure 6.10: RMS calculation for ac signal

6.1.2.5 Average Calculation for DC Signal

Just like the ac signal, average value for dc signal (in digital form) is also calculated to reduce the size of the data sent to SCADA master. Figure 6.11 shows the program fragment of average calculation for dc signal.

```
….

//Add all data samples together

for (SampleCount=1;SampleCount<32;SampleCount++)
{
        RawData[0]=RawData[SampleCount]+RawData[0];
}

RawData[0]=RawData[0]/32;                    //Sum divide by number of samples

…
```

Figure 6.11: Average calculation for dc signal

6.1.2.6 Link Operation

The modem PACTOR mode of operation consist of six states, which are link operation, enter transmit mode, data transmission, enter receive mode, wait for acknowledgement and unlink operation. In order to initiate the link operation of PACTOR mode for modem at remote station and modem at SCADA master, RTU must transmit the SCADA master modem callsign through USART. Only one byte transmitted for each time of transmission. Figure 6.12 shows the program fragment of link operation.

```
….

//Initiate an array for callsign
const unsigned char Callsign[15]={'p','a','c','t','o','r',' ','9','w','3','2','5','2','h','q'};

while (State==S_TransmitMode)
        {
        if (j<15 && !CTS_In && TXIF)
        {
                TXREG=Callsign[j];        //Transmit callsign byte by byte
                j++;
                Delay1ms();               //Delay 1ms
        }
        else if (j==15)
        {
                State=S_EnterC;           //End of callsign transmission
                J=0;
                Delay1ms();
        }
}

…
```

Figure 6.12: Link operation

6.1.2.7 Data transmission

All the information of lighthouse is grouped into an array to allow data transmission from RTU to modem. Data transmission to modem is achieved through USART, sending byte by byte. Figure 6.13 shows the program fragment of data transmission.

```
….

while (State==S_SendData)
{
        if (j<16 && !CTS_In && TXIF)
        {
                TXREG=Data[j];          //Transmit data byte by byte
                j++;
        }

        else if (j==16)
        {
                State=S_EnterD;         //End of data transmission
                j=0;
                Delay1ms();
        }
}

…
```

Figure 6.13: Data transmission

6.1.2.8 Delay Subroutine

A delay subroutine has been written to perform a waiting period. Delay subroutine is usually available in compiler library. Basically, users just have to invoke the delay function without the need to write a program. Anyway, the compiler used in this project, PICC Lite, is actually student version software. There are some limitations on the usage of functions and libraries of the compiler. Therefore, the delay subroutine is written in assembly language to obtain a more precise delay time since the PICC Lite is compatible with assembly language. Figure 6.14 shows the program fragment of the Delay Subroutine for 1s.

```
….

#asm                    //Indicate the starting of assembly language program
MOVLW       26
MOVWF       _Temp3
MOVLW       251
MOVWF       _Temp2
MOVLW       255
MOVWF       _Temp1
DECFSZ      _Temp1,f
GOTO   $-1
DECFSZ      _Temp2,f
GOTO   $-5
DECFSZ      _Temp3,f
GOTO   $-9
#endasm                 //Indicate the ending of assembly language program

…
```

Figure 6.14: Delay subroutine for 1s

6.1.3 Data Format

All the information of lighthouse is grouped into a data frame before being transmitted to modem through USART. The data frame consists of 16 bytes of character and can be divided into three main parts, which are header, data and stop byte. Figure 6.15 shows the data frame where the data structures are:

(i)	AA	:	Header of the whole data frame
(ii)	1	:	Header for first data (ac data)
(iii)	2	:	Header for second data (dc data)
(iv)	3	:	Header for third data (digital data 1)
(v)	4	:	Header for forth data (digital data 2)
(vi)	ZZ	:	Stop byte for the whole data frame

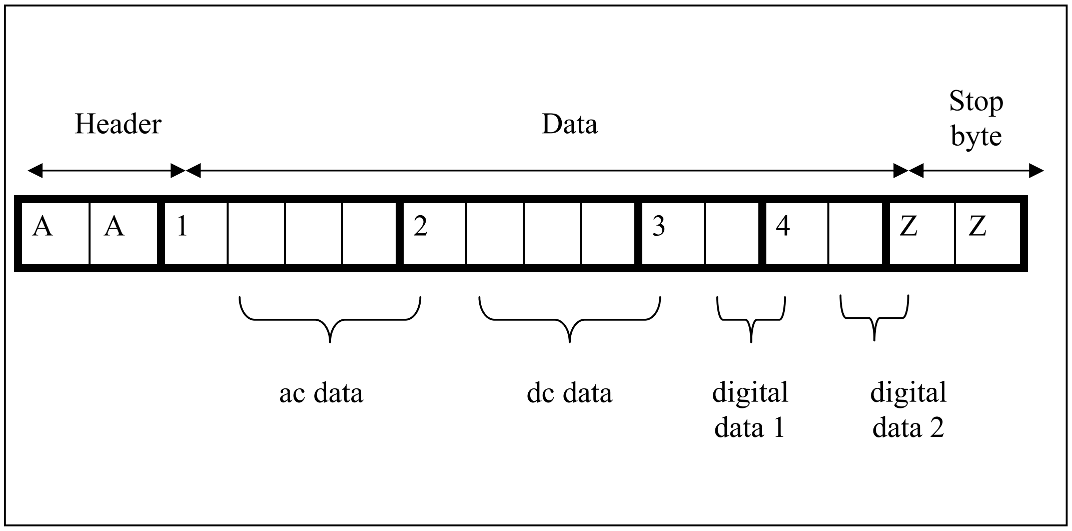
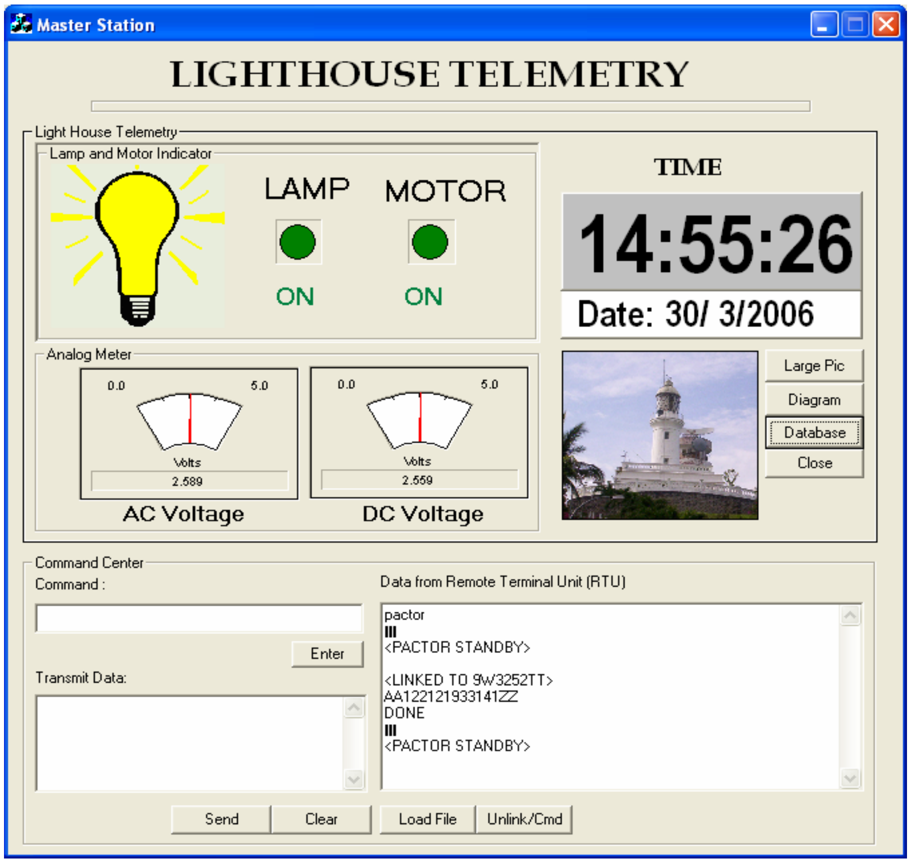


Figure 6.15: Data frame

Two bytes of header field, ‘AA’ are used to indicate the start of data frame. Character ‘1’ is used as header for the first data, indicating the start of ac data frame (4 bytes). Character ‘2’ is used as header for the second data, indicating the start of dc data frame (4 bytes). Character ‘3’ is used as header for the third data, indicating the start of digital data 1 for lamp on off information (2 bytes). Character ‘4’ is used as header for the forth data, indicating the start of digital data 2 for motor on off status (2 bytes). Two bytes of stop byte, ‘ZZ’ are used to indicate the end of the whole data frame.

6.1.4 Graphic User Interface

A software application for master station has been implemented by using Microsoft Visual C++. It is capable to display functionality of lamp and motor of the lighthouse. From the received signal of remote station, the application will display the condition of sensors and saves into database. There are an indicator for lamp and motor, displaying on or off condition. Two analog meters is used to display the ac and dc voltage level. There are also date and time indicator on the GUI. Besides, a command centre has been implemented to display the exact data being transmitted or received through the serial communication. This command indicator is used for troubleshooting purpose.



14:55:26

Date: 30/ 3/2006

2.589

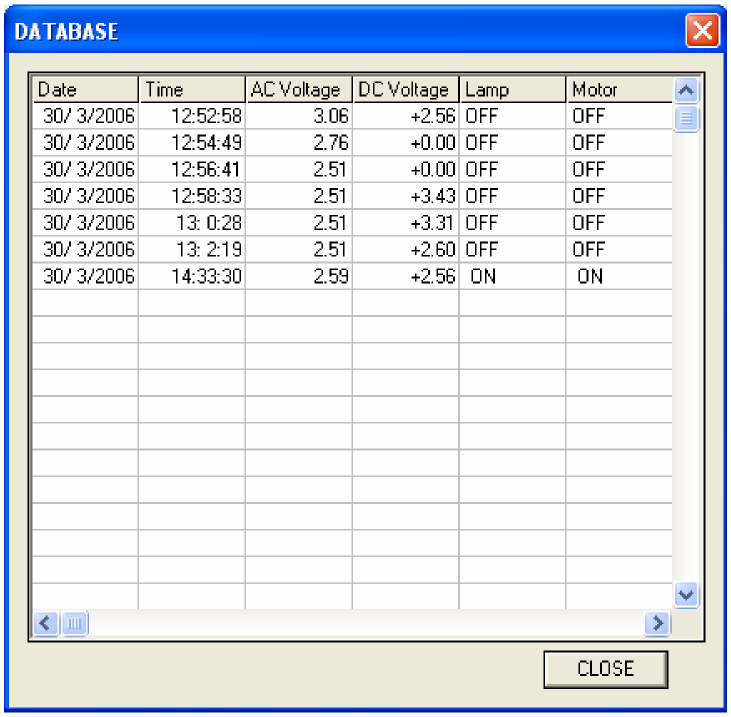
2.559

```
pactor
|||
<PACTOR STANDBY>

<LINKED TO 9W3252TT>
AA122121933141ZZ
DONE
|||
<PACTOR STANDBY>
```

Figure 6.16: Software applications for light house telemetry system

The 'data from Remote Terminal Unit (RTU)' column in the GUI is used to show the communication between remote and master station. '<PACTOR STANBY>' indicates the master station is in waiting state for data receiving from remote station. '<LINKED TO 9W3252TT>' indicates the link operation between remote and master station is successful. The 'AA122121933141ZZ' is the 16 bytes data frame received by master station. 'DONE' is the acknowledgement being sent by master station to the remote station that the data has been successfully received. '<PACTOR STANBY>' indicates the unlink operation is done. It also indicates that master station is ready for the next link operation and data transmission. Figure 6.16 shows the application at master station.

A database also implemented to store information received by master station from time to time. The database is able to store information like the on or off and analog meter reading for both lamp and motor at a particular date and time. The database as shown in Figure 6.17 is important for report generation, future statistical analysis and possibly an evidence for the failure of equipment at lighthouse.



Date	Time	AC Voltage	DC Voltage	Lamp	Motor
30/ 3/2006	12:52:58	3.06	+2.56	OFF	OFF
30/ 3/2006	12:54:49	2.76	+0.00	OFF	OFF
30/ 3/2006	12:56:41	2.51	+0.00	OFF	OFF
30/ 3/2006	12:58:33	2.51	+3.43	OFF	OFF
30/ 3/2006	13: 0:28	2.51	+3.31	OFF	OFF
30/ 3/2006	13: 2:19	2.51	+2.60	OFF	OFF
30/ 3/2006	14:33:30	2.59	+2.56	ON	ON

Figure 6.17: Database of the SCADA master

6.1.5 Results

By using Protel DXP 2004, RTU Printed Circuit Bard (PCB) for remote station is done and ready to use. Figure 6.18 shows the view of RTU PCB. Two digital input and two analog inputs (one ac input and one dc input) are available, which are at the left side of the picture.

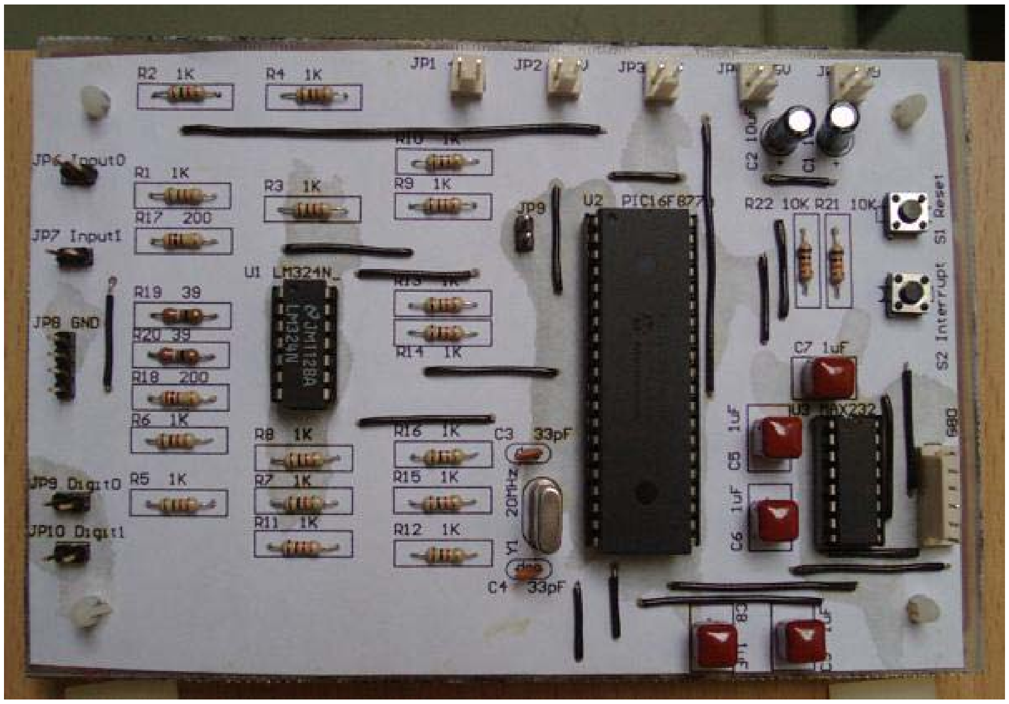


Figure 6.18: Picture of RTU PCB

Figure 6.19 shows the PCB for power supply which is capable of converting the 240V ac voltage from mains to +5V, +12V and –12V to the RTU microcontroller circuit. Since the power source is the 240V ac voltage, therefore, a transformer is used to scale down the voltage level. The transformer has to be connected to the left hand side of the power supply PCB.

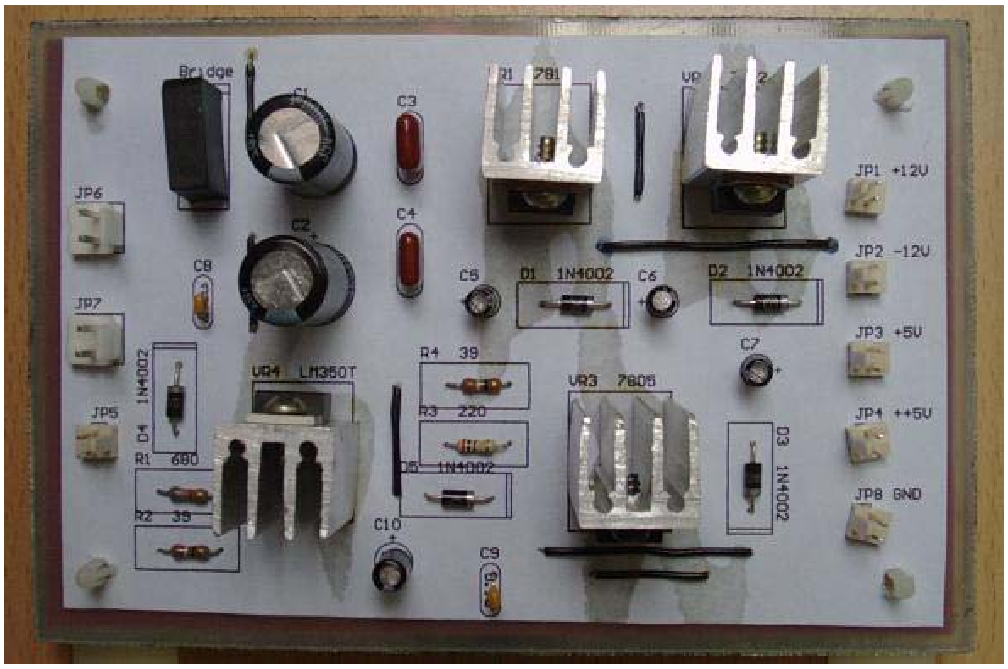


Figure 6.19: Picture of power supply PCB

Due to the difficulties to test the system on real light house, a digital input board has been made to represent the digital input from the control system at lighthouse triggered by the photo sensor. The digital input board consists of two switches and two indication LEDs, representing the lighthouse lamp and motor on or off status. Figure 6.20 shows the picture of the digital input board. By integrate all the equipment as shown in Figure 6.21; a demonstrable prototype of light house telemetry is done.

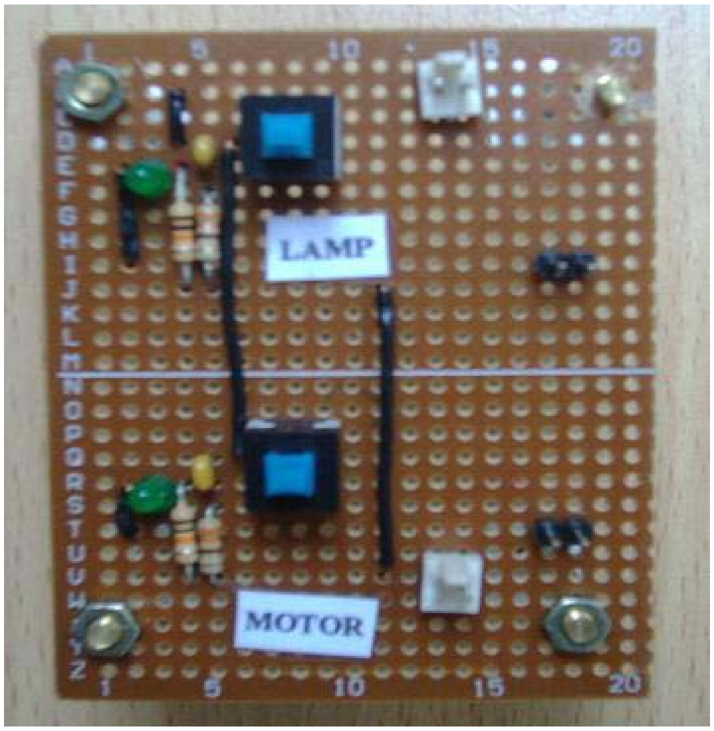
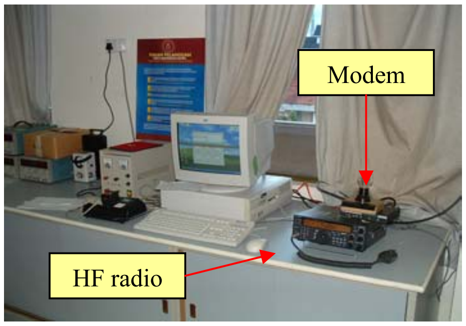
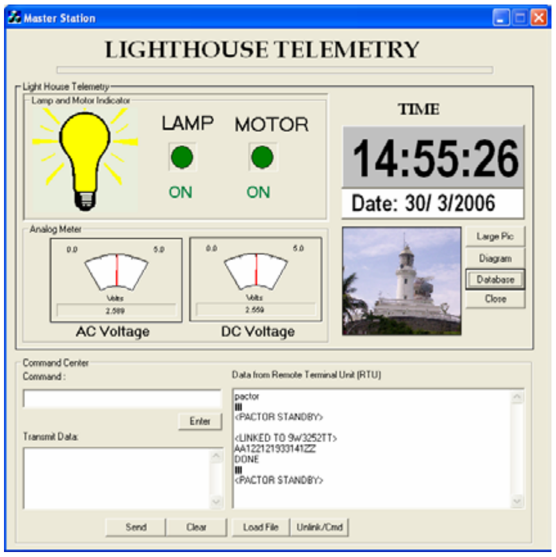


Figure 6.20: Picture of digital input board

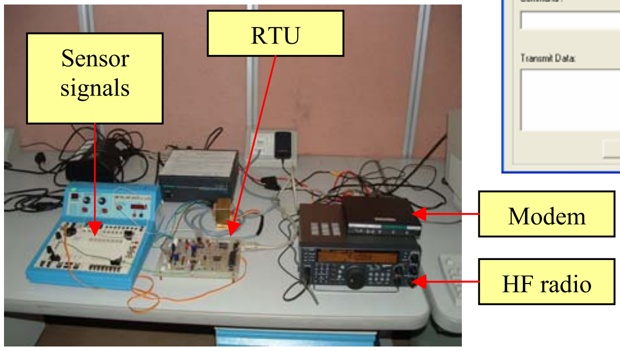


Master station



```
pactor
|||
<PACTOR STANDBY>

<LINKED TO 9W3252TT>
AA12212193314122Z
DONE
|||
<PACTOR STANDBY>
```

GUI for Master Station



Remote station

Figure 6.21: Pictures showing the prototype light house telemetry system: master station, remote station, and graphic user interface (GUI).

6.2 Implementation of Vessel Tracking System

The system is used to monitor the location of the ship from a location to another location. The differences between the system and previous are the RTU is on the ship not at remote area, the information sent and software application for master station in order to display the movement of the ship. The RTU and others equipments are same. Figure 6.22 shows the diagram of vessel tracking system.

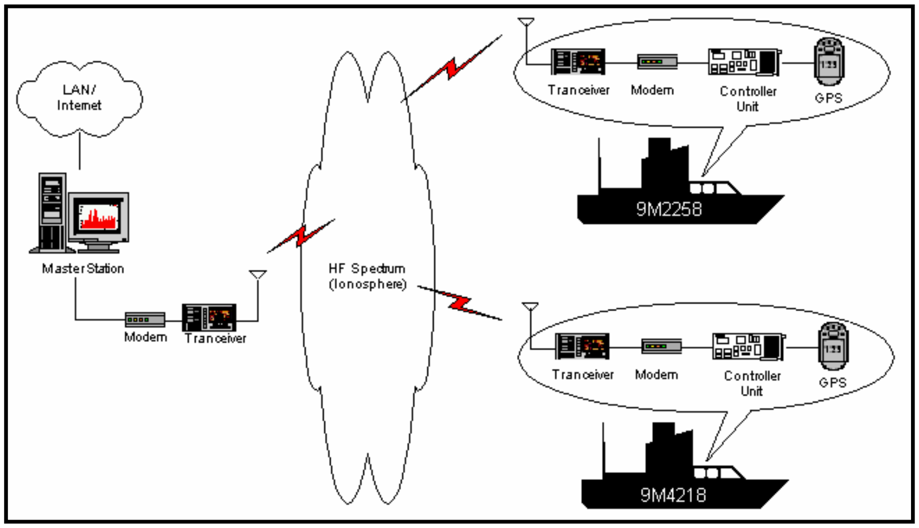
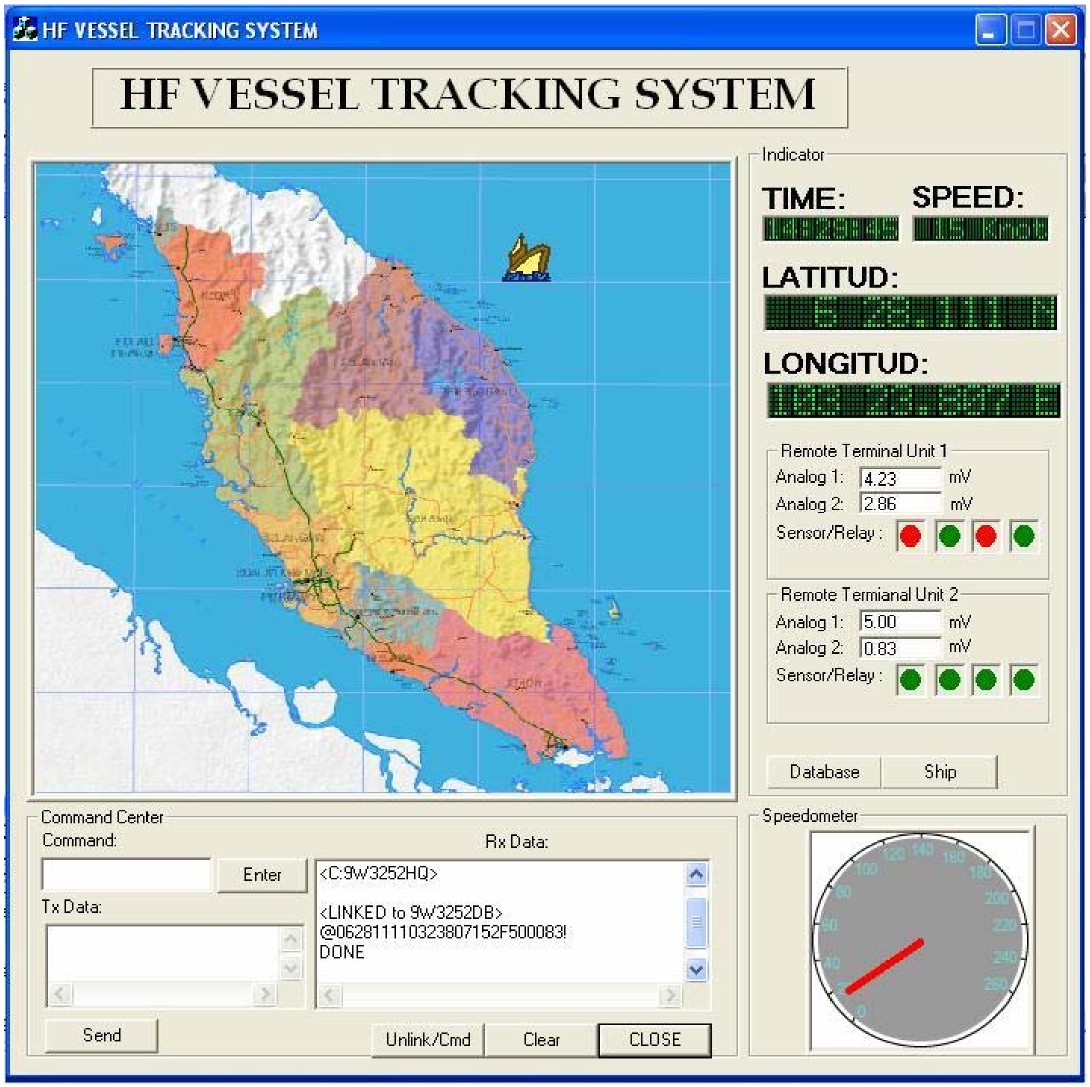


Figure 6.22: Long range HF telemetry system for vessel tracking application.

Instead read the sensors, the RTU read the position from the GPS (Global Positioning System) and transmit to master station. Figure 6.33 is a commercial GPS which a part of the system.

Figure 6.33: Garmin GPS 76 handheld unit

Software application for master stations is developed using Microsoft Visual C++ as shown in Figure 6.34. It will indicate the position of the ship based on latitude and longitude which transmitted from the ship. Each received data will store into database for reference. Figure 6.35 shows the layout of equipments setup of master and remote station for a prototype of vessel tracking system.



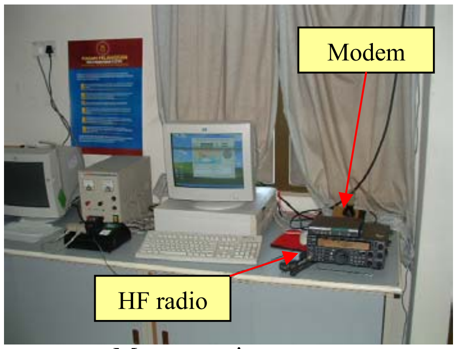
TIME: [illegible]
SPEED: [illegible]
LATITUD: 6 28.111 N
LONGITUD: 103 23.807 E

Remote Terminal Unit 1
Analog 1: 4.23 mV
Analog 2: 2.86 mV
Sensor/Relay : 🟥 🟩 🟥 🟩

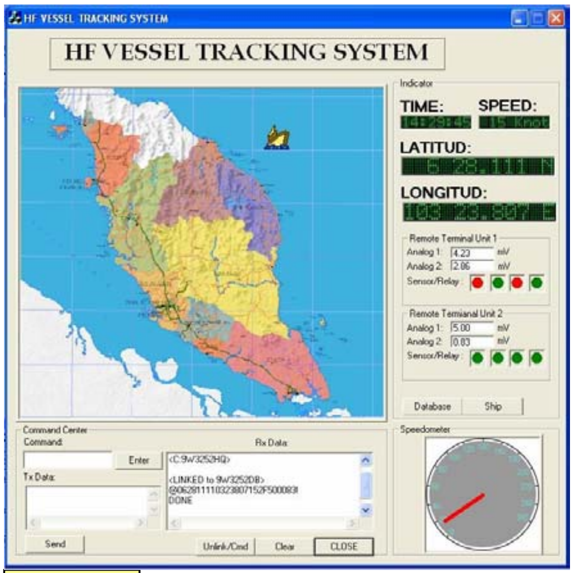
Remote Termianal Unit 2
Analog 1: 5.00 mV
Analog 2: 0.83 mV
Sensor/Relay : 🟩 🟩 🟩 🟩

Rx Data:
```
<C:9W3252HQ>

<LINKED to 9W3252DB>
@0628111103238071 52F500083!
DONE
```

Figure 6.34: Software applications for vessel tracking system

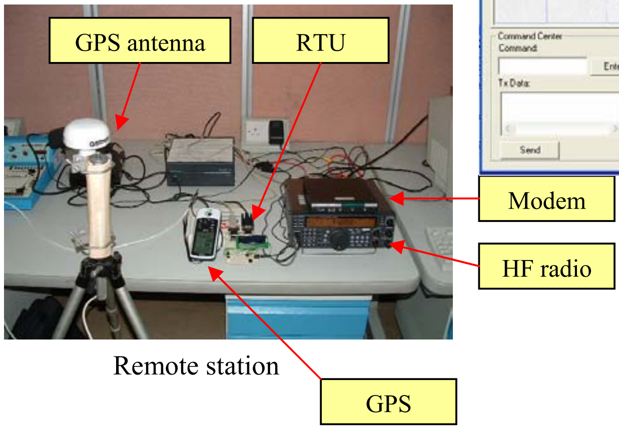


Master station



```
<C:9W3252HQ>

<LINKED to 9W3252DB>
@06281111032380715 2F500083I
DONE
```

GUI for Master Station



Remote station

Figure 6.35: Pictures showing the prototype vessel tracking station : master station, remote station, and graphic user interface (GUI).

6.3 Conclusions

The long range telemetry systems developed are for lighthouse telemetry and vessel tracking system. Both systems are suitable for use in maritime environment where the distances do not allow the use of conventional communication technologies such as line of sight communications such as VHF and UHF radio and cellular communications such as GSM. HF communication technology is proposed due to low cost of operation. The vessel tracking system will allow fleet operators and marine organization to monitor the position of the vessel at all times, while the light house telemetry system allows the organization to monitor the condition of equipment to ensure navigation safety. The present systems are already implemented and tested in the lab

CHAPTER 7

CONCLUSIONS

HF communications is no longer limited to voice and telegraphy but today has included applications such as short messaging, file transfer, email and telemetry. Long distance communication over the HF spectrum is achieved by the refraction of radio waves on the ionosphere. The outcome of this research has produced a prototype HF data transmission system that is capable to transmit images. Additional features of the system include short messaging, telemetry and file transfer, and cryptographic features such as authentication, key distribution and confidentiality. The proposed system is useful any users that operates over large expanse of land and water where the cost of setting up and operating a communication infrastructure is not economical. Possible end user for this product includes the military, law enforcement, deep sea fishing, oil and gas and amateur radio. The project has achieved all of the objectives with the inclusion of telemetry applications.

Some preliminary work was done in the development of robust high speed modem based on the Texas Instrument's TMS320C5416 DSP processor. Due the effect of multipath fading and interference in the HF spectrum, it was concluded that further research should be continued in this area. Future work will also include the inclusion of email function as part of the HF data communication system. With this features, users are able to communicate with existing email services eventhough they are not accessible by the conventional communication infrastructure such as the PSTN (Public Switched Telephone Network) and the cellular telephone network.

REFERENCES

Abdullah, M.A., Husni, E.M.S., and Hassan, S.I. (2003). "Investigation of a rural telecommunication System using VSAT Technology in Malaysia". 9th Asia Pacific Conference on Communications, 2003(APCC). 21-24 September 2003 Penang.

ACP 127(G) (1988). "Communication Instructions Tape Relay Procedures". Allied Communication Publication.

ARRL (2002). "The Arrl Handbook for Radio Ameteurs 2002". *79th edition*. USA: The American Radio Relay League, Inc

Barr, D (2004)., "Supervisory Control and Data Acquisition Systems", *NCS TIB 04-1, National Communications System*, October 2004.

Beker, H., and Piper, F. (1982). "Cipher Systems: Protection of Communications". Northwood Publications, London.

Beker, H., and Piper, F. (1985). "Secure Speech Communications". Academic Press, London.

Blonstein, S.; Katorgi, M.; (2003), "eXpressDSP for DUMMIES", Wiley Publishing Inc, 1st edition 2003

Boyarinov, I.; Martin, I.; Honary, B.; (2000), "High-speed decoding of extended Golay code", Communications, IEEE Proceedings-, Volume: 147, Issue: 6, Dec. 2000

Brakemeier, A.; Lindner, J.; (1988), "Single-tone HF data transmission with 2.4 kbps and 4.8 kbps", HF Radio Systems and Techniques, 1988, Fourth International Conference, 1988

Carr, J.J.; (2001), "Practical Antenna Handbook", McGraw-Hill 4th Edition 2001

Clark, P.D.J.; Horley, N.; Darnell, M.; Honary, B.; (1993), "DSP modem/codec implementation for long-range radio applications", DSP Applications in Communication Systems, IEE Colloquium, 1993

Cook, S.C.; Giles, T.C.; Vyden, B.; Gill, M.C.; (1993), "Error-control options for parallel-tone HF modems", Military Communications Conference, 1993. MILCOM '93. Conference record. 'Communications on the Move', IEEE, Volume: 3, 11-14 Oct. 1993

Couch L.W. II.; (1997), "Digital and Analog Communication Systems", Prentice Hall International Inc 5th edition 1997

Cruiseemail (2004). "*CruiseEmail.com*". http://www.cruiseemail.com/

Crypto AG (2004). *"For communication & information security"*. http://www.crypto.ch

Diffie, W and Hellman, M.E. (1997). "New directions in cryptography". *IEEE Trans. Info. Theory.* **IT-22**, pp. 644 - 654.

Ekdahl, P., and Johansson, T. (2001). "SNOW- a new stream cipher". Lund University Sweden.

Federal Standard 1037C, *"Federal Standard 1037C: Glosary of Telecommunications Terms*". http://glossary .its.bldrdoc.gov/fs-1037/fs-1037c.htm.

Golic, J., and Mihaljevic, M. (1990). "Minimal Linear Equivalent Analysis of a Variable-Memory Binary Sequence Generator". *IEEE Transactions on Information Theory.* **36(1)**: 190-192.

Golomb, S. (1967). "Shift Register Sequences". Holden Day.

Goodman J.M.; (1992), "HF Communications Science and Technology", Van Nostrand Reinhold 1992

Harris Corporation (2002). “RF 3700H Harris Universal Image Transmission Software”. RF Communication Division, Harris Corporation.

Harris Corporation; (1996), “Radio Communications in the Digital Age. Volume I HF Technology”, Harris Corporation 1st edition 1996

Hawkes, P., and Rose, G. (2002). “Guess-and-Determine Attacks on SNOW”. Qualcomm Australia.

Hoult, N.S.; Whiffen, J.R.; Tooby, M.H.; Arthur, P.C.; (2000), “16 kbps modems for the HF NVIS channel”, HF Radio Systems and Techniques, 2000. Eighth International Conference on (IEE Conf. Publ. No. 474), 2000

Johnson, R. (1992). *“Elementary Statistics”.* PWS-Kent.

Johston, J. (1999). *“Southwinds: Local news for Southern Sailors”.* http://www.southwindssailling.com/articles/9905/indek9905.html

Jorgenson, M.B.; Johnson, R.W.; Moreland, K.W.; (2001), “An examination of HF modems platform architectures,” Military Communications Conference, 2001, MILCOM 2001, Communications for Network-Centric Operations: Creating the Information Force. IEEE, Volume: 1, 28-31 Oct. 2001

Jorgenson, M.B.; Johnson, R.W.; Moreland, K.W.; Bova, W.E.; Jones, P.F.; (2000), “Meeting military requirements for increased data rates at HF”, MILCOM 2000. 21st Century Military Communications Conference Proceedings, Volume: 2, 2000

Kantronics Co. (1998). “KAM ’98 Multi-Mode HF/VHF Digital Controller User’s Guide”. Kantronics Co.

Kasser, J.E.; (1991), "Applied digital communications via HF radio", HF Radio Systems and Techniques, 1991, Fifth International Conference, 1991

Kenwood Corp. (1998). "HF Transceiver TS-570D Instruction Manual". Kenwood Corp.

Kotlowski, A.; Brakemeier, A.; (2000), "Shortwave software modem, 14400 bps in 3 kHz", HF Radio Systems and Techniques, 2000, Eighth International Conference on (IEE Conf. Publ. No. 474), 2000 pp 311 –315

Kotsakis, E. (2004). *"Secure Information Exchange".* Electronic Reporting Systems (ERS). https://quickcheckinc.com

Lail, B.M. (2002). "Broadband Network & Device Security". The McGraw-Hill Companies.

Massey, J.L. (1969). "Shift Register Synthesis and BCH Coding Decoding". *IEEE Trans on Information Theory.* **15**, pp 122-127.

Menezes, A., Oorschot, V., and Vanstone, S. (1996). "Handbook of Applied Cryptography", CRC Press.

Mils (2004). *"The secret of unconditional security".* http://www.mils.com

MIL-STD-188-141B (1999). "Interoperability and Performance Standards for Medium and High Frequency Radio System". U.S Department of Defense, March 1999.

Mohamad Kamal, A.R. (2005). "Short-course on wireless communication system". Universiti Teknologi Malaysia.

National Institute of Standards and Technology (NIST) (2001). "Advance Encryption Standard (AES)". *Federal Information Processing Standards Publication 197.*

Nichols, R.K., and Lekkas, P.C. (2002). "Wireless Security: Models, Threats and Solutions". The McGraw-Hill Companies.

Nilsson, J.E.M.; Giles, T.C.; (1997), "Wideband multi-carrier transmission for military HF communication", MILCOM 97 Proceedings, Volume: 2, 1997 pp1046 -1051 vol.2.

NTIA-ITS (1998). "High Frequency Radio Automatic Link Establishment (ALE) Application Handbook". U.S. National Telecommunications and Information Administration (NTIA), U.S. Inst. For Telecommunication Sciences (ITS), September 1998.

Nurhashimah Saad (2004), "Performance Analysis of Differential Phase Modulation for HF Communication", Master Thesis Universiti Technology of Malaysia (2004)

Oppenheim, A.V., Schafer, R.W.; (1999), "Discrete-Time Signal Processing", Prentice Hall Signal Processing Series 2nd edition 1999

Pactor (2004). *"Pactor, your solution for shortwave radio communications*". http://www.scs-ptc.com

Pawliw, B. (2001). "*Block Cipher*". http://searchsecurity.techtarget.com/sDefinition/0,,sid14_gci213593,00.html

Press, W., and Teukolsky, S. (1992). "Numerical Recipes in C". Cambridge University Press, London.

Quirke, J. (2004). "Security in the GSM system". AusMobile.

Reed, D.G.; (2001), "The ARRL Handbook for Radio Amateurs", The National Association for Amateur Radio 79th edition 2001

Reidsradiodata (2004). *"HF Radio Communication network".* http://www.reidsradiodata.com.au/

Rose, G. (2000). "SOBER: A Stream Cipher based on Linear Feedback over GF (2^8)". QUALCOMM Australia.

SailMail (2004). *"Sailmail : Email Services for Yachts via Marine HF SSB Radio".* http://www.sailmail.com/

Scalsky, S.; Chace, M.; (1997), "Digital Signal FAQ", in http://www.qsl.net/py1vhf/ swmodes.txt, Copyright (C) 1995,1996,1997 by Stan Scalsky, Copyright (C) 1995,1996,1997 by Mike Chace

Schneier, B. (1996). "Applied Cryptography". *Second Edition*. John Wiley & Sons, Inc.

Siegenthaler, T. (1984). "Correlation-immunity of nonlinear combining functions for Cryptographic applications". *IEEE Transactions on Information Theory*. **30**, 776–780.

Sklar B.; (2001), "Digital Communications Fundamentals and Application", Prentice Hall Inc 2nd edition 2001

Soyer, L. (2001). "HF Messenger/spl trade/: European trials and R&D efforts". Military Communications Conference. (MILCOM 2001). Blagnac.

Stalings W.; (2000), "Data and Computer Communications", Prentice Hall Internal Editions 6th edition, 2000

Stallings, W. (2003). "Cryptography and Network Security". Prentice Hall.

Thomas, S., and Anthony, D. (2002). "The W7 Stream Cipher Algorithm". University of Waterloo.

Trinder, S.E.; Gillespie, A.F.R.; (2001), "Optimisation of the STANAG 5066 ARQ protocol to support high data rate HF communications", Military Communications Conference, 2001. MILCOM 2001. Communications for Network-Centric Operations: Creating the Information Force. IEEE , Volume: 1 , 2001 pp 482 –486

Tuan Sabri, T.M. (1995). "Analysis & Design of Stream Cipher Encryption Algorithms", Universiti Teknologi Malaysia, Skudai, Johor, Malaysia. Thesis Master.

Willink, T.J.; Davies, N.C.; Clarke, J.; Jorgenson, M.B.; (1996), "Validation of HF channel simulators", Frequency Selection and Management Techniques for HF Communications, IEE Colloquium, 7-8 Feb 1996

Winlink (2000). *"Enhanced digital messaging for amateur radio"*. http://winlink.org/

"Texas Instruments Technology for Innovators, DSP Selection Guide", http://www.ti.dspvillage.com

"TMS320VC5416 Technical Reference", Spectrum Digital Inc, Copyright © 2002

Australian Space Weather Agency, "IPS Radio and Space Services", in http://www.ips.gov.au

APPENDIX A

Below are descriptions or step by step of performing Guess-and-Determine attack on Multiplexing and Linear generator. Although the backward process is not the same between generators but the idea of performing backward processes for both generators can be used as reference for other generators. Next, the verification of cipher system is discussed. It shows the concept of verifying the software design.

1.0 GUESS-AND-DETERMINE ATTACKS ON MULTIPLEXING GENERATOR.

1. First, consider all these following assumptions:

   (i) LFSR 0 become a selector and polynomial of LFSR 0 is GF(2^3):

   (ii) $f(x) = 1 + x^2 + x^3$

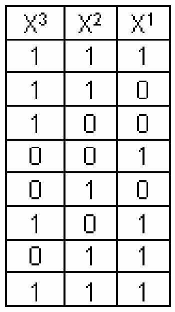
   (iii) LFSR 1 as input and polynomial of LFSR 1 is GF(2^4) :
   $f(x) = 1 + x^3 + x^4$

   (iv) Amount of keystream is known. For example: *K(n) = 1,1,1,0,0,0,0,1*

   (v) Complete knowledge of algorithm. In this case, the algorithm is using 4 to 1 multiplexer and X^3 and X^2 states as selectors.

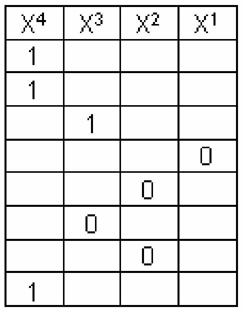
2. Then built a truth table of LFSR 0 and LFSR 1. Guesses the initial condition of LFSR 0. The number of guessing is equal to 2^3. Next, put the keystream bit by bit to each state of LFSR 1 depending on selector value which is X^3 and X^2 states of LFSR 0. Table 7.1 show that every row of truth table filled with the keystream.

Table 7.1: Truth table for both LFSRs



X^3	X^2	X^1
1	1	1
1	1	0
1	0	0
0	0	1
0	1	0
1	0	1
0	1	1
1	1	1

a). LFSR 0



X^4	X^3	X^2	X^1
1			
1			
	1		
			0
		0	
	0		
		0	
1			

b). LFSR 1

3. The next process is filling the truth table of LFSR 1. As we know that, the state values inside the LFSR are delayed from the previous values. Means, values in state X^4 actually delayed from values of state X^3. From this knowledge, the truth table of LFSR is filled as shown in Table 7.2.

Table 7.2: Truth table of LFSR 1 is filled and represented by bold binary bit.

X^4	X^3	X^2	X^1
1	**1**		**1**
1		**1**	
	1		
1			0
		0	**1**
	0	**1**	**0**
0	**1**	0	
1	**0**		

4. Based on polynomial used where the state of X^1 is an output of XOR process between X^3 and X^4, continue filling the truth table. Now, the truth table is become as Table 7.3.

Table 7.3: Another binary bit recovered from the polynomial knowledge.

X^4	X^3	X^2	X^1
1	1		1
1		1	**0**
1	1		
1	**0**		0
		0	1
	0	1	0
0	1	0	
1	0		**1**

5. Repeat the step 3 and 4 until all binary bits is filled in truth table as shown in Table 7.4.

Table 7.4: The secret key is represented by bold binary bit.

X^4	X^3	X^2	X^1
1	**1**	**1**	**1**
1	1	1	0
1	1	0	0
1	0	0	0
0	0	0	1
0	0	1	0
0	1	0	0
1	0	0	1

6. From Table 7.4, secret key of LFSR 1 which is first line of truth table appear and the generator now considered is broken and not secured anymore.

7. As a conclusion, the real strength of this algorithm depends on LFSR 0 and in this case, instead of 2^7 the real strength of Multiplexer Generator is 2^3.

2.0 GUESS-AND-DETERMINE ATTACKS ON LINEAR GENERATOR.

1. Firstly, consider all these following assumptions:

   i. Polynomial of LFSR 0 is GF(2^3): $f(x) = 1 + x^2 + x^3$
   ii. Polynomial of LFSR 1 is GF(2^4) : $f(x) = 1 + x^3 + x^4$
   iii. Polynomial of LFSR 2 is GF(2^5) : $f(x) = 1 + x^2 + x^5$
   iv. Amount of keystream is known. For example: *K(n) = 1,0,1,0,1,1,1*
   v. Complete knowledge of algorithm structure: $z(n) = s_0(n) \oplus s_1(n) \oplus s_2(n)$ where $s_0(n)$, $s_1(n)$ and $s_2(n)$ represent the outputs of LFSR 0 to 2.

2. Next, guesses 2 over 3 LFSR and usually we guesses the first 2 smallest LFSRs to reduce number of trials. Example of output for each LFSR is shown in Table 7.5 and the initial condition of each LFSR is represented by bold binary bits.

Table 7.5: Example of the initial conditions required before backward the process

LFSR 0	**1**	**1**	**1**	0	0	1	0
LFSR 1	**1**	**1**	**0**	**0**	0	1	0
LFSR 2							
Keystream K(n)	1	0	1	0	1	1	1

3. Then, backward the algorithm structure process to determine the output of LFSR 2. This can be done using Equation

$$s_2(n) = s_0(n) \oplus s_1(n) \oplus z(n)$$

4. The secret key of LFSR 2 will appear as shown in Table 7.6. The first 5 bit of LFSR 2 is secret key of generator.

Table 7.6: Secret key of LFSR 2 determined by reverse the linear process

LFSR 0	**1**	**1**	**1**	0	0	1	0
LFSR 1	**1**	**1**	**0**	**0**	0	1	0
LFSR 2	**1**	**0**	**0**	**0**	**1**	1	1
Keystream K(n)	1	0	1	0	1	1	1

5. Now, the algorithm is broken and instead of 2^{12}, the real strength of linear generator in this case is 2^7.

3.0 VERIFICATION OF CIPHER SYSTEM BASED ON LFSR

The verification of the cipher system was done by comparing between the keystream that generated manually by calculation and produced from simulation software. Both keystream should be the same. Below is an example of verification on Improved Geffe generator using small registers. The configurations of the system are:

Register 1:

Size of register	:	3
Coefficient	:	101
Initial	:	011

Register 2:

Size of register	:	5
Coefficient	:	10010
Initial	:	10101

Register 3:

Size of register	:	7
Coefficient	:	1000001
Initial	:	0001111

Table 7.7: Pseudorandom sequences produce by LFSR

Register	Sequences

1	1100 1011 1001 0111 0010 1110 0101 1100 1011 1001 0111 0010 11
2	1010 1000 0100 1011 0011 1110 0011 0111 0101 0000 1001 0110 01
3	1111 0000 0010 0000 1100 0010 1000 1111 0010 0010 1100 1110 10

Table 7.8: Keystream sequences

Keystream Sources	Sequences
Calculation	1110 1000 0000 0011 0010 1110 0001 1111 0011 0000 1101 0110 11
Simulation	1110 1000 0000 0011 0010 1110 0001 1111 0011 0000 1101 0110 11

APPENDIX B

Below are descriptions of theoretically BER calculation based on measured SNR that obtain from field-testing. Then, follow by the examples of corrupted signals due to multipath fading problems.

1.0 THEORETICAL BER CALCULATION BASED ON MEASURED SNR

The SNR is obtained from the field-testing result. The uncoded BER is calculated from the ratio of error and total received bits. The actual uncoded BER is compared with uncoded BER result for comparison purposes. Theoretical BER is calculated based on the measured SNR. Measured SNR is

$$\begin{aligned}\text{SNR (dB)} &= 10\log\left(\frac{signal\ \ power}{Noise\ \ power}\right)\\ &= 10\log\left(\frac{E_b}{N_0}\right) \qquad \text{(B.1)}\end{aligned}$$

where $E_b = \frac{A^2 T_b}{4}$ is energy per bit, A is signal amplitude, T_b is bit duration and N_0 is noise power [Sklar, 2001]. Uncoded BER for DPSK is calculated as

$$BER = \frac{1}{2}\exp\left(-\frac{A^2 T_b}{4N_0}\right) \tag{B.2}$$

where by substituting $E_b = \frac{A^2 T_b}{2}$ into the equation produces

$$BER = \frac{1}{2}\exp\left(-\frac{E_b}{2N_0}\right) \tag{B.3}$$

Referring from Equation (B.1), uncoded BER can be calculated by substituting value of E_b / N_0 into Equation (B.3). Uncoded BER for DQPSK is

$$BER = \exp\left(-\frac{E_b}{2N_0}\right) \tag{B.4}$$

2.0 EXAMPLES OF CORRUPTED SIGNAL IN ENDAU ROMPIN AND BALING

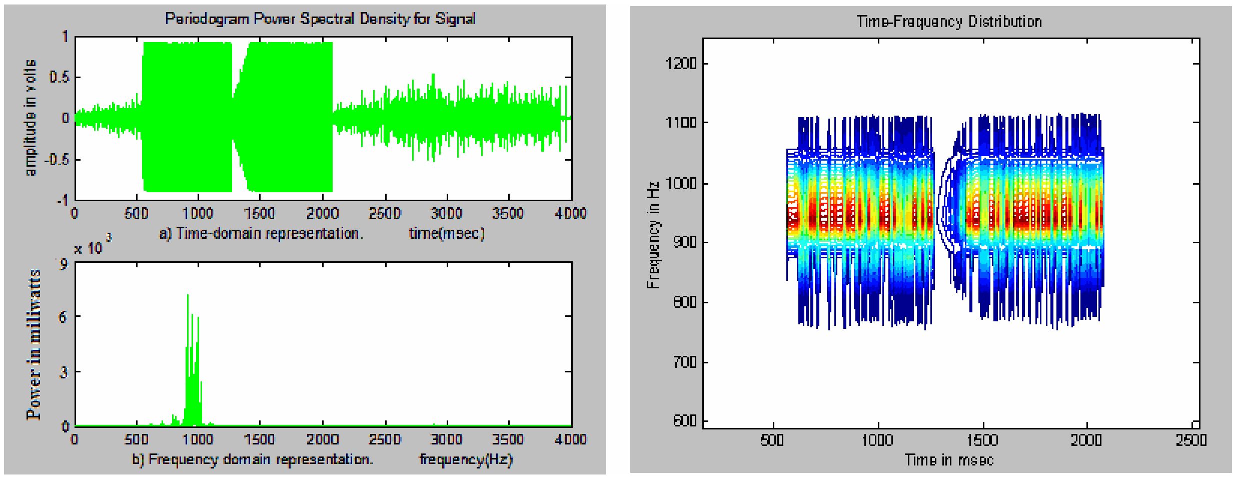


Figure B 1: Example of Corrupted Signal in Endau Rompin

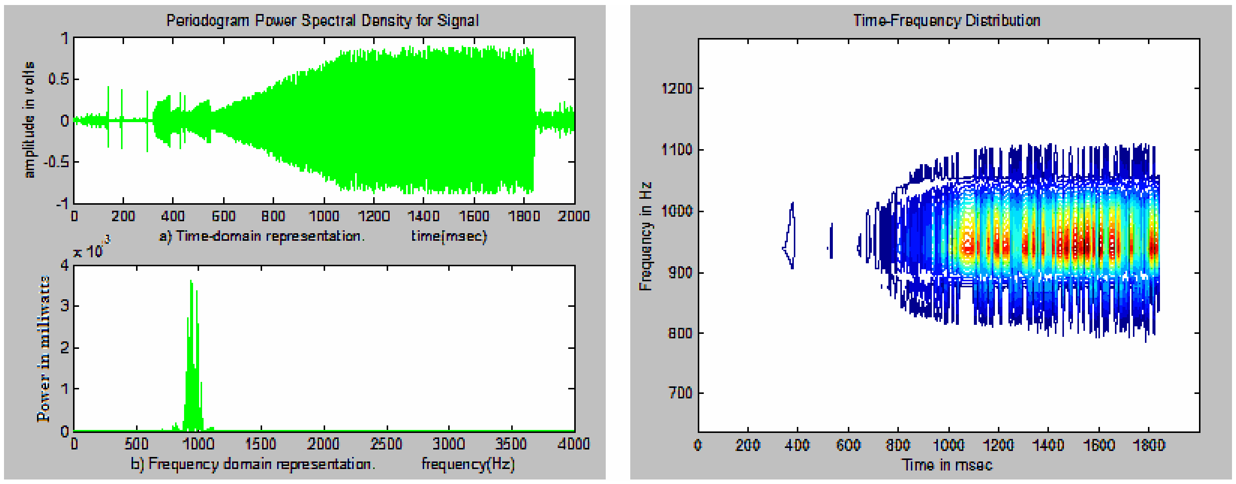
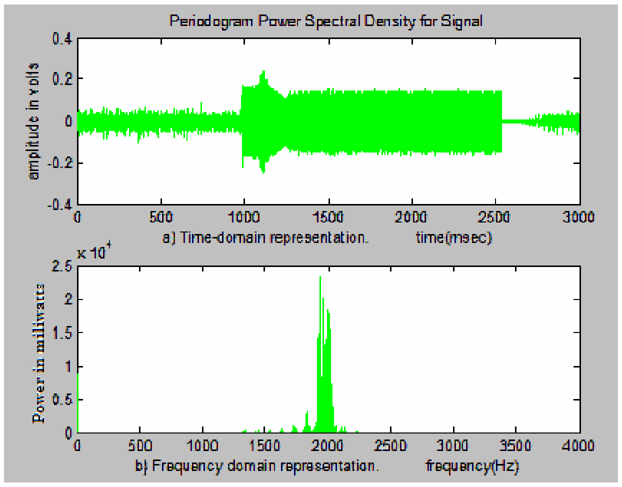


Figure B 2: Example of Corrupted Signal in Endau Rompin



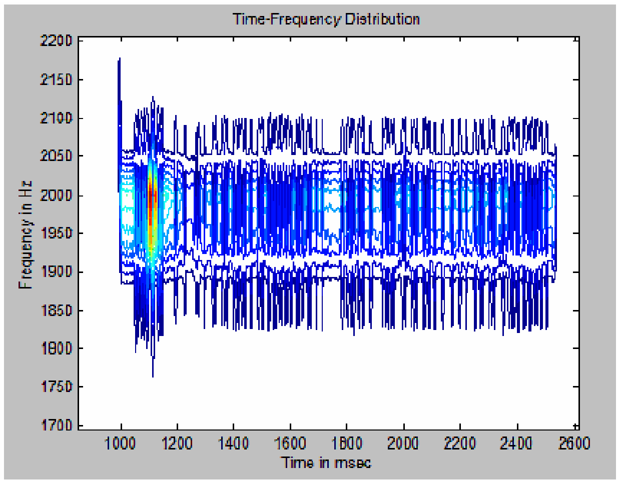
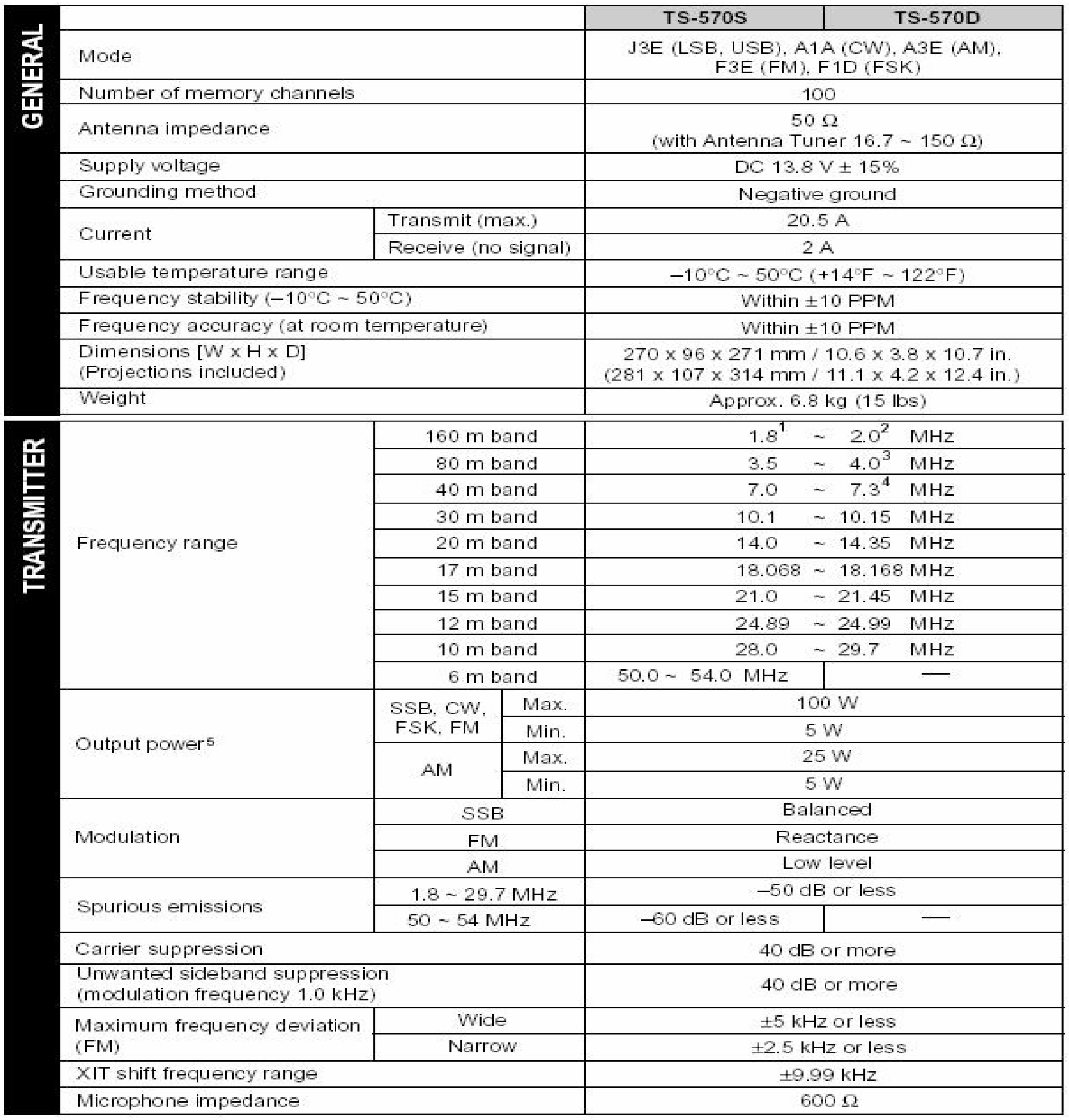


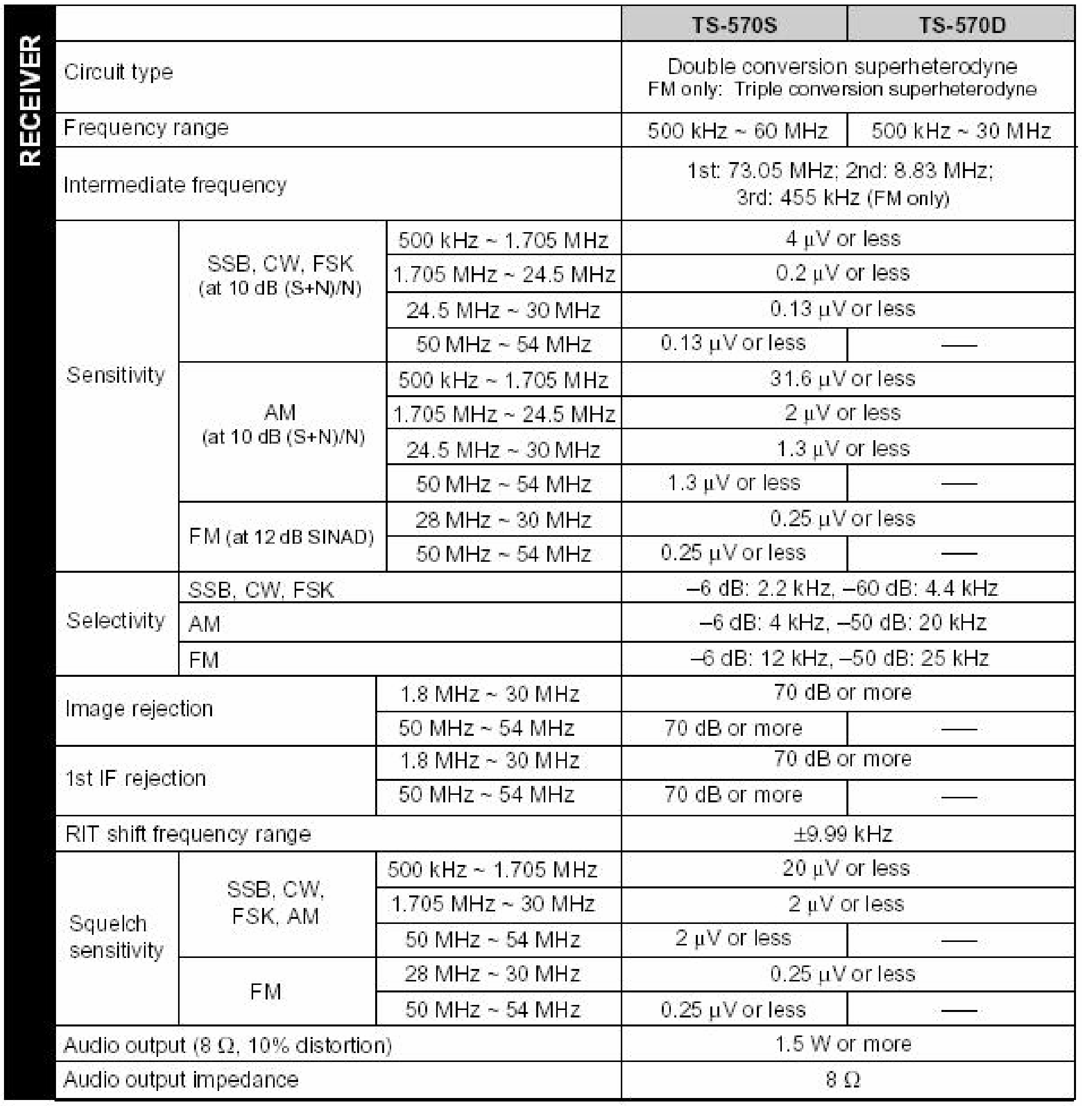
Figure B 3: Example of Corrupted Signal in Baling

APPENDIX C

1.0 HF TRANSCEIVER TS-570D SPECIFICATION

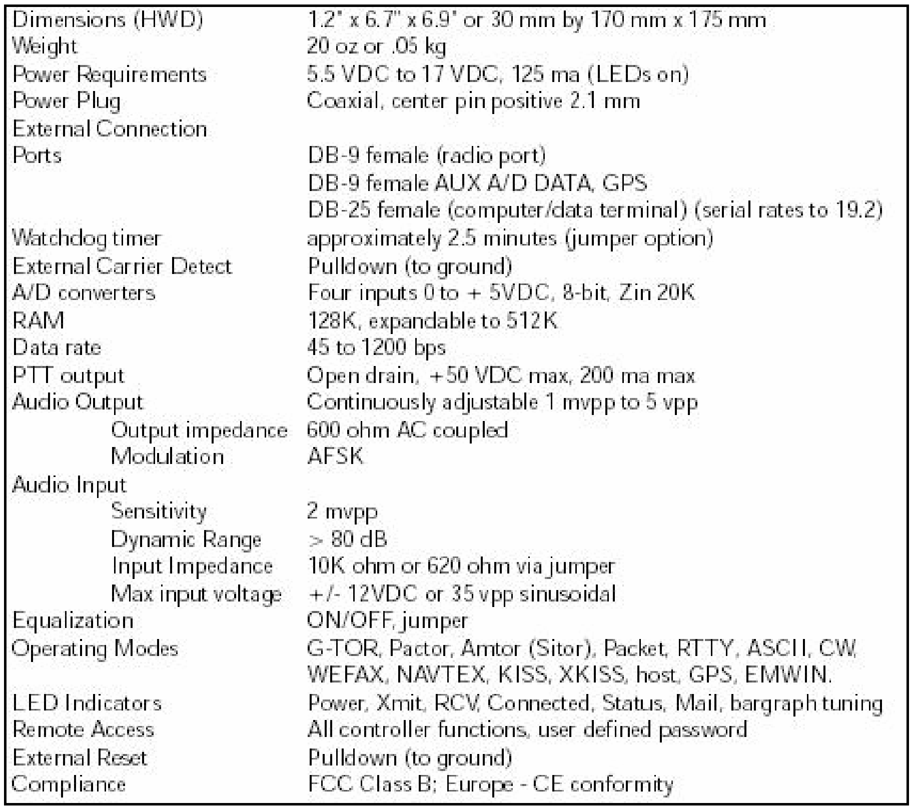


				TS-570S	TS-570D
GENERAL	Mode			J3E (LSB, USB), A1A (CW), A3E (AM), F3E (FM), F1D (FSK)	
	Number of memory channels			100	
	Antenna impedance			50 Ω (with Antenna Tuner 16.7 ~ 150 Ω)	
	Supply voltage			DC 13.8 V ± 15%	
	Grounding method			Negative ground	
	Current	Transmit (max.)		20.5 A	
		Receive (no signal)		2 A	
	Usable temperature range			–10°C ~ 50°C (+14°F ~ 122°F)	
	Frequency stability (–10°C ~ 50°C)			Within ±10 PPM	
	Frequency accuracy (at room temperature)			Within ±10 PPM	
	Dimensions [W x H x D] (Projections included)			270 x 96 x 271 mm / 10.6 x 3.8 x 10.7 in. (281 x 107 x 314 mm / 11.1 x 4.2 x 12.4 in.)	
	Weight			Approx. 6.8 kg (15 lbs)	
TRANSMITTER	Frequency range	160 m band		1.8[1] ~ 2.0[2] MHz	
		80 m band		3.5 ~ 4.0[3] MHz	
		40 m band		7.0 ~ 7.3[4] MHz	
		30 m band		10.1 ~ 10.15 MHz	
		20 m band		14.0 ~ 14.35 MHz	
		17 m band		18.068 ~ 18.168 MHz	
		15 m band		21.0 ~ 21.45 MHz	
		12 m band		24.89 ~ 24.99 MHz	
		10 m band		28.0 ~ 29.7 MHz	
		6 m band		50.0 ~ 54.0 MHz	—
	Output power[5]	SSB, CW, FSK, FM	Max.	100 W	
			Min.	5 W	
		AM	Max.	25 W	
			Min.	5 W	
	Modulation	SSB		Balanced	
		FM		Reactance	
		AM		Low level	
	Spurious emissions	1.8 ~ 29.7 MHz		–50 dB or less	
		50 ~ 54 MHz		–60 dB or less	—
	Carrier suppression			40 dB or more	
	Unwanted sideband suppression (modulation frequency 1.0 kHz)			40 dB or more	
	Maximum frequency deviation (FM)	Wide		±5 kHz or less	
		Narrow		±2.5 kHz or less	
	XIT shift frequency range			±9.99 kHz	
	Microphone impedance			600 Ω	



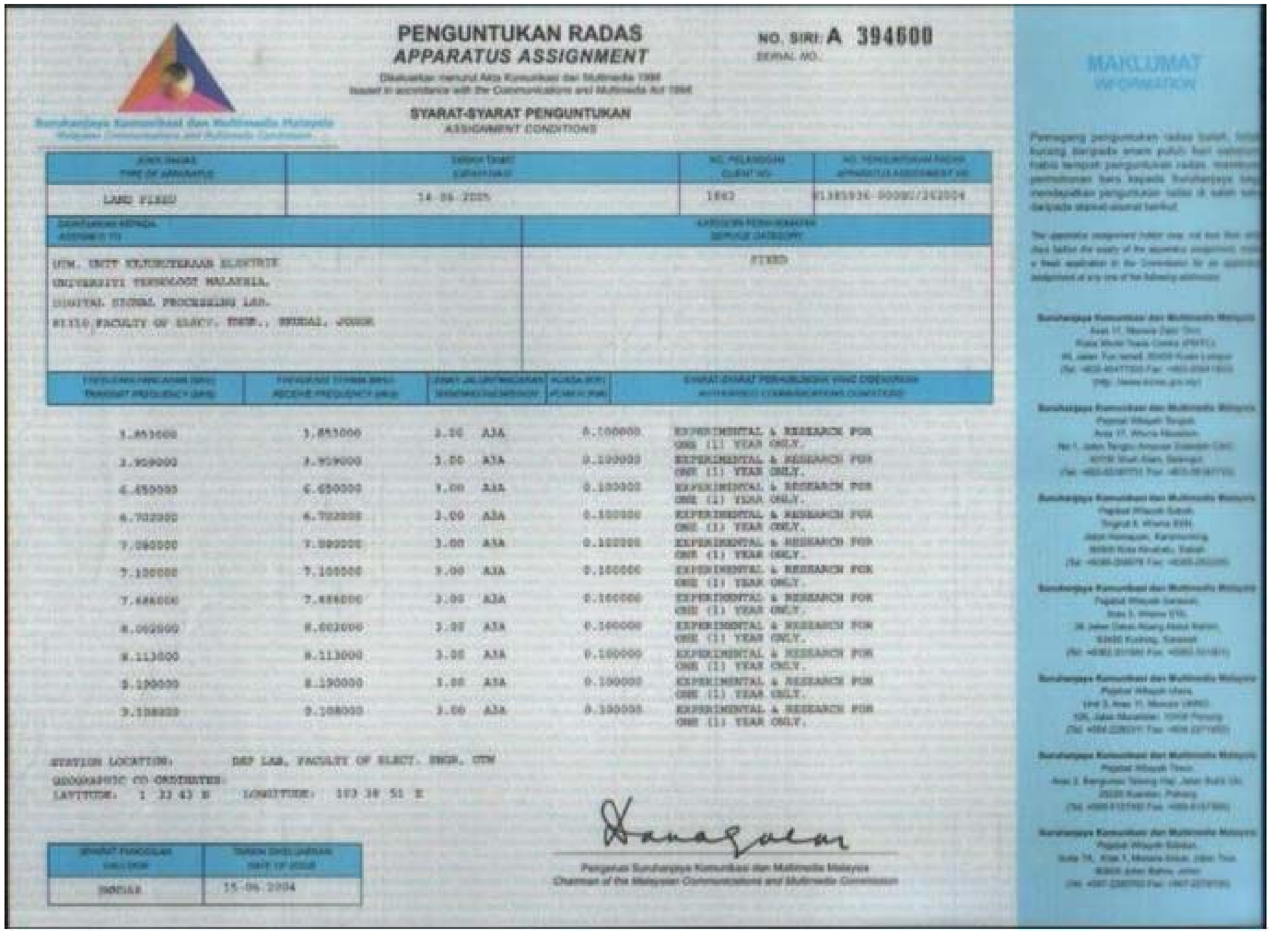
RECEIVER				TS-570S	TS-570D
	Circuit type			Double conversion superheterodyne FM only: Triple conversion superheterodyne	Double conversion superheterodyne FM only: Triple conversion superheterodyne
	Frequency range			500 kHz ~ 60 MHz	500 kHz ~ 30 MHz
	Intermediate frequency			1st: 73.05 MHz; 2nd: 8.83 MHz; 3rd: 455 kHz (FM only)	1st: 73.05 MHz; 2nd: 8.83 MHz; 3rd: 455 kHz (FM only)
	Sensitivity	SSB, CW, FSK (at 10 dB (S+N)/N)	500 kHz ~ 1.705 MHz	4 µV or less	4 µV or less
			1.705 MHz ~ 24.5 MHz	0.2 µV or less	0.2 µV or less
			24.5 MHz ~ 30 MHz	0.13 µV or less	0.13 µV or less
			50 MHz ~ 54 MHz	0.13 µV or less	—
		AM (at 10 dB (S+N)/N)	500 kHz ~ 1.705 MHz	31.6 µV or less	31.6 µV or less
			1.705 MHz ~ 24.5 MHz	2 µV or less	2 µV or less
			24.5 MHz ~ 30 MHz	1.3 µV or less	1.3 µV or less
			50 MHz ~ 54 MHz	1.3 µV or less	—
		FM (at 12 dB SINAD)	28 MHz ~ 30 MHz	0.25 µV or less	0.25 µV or less
			50 MHz ~ 54 MHz	0.25 µV or less	—
	Selectivity	SSB, CW, FSK		–6 dB: 2.2 kHz, –60 dB: 4.4 kHz	–6 dB: 2.2 kHz, –60 dB: 4.4 kHz
		AM		–6 dB: 4 kHz, –50 dB: 20 kHz	–6 dB: 4 kHz, –50 dB: 20 kHz
		FM		–6 dB: 12 kHz, –50 dB: 25 kHz	–6 dB: 12 kHz, –50 dB: 25 kHz
	Image rejection		1.8 MHz ~ 30 MHz	70 dB or more	70 dB or more
			50 MHz ~ 54 MHz	70 dB or more	—
	1st IF rejection		1.8 MHz ~ 30 MHz	70 dB or more	70 dB or more
			50 MHz ~ 54 MHz	70 dB or more	—
	RIT shift frequency range			±9.99 kHz	±9.99 kHz
	Squelch sensitivity	SSB, CW, FSK, AM	500 kHz ~ 1.705 MHz	20 µV or less	20 µV or less
			1.705 MHz ~ 30 MHz	2 µV or less	2 µV or less
			50 MHz ~ 54 MHz	2 µV or less	—
		FM	28 MHz ~ 30 MHz	0.25 µV or less	0.25 µV or less
			50 MHz ~ 54 MHz	0.25 µV or less	—
	Audio output (8 Ω, 10% distortion)			1.5 W or more	1.5 W or more
	Audio output impedance			8 Ω	8 Ω

2.0 HF MODEM KAM'98 SPECIFICATION



Dimensions (HWD)	1.2" x 6.7" x 6.9" or 30 mm by 170 mm x 175 mm
Weight	20 oz or .05 kg
Power Requirements	5.5 VDC to 17 VDC, 125 ma (LEDs on)
Power Plug	Coaxial, center pin positive 2.1 mm
External Connection	
Ports	DB-9 female (radio port)
	DB-9 female AUX A/D DATA, GPS
	DB-25 female (computer/data terminal) (serial rates to 19.2)
Watchdog timer	approximately 2.5 minutes (jumper option)
External Carrier Detect	Pulldown (to ground)
A/D converters	Four inputs 0 to + 5VDC, 8-bit, Zin 20K
RAM	128K, expandable to 512K
Data rate	45 to 1200 bps
PTT output	Open drain, +50 VDC max, 200 ma max
Audio Output	Continuously adjustable 1 mvpp to 5 vpp
Output impedance	600 ohm AC coupled
Modulation	AFSK
Audio Input	
Sensitivity	2 mvpp
Dynamic Range	> 80 dB
Input Impedance	10K ohm or 620 ohm via jumper
Max input voltage	+/- 12VDC or 35 vpp sinusoidal
Equalization	ON/OFF, jumper
Operating Modes	G-TOR, Pactor, Amtor (Sitor), Packet, RTTY, ASCII, CW, WEFAX, NAVTEX, KISS, XKISS, host, GPS, EMWIN.
LED Indicators	Power, Xmit, RCV, Connected, Status, Mail, bargraph tuning
Remote Access	All controller functions, user defined password
External Reset	Pulldown (to ground)
Compliance	FCC Class B; Europe - CE conformity

3.0 EXPERIMENTAL LICENSE



Suruhanjaya Komunikasi dan Multimedia Malaysia
Malaysian Communications and Multimedia Commission

PENGUNTUKAN RADAS
APPARATUS ASSIGNMENT

Dikeluarkan menurut Akta Komunikasi dan Multimedia 1998
Issued in accordance with the Communications and Multimedia Act 1998

NO. SIRI: A 394600
SERIAL NO.

SYARAT-SYARAT PENGUNTUKAN
ASSIGNMENT CONDITIONS

JENIS RADAS / TYPE OF APPARATUS	TARIKH TAMAT / EXPIRY DATE	NO. PELANGGAN / CLIENT NO.	NO. PENGUNTUKAN RADAS / APPARATUS ASSIGNMENT NO.
LAND FIXED	14-06-2005	1862	01385936-00000/262004

DIUNTUKKAN KEPADA / ASSIGNED TO	KATEGORI PERKHIDMATAN / SERVICE CATEGORY
UTM. UNIT KEJURUTERAAN ELEKTRIK UNIVERSITI TEKNOLOGI MALAYSIA, DIGITAL SIGNAL PROCESSING LAB. 81310 FACULTY OF ELECT. ENGR., SKUDAI, JOHOR	FIXED

FREKUENSI PANCARAN (MHz) / TRANSMIT FREQUENCY (MHz)	FREKUENSI TERIMA (MHz) / RECEIVE FREQUENCY (MHz)	JENIS JALUR/PANCARAN / BANDWIDTH/EMISSION	KUASA (W) / POWER (W)	SYARAT-SYARAT PERHUBUNGAN YANG DIBENARKAN / AUTHORISED COMMUNICATIONS CONDITIONS
3.853000	3.853000	3.00 AJA	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.
3.959000	3.959000	3.00 AJA	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.
6.650000	6.650000	3.00 AJA	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.
6.702000	6.702000	3.00 AJA	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.
7.080000	7.080000	3.00 AJA	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.
7.100000	7.100000	3.00 AJA	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.
7.686000	7.686000	3.00 AJA	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.
8.002000	8.002000	3.00 AJA	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.
8.113000	8.113000	3.00 AJA	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.
8.190000	8.190000	3.00 AJA	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.
9.108000	9.108000	3.00 AJA	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.

STATION LOCATION: DSP LAB, FACULTY OF ELECT. ENGR, UTM
GEOGRAPHIC CO-ORDINATES:
LATITUDE: 1 33 43 N LONGITUDE: 103 38 51 E

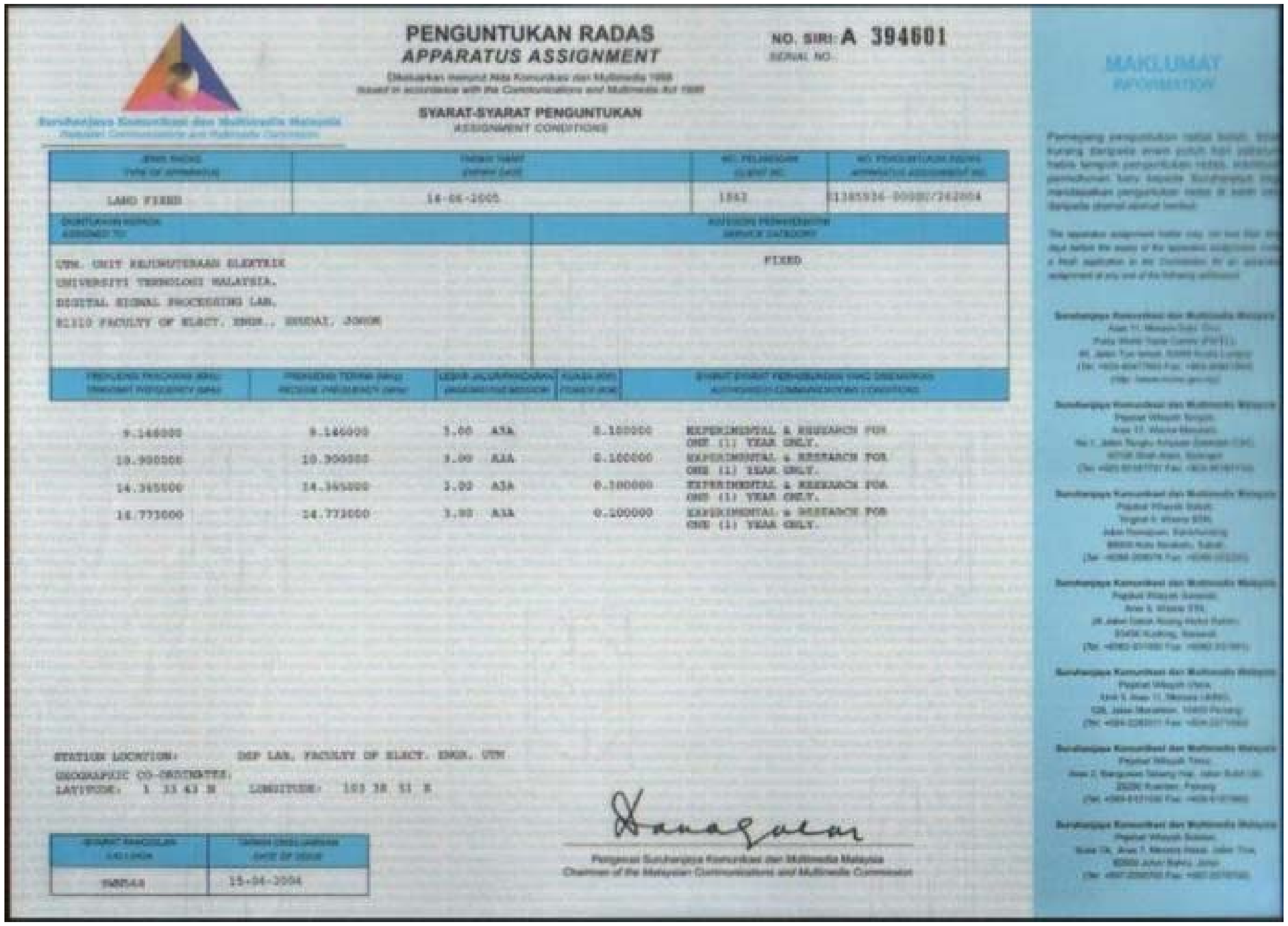
[illegible] / VALIDITY	TARIKH DIKELUARKAN / DATE OF ISSUE
[illegible]	15-06-2004

[illegible]

Pengerusi Suruhanjaya Komunikasi dan Multimedia Malaysia
Chairman of the Malaysian Communications and Multimedia Commission

MAKLUMAT
INFORMATION

[illegible]



Suruhanjaya Komunikasi dan Multimedia Malaysia
Malaysian Communications and Multimedia Commission

PENGUNTUKAN RADAS
APPARATUS ASSIGNMENT

Dikeluarkan menurut Akta Komunikasi dan Multimedia 1998
Issued in accordance with the Communications and Multimedia Act 1998

NO. SIRI: **A 394601**
SERIAL NO.

SYARAT-SYARAT PENGUNTUKAN
ASSIGNMENT CONDITIONS

JENIS RADAS / TYPE OF APPARATUS	TARIKH TAMAT / EXPIRY DATE	NO. PELANGGAN / CLIENT NO.	NO. PENGUNTUKAN RADAS / APPARATUS ASSIGNMENT NO.
LAND FIXED	14-06-2005	1862	1185536-0000/262004

DIUNTUKAN KEPADA / ASSIGNED TO	KATEGORI PERKHIDMATAN / SERVICE CATEGORY
UTM. UNIT KEJURUTERAAN ELEKTRIK UNIVERSITI TEKNOLOGI MALAYSIA. DIGITAL SIGNAL PROCESSING LAB. 81310 FACULTY OF ELECT. ENGR., SKUDAI, JOHOR	FIXED

FREKUENSI PANCARAN (MHz) / TRANSMIT FREQUENCY (MHz)	FREKUENSI TERIMA (MHz) / RECEIVE FREQUENCY (MHz)	LEBAR JALUR PANCARAN / EMISSION DESIGNATION	KUASA (KW) / POWER (KW)	SYARAT-SYARAT PERHUBUNGAN YANG DIBENARKAN / AUTHORISED COMMUNICATIONS CONDITIONS
9.146000	9.146000	3.00 A3A	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.
10.900000	10.900000	3.00 A3A	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.
14.365000	14.365000	3.00 A3A	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.
14.773000	14.773000	3.00 A3A	0.100000	EXPERIMENTAL & RESEARCH FOR ONE (1) YEAR ONLY.

STATION LOCATION: DSP LAB, FACULTY OF ELECT. ENGR. UTM
GEOGRAPHIC CO-ORDINATES:
LATITUDE: 1 33 43 N LONGITUDE: 103 38 51 E

STESEN PANGGILAN / CALL SIGN	TARIKH DIKELUARKAN / DATE OF ISSUE
9WM544	15-06-2004

[illegible]

Pengerusi Suruhanjaya Komunikasi dan Multimedia Malaysia
Chairman of the Malaysian Communications and Multimedia Commission

MAKLUMAT
INFORMATION

[illegible]

4.0 THE HUFFMAN-COMPRESSED ASCII TABLE

Char	ASCII	Huffman (LSB [sent first] on left)	Char	ASCII	Huffman (LSB [sent first] on left)
space	32	10	M	77	111101010
e	101	011	9	57	0001010010
n	10	0101	W	87	0001010100
i	105	1101	5	53	0001010101
r	114	1110	y	121	0001010110
t	116	00000	2	50	0001011010
s	115	00100	3	51	0001011011
d	100	00111	4	52	0001011100
a	97	01000	6	54	0001011101
u	117	11111	7	55	0001011110
l	108	000010	8	56	0001011111
h	104	000100	H	72	0010100010
g	103	000111	J	74	1100000110
m	109	001011	U	85	1100000111
<CR>	13	001100	V	86	1100011000
<LF>	10	001101	<FS>	28	1100011001
o	111	010010	x	120	1100011010
c	99	010011	K	75	1100110100
b	98	0000110	?	63	1100110101
f	102	0000111	=	61	1111000010
w	119	0001100	q	113	1111010110
D	68	0001101	Q	81	1111010111
k	107	0010101	j	106	00010100110
z	122	11000010	G	71	00010100111
.	46	1100100	-	45	00010101111
,	44	1100101	:	58	00101000111
S	83	1111011	!	33	11110011101
A	65	00101001	/	47	11110011110
E	69	11000000	*	42	001010001100
P	112	11000010	%	37	110001101101
v	118	11000011	&	38	111100111001
O	48	11000111	+	43	111100111110
F	70	11001100	>	62	0001010111000
B	66	11001111	@	64	0001010111001
C	67	11110001	$	36	0001010111010
I	73	11110010	<	60	00001010111010
T	84	11110100	X	88	0001010111011
O	79	000101000	#	35	0010100011011
P	80	000101100	Y	89	00101000110101
1	49	001010000	;	59	11110000110100
R	82	110000010	\	92	11110000110101
(	40	110011011	[	91	001010001101000
)	41	110011100	]	93	001010001101000

L	76	110011101	<DEL>	127	110001101111000
N	78	111100000	~	126	110001101111001
Z	90	111100110	}	125	110001101111010
|	124	110001101111011	{	123	110001101111100

5.0 EXAMPLES OF TEXT FILES

5.1 4 Kbytes Text File

```
========================================================================
       MICROSOFT FOUNDATION CLASS LIBRARY : comm
========================================================================
```

AppWizard has created this comm application for you. This application
not only demonstrates the basics of using the Microsoft Foundation classes
but is also a starting point for writing your application.

This file contains a summary of what you will find in each of the files that
make up your comm application.

comm.dsp

This file (the project file) contains information at the project level and
is used to build a single project or subproject. Other users can share the
project (.dsp) file, but they should export the make files locally.

comm.h

This is the main header file for the application. It includes other
project specific headers (including Resource.h) and declares the
CCommApp application class.

comm.cpp

This is the main application source file that contains the application
class CCommApp.

comm.rc

This is a listing of all of the Microsoft Windows resources that the
program uses. It includes the icons, bitmaps, and cursors that are stored
in the RES subdirectory. This file can be directly edited in Microsoft

Visual C++.

comm.clw

This file contains information used by ClassWizard to edit existing classes or add new classes. ClassWizard also uses this file to store information needed to create and edit message maps and dialog data maps and to create prototype member functions.

res\comm.ico
This is an icon file, which is used as the application's icon. This icon is included by the main resource file comm.rc.

res\comm.rc2

This file contains resources that are not edited by Microsoft

Visual C++. You should place all resources not editable by the resource editor in this file.

///

AppWizard creates one dialog class:

commDlg.h, commDlg.cpp - the dialog

These files contain your CCommDlg class. This class defines the behavior of your application's main dialog. The dialog's template is in comm.rc, which can be edited in Microsoft

Visual C++.

///
Other standard files:

StdAfx.h, StdAfx.cpp

These files are used to build a precompiled header (PCH) file named comm.pch and a precompiled types file named StdAfx.obj.

Resource.h

This is the standard header file, which defines new resource IDs. Microsoft Visual C++ reads and updates this file.

///

Other notes:

AppWizard uses "TODO:" to indicate parts of the source code you should add to or customize.

If your application uses MFC in a shared DLL, and your application is
in a language other than the operating system's current language, you
will need to copy the corresponding localized resources MFC42XXX.DLL
from the Microsoft Visual C++ CD-ROM onto the system or system32 directory,
and rename it to be MFCLOC.DLL. ("XXX" stands for the language abbreviation.
For example, MFC42DEU.DLL contains resources translated to German.) If you
don't do this, some of the UI elements of your application will remain in the
language of the operating system.

///

5.2 3 Kbytes text file

1.0 Title
Performance Analysis of Differential Phase Modulation for HF Digital
Communication

2.0 Introduction
The existence of essential electrons in ionosphere makes long distance communication possible. Some of ionosphere layers act like mirror where the signal in the ionosphere experience maximum refraction, that they are bent back toward the earth's surface. This characteristic makes skywave propagation using high frequency (HF) available while for short distance transmissions, groundwave propagation will be used.

Transmission using HF spectrum (3-30MHz) is required to get a system that available to operate over a broad range of adverse channel, due to ionosphere variability. These problems makes HF left behind compared to satellite and fiber optic communication network. However, HF spectrum is still widely used for tactical and strategic military purpose.

Besides that, HF communication system requires minimum infrastructure at low cost, on the other hand satellite communication requires a very high cost and frequent maintenance. Transmission over HF communication system is operated without the need to use the service of third party which much more secure compared to transmission using satellite. The sender and the receiver will only require HF transceiver and HF modem. Privacy is guaranteed for HF communication because the medium is not control by anyone whereas for satellite communication, the satellite company will undoubtedly have the access to the information. The problem of wear and tear will arise in satellite communication, for HF communication this problem does not exist.

The purpose of this project is to develop a digital communication system through HF. Design and analyze of multi-phase digital modulation technique that combat variability's of channel effect and perform higher data transmission rate through HF.

3.0 Problem Statement

In HF communication, the variability of ionosphere results multipath fading phenomenon. This phenomenon gives several affects in the communication, which are time delay spread, Doppler shift and time selective fading. Due to time delay spread problem, system can only transmit data to 100 boud per second. A serious time delay spread problem will cause for inter symbol interference (ISI). By limiting the data transmission rate to 100 baud per

There are several problems to be focused as listed below:

1. How to combat the nature of the channel, and
2. How to improve the reliability in data transmission that enables data transmission rate greater than 100 bits per second.
3. What is the technique can be used in order to improve the reliability in data transmission.

As a solution, to increase the data transmission rate without changing or increasing the baud rate, differential phase modulation is used.

4.0 Objective

The main objective of this project is to design, simulate and analysis a HF communication system that combats the variability's of channel effects

6.0 EXAMPLES OF JPEG IMAGE

6.1 5 Kbytes image

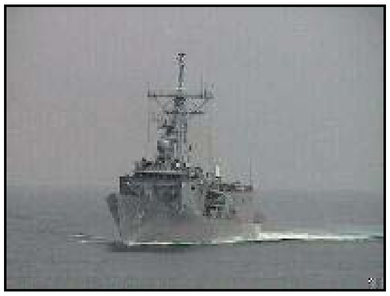
6.2 6 Kbytes image

6.3 10 Kbytes image

6.4 12 Kbytes image

6.5 4 Kbytes image

6.6 9 Kbytes image



APPENDIX D

1.0 IMPLEMENTATION OF AES 128 AND AES 256

```
#include <stdio.h>
#include <stdlib.h>

void AES_ENCRYPT128();
void AES_DECRYPT128();
void AES_ENCRYPT256();
void AES_DECRYPT256();

static word8 shifts[4][2] = {
  0, 0,
  1, 3,
  2, 2,
  3, 1,
};

//Global Initialize
word8 text[16], key[32], out_text[16], t[4][4], k[4][MAX_Nk],
roundKey[MAX_Nr+1][4][4];

/* multiplication operation of two elements of GF(2^m) needed for MixColumn and
InvMixColumn */
word8 mul(word8 a, word8 b)
{
        if (a && b)
                return Alogtable[(Logtable[a] + Logtable[b])%255];
        else return 0;
}

void AddRoundKey(word8 a[4][4], word8 rk[4][4])
{
        int i, j;
        for(i = 0; i < 4; i++)
                for(j = 0; j < 4; j++)
                        a[i][j] ^= rk[i][j];
}
```

```
void ShiftRow(word8 a[4][4], word8 d)
{
        word8 tmp[4];
        int i, j;
        for(i = 1; i < 4; i++)
         {
                for(j = 0; j < 4; j++)
                        tmp[j] = a[i][(j + shifts[i][d]) % 4];
                for(j = 0; j < 4; j++)
                        a[i][j] = tmp[j];
        }
}

void SubByte(word8 a[4][4], word8 box[256])
{
        int i, j;
        for(i = 0; i < 4; i++)
                for(j = 0; j < 4; j++)
                        a[i][j] = box[a[i][j]] ;
}

void MixColumn(word8 a[4][4])
{
        word8 b[4][4];
        int i, j;
        for(j = 0; j < 4; j++)
                for(i = 0; i < 4; i++)
                        b[i][j] = mul(2,a[i][j])
                                        ^ mul(3,a[(i + 1) % 4][j])
                                        ^ a[(i + 2) % 4][j]
                                        ^ a[(i + 3) % 4][j];
        for(i = 0; i < 4; i++)
                for(j = 0; j < 4; j++)
                        a[i][j] = b[i][j];
}

/* This is the opposite operation of Mixcolumn */
void InvMixColumn(word8 a[4][4])
 {
        word8 b[4][4];
        int i, j;
        for(j = 0; j < 4; j++)
        for(i = 0; i < 4; i++)
                b[i][j] = mul(0xe,a[i][j])
                                ^ mul(0xb,a[(i + 1) % 4][j])
                                ^ mul(0xd,a[(i + 2) % 4][j])
                                ^ mul(0x9,a[(i + 3) % 4][j]);
        for(i = 0; i < 4; i++)
                for(j = 0; j < 4; j++)
                        a[i][j] = b[i][j];
```

```
}


/* Calculate the necessary round keys
 * The number of calculations depends on AES type */

int KeySched (word8 k[4][MAX_Nk], int AES, word8 W[MAX_Nr+1][4][4])
{
        int Nk, Nr;
        int i, j, t, rconpointer = 0;
        word8 tk[4][MAX_Nk];

        switch (AES) {
        case 128: Nk = 4; Nr = 10; break;
        case 192: Nk = 6; Nr = 12; break;
        case 256: Nk = 8; Nr = 14; break;
        default : return 0;
        }

        for(j = 0; j < Nk; j++)
                for(i = 0; i < 4; i++)
                        tk[i][j] = k[i][j];
        t = 0;

        /* copy values into initial round key array, W[Nr+1][4][4] */
        for(j = 0; (j < Nk) && (t < (Nr+1)*4); j++, t++)
                for(i = 0; i < 4; i++)
                {       W[t / 4][i][t % 4] = tk[i][j]; }

        /* calculate the remaining round keys for round key array */
        while (t < (Nr+1)*4) {

                for(i = 0; i < 4; i++)
                        tk[i][0] ^= S[tk[(i+1)%4][Nk-1]];
                tk[0][0] ^= rcon[rconpointer++];

                if (Nk != 8)
                        for(j = 1; j < Nk; j++)
                                for(i = 0; i < 4; i++)
                                        tk[i][j] ^= tk[i][j-1];
                else {
                        for(j = 1; j < Nk/2; j++)
                                for(i = 0; i < 4; i++)
                                        tk[i][j] ^= tk[i][j-1];
                        for(i = 0; i < 4; i++)
                                tk[i][Nk/2] ^= S[tk[i][Nk/2 - 1]];
                        for(j = Nk/2 + 1; j < Nk; j++)
                                for(i = 0; i < 4; i++)
                                        tk[i][j] ^= tk[i][j-1];
                        }
        /* copy generated values into round key array */

        for(j = 0; (j < Nk) && (t < (Nr+1)*4); j++, t++)
                for(i = 0; i < 4; i++)
                {       W[t / 4][i][t % 4] = tk[i][j];   }
        }
        return 0;
}

int Encrypt (word8 a[4][4], int AES, word8 rk[MAX_Nr+1][4][4])
{
        /* Encryption of one block */
        int r, Nr;
        switch (AES) {
        case 128: Nr = 10; break;
        case 192: Nr = 12; break;
        case 256: Nr = 14; break;
        default : return 0;
        }

        /* begin with a key addition */
        AddRoundKey(a,rk[0]);

        /* For Rounds, r = 1 to (Nr-1) */
        for(r = 1; r < Nr; r++) {
                SubByte(a,S);
                ShiftRow(a,0);
                MixColumn(a);
                AddRoundKey(a,rk[r]);
        }

        /* Last round is without MixColumn */
        SubByte(a,S);
        ShiftRow(a,0);
        AddRoundKey(a,rk[Nr]);

        return 0;
}

int Decrypt (word8 a[4][4], int AES, word8 rk[MAX_Nr+1][4][4])
{
        int r, Nr;
        switch (AES) {
        case 128: Nr = 10; break;
        case 192: Nr = 12; break;
        case 256: Nr = 14; break;
        default : return 0; /* this cannot happen */
        }
        AddRoundKey(a,rk[Nr]);
        SubByte(a,Si);
        ShiftRow(a,1);

        for(r = Nr-1; r > 0; r--) {
                AddRoundKey(a,rk[r]);
                InvMixColumn(a);
                SubByte(a,Si);
                ShiftRow(a,1);
        }

        AddRoundKey(a,rk[0]);

        return 0;
}

/* MAIN PROGRAM*/

void main ()
{


        /*AES-128 bits Encryption*/
        AES_ENCRYPT128();

        /*AES-128 bits Decryption*/
        AES_DECRYPT128();

        /*AES-256 Encryption */
        AES_ENCRYPT 256();

        /*AES-256 bits Decryption*/
        AES_ENCRYPT256();

}
void AES_ENCRYPT 128();
{
        int AES=128,Nk=4,Nr=10;
        int i, j, m;
        /* Chunking input text into text[16] array */
        for (j=0; j<4; j++)
        {       for (i=0; i<4; i++)
                        {t[i][j] = text[4*j+i] & 0xFF; } //text[] is a plaintext 128 bits
        }

        /* Chunking key into key[32] array */
        for (j=0; j<Nk; j++)
        {       for (i=0; i<4; i++)
                {       k[i][j] = key[4*j+i] & 0xFF;  }//key is secret key 128 bits
        }

        /* Round key generation */
        KeySched (k, AES, roundKey);
        /*Encryption */
        Encrypt (t, AES, roundKey);

        /*Arrange the Cipher Text in Array 128 bits */
        for (m=0; m<16; m++)
        {       for (j=0; j<4; j++)
                {       for (i=0; i<4; i++)
                        {       out_text[4*j+i] = t[i][j]; //out_text is a cipher text 128
bits
                        }
                }
        }
}

void AES_DECRYPT128();
{
        int AES=128,Nk=4,Nr=10;
        int i, j, m;
        /* Chunking input text into text[16] array */
        for (j=0; j<4; j++)
        {       for (i=0; i<4; i++)
                        {t[i][j] = text[4*j+i] & 0xFF; } //text[] is a cipher text 128 bits
        }

        /* Chunking key into key[32] array */
        for (j=0; j<Nk; j++)
        {       for (i=0; i<4; i++)
                {       k[i][j] = key[4*j+i] & 0xFF;  }//key is a secret key 128 bits
        }

        /* Round key generation */
        KeySched (k, AES, roundKey);
        /*Decryption */
        Decrypt (t, AES, roundKey);

        /*Arrange the Plain Text in Array 128 bits */
        for (m=0; m<16; m++)
        {       for (j=0; j<4; j++)
                {       for (i=0; i<4; i++)
                        {       out_text[4*j+i] = t[i][j]; //out_text is a plainctext 128
bits
                        }
                }
        }
}


void AES_ENCRYPT256 ();
{
	int AES=256,Nk=8,Nr=14;
	int i, j, m;
	/* Chunking input text into text[16] array */
	for (j=0; j<4; j++)
	{	for (i=0; i<4; i++)
			{t[i][j] = text[4*j+i] & 0xFF; } //text[] is a plaintext 256 bits
	}

	/* Chunking key into key[32] array */
	for (j=0; j<Nk; j++)
	{	for (i=0; i<4; i++)
		{	k[i][j] = key[4*j+i] & 0xFF;   }//key is a secret key 256 bit
	}

	/* Round key generation */
	KeySched (k, AES, roundKey);
	/*Encryption */
	Encrypt (t, AES, roundKey);

	/*Arrange the Cipher Text in Array 128 bits */
	for (m=0; m<16; m++)
	{	for (j=0; j<4; j++)
		{	for (i=0; i<4; i++)
			{	out_text[4*j+i] = t[i][j]; //out_text is a cipher text 256
bits
			}
		}
	}
}

void AES_DECRYPT256();
{
	int AES=256,Nk=8,Nr=14;
	int i, j, m;
	/* Chunking input text into text[16] array */
	for (j=0; j<4; j++)
	{	for (i=0; i<4; i++)
			{t[i][j] = text[4*j+i] & 0xFF; } //text[] is a cipher text 128 bits
	}

	/* Chunking key into key[32] array */
	for (j=0; j<Nk; j++)
	{	for (i=0; i<4; i++)
		{	k[i][j] = key[4*j+i] & 0xFF;   }//key is a secret key 256 bit
	}

	/* Round key generation */
	KeySched (k, AES, roundKey);
	/*Decryption */
	Decrypt (t, AES, roundKey);
```

```
        /*Arrange the Plain Text in Array 128 bits */
        for (m=0; m<16; m++)
        {       for (j=0; j<4; j++)
                {       for (i=0; i<4; i++)
                        {       out_text[4*j+i] = t[i][j]; //out_text is a plainctext 128
bits
                        }
                }
        }
}
```

2.0 IMPLEMENTATION OF W7 CIPHER SYSTEM

```
#include <stdlib.h>
#include <stdio.h>
#include <conio.h>
#include <math.h>

#define REGLNG 30000
#define SEQLNG 30000

void setNLFSR();
void LFSR(int ncof,int nbits,int reg[],int cof[],int *seq);
void W7(int ndat,int *seq,int *seq1,int *seq2);

int temp[30000];                        //temp keystream

void main()
{
        int *seq,*msg,*seq1,*seq2;
        /*polynomial coefficients*/
        int cof0[19]={1,1,1,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0};
        int cof1[23]={1,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0};
        int cof2[29]={1,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0}
        int reg0[REGLNG], reg1[REGLNG], reg2[REGLNG];

/*Initialize memory *seq & *msg.*/

        seq=(int*)malloc(SEQLNG*sizeof(int));       /* to set seq memory loccation*/
        if(seq==NULL)                               // if connot setting seq memory
        {       printf("\n Memory allocation fail!");  // exit
                exit(0);
        }

        seq1=(int*)malloc(SEQLNG*sizeof(int));      /* to set1 seq memory
loccation*/
        if(seq1==NULL)                              // if connot setting seq memory
        {       printf("\n Memory allocation fail!");  // exit
                exit(0);
        }

        seq2=(int*)malloc(SEQLNG*sizeof(int));      /* to set1 seq memory
loccation*/
        if(seq2==NULL)                              // if connot setting seq memory
        {       printf("\n Memory allocation fail!");  // exit
                exit(0);
        }
```

```
	msg=(int*)malloc(SEQLNG*sizeof(int));	/* to set msg memory 
loccation*/
	if(msg==NULL)
	{	printf("\nMemory allocation fail.");	// if connot setting msg memory
		exit(0);
	}

	for(i=0;i<=SEQLNG;i++)			/* to empty the msg and the seq 
loccation*/
	{
		*(msg+i)=0;*(seq+i)=0;
		*(seq1+i)=0;*(seq2+i)=0;
	}

	setNLFSR();				//setup the LFSR
	LFSR(19,10000,reg0,cof0,seq);		//Generate LFSR sequence and save to 
m1	LFSR(23,10000,reg1,cof1,seq1);		//Generate LFSR sequence and save to 
m2
	LFSR(29,10000,reg2,cof2,seq2);		//Generate LFSR sequence and save to 
m3
	W7(10000,seq,seq1,seq2);		//Generate W7 keystream
}

/*Routine for Linear Feedback Shift Register.		*/
void LFSR(int ncof,int nbits,int reg[],int cof[],int *seq)
{
	int i,j,k,sum=0,temp;
	for(i=0;i<=(nbits-1);i++)
	{
		*(seq+i)=reg[0];
		for(j=0;j<=(ncof-1);j++)
		{
			temp=reg[j] & cof[j];
			/*Perform modulo 2 addition.*/
			sum=sum^temp;		//  sum = sum exor temp
		}
		for(j=0;j<=(ncof-2);j++)
			reg[j]=reg[j+1];

		reg[ncof-1]=sum;
		sum=0;
	}
}


/* Routine for setup the Nonlinear feedback Shift Register*/
void setNLFSR()
{
	int a,i;
```

```
        for(i=0;i<19;i++)
        {       reg0[i]=session_key[a];         //put the session key as initial condition
                a++
        }
        for(i=0;i<23;i++)
        {       reg1[i]=session_key[a];         //put the session key as initial condition
                a++
        }

        for(i=0;i<29;i++)
        {       reg0[i]=session_key[a];         //put the session key as initial condition
                a++
        }
}

void W7(int ndat, int *n,int *p, int *q)
{
        int a0,a1,a2,a3,a4,a5,a6,a7,i;          //taps for filters
        int sum_a1, sum_a2, sum_a3;             //sum of filters
        int sum1, sum2, sum3;                   //sum of each lfsr
        int c1=0, c2=0, c3=0;                   //clock taps
        int a=0, b=0, c=0;                      //a-lfsr0; b-lfsr1; c-lfsr2

        for(i=0;i<ndat;i++)
        {       //LFSR 0
                a0 = *(n+a);            //state of 19
                a1 = *(n+a+2);          // state of 16
                a2 = *(n+a+3);          // state of 17
                a3 = *(n+a+6);          // state of 13
                a4 = *(n+a+7);          // state of 12

                a5 = *(n+a+9);          // state of 10
                a6 = *(n+a+12);         // state of 7
                a7 = *(n+a+13);         // state of 6
                /*nonlinear combining function*/
                sum_a1 = a1&a2;
                sum_a2 = a3&a4;
                sum_a3 = a5&a6&a7;
                sum1 = a0^sum_a1^sum_a2^sum_a3;


                //LFSR 1
                a0 = *(p+b);            // state of 23
                a1 = *(p+b+4);          // state of 19
                a2 = *(p+b+5);          // state of 18
                a3 = *(p+b+9);          // state of 14
                a4 = *(p+b+11);         // state of 12
                a5 = *(p+b+14);         // state of 9
                a6 = *(p+b+15);         // state of 8
                a7 = *(p+b+18);         // state of 5
                /*nonlinear combining function*/
                sum_a1 = a1&a2;
                sum_a2 = a3&a4;
                sum_a3 = a5&a6&a7;
                sum2 = a0^sum_a1^sum_a2^sum_a3;

                //LFSR 2
                a0 = *(q+c);             // state of 29
                a1 = *(q+c+6);           // state of 23
                a2 = *(q+c+7);           // state of 22
                a3 = *(q+c+10);          // state of 19
                a4 = *(q+c+11);          // state of 18
                a5 = *(q+c+14);          // state of 15
                a6 = *(q+c+18);          // state of 11
                a7 = *(q+c+19);          // state of 10
                /*nonlinear combining function*/
                sum_a1 = a1&a2;
                sum_a2 = a3&a4;
                sum_a3 = a5&a6&a7;
                sum3 = a0^sum_a1^sum_a2^sum_a3;
                /*results of keystream*/
                *(msg+i) = sum1^sum2^sum3;
                //clock taps
                c1 = *(n+a+8);
                c2 = *(p+b+10);
                c3 = *(q+c+15);

                if(c1==0 && c2 ==0 && c3==0){
                        a=a+1;b=b+1;c=c+1;}
                if(c1==0 && c2 ==0 && c3==1){
                        a=a+1;b=b+1;c=c;}
                if(c1==0 && c2 ==1 && c3==0){
                        a=a+1;b=b;c=c+1;}
                if(c1==0 && c2 ==1 && c3==1){
                        a=a;b=b+1;c=c+1;}
                if(c1==1 && c2 ==0 && c3==0){
                        a=a;b=b+1;c=c+1;}
                if(c1==1 && c2 ==0 && c3==1){
                        a=a+1;b=b;c=c+1;}
                if(c1==1 && c2 ==1 && c3==0){
                        a=a+1;b=b+1;c=c;}
                if(c1==1 && c2 ==1 && c3==1){
                        a=a+1;b=b+1;c=c+1;}
        }
}
```

3.0 IMPLEMENTATION OF RADIX 64

```
#include <stdlib.h>
#include <stdio.h>

void Radix64_encoder();
void Radix64_decoder();
/*Global Initialize*/
CString input, output;              //input is a cryptogram given by Main Program
Char data[1250],data1[1250];        //1250 for 10,000 bit of keystream
int input_len, output_len;
void  Main()
{
        int i;

        Radix64_encoder();                  //encode the cryptogram
                                            //the result saves in the output and ready
                                            // to transfer to HF modem via serial
                                            //communication

        Radix64_decoder();                  //decode the receive message before
                                            //decrypting
}


void Radix64_encoder()
{       int a;
        char c,c_bar,d,d_bar,e,e_bar;
        CString temp;

        input_len=input.GetLength();        //check the cryptogram length
        for(i=0;i<input_len;i++)            //put the cryptogram in array
        {       data[i] = input[i]};

        for(a=0;a<input_len;a++)
        {
                c = data[a];                //take the input 8 bits
                c_bar = c & 0xfc;           //masking to delete last 2 bits
                c_bar = c_bar >> 2;         //shift right 2 bits
                data1[i] = c_bar & 0x3f;    //masking to ensure first 2 bits are 0
                temp = cryptogram1[i]+40;   //adding with the offset
                output = output + temp;

                i = i + 1; a = a + 1;
                c_bar = c & 0x03;
                c_bar = c_bar << 4;         //shift left 4 bits
                d = data[a];
```

```
                        d_bar = d & 0xf0;
                        d_bar = d_bar >> 4;
                        d_bar = d_bar & 0x0f;
                        c_bar = c_bar | d_bar;
                        data1[i] = c_bar & 0x3f;
                        temp = data1[i]+40;
                        output = output + temp;

                        a = a + 1;
                        d_bar = d & 0x0f;
                        d_bar = d_bar << 2;

                        e = data[a];
                        i = i + 1;
                        e_bar = e & 0xc0;
                        e_bar = e_bar >> 6;
                        e_bar = e_bar & 0x03;
                        e_bar = d_bar | e_bar;
                        data1[i] = e_bar & 0x3f;
                        temp = data1[i]+40;
                        output =output + temp;

                        i = i + 1;
                        data1[i] = e & 0x3f;
                        temp = data1[i]+40;
                        output = output + temp;
                        i = i + 1;
            }
}


void Radix64_decoder()
{
            int a;
            char k, k_bar, l, l_bar, m, m_bar, n;
            char temp;

            output_len=output.GetLength();                //check the receive message
                                                          //length
            for(i=0;i<output_len;i++)                     //put the message in array
            {           temp = output[i];
                        temp = temp-40;                   //minus the 40 offset
                        data[i] = temp;}




            int p=0;
            for(a=0;a<output_len;a++)               //rearrange the cryptogram
            {
                        k = data[a];
                        k_bar = k << 2;
                        a = a + 1;
                        l = data[a];
                        l_bar = l & 0x30;
                        l_bar = l_bar >> 4;
                        data1[p] = k_bar | l_bar;
                        p = p + 1;
                        l_bar = l & 0x0f;
                        l_bar = l_bar << 4;
                        a = a + 1;
                        m = data[a];
                        m_bar = m & 0x3c;
                        m_bar = m_bar >> 2;
                        data1[p] = l_bar | m_bar;
                        a = a + 1;
                        p = p + 1;
                        m_bar = m & 0x03;
                        m_bar = m_bar << 6;
                        n = data[a];
                        data1[p] = m_bar | n;
                        p = p + 1;
            }
}
```