VHF DATA TECHNOLOGY IN AIR TRAFFIC SERVICES

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED
SCIENCES OF
ÇANKAYA UNIVERSITY

BY
AHMET EREN BELLİKLİ

IN PARTIAL FULLFILMENT OF THE REQUIREMENTS FOR THE
DEGREE OF
MASTER OF SCIENCE
IN
THE DEPARTMENT OF
ELECTRONIC AND COMMUNICATION ENGINEERING

SEPTEMBER 2006

Title of the Thesis : VHF Data Technology in Air Traffic Services

Submitted by Ahmet Eren Bellikli

Approval of the Graduate School of Natural and Applied Sciences, Çankaya University

Prof. Dr. Yurdahan GÜLER
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

YBaykal
Prof. Dr. Yahya Kemal BAYKAL
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

YBaykal
Prof. Dr. Yahya Kemal BAYKAL
Supervisor

Examination Date : **11.09.2006**

Examining Committee Members

Prof. Dr. Yahya Kemal BAYKAL (Çankaya Univ.) YBaykal

Assoc. Prof. Dr. Aydan CAVCAR (Anadolu Univ.)

Asst. Prof. Dr. Halil Tanyer EYYUBOĞLU (Çankaya Univ.)

Statement of Non-plagiarism Page

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name :Ahmet Eren Bellikli

Signature : Eren Bellikli.

Date : 11.09.2006

ABSTRACT

VHF DATA TECHNOLOGY IN AIR TRAFFIC SERVICES

BELLİKLİ, Ahmet Eren
M.S., Department of Electronic and Communication Engineering
Supervisor: Prof. Dr. Yahya Kemal BAYKAL
September 2006, 83 pages

In this thesis, we have introduced communication, navigation and surveillance system's working principles and bottlenecks based on working performances used in Air Traffic Control systems. We investigated the possible system solution to meet current bottlenecks, safety issues and Air Traffic growth handling for today and in the future.

Air Traffic Navigation continuation and communication quality regarding safety issues are directly dependent on the chosen technology base. Choosing the right technology to meet requirements is what we have searched in this thesis.

The baseline technology of Broadband -VHF project is as in the fourth generation (4G) mobile communications.

B-VHF approaches communication in two different ways The one from ground stations to aircrafts (forward link) is based on combination of OFDM-CDMA called MC-CDMA and the second link from aircraft to ground (reverse link) is based on combination of OFDM-FDMA. We added Code Division Multiplexing into the reverse link to enhance the link robustness against interferences and data security. In order to realize this, we developed a Matlab code to simulate its performances to observe whether this combination provides robustness against interferences. Using the simulation we have obtained BER results at different cyclic prefix, number of OFDM symbols, code length size and channel settings. BER obtained with the inclusion of CDM are slightly favorable as compared to OFDM only reverse link, however, the performance improvement is not within the expected scale.

Key Words: Broadband – VHF, Orthogonal Frequency Division Multiplexing, Orthogonal Frequency Division Multiple Access, Code Division Multiplexing, Frequency Division Multiple Access, Multi Carrier- Code Division Multiple Access

ÖZ

HAVA TRAFİK HİZMETLERİNDE VHF VERİ TEKNOLOJİSİSİ

BELLİKLİ, Ahmet Eren
Yüksek Lisans, Elektronik ve Haberleşme Mühendisliği Bölümü
Tez Yöneticisi: Prof. Dr. Yahya Kemal BAYKAL
Eylül 2006, 83 sayfa

Bu tezde, Hava Trafik Kontrol sistemlerinde kullanılan haberleşme, seyrüsefer ve gözetim sistemlerinin çalışma performanslarını temel alarak çalışma prensipleri ve darboğaz tanımlamalarını yaptık. Günümüzde ve gelecekte karşılaşabileceğimiz darboğaz, güvenlik ve artan hava trafik sorunlarını karşılayabilecek muhtemel çözümleri araştırdık.

Hava Trafik Seyrüsefer devamlılığı, haberleşme kalitesine bağlı güvenilirlik sorunları doğrudan seçilen teknolojiye bağlıdır. Bu tezde yapılan araştırma, ihtiyaçlarını karşılayabilecek doğru teknolojinin seçiminin sağlanmasıdır.

B-VHF projesinde temel alınan teknoloji 4G mobil haberleşmesinde olduğu gibidir. B-VHF haberleşmesi, iki farklı yöntem ile yapılmıştır. Birincisi yer istasyonundan, uçağa yapılan haberleşme olup (forward link) burada OFDM-CDMA kullanılmıştır ve ikincisi ise uçaktan yer istasyonuna yapılan (reverse link) haberleşme olup OFDM-FDMA kullanılmıştır. Enterferanslara karşı direnç ve veri emniyetinin artırılması amacı ile reverse link'e CDM ekledik. Bu çalışmayı gerçekleştirmek için Matlab kodu geliştirerek CDM eklenmesi ile enterferanslara karşı direnç sağlanıp sağlanmadığını gözlemleyebilmek üzere simulasyon geliştirdik. Bu simulasyona göre farklı cyclic prefix, OFDM sembol sayıları, kod uzunluğu ve kanal ayarlamaları ile BER hesaplamaları yaptık. CDM eklenerek elde edilen BER değerlerinin az da olsa OFDM'e göre daha iyi olduğu gözlenmekle birlikte performans iyileştirmesi beklenildiği ölçekte değildir.

Anahtar Kelimeler: Broadband – VHF, Orthogonal Frequency Division Multiplexing, Orthogonal Frequency Division Multiple Access, Code Division Multiplexing, Frequency Division Multiple Access, Multi Carrier- Code Division Multiple Access

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation and gratitude to my advisor Prof. Dr. Yahya Kemal BAYKAL. His vast experience and nice nature has given me a very great learning experience during the course of this research.

I would like to thank Dr. Halil Tanyer EYYUBOĞLU with discussions about the Matlab programming. His advises helped me to gain a lot of insight into difficult issues.

I thank my wife and my sons who have been a great source of love and motivation always.

TABLE OF CONTENTS

CHAPTERS:

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

A/G	Air-Ground
ACARS	Aircraft Communications Addressing and Reporting System
ADF	Automatic Direction Finder
ADS	Automatic Dependent Surveillance
ADS-B	Automatic Dependent Surveillance- Broadcast
AM	Amplitude Modulation
AMCP	Aeronautical Mobile Communications Panel
ASM	Air Space Management
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATIS	Automatic Terminal Information Service
ATM	Air Traffic Management
ATN	Aeronautical Telecommunications Network
ATS	Air Traffic Services
AWGN	Additive White Gaussian Noise
BC	Broadcast
BER	Bit Error Rate
BSS	B-VHF Special Services
B-VHF	Broadband Very High Frequency
CDMA	Code Division Multiple Access
CNS	Communication Navigation Surveillance

CPDLC	Controller Pilot Data Link Communications
CSMA	Carrier Sense Multiple Access
D8PSK	Differential 8 Phase Shift Keying
DLS	Data Link Service
DME	Distance Measurement Equipment
DSB-AM	Double Side-Band Amplititude Modulation
FCH	Fast Channel
FDMA	Frequency Division Multiple Access
FEQ	Frequency Equalization
FFT	Fast Fourier Transform
FL	Forward Link
FRUIT	False Reply Unsyncronized In Time
GFSK	Gaussian Frequency Shift Keying
GNSS	Global Navigation Satellites System
GS	Ground Station
HF	Hyper Frame
ICAO	International Civil Aviation Organization
ICI	Inter Carrier Interference
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transformation
ILS	Instrument Landing Systems
ISI	Inter Symbol Interference
ISO	International Standard Organization
kHz	Kilo Hertz
LME	Link Management Entity
LOS	Line Of Sight
MAC	Media Access Control
MC-CDMA	Multi Carrier- Code Division Multiple Access
METAR	Meteorological Aerodrome Report
MF	Multi Frame
MHz	Mega Hertz
MSK	Minimum Shift Keying

MSSR	Monopulse Secondary Surveillance Radar
NDB	Non Directional Beacon
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSI	Open Systems Interconnection
PP	Point to Point
PSK	Phase Shift Keying
PSR	Primary Surveillance Radar
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RA	Random Access
RACH	Random Access Channel
RF	Radio Frequency
RL	Reverse Link
SARPS	Standards and Recommended Practices
SCH	Slow Channel
SF	Super Frame
SNR	Signal to Noise Ratio
SPI	Special Purpose Identification
SSR	Secondary Surveillance Radar
STDMA	Self Organizing Time Division Multiple Access
TACAN	Tactical Air Navigation
TDMA	Time Division Multiple Access
VDL	Very High Frequency Digital Link
VHF	Very High Frequency
VOR	VHF Omnidirectional Range

CHAPTER 1

INTRODUCTION

Air Traffic Control systems are currently being investigating new technologies for use in modern surveillance, communication and navigation systems.

1.1 Objectives of the Study

The aim of this thesis is to find possible solution to today's air traffic growth and the bottlenecks of current ATC (Air Traffic Control) systems. For this purpose we first analyzed the current systems' provisions to air traffic control which are communication navigation and surveillance.

We found out whether on going systems meets all current and future requirements in physical layer, in relation to robustness against interferences, safety issues rather than additional operational features.

The air traffic will continuously increase over the next years. Compared to today's air traffic load, it is expected, that the air traffic will approximately be doubled in 2015. The tremendous increase will lead to bottlenecks in air traffic handling.

The frame of this study is mainly composed of two parts. In the first part, we study the current systems and the bottlenecks and in the second part we study the ongoing researches and their provisions to ATC needs.

We have particularly investigated the effect of introducing CDM (Code Division Multiplexing) in the OFDM (Orthogonal Frequency Division Multiplexing) structure of the reverse link in B-VHF (Broadband Very High Frequency) system.

By means of the current communication systems, voice link is established between air traffic controllers and pilots. This includes transmitting and receiving information in air/air, air/ground and ground/ground data and voice communication systems.

Navigation systems assist pilots in flying from one airport to another. These systems help both pilots and air traffic controllers determine an aircraft's position relative to the ground and to other aircraft. Apart from the navigation systems, pilots use a system known as the ILS (Instrument Landing Systems) to guide aircraft to a safe landing and take off.

Surveillance is a means of acquiring the aircraft’s position so that a controller can maintain separation minima. Controllers require a reliable and accurate surveillance picture in order that they can have sufficient confidence to apply separations close to the operationally allowed separation minima. [1] The separation minima precision, which depends both on the source and radar data processor reliability, increases the capacity. The current surveillance sources are primary and secondary radars. Radar gives very little and often inaccurate information. The update rate is generally slow, since it is equal to the rotation rate of the radar dome. Partly due to the shortcomings of radar, aircrafts are required to fly with large spacing. This introduces traffic delays, which is quite costly for commercial airlines.

We have researched all upcoming technologies; to overcome existing technological gaps without neglecting security to meet exceeding air traffic growth.

A surveillance system and a communication system, based on other means than radar and VHF transmitter/receiver respectively, can introduce new benefits.

The data link technology has been seen as allowing the provision of more and different kinds of information to users.

This data link technology reduces congestion on voice channels and mistakes due to verbal communications by means of current communication systems. This data link also provides more precise aircraft position derived from board of aircraft systems and broadcast to all ground based stations and interested neighbour aircrafts by means of current surveillance systems. All VHF data link technologies VHF Mode 2, Mode 3 and Mode 4 will be in short provide to fulfill security and safety requirements for future voice and data services due to their physical characteristics.

The B-VHF project provides same superiority in the sense of operational features as well as data link provisions. The B-VHF project conducts bottom up research on MC (multi-carrier) technology for aeronautical communications in the VHF band for a future MC broadband VHF (B-VHF) system. The baseline technology is MC-CDMA, high capacity communications technology is also discussed for the fourth generation (4G) mobile communications systems. One and the proposed research project B-VHF emerged under the design and development of a high flexible and scalable next generation mobile radio access concept with respect to high data rates and spectral efficiency. This system will be the main base to new technology defined on OFDM, CDMA (Code Division Multiple Access) and MC-CDMA.

1.2 Organization of the Thesis

This thesis comprises seven chapters. Chapter 1 is an introduction to this study which contains the objective of this thesis.

Chapter 2 introduces CNS/ATM and defines the current air/ground communication, Surveillance and Navigation systems.

Chapter 3 emphasizes bottlenecks in the current air traffic control systems and future CNS/ATM systems.

Chapter 4 defines data link systems. The data link systems ACARS (Aircraft Communications Adressing and Reporting System), Very High Frequency Data Link Mode 2, Mode 3, Mode 4 are examined.

Broadband Very High Frequency (B-VHF) project physical structure of OFDM, MC-CDMA and OFDMA (Orthogonal Frequency Division Multiple Access) methods, definitions and applications in B-VHF system are defined in Chapter 5.

In Chapter 6, we proposed OFDMA-CDM method instead of OFDMA alone in the reverse link. The proposal based on OFDM-CDM as an single user in the reverse link by means of robustness against interference and frequency diversity.

Chapter 7 concludes with the simulation results why B-VHF system with the proposed OFDMA-CDM configuration matches future air traffic control systems needs.

CHAPTER 2

CNS/ATM SYSTEMS

2.1 Introduction to CNS/ATM systems:

Although CNS/ATM concept is used essentially for future and new technology aided air traffic control systems; communication, navigation and surveillance cover all existing, projected and still under conceptual-research of air traffic control systems.

ATM is the aggregation of airborne functions and ground-based functions required to ensure [2] the safe, economical and efficient movement of aircraft during all phases of operation. ATM is also used to describe airspace and air traffic management activities that are carried out jointly by aeronautical authorities concerned with the planning and organization for the effective use of airspace and its movements within their regions of responsibility. The ATM operational concept must have a visionary scope and be referred to the concept of endurance of flight, shared separation assurance and situational awareness in the cockpits. The general objective of the ATM is to allow aircraft operators to comply with the estimated times of departure and arrival and to follow preferred flight profiles with a minimum of limitations and without jeopardizing agreed level of safety. ATM consists of an air and a ground component, both closely integrated through well-defined procedures and interfaces. The ground component is made up of air space management (ASM), air traffic flow management (ATFM) and Air traffic services (ATS).

The process of getting an aircraft safely and efficiently from its origin to destination requires air traffic management systems. Communications is the exchange of voice between the pilot and air traffic controllers. Navigation pinpoints the location of the aircraft for the air crew.

Surveillance pinpoints the location of the aircraft for air traffic controllers. It includes communication of navigation information from aircraft to air traffic control centers which facilitates the continuous mapping of the relative positions of aircraft. The ICAO (International Civil Aviation Organization) calls the three functions as the CNS systems and regards them as forming the basic support services of air traffic management systems.

2.2 Current Communication Systems:

The ATC system is based on voice communications between air traffic controllers and pilots to transmit control instructions and other information related to the flight. There is also communication between pilots in order to exchange information. These communications acts are required to support co-ordination of aircraft movement in all phases of flight.

The communication between pilot and air traffic controllers are provided by HF (high frequency), VHF (very high frequency) and UHF (ultra high frequency) voice radio.

Aircraft radio transceivers exchange voice information through the use of double side-band amplititude modulation (DSB-AM) in which the aeronautical allocated frequency band of 118-136 MHz is currently used for VHF. There are 760 each 25 kHz channel; two thirds (506) are allocated for air traffic control communications while the rest are reserved for airline operational communications.

The direct wave is the ground-wave component that travels directly from the transmitting antenna to the receiving antenna. In terrestrial communications, the direct path is limited by the distance to the horizon from the transmitter. This is essentially line-of-sight distance. It can be extended by increasing the height of the transmitting antenna, the receiving antenna, or both. The direct path is also useful for extraterrestrial communications. It is useful in air/ground/air communications because most short-distance air/ground services are now on VHF or UHF. The UHF band (225-400 MHz) is allocated for the Military aircrafts.

This mode of operation permits to have a permanent connection between controllers and pilots but several drawbacks can be noticed:

- Risk of misunderstanding between controllers and pilots,
- Slow rate of information transfer, and
- An increase of the crew and controllers workload.

Due to the inherent line of sight limitations of VHF radio equipment used for communications in international oceanic airspace, communications capability assigned on the HF frequencies. The HF frequencies of the transmitters and the receivers are common for all the airports and are 3015 KHz and 5638 KHz.

As air travel continues to increase, controller-pilot communication has increased to the saturation point (one of the main problems is the congestion of the VHF frequencies) during peak traffic periods at many locations.

2.3 Current Surveillance Systems:

The surveillance systems presently in use can be divided into two main types: dependent surveillance and independent surveillance. In dependent surveillance systems, aircraft position is determined on board and then transmitted to ATC. The current voice position reporting is a dependent surveillance systems in which the position of the aircraft is determined from on-board navigation equipment and then conveyed by the pilot to ATC by radio telephony. Independent surveillance is a system which measures aircraft position from the ground. Current surveillance is either based on voice position reporting or based on radar PSR (primary surveillance radar) [3] or SSR (secondary surveillance radar) which measures range and azimuth of aircraft from the ground station.

Voice position reporting. Surveillance through voice position reporting is mainly used in oceanic airspace and aerodrome control service or area control service outside radar coverage. Pilots report their position using VHF and/or HF radios.

Primary surveillance radar (PSR) Primary radar does not require anything special of the aircraft other than it presents a reasonable radar-reflecting surface. [4] The primary radar principle is the radiation from a known point that is reflected by discontinuities in the atmosphere. Some of this wave is gathered at another known point, amplified, detected and displayed in a manner such that the observer can tell the location of the discontinuity. It is usual for the wave to be radiated and gathered by the same antenna. Primary radar systems work in practice for three reasons:

i- The velocity of the radiation (i.e., the velocity of light) to and from the reflecting object is constant

ii- Sufficient effective radiant power can be generated to create measurable reflected energy.

iii- Receivers of adequate sensitivity are available to detect the resultant signals.

Turkish Civil Air Traffic Service Provider (DHMI) provides radar coverage to main Airports terminal management areas by S –band Primary Radars, which are 60 nautical miles range coverage, 10 KW peak output power solid-state transmitter (no magnetron or klystron used), weather channel , 15 rpm, dual channel (Ch-A: 2740MHz, Ch-B: 2840MHz) and remote controlling and monitoring. All primary radar antennas are on-mounted with the secondary radar antennas.

Secondary surveillance radar (SSR). An SSR system [5] which includes both ground-based and airborne elements. The ground station emits pulses of radio frequency energy via the directional beam of a rotating antenna using a frequency of 1030 MHz for interrogation. The transponder detects the emitted interrogation signal and reply on a frequency of 1090 MHz. Depending on this reply, the plot extractor processes and measures the range, bearing and decodes the aircraft’s replies. The plot extractor determines the flight identity, level and passes the data to radar displays at an ATC center.

The use of an airborne transponder permits the transponder reply frequency to be different from the ground transmitter frequency, thereby avoiding the problems of clutter returns experienced by primary radar.

SSR interrogators comprise of two transmitting antennas. One is a directional antenna (main beam), the other is a more or less omni-directional antenna producing a "control pattern". The two interrogation pulses (P1 and P3) are sent out on the main beam. This narrow beam of the rotating antenna head sends these pulses out in a narrow beam width between 2° and 3° of azimuth. However, a third pulse, called P2 is also sent out via the control pattern of an isotropic radiator. The main beam radiating P1 and P3 pulses and the control beam radiating P2 pulse are shown in Figure 2-1. The spacing between P1 and P3 will determine the data content of the transponder reply (Mode A or Mode C) as described below.

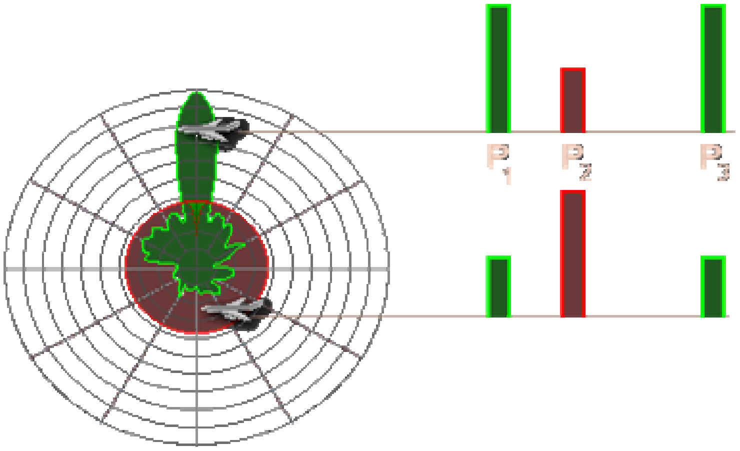

Figure 2-1 SSR P1,P2,P3 pulses

What is the code; The controller wants to know the identity of the aircraft "Who are you?" (Mode A). The radar gives a 2 dimensional position fix of the aircraft, but air traffic control is very much like a 3 dimensional process, so "What height are you?"

(Mode C) completes the positional fix. These different questions determine the MODE of operation. The aircraft's transponder replies with a code.

Each interrogation starts with the P1 pulse. This is followed shortly afterwards by a P2 pulse on the control pattern. An aircraft's transponder will always measure the relative signal strengths of the two pulses and will only ever respond to interrogations where the P1 pulse is at least 9 dB stronger than the P2 pulse

As the result the following conditions arise:

- The maximum amplitude of the P2 pulse is <9 dB below the amplitude of the P1 pulse. In this condition, targets are in the main beam and the transponder must reply therefore.
- The maximum amplitude of the P2 pulse is higher than the amplitude of the P1 pulse. In this condition, transponders may not reply.

The Reply Message; The SSR down link format consists of a number of pulses, nominally 0.45 μs (±0.1 μs). F_1 and F_2 are always present and separated by 20.3 μs (±0.1 μs) – they are often referred to as a bracket or framing pair, shown in Figure 2-2. Other pulse positions within this framing pair are spaced by 1.45 μs and are used to convey the required reply information in answer to the specific interrogation

(e.g Mode A identity or Mode C flight level values). The pulses are identified to give the bits of an octal code (ABCD). The X pulse at the centre of the reply is not used. The three blank positions may not be occupied by pulses, otherwise some decoders may reject the entire answer as interference. Note that the reply information itself does not contain any information to indicate which mode it is a reply to. The interrogator will assume that the replies received are in answer to it in the latest mode of interrogation. Emergency codes are given in Table 2.1

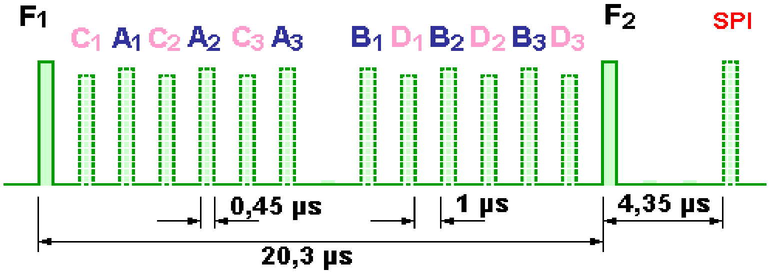

Figure 2-2 SSR Reply message link format

In the case of Mode A, the octal code (ABCD) is set by a control panel in the cockpit. In the case of mode C, the flight level is encoded in a special way (by a special form of Gray code known as Gillham code - this has the characteristic of only one bit changing for each change in flight level).

Table 2-1 Emergency Codes

Code	Mode	Meaning
7700	3/A	General air emergency
7600	3/A	Loss of radio
7500	3/A	Hijacking

The SPI (Special Purpose Identification) pulse is used by air traffic controllers to confirm the identity of certain aircraft. The controller will ask the pilot to squawk ident – the pilot pressing a button on the control panel which adds the SPI pulse to SSR replies for a certain period (18±1 s). The display system will then highlight aircraft with SPI. (The SPI pulse may have been appropriate to distinguish aircraft on older display systems before fully plot extracted displays became available). The output of frame position of the SPI pulse is somewhat strange and, the SPI pulse position chosen introduces rather unfortunate complications for automatic decoding purposes. According to ICAO the SPI-pulse will be added to Mode A reply only.

Automatic dependent surveillance (ADS). The introduction of air-ground data links, together with sufficiently accurate and reliable aircraft navigation systems, present the opportunity to provide surveillance services in areas which lack such services in the present infrastructure, in particular oceanic and other areas where the current systems prove difficult, uneconomic, or even impossible implementation. ADS is an application for use by ATS in which aircraft automatically transmits, via a data link, data derived from on-board navigation systems. As a minimum, the data include the four-dimensional position, but additional data may be provided as appropriate. The ADS data would be used by the automated ATC system to present information to the controller. In addition to providing traffic position information in non-radar areas, ADS will find beneficial application in other areas, including high-density areas, where ADS may serve as an adjunct and/or back-up for SSR, thereby reducing the need for primary radar. In some circumstances, it may even be a substitute for secondary radar. As with current surveillance systems, the full benefit of ADS is obtained by supporting complementary two-way pilot/controller data and/or voice communication (voice for at least emergency and non-routine communication). ADS-B is an expansion of the ADS technique that involves broadcast of position information to multiple aircraft or multiple ATM units. Each ADS-B-equipped aircraft or ground vehicle periodically broadcasts its position and other relevant data derived from on-board equipment. Any user segment, either airborne or ground-based, within range of this broadcast, can process the information. ADS-B is currently defined only for line-of-sight operations (e.g. broadcast over VHF digital link or by SSR Mode S extended squitter). ADS-B is also envisaged to be applied for surface movement, thus being an alternative to surface radars such as airport surface detection equipment.

2.4 Current Navigation Systems:

This is an important element of the ATC ground system because of its strong influence on the current ATM structure. The actual organization of the airspace is based on structured airways, defined by navigational aids located on the ground.

*VOR (VHF Omnidirectional Range);*The VOR is a ground based navigation aid that transmits a VHF navigational signal 360 degree in azimuth. It transmits to the aircraft an infinite number of navigation courses, which are selectable by the pilot.

This is the primary radio navigation aid that operates in the VHF band immediately below the frequencies used for communications (from 108.10 MHz to 117.90 MHz).

The transmission is modulated by two signals:

- Reference phase signal constant in all directions, and
- Variable phase signal variable with azimuth.

The receiver onboard the aircraft measures the difference between the two signals to determine the azimuth angle of the aircraft with respect to the VOR ground transmitter.

Some factors of inaccuracy exist and have to be taken into account:

- Inaccuracy of onboard equipment is about +/-3°.
- Inaccuracy of the ground station is about +/- 2°.
- Obstacles (mountains, building…) block VOR signal
- Furthermore, the VOR cannot be used when the aircraft passes vertically to the station (within an angle of . = 45° also called cone-of-silence).

The DME (Distance Measurement Equipment); is a pulsed distance measuring equipment located on the ground. After determining in which radial the aircraft is located, the pilot uses DME to determine the aircraft's distance from the ground station. This system operates in the UHF frequency band.

The DME consists of an interrogator (send pulse) located onboard the aircraft and a ground receiver which transmits back the signal at 63 MHz or lower.

The interrogator transmits a coded pulse (the frequency is around 1000 MHz) and when the ground based DME receives it, it replies using a different frequency. The DME equipment onboard computes the elapsed time between the transmission of the signal and the reply. The distance from the DME ground station (named slant range) is then obtained by dividing this time by 12.361µs.

As for VOR ground station several drawbacks exist:

- Inaccuracy (about 0.2Nm) has to be taken into account.
- Limited number of pulse pairs that lead to a maximum number of aircraft (i.e. less than 100).

DME ground station can be overloaded and in this case interrogations from new airborne transponders are rejected.

VORTAC: This system is a combination of two navigation aids, VOR and TACAN (tactical air navigation). The last one has been developed and used by military aircraft because of the inadequacy of VOR/DME ground station for specific military operation (VOR need an extended to clear zone and DME ground station can be saturated if too many aircraft are located in its vicinity). TACAN provides bearing and distance information and its main advantage is that it is smaller and easier to handle compared to the VOR/DME

TACAN is an Ultra High Frequency electronic navigation aid, which provides an indication of bearing and distance to the selected TACAN station. The azimuth is measured, like VOR, as the phase difference between a reference signal and an azimuth dependent signal.

The VORTAC system has the capacity to provide information about bearing and distance for both military and civilian aircraft. To use this equipment, the pilot has to select the appropriate VOR frequency and the DME interrogator can automatically contact TACAN UHF frequency so that information regarding to distance and direction will be available.

NDB (Non Directional Beacon): The non-directional radio beacon is a navigational aid instrument aimed to indicate to the pilot only bearing information. This method of navigation is based on a ground station (called NDB) and a receiver located on the aircraft (called ADF).

The range time for a signal to travel 1NM and return is 12.36µs. The NDB transmits a uniform signal omni-directionally (i.e. in all the direction) from the transmitter (located on the ground) using 190-540 kHz frequency band. The receiver located onboard the aircraft, called Automatic Direction Finder (ADF), automatically determines the bearing to the NDB and displays the information to the pilot.

Using ADF and the aircraft's heading indicator, the pilot can easily determine the aircraft's relative bearing from the station and then use this information to find the correct heading that would lead to the beacon.

CHAPTER 3

BOOTLENECKS OF SYSTEMS

3.1 Bottlenecks in The Current Air Traffic Control Systems

The bottlenecks are both within the traditional infrastructure area such as runways and taxiways but also within the operative and support systems such as communication, navigation and surveillance. To allow a continuous growth of air traffic, the technical systems must support higher amounts of air traffic.

Compared to today's air traffic load, it is expected, that the air traffic will approximately be doubled in 2015. Today's aeronautic communication and surveillance systems which is described in Chapter 1 have a number of bottlenecks which already today at occasions cause problems, and which may disturb a restrained growth of air traffic.

Since VHF voice channels are already at least in Europe at their capacity limits and the volume of air traffic still increases, 8.33 kHz channel spacing has been suggested and recently implemented. This step slightly increases the current limits and pushes the deadline for running out of capacity a little into future.

In addition to frequency limitations of voice communications, the operational constraints which are described in the previous chapter are major bottlenecks in the communication aspects of air traffic safety navigation growth.

- Risk of misunderstanding between controllers and pilots, (interference)
- Slow rate of information transfer, and
- An increase of the crew and controllers workload.

The disadvantages of PSR are that,

- It provided only a 2-dimensional position of aircraft , as no altitude can be detected by such a system
- Due to reflections on various aircraft around, positions were detected but those of the aircraft to receive services had to be identified. In other words this radar can not understand the who-is-who of what it sees. The controller has to tell the difference by an identification method usually consisting of track deviations
- The identification methods used were cumbersome and with some possibility of severe errors to happen
- Almost half of the observed 'targets' on the screen were not the controlled aircraft and separation between 'known - unknown' traffic was very important leading to continuous restrictions in maneuvers
- Apart from aircraft a number of other reflections caused by interference or hills, obstacles, towers, bridges etc. was cluttering the screens
- Intense radio contact with pilots was necessary to verify all related ATC elements like altitude / flight level, track, speed etc.
- Signal attenuation due to heavy rain may cause the displayed target to 'fade'
- When PSR was the only type of radar available, this was typically achieved by the controller observing a directed turn by the aircraft, or by correlating a DME (Distance Measurement Equipment) distance report by the aircraft with the position of a particular return along a known track.

Not the only because of the above reasons but also because of today’s ATC coverage and traffic separation minima (vertical and horizontal) requires at least double coverage to provide track correlation with respect to geography, aircraft identity (SSR-Mode A) and altitude level.

In accordance with the Eurocontrol Radar Surveillance standard, the radar coverage required to support both terminal and en-route air traffic services shall be:

Duplicated SSR coverage used for en-route airspace single PSR coverage for major terminal area. Hence PSR usage not a determining factor as much as SSR.

In contrast to PSR, SSR has proved to be very great value to ATC. However, it has its imperfections.

- When there are aircrafts in close vicinity, that is close distance and/or close direction, their SSR replies can overlap, the ground decoder is confused and finally their information is lost. This term is known as Garbling
- When there are many SSR stations around the aircraft replies received by other SSR stations that did not 'ask' for these replies, were received and calculated as valid ones resulting in confusion and finally rejection due to errors. This phenomenon is known as FRUIT (False Reply Unsynchronized In Time) and results from the fact that an aircraft SSR reply is received not only by the SSR that triggered it but by all the others around. The unexpected reply thus arriving to these other SSRs in the area results in wrong decoding and/or inconsistent position measurements which finally force the computer to reject the SSR information
- The total number of different SSR codes you may allocated to various aircraft is consisted of 12 pulses and seems huge as it is 4096 (result of 8X8X8X8=4096) or the same 2^{12}(=4096, for 12 pulses on a 2-state digit - pulse on or off). But in practical terms and for the present needs it is already insufficient as large number of them is reserved by different units and for traffic arriving at different times. If the same SSR code is used in neighboring areas, then the computer systems have a problem in allocating the same to 2 different flights and usually they do not, or they have to be redesigned to accept them both but always within ordered and well coordinated number limits ('code families')

  Unfortunately good co-ordination with all neighboring ATC units is not the rule and the proper SSR code allocation is not respected even now by all adjacent units. The feasibility of a technical achievement in theory gets worse in implementation due to the ineffectiveness of our ATC systems due to the disharmony of the varying technologies implemented so far.

The SSR reply of about 21 ms and 14 pulses had now to become 112 ms with 56 the ability of the MSSR to de-garble overlapping replies that did not look as terrible in the beginning. Of course there is no longer room for the old SSR in such a business and the end of 1999 has signed the death of the SSR in the 21st century.

Yet, this new channel of contact between the controller and the pilot can not accept probabilities of garbling even at a rate of certain percentage and should be of course unique, that is it should refer to one specific aircraft at a time and vice versa. This is why a new method of 'calling' the aircraft was found by which into the signals of the 'calling' (interrogating) radar and to the answering aircraft their identity is included.

There is one identity for the radar that is calling (a number obviously) and one other similar from the aircraft that answers. In such a way a unique one-to-one contact can be established. All other radars or aircrafts that do not identify their own numbers are not involved in this ‘discussion’. There is a Selective Addressing here like one mobile telephone number that belongs to one person. The word Selective provided its first letter S for this new way of contact or mode, becoming thus the Mode-S. In fact Mode-S is the continuation or extension of the old SSR idea and can be considered as a 'Super-SSR’. It can be implemented, however, only by the use of SSRs .

This unique addressing, the one-to-one contact, is by definition the total lack of garbling and FRUIT since there is only one reply at a time to be processed by the SSR. So this technique is the perfect solution for the old SSR.

The information was to be down and/or up-linked between controller and aircraft;

- Any clearance to the aircraft
- Any request by the pilot
- All cockpit data appear in front of the controller without having to ask
- All non-control data as ATIS (Automatic Terminal Information Service), METAR (Meteorological Aerodrome Report), Route-info, SLOTS etc. can be directly received by the pilot also without having to ask

- Many aircraft parameters can be fed to the tracking system and help the accuracy and speed of position calculations

The identity via the Mode-S system is supported by 24 pulses which allow for a total number of 224 = (4096)2 = 16777216 codes in all. That means that all aircraft in the world may permanently have their own unique code for addressing that never changes. Correlation is done by the Flight Plan that contains both the call sign and the unique aircraft code via the Flight Plan Processing. So the SSR codes are no longer to be used**.**

The Mode-S system needs not so much on the air as on the ground. Nowadays the air part is actually the Mode-S transponder which equips all modern aircrafts. On the ground installations, however, all the existing systems had to change accordingly and the cost is very high.

Additionally the Mode-S had to use this selective calling (Roll-Call) for known aircraft but at regular intervals had to interrogate in the classic SSR (All-Call) way just to detect the 'new comers' into the system yet unknown to it. Even then all linking had to rely on the radar rotation. That is an instruction to the pilot input by a controller would have to wait until the radar faces towards the aircraft and then send it.

Additionally the ADS (Automatic Dependent Surveillance) based again on the satellites gave a simple solution on the aircraft detection and communications: The position instead of deriving from the radar could be known simply by a transmission made by the aircraft itself - by the automatic pilot or rather its FMS (Flight management System). VHF Data-Link appeared first and was implemented easily while ADS is still on the fight to gain its position in ATC.

To reduce the need for R/T, the radio contact between pilot and controller, the VHF Data-Link is better. The ADS can replace radar at least in areas impossible to cover with and may provide a radar display to pilots for self monitoring of the traffic around for advanced traffic information.

3.2 Future CNS/ATM Systems

The need for change in the current CNS/ATM is due to two principal factors: Due to inherent limitations and bottlenecks in the current system, it will not be able to cope-up with the growing demand of air traffic; and the need for global consistency in providing air traffic services (ATS) while progressing towards a seamless CNS/ATM system.

Based on the anticipated future operational requirements, it is expected that the future communications system will need to support the following information exchanges.

- Voice
- Data
- Air to ground/Air to air
- Point to point (addressed, two way communications)
- Broadcast
- Surveillance information
- Security

Future Navigation technology will improve the accuracy of position determination and to provide better predictions of future position to enable aircraft to fly more accurate and well defined profiles. Improvement in position accuracy is also a prerequisite for the introduction of reduced separation minima. The GNSS (Global Navigation Satellites System) is the solution for seamless navigation.

GNSS define any world-wide positioning and time-determining system that includes one or more satellite constellations, aircraft receivers and various integrity monitoring systems including the required augmentation system for meeting operational performance requirements. The core constellation of the GNSS is GPS, GLONASS and Galileo.

Future Surveillance technology will be combination of communication techniques and ADS (Air Dependent Surveillance) systems rather than ground dependent (PSR, SSR) systems.

CHAPTER 4

VHF DATA LINK SYSTEMS

4.1 The Air-Ground Data Link Systems

Data link is the basic component of communication between air traffic controller units and aircraft. Data links were initially used for ACARS communications but new equipments are compatible with ATN (Air Traffic Network) communications, which will improve the efficiency and compatibility of aeronautical VHF data channels.

The aeronautical data communications system planned for the CNS/ATM enables different computer systems to communicate with each other. A global telecommunications network is required to interconnect the variety of aircraft and ground based computers. The internetworking infrastructure for this network is the ATN which is based on the ISO(International Standard Organization) OSI (Open Systems Interconnection) model, and it links the various air-ground and ground-ground data systems together.

The ATN is in principle independent of the physical means provided to transmit the data. The air-ground network contains satellite, VHF data links, SSR-Mode S and HF communication links.

Controller Pilot Data Link Communications (CPDLC) is a data link application provides for routine air traffic management communications via data link that are currently conducted via voice communications.

4.2 Aircraft Communications Addressing and Reporting System

ACARS: The VHF Aircraft communications, addressing and reporting system (ACARS) is an air to ground radio data system. The main purpose of the ACARS is to provide VHF data link to manage logistical complexity of commercial flight operations through the use of Airline Operational Control a central operation system.

ACARS sub-network operated similarly to today's electronic mail system, transmitting 2400 bps over amplitude modulation (AM) using minimum shift keying (MSK) at 25 kHz channel spacing. [6]

To ensure optimum flight management from departure to arrival, ACARS provides automated position reports of the aircraft, data sensors on-board the aircraft registered which are fed into an airborne computer, converted into data packets and transmitted via VHF radio to ground stations. This allows ground control computers to continuously monitor an aircraft.

ACARS can only provide a text based exchange; burst transmissions are used with a limit of 220 characters per message. Transmissions often last less than one second. As a text based system it is constrained both by the presentation of information and the length of the message. The sub-network is composed of three elements: physical channel, media access control layer and data link sub-layer. The physical channel requirements include a dedicated 25 kHz channel, it can only provide data link service to one aircraft at a time, thus using spectrum inefficiently. Secondly, to detect whether or not a channel is idle, the carrier sense multiple access (CSMA) protocol controls media access.

The limitations and problems of ACARS system falls short of meeting today's requirements and can be overcome by using VHF Data Link technology.

VDL (VHF Data Link): Literally there are four defined (VDL Mode 1, VDL mode 2, VDL mode 3 and VDL 4) VHF data link technology. VDL Mode 1 is an evolutionary development of the ACARS which is defined above.

4.3 VHF Mode 2

VHF Digital Link (VDL) -2 :[7] VDL Mode 2 uses digital radio techniques. The nominal data rate of 31.5 kbits/s is compatible with the 25 kHz channel spacing used for existing VHF analog radios. The modulation scheme used in Modes 2 is Differential 8 Phase Shift Keying (D8PSK).

This is 10 times the VHF ACARS 2.4 kbps rate using DSB-AM. It is the highest possible bit rate that can be supported by a 25 kHz channel while providing a range of 200 nautical miles.

Aircraft and ground stations exchange their user data in frames. Four frames can be sent before an acknowledgement is required. ACARS on the other hand, must stop and wait after each transmission. VDL Mode 2 is faster transmission of multi block messages. On one dedicated channel which is called common signaling channel at 136.975 MHz, aircrafts listens for broadcast Ground Station Identification frames identifying the service provider and services offered by that ground station.

The aircraft decides which ground station is best after hearing one or more Ground Station Identification frames (based on service provider preference, offered services, and signal strength) and then makes a logical connection to the selected ground station. As the aircraft transits through the airspace, it keeps track of all the ground stations that it can hear. When the signal quality of the currently connected ground station degrades due to range effects, the aircraft will then select the best candidate ground station from the list and make a logical connection to this ground station (hand-off). In this manner, the logical air/ground connections make a seamless transition as the aircraft flies through the airspace.

The VDL Mode 2 CSMA operation is superior to that of ACARS as it detects a clear channel much quicker. This in turn results in reduced message delay and higher success rates under heavy loading conditions. A major benefit of CSMA is the small overhead since each ground station and aircraft is independent and does not require synchronization or timing signals from a central source.

VDL Mode 2 is a bit-oriented system, which means that messages are sent more efficiently. ACARS transmission is limited to letters and numbers, while VDL Mode 2 sends coded data. A simple clearance such as, climb to and maintain FL330, would take at least 224 bits using ACARS. With VDL this could be encoded to take only 10 bits! Bit-oriented communications will also support graphics to the cockpit opening up new opportunities.

As stated above the digital modulation scheme is D8PSK [8] and no voice available in this mode contributes its failures. Due to D8PSK modulation is sensitive to noise, two guard channels are required to protect the fundamental signal from noise. That means three frequencies are required to service a single aircraft.

4.4 VHF Mode 3

VHF Digital Link (VDL) -3 VDL Mode 3 uses a time division multiple access (TDMA) technique [9] and is capable of integrating both voice and data communication systems. The improved utilization of the VHF spectrum is achieved through the provision of four separate radio channels over one carrier with 25 kHz channel spacing. The operating concept for VDL Mode 3 is similar to that of existing ATS analog in that all the aircraft in an ATC sector are assigned to the circuit used by the ATC controller for that sector. These aircraft decode all transmissions so that the pilots have the same impression as when they use analog VHF voice. They need to listen out to hear whether the circuit is free before talking, in the same way as for analog VHF voice channels.

The VDL Mode 3 protocol divides time into super slots of 120 milliseconds, which it subdivides into either four 30-millisecond slots for normal operations or three 40 milliseconds for long range operation. Each slot is allocated to logical circuit. In each 30 millisecond slot about 10 ms are used for channel management data and 20 ms for the exchange of user data, which gives time for about 600 bits. The user data can be either digitized voice generated by a codec in the VHF Data Radio or a data message.[10]

The limitations are modulation scheme which is same as VDL Mode 2 very sensitive to interference, guard channel requirement and media access CSMA contribute to its shortcomings for high data capacity. [11]

4.5 VHF Mode 4

VHF DIGITAL LINK (VDL) -4: VDL Mode 4 is a digital communications system [12] that provides communications from aircraft to aircraft, aircraft to ground and ground to aircraft. It transmits digital data in a standard 25 kHz VHF communication channel with a rate of 19.2 Kbps Gaussian Frequency Shift Keying (GFSK) modulation and it is based upon the STDMA (Self Organizing Time Division Multiple Access) technology.

In VDL Mode 4, time is divided into a series of time slots of equal period. Each VDL Mode 4 burst transmission starts at the beginning of a slot. There are 4500 available slots/min, and there can be 256 bits/slot transmitted.

A 27 bit identifier is used to uniquely specify a VDL Mode 4 station. The range of the VDL Mode 4 transponders are limited by the transfer delay from one transponder to another and it is set to 200 nautical miles.

Gaussian Filtered Frequency Shift Keying (GFSK) modulation is a continuous-phase frequency shift keying technique using two tones and a Gaussian Pulse shape filter.

The first bit transmitted in the training sequence shall be a high tone and the transmitted tone shall toggle transmitting a 0.

Self-Organizing Time Division Multiple Access (STDMA) is multiple access scheme based on time shared use of a radio frequency channel employing

1- Discrete contiguous time slots as the fundamental shared resource
2- A set of operating protocols that allows users to mediate access to these time slots without reliance on a master control station.

The communication channels are first divided by the time segments, by specifying a superframe. One superframe lasts for 60 seconds. The superframe is then divided into time slots (4500) The start of each time slot is an opportunity for a station to transmit.

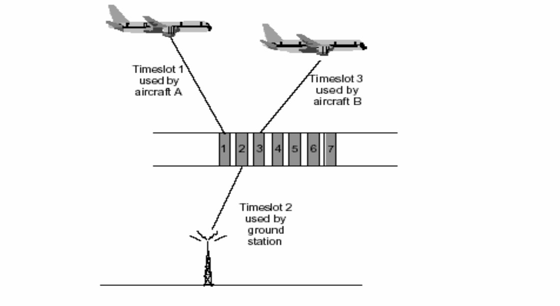

Figure 4-1 STDMA slot allocation

While VDL Mode 4 has the potential for becoming a unified data link solution for all CNS/ATM data link applications, there are also potentially serious issues of its use as the end state CNS/ATM data link for all or even some of these applications.

VDL Mode 4 is a relative newcomer to the various ATC industries that are developing data link applications and may have difficult time gaining acceptance since other solutions are already well along in the development and validation phase.

In this thesis we will focus one of technology is still under developing phase which is B-VHF explained in Chapter 5.

4.6 Examination of VHF Data Link Mode 2-3-4

All VDL candidates (Modes 2,3,4) provide ATN compatible, addressed communication protocols and essentially use the same data link service (DLS) sublayer based on the aviation VHF Link Control.

As indicated above, among the VDL Modes differences [13] occur due to the physical layer modulation waveform (D8PSK versus GFSK) and the Media Access Control (MAC) sublayer (CSMA versus TDMA structure). [14]

VDL Mode 2 is a simple data link protocol ideally suited for low capacity ATN-compatible data link applications, where CSMA protocols provide simple and efficient channel access.

VDL Mode 3 is well suited for ATC/ATS digital voice and data communications and has the needed flexibility to accommodate a wide range of data link services that can accommodate ~3 seconds end to end transfer delays.

VDL Mode 4 is a highly flexible, ATN compatible, addressed data link. Similar to Mode 2, VDL Mode 4 is a data only (no voice) data link, requiring an additional radio resource for providing simultaneous voice and data communications that will be required in the future CNS/ATM systems.

CHAPTER 5

BROADBAND DATA LINK SYSTEM

5.1 Broadband-VHF (B-VHF)

In Chapter 4, all VHF data link technologies and the related aeronautical services are analyzed. Within all given analyses and references, these VHF Mode 2, Mode 3 and Mode 4 will be in short to provide sufficient capacity (Eurocontrol's Communications Strategy indicates the need of alternative communications systems as the saturation point of the current system is reached around 2015) and fulfill security and safety requirements for future voice and data services.

We have taken the capacity measurements and comparisons according to UK airspace structure as reference criteria to continue this work is given in [15].

In order to meet both current and futuristic demands, researchers carry on searching for new technologies. B-VHF is one of the most powerful candidate technology. This program is 50% funded by the European Commission under Framework 6.

The B-VHF project conducts bottom up research on multi-carrier technology (MC) for aeronautical communications in the VHF band for a future MC broadband VHF (B-VHF) system. The baseline technology is MC-CDMA, high capacity communications technology is also discussed for the fourth generation (4G) [16] mobile communications systems. [17]

Before going further in detailed analysis of MC-CDMA, we have outlined the B-VHF system architecture design in the following paragraphs.

B-VHF system provides both voice and data communications between aircraft and ground-based users and also supports voice and data exchanges between aircraft by using MC-CDMA (OFDM) technology.

The B-VHF communication functions and system architecture is supporting safety-critical ATC services such as

- Voice/Data communications for Air Traffic Control, Air Traffic Services and Air Traffic Management, including Flight Information Exchanges.
- Air Surveillance Communications
- Aeronautical Operational Communications

Basically B-VHF system communication possibilities are composed of two types of architecture:

1. Direct mode: Communication between two mobile users is established directly
2. Relay mode: Communication between two users is established via a relay station

As we have mentioned in Chapter 1 the current analogue VHF voice system architecture is based on Double Side-Band Amplititude Modulation (DSB-AM) direct mode.

Relay mode is the basic mode of B-VHF project and direct mode as an option for a possible follow on B-VHF project. If the ground station (GS) is available, it acts as relay station. For that purpose there are two kinds of links defined. First, Forward Link (FL): From Ground station (GS) to an aircraft which can be on ground or on air. Second, Reverse Link (RL): From aircraft to a controlling station.

Forward Link Communication Functionalities: Three transmission functionalities exist on forward link for both voice and data communications:

i. Point-to Point (PP) FL communications, where the GS uses specific discrete aircraft addresses
ii. Multicast (MC): The GS FL transmissions are received by the members of specific group
iii. Broadcast (BC): Ground Station Forward link broadcast is directed to and can be received by all users within transmission range.

B-VHF system ground station also supports all kinds of communication between aircrafts. There are two possible modes to communicate between aircrafts;

1- Pilot ATC voice party-line transmission; Pilot's voice transmission is sent to the GS and forwarded to the controller and to enable other pilot's to listen this voice transmission, the voice packets are automatically retransmitted by the ground station right after the reception and can be received by all aircraft within the GS coverage area.

2- Pilot point to point communication with another aircraft; since the direct mode left for follow on B-VHF project we will define relay mode air-air communication. The aircraft sends its voice packets to the GS by using its dedicated RL voice channel where they are automatically retransmitted to the other aircraft using another dedicated forward link voice channel. Similarly the reverse link response of the second aircraft is put by the ground station into the forward link of the first dedicated voice channel and forwarded to the first aircraft. The other pilots within the ATC sector are not aware of this information exchange and are not able to listen to this communication.

B-VHF Cellular Concept: In the current ATC communication systems each ATC sector is controlled by one controller using a dedicated VHF channel. There are three types of sectors defined: 1- Tower area; within a radius of 25 nautical miles, responsible for landing, take-off and related airport services

2- Terminal Area (approach area) within a radius 60 nautical miles, responsible for between tower and en-route area, approach and terminal area services 3- En-route within a radius 175 nautical miles, responsible for all aircraft navigation between terminal areas. B-VHF ground station might have implemented several transmit/receive units and is thus capable to support several VHF channels to cover several ATC sectors. As a result, one B-VHF cell might cover several ATC sectors or sector parts, similarly a single ATC sector might belong to several B-VHF cells. By this way, B-VHF cells are effectively de-coupled from ATC sectors. Consequently, the required B-VHF RF bandwidth depends on the required cell capacity that in turn depends on the cell size.

B-VHF Protocol Description: The B-VHF system covers the three lowest layers of the ISO-OSI model.

1- Physical Layer: Provides transceiver frequency control, bit exchanges over radio media, and notification functions. In this layer voice sub system, data sub system and different characteristics in forward link and reverse link directions are being shared.
2- Data Link Layer: This layer is composed of four sub layers.
    a. Media Access Control (MAC) sub layer
    b. B-VHF Special Services (BSS) sub layer
    c. Data Link Services (DLS) sub-layer
    d. Link Management Entity (LME)
3- Lowest Sub-Layer: Subnetwork Access Protocol, (SNAcP): Provides packet exchanges, header compression, sub-network connection management function and support error recovery, flow control and packet fragmentation.

In the subsequent sections we will essentially focus on Physical Layer to understand forward link and reverse link on proposed MC-CDMA technology. B-VHF overlay system is based on Multi Carrier technology.

Literature provides several proposals for combining Multi-Carrier with Direct Sequence Spread Spectrum (DS-SS) but all schemes can be categorized into two major types. The first type is combining of orthogonal frequency division multiplexing (OFDM) and CDMA. The second approach spreads the serial to parallel converted data streams using a spread code, and then it modulates different sub carriers with each of the data streams. This is parallel transmission of narrowband direct sequence (DS) CDMA waveforms in the frequency domain. In the B-VHF MC-CDMA system, CDMA technique is applied on top of OFDM.

Multi-Carrier Code Division Multiple Access (MC-CDMA): There are three standard multiple access possibilities based OFDM technique [18]. 1- Combining TDMA with OFDM becomes in OFDM-TDMA. 2- Combining FDMA with OFDM becomes in OFDM-FDMA or just OFDMA, this technique is not used yet used in a standard but discussed for use in future mobile communications systems, especially in the reverse link and finally 3- Combining OFDM with CDMA results in MC-CDMA. MC-CDMA has the potential to exploit the mobile aeronautical channel better than any currently discussed VHF communication alternatives. It increases voice and data capacity and addresses security and safety issues with a service level unknown to the aeronautics user today. Broadband VHF aeronautical communications system based on multi-carrier technology as overlay concept.

In this chapter we will analyze the B-VHF project in which OFDM is used on both forward link (down link) and reverse link (uplink) environment and in forward link OFDM combined with CDMA and in reverse link OFDM combined with FDMA.

5.2 OFDM (Orthogonal Frequency Division Multiplexing)

OFDM is a multicarrier transmission technique, which divides the available spectrum into many parallel carriers that simultaneously transmit, each one being modulated by a low rate data stream.

OFDM uses the spectrum by spacing the channels closer together. This is achieved by making all the carriers orthogonal to one another, preventing interference between the closely spacing carriers. The information signals of OFDM transmission from multiple sources are combined into a single multiplexed stream of data. This data is then transmitted using an OFDM that is made up from a dense packing of many subcarriers. All the subcarriers within the OFDM signal are time and frequency synchronized to each other, allowing the interference between subcarriers controlled. These multiple subcarriers overlap in the frequency domain, but does not cause Inter-Carrier Interference due to the principle of OFDM which splits a high-rate data stream into a number of lower rate streams that are transmitted simultaneously over a number of subcarriers.

Allowing multiple information signals to be transmitted over a common channel without interference is achieved by orthogonality. Loss of orthogonality results in blurring between these information signals and degradation in communications. The subcarriers in an OFDM signal are spaced as close as is theoretically possible while maintaining orthogonality between them. Each of these sub-streams is modulated on one of the N_c sub carriers. OFDM can be visualized as shown in 5-1. The subcarrier frequencies are chosen as in equation 5.1 to provide orthogonality.

$$f_n = \frac{n}{T}, n = 0,.....,N \ -1 \qquad (5.1)$$

where T is the OFDM symbol duration

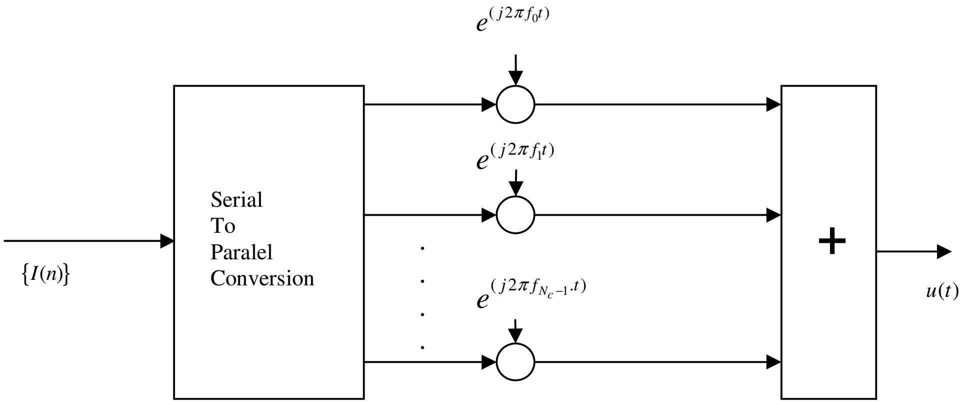

Figure 5-1 OFDM

Summing up of N_c sub-carrier signals gives OFDM transmission signal, $u(t)$.

$$u(t) = \frac{1}{N_c} \sum_{n=0}^{N_c-1} I(n) e^{(j2\pi f_n t)}, \qquad 0 \le t < T \tag{5.2}$$

The overall bandwidth of the OFDM signal is $B = N_c \Delta f$

The parallel modulated data symbols is T and its duration can be obtained by the number of parallel modulated data symbols multiplied by the original data duration T_S, i.e., $T = N_c T_S$.

In B-VHF project OFDM is used on both forward link (down link) and reverse link (uplink) environment and this environment may cause the channel fade due to physical environment (different echo delays that are encountered from multipath propagation). To overcome this problem the inter carrier spacing has to be chosen large (in the form of cyclic prefix). [19] A cyclic prefix is a copy of the last part of the OFDM symbol which is prepended to the transmitted symbol. Cyclic prefix also avoids ICI (Inter Carrier Interference) by maintaining the orthogonality between the sub carriers.

The difficulty in using the parallel data stream is the complexity of the equipment needed for the implementation of the system. Severe mutual interference between the subcarriers is possible and filters of accurate cut-off frequencies will be needed. The complexity is QAM/QPSK encoding the information in the transmission path and QAM/QPSK decoding in the receing path. This could be reduced by using the Discrete Fourier Transform to implement the modulation process. A Fourier Transform of the original stream and the bank of coherent demodulators at the receiver is an Inverse Fourier Transform operation.

5.3 MC – CDMA (Multi Carrier- Code Division Multiple Access)

As we have analyzed Orthogonal Frequency-Division Multiplexing (OFDM) in the previous section is a method of digital modulation in which a signal is split into several narrowband channels at different frequencies.

CDMA is a form of multiplexing, which allows numerous signals to occupy a single transmission channel, optimizing the use of available bandwidth. Multiplexing is sending multiple signals or streams of information on a carrier at the same time in the form of a single, complex signal and then recovering the separate signals at the receiving end.

Multi-Carrier (MC) CDMA is a combined technique of CDMA and OFDM. In an OFDM transmission each data symbol is transmitted on an individual sub carrier, the data symbol in an MC-CDMA transmission is distributed. In this transmission environment forward link (downlink) from base station (Ground station) to mobile station (aircraft) needs to transmit more than one information and hence more than one data symbols spread several data symbols over the same group of sub carriers. The combination of OFDM and CDMA has one major advantage. It can lower the symbol rate in each sub carrier compared to OFDM so that longer symbol duration makes it easier to synchronize. The MC-CDMA not only mitigates the ISI (inter symbol interference) but also exploits the multipath.

A standard MC-CDMA transmitter is shown in the Figure 5-2. The data symbols $I^{(k)}$ of each user k, k= 1,….K, within a group of K users is first spread with a user specific spreading code vector $C^{(k)}$ of length L.

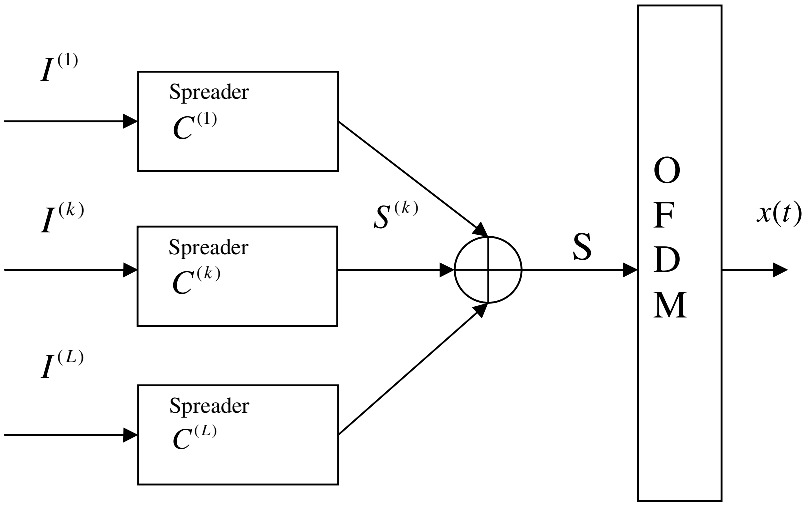

Figure 5-2 MC-CDMA Transmitter

Using orthogonal spreading sequences (Walsh Hadamard codes) up to $K_{\max} = L$ user can be transmitted simultaneously within such a standard MC-CDMA system. After spreading the original data symbol $I^{(k)}$ has been divided into L chips. The chips of all users are summed up and an OFDM modulation is applied to the resulting vectos **S**. The OFDM operation comprises serial to parallel conversion, IDFT/IFFT, addition of a guard interval, parallel to serial conversion and digital to analog conversion. Thus the one user symbol which is L chips are distributed on the $N_c = L$ sub-carriers, and the chips of other user symbols are superimposed on the sub-carriers. User discrimination is achieved by CDMA with user specific orthogonal codes. In short, MC-CDMA is OFDM for the chips of a user data symbol. At the MC-CDMA receiver first the inverse OFDM operation is applied then the chips on the different sub-carriers are despread and combined again. The original data symbols are retrieved from the received signal.

5.4 OFDMA (Orthogonal Frequency Division Multiple Access)

OFDMA is a reverse link multiple access for the B-VHF system. As we have stated earlier, OFDMA is combination of FDMA with OFDM. In this section we will describe the M and Q modifications on MC-CDMA and then describe the OFDMA technique and its application on B-VHF project.

Other well known multiple access technique is Frequency Division Multiple Access (FDMA) and in this technique the available bandwidth is subdivided into a number of narrower band channels. Each user is allocated a unique frequency band in which they transmit and receive. Once we have assumed to establish the MC-CDMA technique on ground stations, we prefer to access the OFDMA by using the MC-CDMA technique.

There are two different modifications of the standard MC-CDMA system, first the M modification and the second Q modification. In the M modification each user is allowed to transmit $M > 1$ data symbols simultaneously and this can be accomplished by introducing an additional OFDM component to the standard MC-CDMA system. The chips of the M data symbols are multiplexed different sub carriers using OFDM. All M data symbols $I_m^{(k)}, m = 1, ..., M$ of user $k, k = 1, ..., K,$ are transmitted with a separate standard MC-CDMA system. The different MC-CDMA systems are OFDM multiplexed on $N_c = ML$ sub-carriers. Interleaving is foreseen in order to distribute the chips of one data symbol on sub-carriers as far apart as possible in order to achieve the maximal frequency diversity.

In addition to the M modification the Q modification can be applied. In the Q modification, different as compared to M modification is that instead of additionally introducing OFDM, an additional FDMA component is introduced. Thus, instead of increasing the number M of simultaneous transmitted data symbols, the number of simultaneously transmitting users is increased by introducing $Q > 1$ user groups divided by FDMA. Each user group can support up to $K = L$ users which are divided by the FDMA component as shown on Figure 5-3.

The number of subcarriers of an MC-CDMA system applying M and Q modification is given by $N_c = MLQ$. Assuming a system with a fixed number N_c of subcarriers, the parameters M, L, Q can be adjusted arbitrarily. The parameter L is the spreading length and is responsible for the achievable frequency diversity. Values in the range $L = 4,...16$ are a suitable choice depending on the transmission environment. After L is chosen for a certain system design, the product MQ can be split into certain values for M and Q. This can be done adaptively depending on the required transmission data rate and required user capacity. In the case large number of users has to be served, Q is chosen large and M is reduced. In case of low user capacity requirements Q can be chosen small, thus allowing M to be increased and with that the available data per user.

The basis of OFDMA is a special case of MC-CDMA. Setting $L = 1$ and with that removing CDMA component changes MC-CDMA with M and Q modification into OFDMA.

User discrimination, in other words aircraft discrimination is done only by FDMA by assigning different subcarriers to the different users. OFDMA is advantageous for application in the reverse link, since the channel estimation can be established with a simple pilot based approach. Since the pilot based channel estimation fails because of CDMA component, Frequency Division Duplex systems channel estimation for the reverse link can be done using blind estimation algorithm.

OFDMA scheme consists of partitioning the set of N_c carriers into M subsets of N_c / M carriers each and assigning a group of carriers to different users. In this way, resources can be allocated to different N_c / M users at the same time. OFDMA increases the cell range on the channel, because it transmits the available power in a small fraction of the channel bandwidth. Assuming that the signal attenuation is proportional to the squared distance, an OFDMA system with M =8 will increase the cell coverage on the uplink by 18 dB. Cell range extension can also be achieved on the downlink by allocating more power to the carriers assigned to distant users than to carriers assigned to users that are close to the base station.

Main reason that we are analyzing B-VHF system as a future communication and data link system is lying on the overlay concept. B-VHF uses same spectrum as legacy VHF system use. There are two design challenges via using same spectrum. The one is that to avoid interference legacy VHF system from B-VHF and the second is to suppress or mitigate interference from legacy VHF system near the B-VHF spectrum area or inside. More than the system design details, OFDM sidelobe suppression is already around 20-30 dB. B-VHF system is able to skip certain sub-carriers which are already occupied by transmissions of legacy VHF systems use.

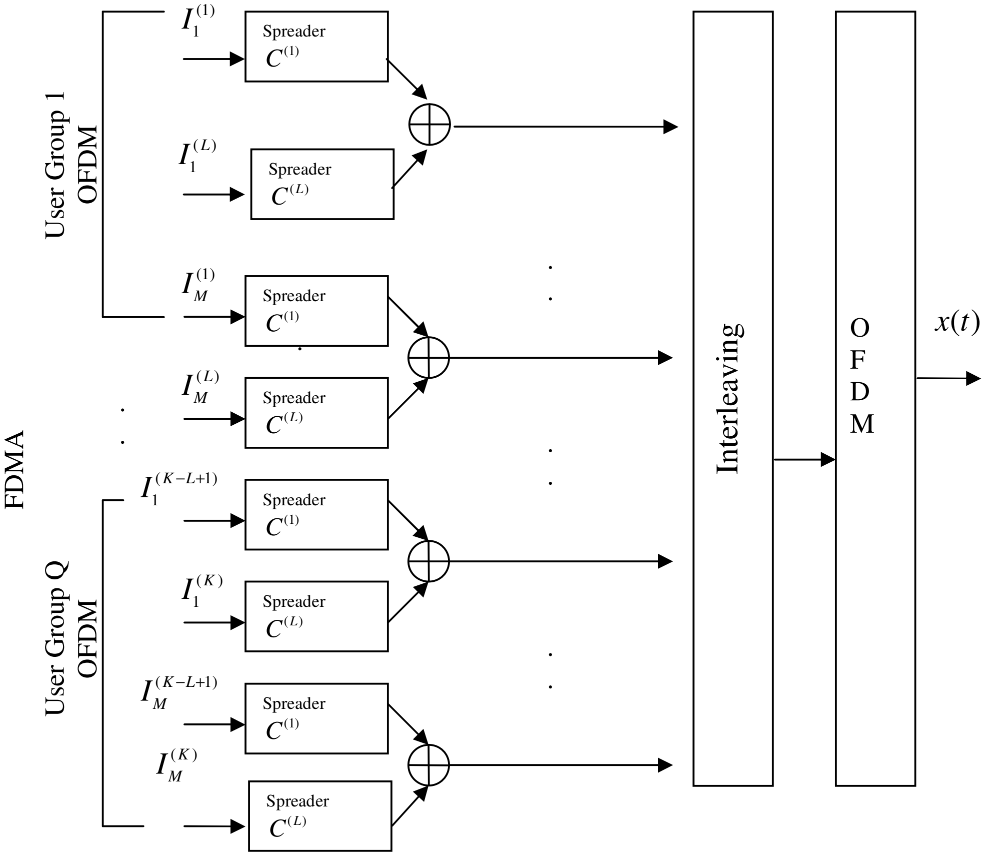

Figure 5-3 OFDMA

5.5 B-VHF Time Frame Structure:

For voice and data transmission between ground station and the mobile station time division duplexing is used. As shown in the Figure 5-4 there is three defined frames, hyper frame which is 1920 ms long and consists of 8 super frames (SF). Each Super frame is 240 ms long and consists of 4 multi-frames (MF), each being 60 ms long.

There are two types of multi- frames; the odd numbered multi-frames carry an unsynchronized random access channel, whereas the even numbered multi-frames carry two synchronized random access channels in the corresponding RA slot.

Four B-VHF slots are defined in the multi frame:

i. BC: Broadcast B-VHF Slot: Detect the allocated subcarriers in the mobile station for the current and neighboring cell and also disseminate information which is necessary for the B-VHF net entry and B-VHF cell handover.
ii. FL: Forward Link B- VHF Slot; for the transmission of the data from ground station to the mobile stations.
iii. RL: Reverse Link B-VHF Slot; for the transmission of the data from mobile station to the ground station.
iv. RA: Random Access B-VHF Slot; for initial net entry of mobile stations in the current cell and for the transmission of resource request messages.

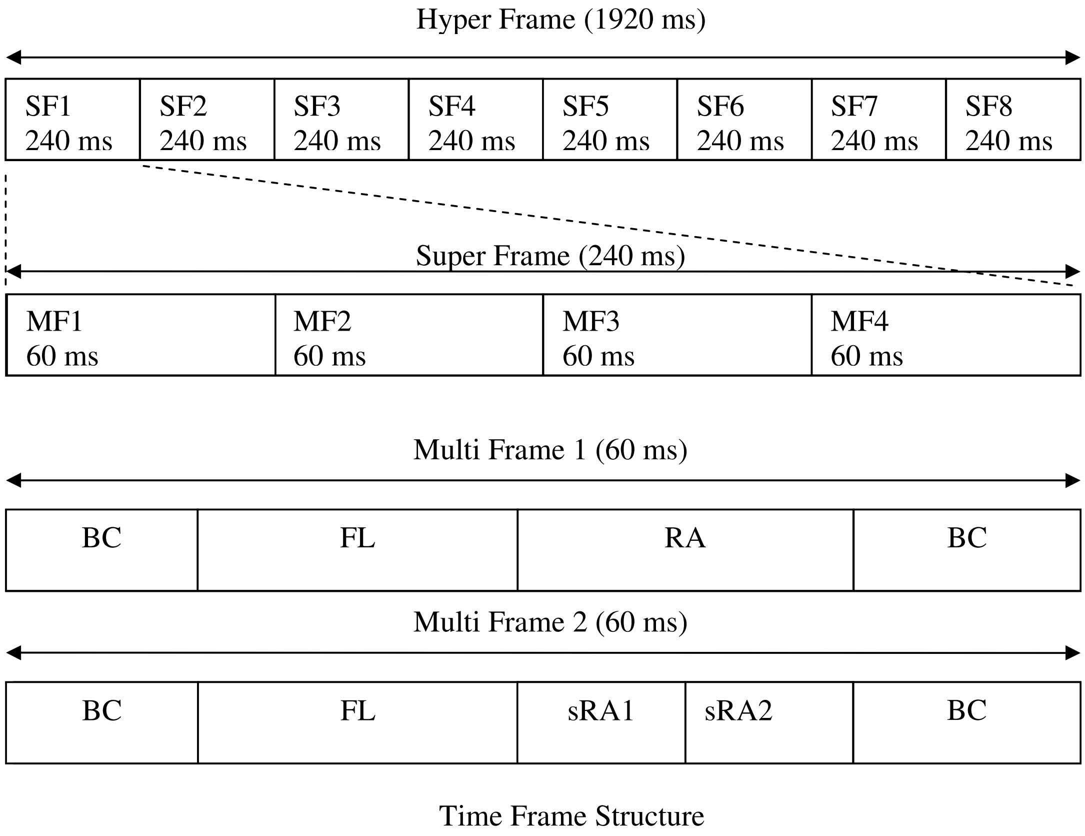

Figure 5-4 B-VHF Time Frame Structure

5.5.1 B-VHF Forward Link

In the forward link MC-CDMA with M&Q modification has been selected. For each user a single symbol is spread, multiplexed with symbols of other users, and finally transmits over $N_c = L$ sub carriers. With the M modification, for each user, M symbols are transmitted over N_c carriers. The number of required carriers is $N_c = ML$ and an additional OFDM component is introduced into the MC-CDMA system. By the transmission of M parallel symbols of each user, bandwidth efficiency is increased. The increase of the number of sub carriers N_c, while maintaining constant spreading sequence length L and the maximum number of users, leads to an increase of the OFDM symbol duration. This cause a guard interval decrease due to loss of the bandwidth efficiency.

Q modification is the setting of the number of subcarriers $N_c = QL$. (Q defines number of user). If adequate frequency interleaving is applied prior to the OFDM encoding, short spreading sequence lengths of $L = 4, 8\, or\, 16$ can already achieve a large diversity gain. The maximum number of users K with $M \& Q$ modification equals $K = QL$.

Combining the M and Q modification we arrive at the $M \& Q$ modification for which $N_c = MQL$ is valid. MC-CDMA with $M \& Q$ modification can be viewed as MC-CDMA with additional OFDM and FDMA components. The special case $L = 1$, the MC-CDMA system with M&Q modification reduces OFDMA as mentioned in section 5.2 OFDM. OFDMA can be viewed as MC-CDMA with $M \& Q$ modification without applying spreading with spreading codes.

5.5.2 B-VHF Reverse Link

For the B-VHF reverse link, OFDMA has been selected as multiple access scheme. In 5-5 $M \& Q$ modified MC-CDMA Forward Link and OFDMA based Reverse Link are summarized.

The aeronautical allocated frequency band of 118-136 MHz is currently used for legacy VHF system and under the overlay concept there are 19 channels is seen in Figure (5-5). On each channel, forward link and reverse link access available.

In reverse link, Random Access Channel (RACH) uses the whole OFDM frame. The RA: Random Access B-VHF Slot; for initial net entry separated in time from FL and RL frames. During the RA slot only random access is possible for airborne users. Reverse Link transport channels use distinct groups of OFDM carriers, which are separated by applying OFDMA. They carry either permanent services or temporary services.

We will not analyze the service requirements on both ground and mobile stations. We will focus on physical layer in the Chapter 6 and will not investigate the data link layer and sub-layer in this thesis.

-FDMA Seperated B-VHF channels within VHF COM Range from 118 to 137 MHz-

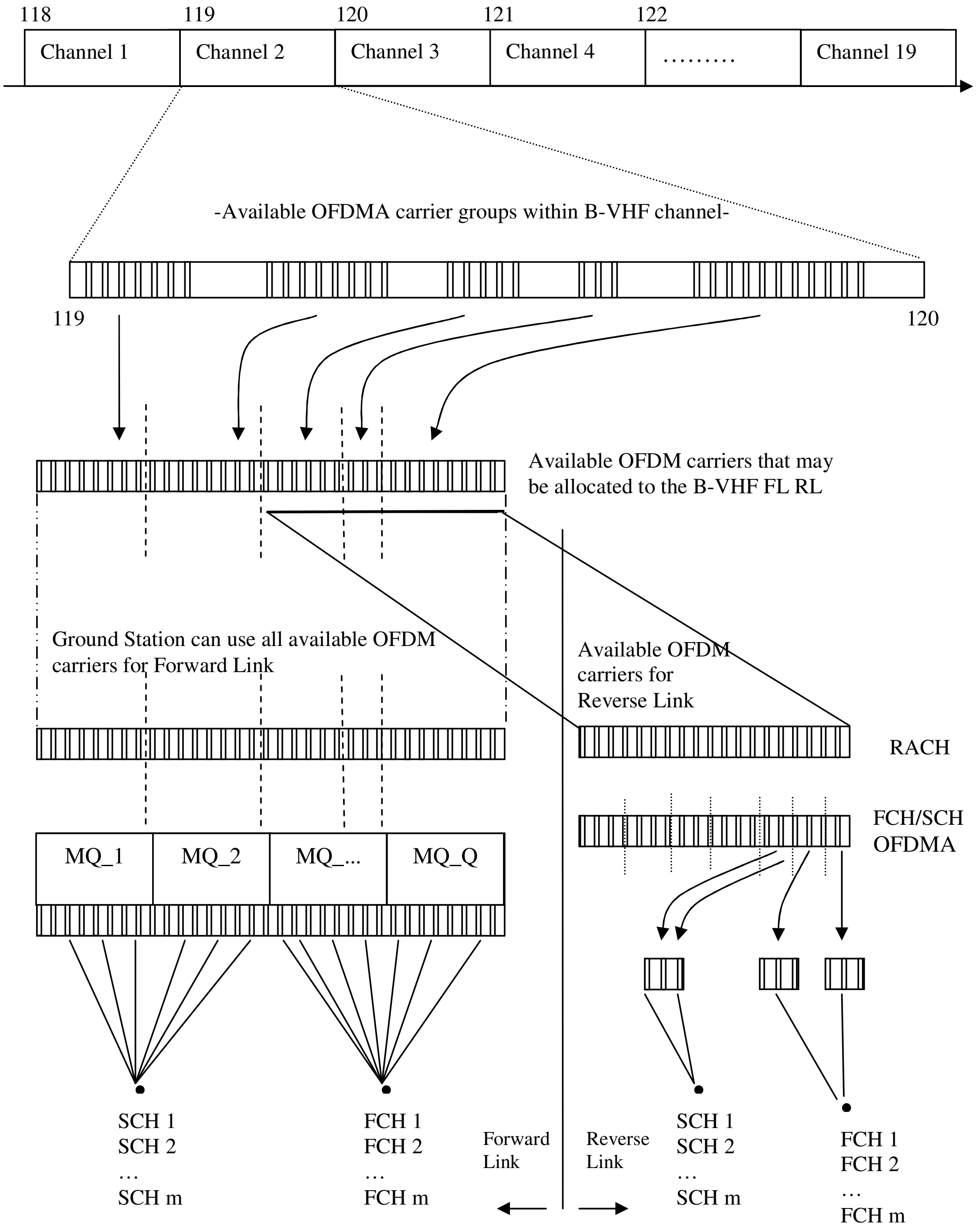

Figure 5-5 B-VHF MC-CDMA at FL and OFDMA at RL

CHAPTER 6

OFDM-CDM SIMULATION

6.1 B-VHF System Communication Performance

The B-VHF system spectral efficiency compared to legacy solutions bring potential for significant increase. (Supports an increased number of users within the same VHF spectrum 118-136 MHz) In addition, the B-VHF broadband channel promises much higher aggregate channel throughput than the sum of legacy systems occupying the same spectrum.

6.2 Proposed Configuration in B-VHF Reverse Link

Before going further in our analysis, the difference between the OFDMA and OFDM should be made clear. IEEE 802.16d (fixed service) uses Orthogonal Frequency Division Multiplexing (OFDM). IEEE 802.16e (mobile) uses Orthogonal Frequency Division Multiple Access (OFDMA). OFDM allows only one user on the channel at any given time as stated in Chapter 4. To accommodate multiple users, an OFDM system must employ Time Division Multiple Access (TDMA) (separate time frames) or Frequency Division Multiple Access (FDMA) (separate channels). Neither of these techniques is time or frequency efficient. OFDMA is a multi-user OFDM that allows multiple accesses on the same channel (a channel being a group of evenly spaced subcarriers). OFDMA extended OFDM accommodates many users in the same channel at the same time. OFDMA distributes subcarriers among users so all users can transmit and receive at the same time within a single channel on subchannels. Subcarrier-group subchannels can be matched to each user to provide the best performance, meaning the least problems with fading and interference, based on the location and propagation characteristics of each user. B-VHF system reverse link is based on OFDMA. Instead of CDM application on top of OFDMA, for multi user environment, we will focus on OFDM-CDM technique. In OFDMA, available subcarriers are distributed among all users for transmission at any time instant and therefore each user is allocated a pre-determined band of subcarriers. OFDM systems require additional methods to exploit diversity, since the performance of uncoded OFDM systems in time and frequency selective channel is poor.

CDM application on OFDM or OFDMA where the only differences in practical [20] sense is the reserve available or a certain bunch of subcarriers is distributed among the users. We propose that CDM application will increase security, provide interference robustness and frequency diversity.

The fading difference at different frequencies is the increasing frequency diversity. When there is a fade at one frequency, there may not be a fade at another. To make use of this, one should transmit signal on two frequencies or in different sub carriers. At the receiving end, a circuit measures the signal-to-noise ratio in two receivers and automatically selects the best at any instant in time. This technique is well suited in reverse link since each user sends a number of information to ground station. Providing security against unwanted third party listeners is achieved by CDM. [21]

As soon as the interleaving is not perfect, the diversity offered by the channel is smaller than the spreading code length L, or we apply CDM where SI (Symbol Interference) and noise amplification occur at the receiver. For $L=1$ the performance of an uncoded OFDM system is obtained which can not exploit any diversity.

Achieving diversity in OFDM systems is channel coding, where the information of each bit is spread over several code bits.

6.3 OFDM-CDM

When combining OFDM-CDM with channel coding, this scheme can benefit from the spreading gain. The typical transmitter of an OFDM system with CDM is shown in Figure (6-1).

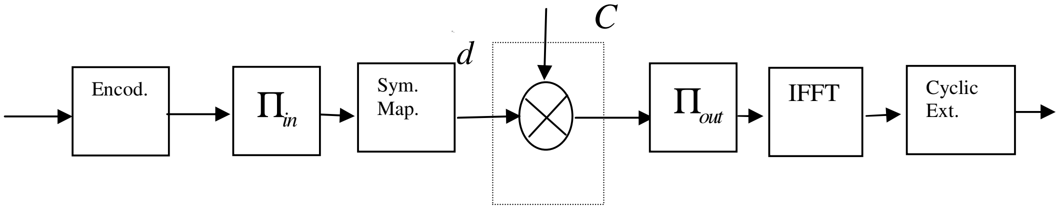

Figure 6-1 OFDM-CDM Typical Transmitter

After channel encoding, outer interleaving Π_{out} and symbol mapping, the complex valued data symbols d are multiplied. The data symbols d are of duration $T_d = LT_c$ where T_c is the duration of a chip, and L is the length of a spreading code. As a result of the inner encoder the spreading does not change the bit rate. Given the vector,

$$d = (d_1, d_2, ..., d_L)^T \tag{6.1}$$

consisting of L subsequent data symbols, the inner encoding results in the encoded sequence s is given by,

$$s = C_L d = (S_1, S_2, ..., S_L)^T \tag{6.2}$$

Variables which can be interpreted as values in the frequency domain like the symbols S_l, $l = 1, ..., L$ each modulating another subcarrier frequency are written in capital letters. The transpose is denoted by $(\cdot)^T$

The resulting L columns c_l of the matrix C_L represent the orthogonal spreading codes. After the interleaving operation Π_{in}, the sequence is modulated onto different OFDM symbols, depending on the depth I_{in} of the inner interleaver. The total number of subcarriers is N_c. The interleaver Π_{in} with size performs frequency interleaving for $I_{in} \leq N_c$ and time and frequency interleaving for $I_{in} > N_c$. Moreover $L << N_c$ reduces the complexity of the receiver. Thus, several sequences can be modulated in parallel. OFDM comprises the blocks inverse fast Fourier transform (IFFT) and cyclic extension of an OFDM symbol as guard interval.

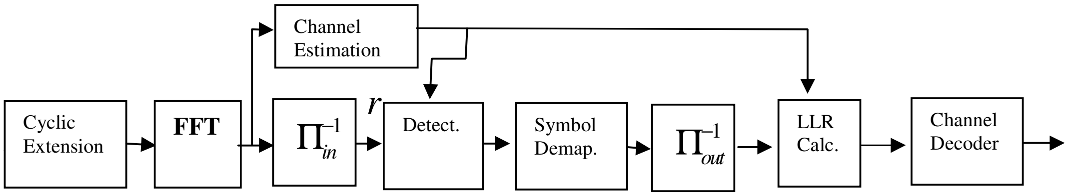

Figure 6-2OFDM-CDM Typical Receiver

An OFDM-CDM receiver is shown in Figure 6-2 above. Two types of detection techniques can be distinguished: 1) single symbol detection where one data symbol d is detected, not taking into account any information about the SI, and 2) multisymbol detection where knowledge about the SI is exploited.

6.4 Simulation on OFDM-CDM

We have developed a matlab code which is given in the Appendix and using this code we have taken numerical results to compare the BER performance between the reverse link channels of OFDM alone and OFDM-CDM combination. In order to simplify the simulation design we have taken OFDM-CDM instead of OFDMA-CDM combination. OFDMA usage in practical sense is to allocate available subcarriers to different users but on the other hand OFDM allocate all subcarriers to a user (aircraft) at B-VHF reverse link. Hence, CDM simulation performance makes no difference whether it is applied to OFDM or OFDMA. Hereinafter we have taken OFDM substitude of OFDMA Basically we have followed the following Figure (6-3) while generating the matlab code.

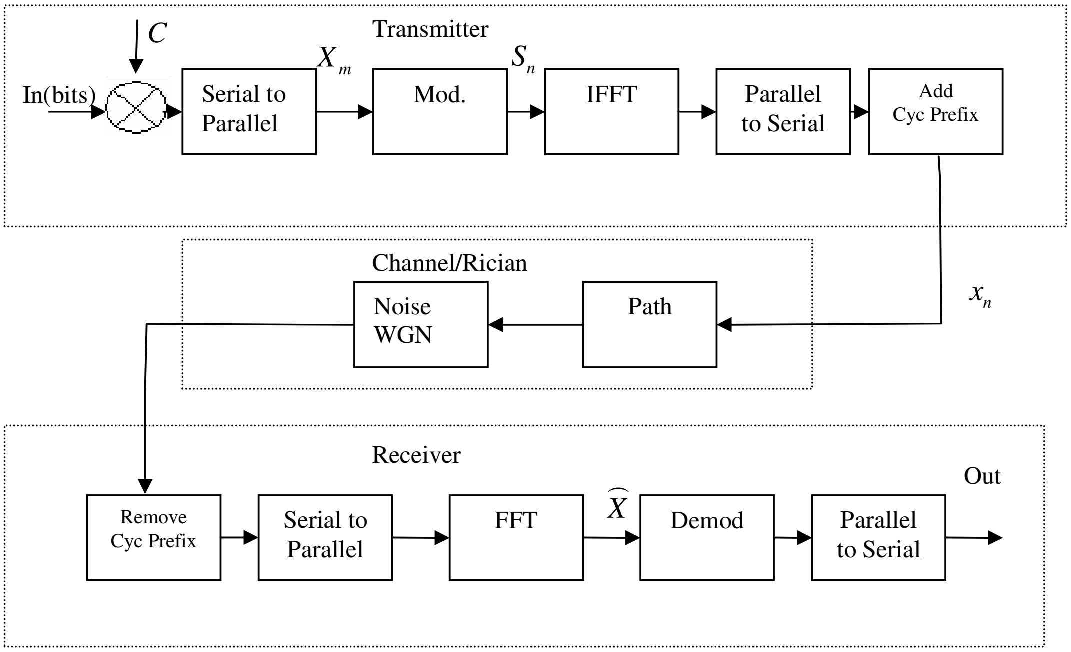

Figure 6-3 OFDM/ OFDM-CDM

In the construction of simulation model random numbers uniformly distributed between 0 and 1 bits generated. The generated numbers decided 1 if the numbers are greater and equal to 0.5 and otherwise -1. The length of the randomly generated bits depends on the size of the Fast Fourier Transform at the receiver end or the Inverse Fast Fourier Transform at the transmitter. An Inverse Fourier Transform converts the frequency domain data set into samples of the corresponding time domain representation of this data. Specifically, the IFFT is useful for OFDM because it generates samples of a waveform with orthogonal frequency components.

The generated digital signals in bipolar form, that is +1s and -1s, are demultiplexed out into I and Q form to obtain QPSK. The reason why we have taken QPSK among all other digital modulations is that fairly resistant to noise.

The transmitter first converts the input QPSK data from a serial stream to parallel sets. Each set of data contains one symbol, for each subcarrier. A set of $(N-2)$ data would be $[S_0, S_1 \ldots\ldots S_{N-1}]$. Hereinafter N will be called FFT size in order to use the same terminology as used in the matlab code. For more accuracy when considering the DC offset, all parallelized blocks are zero-padded.

In order for the IFFT/FFT to create an ISI-free channel, orthogonal OFDM symbol must be kept independent of each of the others. When an input data stream $x_{[n]}$ is sent through a linear time-invariant channel $h_{[n]}$, the output is the linear convolution of the input and the channel $y_{[n]} = x_{[n]} * h_{[n]}$. It is possible to compute $y_{[n]}$ in terms of circular convolution.

$$y_{[n]} = x_{[n]} * h_{[n]} = h_{[n]} * x_{[n]} \qquad (6.3)$$

where

$$x_{[n]} * h_{[n]} = h_{[n]} * x_{[n]} \triangleq \sum_{k=0}^{N-1} h[k]x[n-k]_N \qquad (6.4)$$

and the circular function $x[n]_N = x[n \bmod N]$ is a periodic version of $x_{[n]}$ with period N. In this case of circular convolution, it would then be possible to take the FFT of the channel output $y_{[n]}$ to get

$$FFT\{y_{[n]}\} = FFT\{x_{[n]} * h_{[n]}\} \qquad (6.5)$$

which yields in the frequency domain,

$$Y_{[m]} = H_{[m]} X_{[m]} \qquad (6.6)$$

The duality between circular convolution in the time domain and simple multiplication in the frequency domain is a unique to the FFT. The N point FFT is;

$$FFT\{x_{[n]}\} = X[m] \triangleq \frac{1}{\sqrt{N}} \sum x[n] e^{-i\frac{2\pi nm}{N}} \qquad (6.7)$$

and the inverse of the FFT is IFFT;

$$IFFT\{X[m]\} = x_{[n]} \triangleq \frac{1}{\sqrt{N}} \sum X[m] e^{i\frac{2\pi nm}{N}} \qquad (6.8)$$

The formula given by Eq. 6.8 describes an ISI-free channel in the time domain. Since the given $X_{[m]}$ is complex valued, the channel frequency response becomes trivial to compute. In our simulation program, an ISI free channel is generated with a low complexity, a cyclic prefix is added to the transmitted signal with the given parameter.

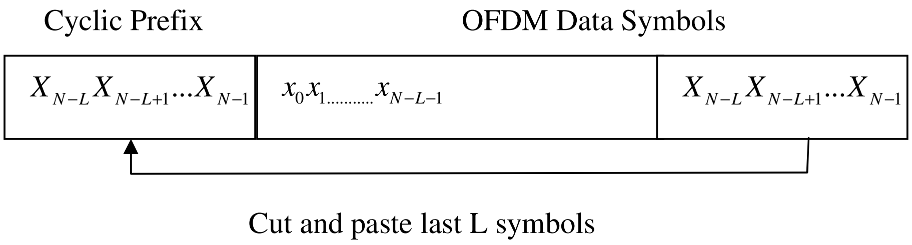

Figure 6-4 Cyclic Prefix

An OFDM symbol in the time domain with length N gives $x=[x_1x_{2\dots\dots}x_N]$ and after applying a cyclic prefix of length L, the actual transmitted signal becomes, $x_{cp}=[x_{N-L}x_{N-L+1\dots\dots\dots\dots\dots}x_{N-1}x_0x_1\dots\dots\dots\dots x_{N-1}]$. Although cyclic prefix addition to a OFDM symbol is simple, the power loss $10\log_{10}\frac{L+N}{N}$ and bandwidth requirement from B to $B10\log_{10}\frac{L+N}{N}$ is the penalty of usage cyclic prefix. So that we can conclude to choose the length of cyclic prefix in a reasonable range $N>>L$. In our simulation, the length L is chosen with respect to the length of N. The data is then prepared for transmission, i.e., serialized and appended with a cyclic prefix.

The most frequently assumed model for a transmission channel is the additive white Gaussian noise (AWGN) channel. Using Matlab for digital communication systems simulation, one has the advantage of exploiting the powerful features of its Communication Toolbox. [22] The radio channel is characterized by two types of fading effects: large-scale fading and small scale fading. Large scale fading is the slow variation of the mean (distant-dependent) signal power over time. This depends on the presence of obstacles in the signal path and on the position of the mobile unit. Since the large scale fading is assumed to be slow process and is commonly modeled as having lognormal statistics. Small scale fading is called Rayleigh and Rician fading because if a large number of reflective paths is encountered, the received signal envelope is described by a Rayleigh or a Rician probability density function. In these fading channels there is also flat fading since there is no ISI. With the modeling of fading channel, the main difference with respect to an AWGN channel resides in the fact that fading amplitudes are now Rayleigh or Rician distributed random variables, whose values affect the signal amplitude of the received signal. In our simulation Rayleigh fading is not preferred since in the Rayleigh fading channel multiple reflective paths are large in number and there is no dominant line of sight (LOS) propagation path. In the proposed configuration of B-VHF Project and the application of radio channel in all aspects of forward link and reverse link is more convenient with Rician fading channel since the LOS path is dominant. The best and worst case Rician fading channels associated with K factors are 0 and ∞. $K = \beta^2 / 2\sigma_0^{\ 2}$ where β is the amplitude of the specular component and $\sigma_o^{\ 2}$ is Gaussian random processes variance. In practical terms we used Matlab Simulink Rician fading channel with the setting using the given parameters of the channel, the K factor being 100, 10 and 1. The only available channel model in the current Communication Toolbox is the wgn m-file, which we used in the Matlab code. After OFDM symbol generated and passed through the Rician channel, the noise signal generated using the wgn function and is subsequently added to the resulting signal.

At the receiver, the cyclic prefix is discarded, and the N received symbols are demodulated using FFT operation, which results in N data symbols. Each subcarrier equalized via FEQ by simply dividing $\widehat{X}$ subcarrier by the complex channel gain (y_rmCP). We have neglected a number of issues thus far. For example, we assumed that the transmitter and receiver are perfectly synchronized, and that the receiver perfectly knows the channel in order to perform the FEQ.

After achieving OFDM transmitter, receiver and a channel we implement a randomly generated chip code which is called *pn* in Matlab code in order to achieve diversity in OFDM system as shown in Figure 6-3. The information of each data bit is spread over several code bits.

The diversity gain can be obtained due to the selection of appropriate coding and decoding algorithms. The given vector in simulation is; $d = (d_1, d_2, ..., d_L)^T$ where d represents bits vector. Consisting of N subsequent data symbols, the inner encoding results in the encoded sequence s given by,

$$s = C_{pn} d = (S_1, S_2, ..., S_N)^T$$

Variables which can be interpreted as values in the frequency domain like the symbols S_l, $l = 1, ..., N$ each modulating another subcarrier frequency are written in capital letters. The transpose is denoted by $(\cdot)^T$

The resulting N columns c_l of the matrix C_L represent the orthogonal spreading codes and same as OFDM symbol reproducing, each subcarrier is equalized via FEQ by simply dividing by complex channel gain (y_cur1) fort $\widehat{X}_1$ subcarrier. In both case to take a numerical comparison, number of bits has been taken between [-1,+1] and -1 bits converted to 0 in order to use **biterr** m-function to get number of bits with errors. [23] The probability of error, BER, denoted by P_e can be computed in the formula, $P_e = \sum_{e=1}^{n} \rho_e / n,$ where n is the number of output bits_out for OFDM and bits_out1 for OFDM-CDM.

If an error has occurred $\rho_e = 1$, and otherwise $\rho_e = 0$. By repeating the same transmitted signal for several successive SNR values (0….12) we obtain a graph of probability of error, BER, against SNR. γ_b is the ratio of symbol energy E_b to noise spectral density N_0.

6.5 Simulation Results

In this section, several simulation results are presented which are obtained by using OFDM-CDM and only OFDM systems. Bit error rates with the indicated parameters are calculated versus the signal to noise ratio are calculated and provided in Figures (6-5) – (6.8).

Setting the cyclic length (L), FFT size (N), PN code length (T), Rician Fading Channel factor (*K*) and noise parameters we get the following Figures.

In Figures (6-5) – (6.8), the curves with continuous lines represent BER values in OFDM channel while the curves with dashed lines indicate BER values in OFDM-CDM channel. BER results are plotted versus the SNR points by means of the Matlab function **semilogy** and Figures (6-5) – (6.8) are obtained under the same channel and noise constraints in order to compare OFDM only BER results with the OFDM-CDM combination BER results versus SNR.

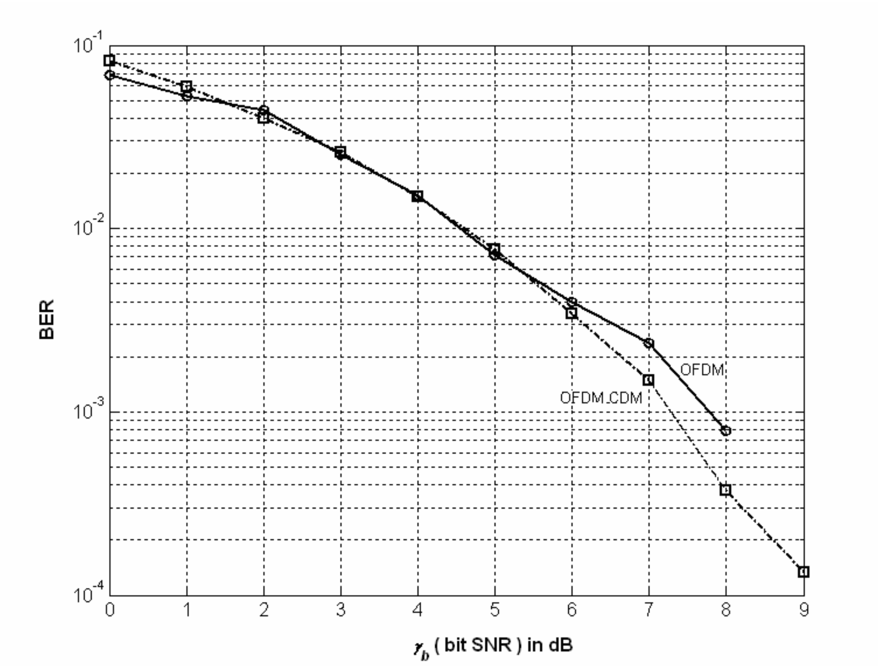

Figure 6-5 K=100, num=100, L=4, N=64, T=31

In Figure (6-5), we set Rician channel K factor to 100, OFDM symbol number to 100, symbol length cyclic prefix to 4, spreading code length to 31and FFT size to 64. It can be seen in Figure (6-5) that as SNR values increase OFDM-CDM curve behaves favorable as compared to OFDM only curve.

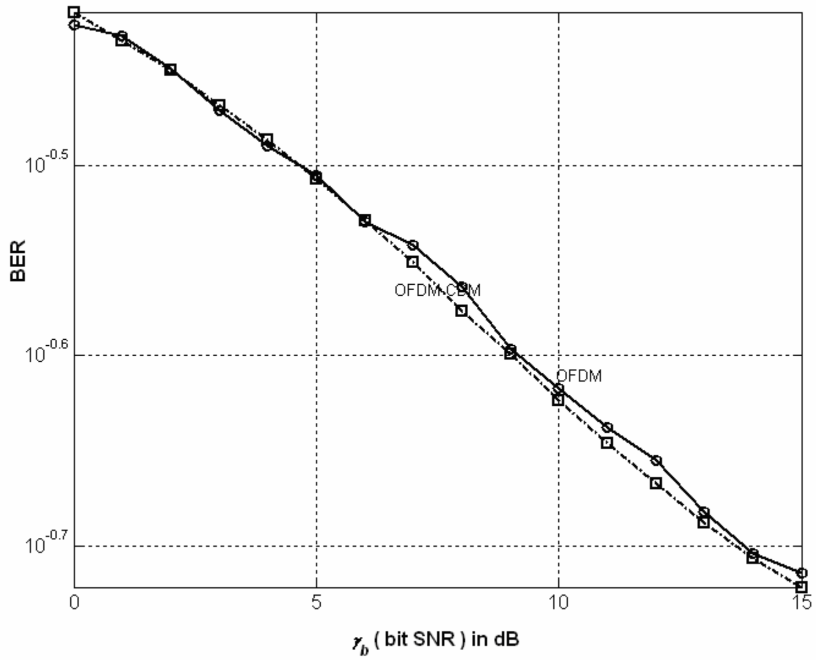

Figure 6-6 K=1, num=100, L=8, N=64, T=31

In Figure (6-6), we set Rician channel K factor to 1, OFDM symbol number to 100, symbol length cyclic prefix to 4, spreading code length to 31and FFT size to 64. The differences of OFDM-CDM BER values against OFDM BER are slightly better for values of SNR ranging from moderate to high.

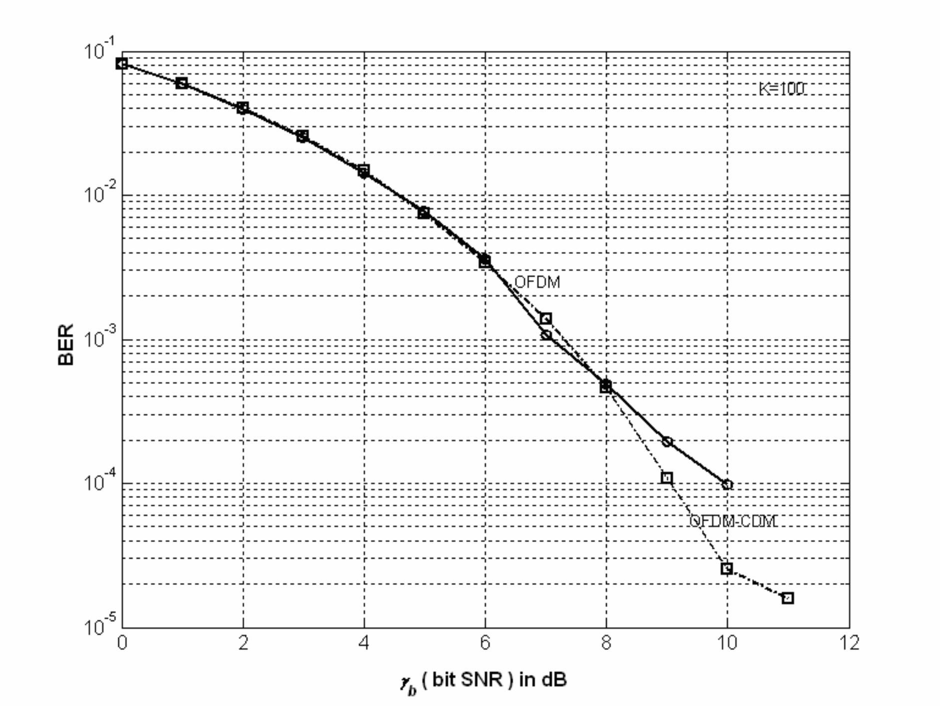

Figure 6-7 K=100, num=10, N=1024,L=16, T=31

In Figure (6-7), we set Rician channel K factor to 100, OFDM symbol number to 10, symbol length cyclic prefix to 16, spreading code length to 31and FFT size to 1024. As seen in Figure (6-7) for large SNR values OFDM-CDM becomes advantageous over OFDM in terms of BER.

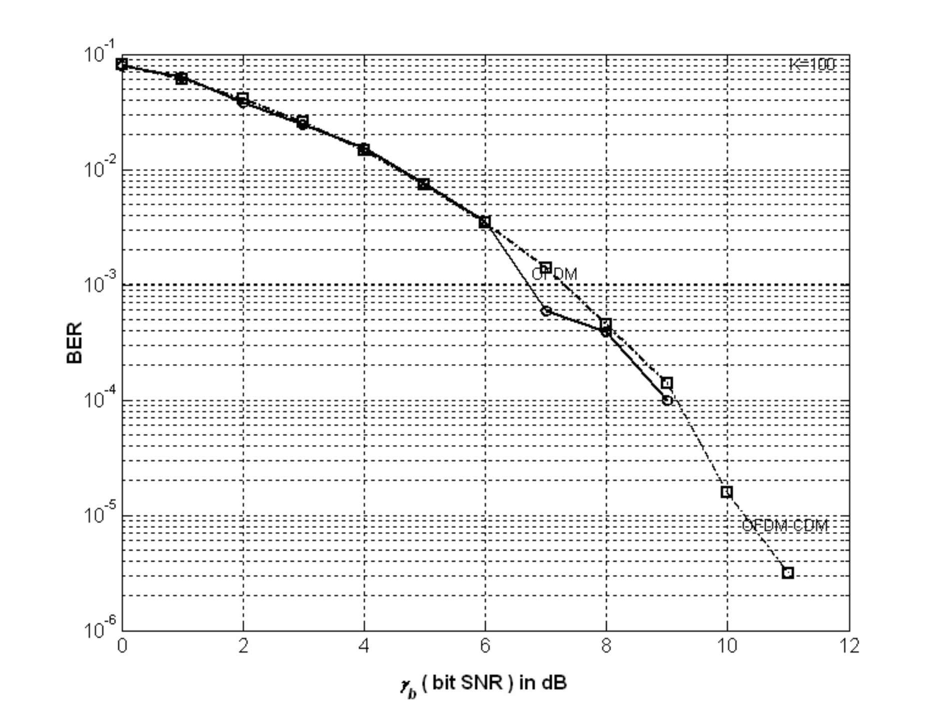

Figure 6-8 K=100, num=10, N=1024,L=32, T=31

In Figure (6-8), we set Rician channel K factor to 100, OFDM symbol number to 10, symbol length cyclic prefix to 32, spreading code length to 31and FFT size to 1024. The difference between Figure (6-7) and Figure (6-8) is the length of cyclic prefix length. In Figure (6-8), the situation observed is reversed so that at SNR values between 6 and 8, this time OFDM BER values are slightly better than OFDM-CDM BER values.

CHAPTER 7

CONCLUSIONS

We have studied both current and ongoing Air Traffic Control Communication, Navigation and Surveillance systems. The bottlenecks of current Communication, Navigation and Surveillance systems are discussed in detail. VHF Data Links are analyzed by considering the physical layer. Broadband -VHF Project with its physical layers of OFDM, OFDMA and MC-CDMA are examined. We proposed substitution of OFMDA-CDM for OFDMA in the reverse link. We developed Matlab Code to simulate OFDM-CDM in order to receive numerical results and its advantages.

We have also analyzed VHF Datalinks Modes. VHF Mode 2 and Mode 3 use D8PSK digital modulation and it is sensitivity to noise. VHF Mode 4 transmits with GFSK modulation scheme but only provides data link which means voice communication needs can not be supplied as in VDL Mode 2. All these technologies are based on TDMA and this multiple access protocol can not cover future needs.

The baseline technology of B-VHF project is MC-CDMA as in the fourth generation (4G) mobile communications. It increases voice and data capacity and addresses security and safety issues with a service level.

B-VHF approaches communication in two different ways by considering the inherit aeronautics communications needs.
The one from ground stations to aircrafts (forward link) is based on combination of OFDM-CDMA called MC-CDMA and the second link from aircraft to ground (reverse link) is based on combination of OFDM-FDMA.

In the B-VHF system forward link design is inherently robust against narrow band jammers since the FL is based MC-CDMA technology. In the reverse link (RL) additional frequency diversity can be obtained with OFDMA-CDM by spreading each data symbol in frequency and time.

The RL simulation developed throughput this thesis to verify CDM application is expected to improve the performance. We have prepared a Matlab simulation to introduce CDM into the OFDM reverse channel. However, within the limitations of our simulation, BER results did not fully meet our expectations that introduction of CDM would lower BER values in a distinct manner.

In future, Rayleigh channel, Hadamard codes, interleaving, M-QAM symbols, M-PSK or passband signals can be added to our simulator to obtain results in different forms of OFDM-CDM transmitters and receivers.

REFERENCES

[1] Advance Aviation Technology, (2005), *Global Airline Operational Communication*,England.

[2] Eurocontrol (2006), *Civil-Military CNS/ATM Interoperability Roadmap*,Brussels.

[3] **MAHAFAZA, B.R.** (1998), *Introduction to Radar Analysis*, CRC Press, Alabama.

[4] **COLE, H.W**.(1992), *Understanding Radar*,Blackwell Scientific Publications, Oxford,London.

[5] **STEVENS, M.C.**, (1988), *Secondary Surveillance Radar*, Artech House INC., Norwood, England.

[6] **FLYNN. E**., (1995), *Understanding Acars*, Universal Radio Research, Columbia, U.S.A.

[7] VDL and ATN services, (2006), *SITA*, Geneva, Switzerland.

[8] Advance Aviation Technology, (2005), *Datalink: Sorting the Facts from the Fiction*,England.

[9] **CLINCH, P**., (2005), *Aircraft Communications Link Selection*, Reference no: ACLS/V1.4, Sita, Geneva, Switzerland.

[10] **KABASERVICE,P.,T**., (2004),*Technical and Economic Benefits of VHF Digital Link Mode 3 Integrated Voice and Data Link for Air Traffic Control Communications*, Phd. Thesis dissertation, University of Yale, U.S.A.

[11] **ROBINSON, D.C**., (2001), *Air Traffic Control Improvement Using Prioritized CSMA,* Glenn Research Center, Cleveland, Ohio.

[12] ICAO SARPS Doc.9816 AN/448, (2004), Manual on *VHF Digital Link (VDL) Mode4*, Montreal, Canada.

[13] **PEREIRA,M.S**. (2002), Choosing the Right VHF Data Link Technology for Commercial Aviation Air Traffic Services, Ms Dissertation, University of Colorado, U.S.A.

[14] **KOCZO.S.,** (1998) *Integrated Airport Surface Operations*,Rockwell Collins Avionics and Communications Advanced Technology Center Cedar Rapids, Iowa.

[15] GMBH-FREQUENTIS (Project Co-ordinator), (2005), *Aeronautical Communications System Based on MC-CDMA,* Vienna, Australia.

[16] **VENKATASUBRAMANIAN,R.,** (2003), *Beamforming for MC-CDMA*,Msc.Thesis,Virginia Polytechnic Institute and State University.

[17] **Haindl B**., et.,al, (in preparation) *B-VHF – A Multi-Carrier Broadband Communications Concept For Air Traffic Management in The VHF Band.*

[18] **LAWREY. E**., (1997), *The Suitability of OFDM as a Modulation Technique for Wireless Telecommunications, with a CDMA Comparison,* Bsc. Thesis, James Cook University, Australia.

[19] **EDFORS O**., et.al, *An introduction to orthogonal frequency-vision multiplexing”*
http://digitalsignallabs.com/esb96rc.pdf

[20] **COSOVIC, I**., (2003) *OFDMA Code-Division Multiplexing with Pre-Equalization for Mobile Communications,* Institute of Communication and Navigation*, Germany.*

[21] **KAISER, S**., (2002) OFDM Code Division Multiplexing in Fading Channels*, IEEE Transactions on Communications*, Vol,50 No:8.

[22] **KOSTOV, N**., (2003) Mobile Radio Channels Modeling in MATLAB*, Radio Engineering*, Vol. 12, No:4.

[23] **AT, N., EYYUBOĞLU, H.T**., (in preparation) Simulation of PSK and QAM for AWGN, Rayleigh, and Rician Channels.

APPENDIX

MATLAB PROGRAM USED IN THIS THESIS
(OFDM TX/RX&OFDM-CDM TX/RX)

```
% One OFDM/CDM Symbol transmitter and receiver including Rician channel
% QPSK transmitter for OFDM
clear;clc;tic;
N=2048;% N is the FFT size
T=8; % pn code length
num=10;% num is the number of OFDM symbol to produce
L=8;% L is the cyclic prefix length
n=(N/2-1)*2*num; %OFDM block length
n1=(N/2-1)*2*num*T; % OFDM-CDM block length
M=4;
% generatate random input sequence of 1 and -1
for i = 1:(N/2-1)*2*num
   if unifrnd(0,1) >= 0.5
      bits(i) = 1;
   else
      bits(i) = -1;
   end
end
%Generating pn code
pn=(2*randint(1,T)-1);
```

```
%Spreading operation
bits1=[];m=length(bits);
for g=1:m;
   st1=bits(g).*pn;
   bits1=[bits1 st1];
end
input=(bits+1)/2;%convert -1 to 0 in order to comparion at bit error number of
(I(n))
input1=(bits1+1)/2;%convert -1 to 0 in order to comparion at bit error number of
(I(n)) for OFDM-CDM
real_index = -1; simag_index = 0; % initial value
new_out=[];
for a=1:num
real_index = max(real_index)+2:2:max(real_index)+N-1;
imag_index = max(imag_index)+2:2:max(imag_index)+N-1;
X = (bits(real_index) + j*bits(imag_index))/2;
X=[0 X 0]; % zero nyquist and DC
x_sym=sqrt(N)*ifft([X,conj(fliplr(X(2:length(X)-1)))]); %Baseband so
Symmetric
x_sym=[x_sym(length(x_sym)-L+1:length(x_sym)),x_sym]; % Add CP
new_out=[new_out,x_sym];
end
real_index1 = -1; % initial values
imag_index1 = 0;new_out1=[];
for b=1:(num*T)
real_index1 = max(real_index1)+2:2:max(real_index1)+N-1;
imag_index1 = max(imag_index1)+2:2:max(imag_index1)+N-1;
X1 = (bits1(real_index1) + j*bits1(imag_index1))/2;
X1=[0 X1 0]; % zero nyquist and DC
x_sym1=sqrt(N)*ifft([X1,conj(fliplr(X1(2:length(X1)-1)))]); %Baseband so
Symmetric
x_sym1=[x_sym1(length(x_sym1)-L+1:length(x_sym1)),x_sym1]; % Add CP
```

```
new_out1=[new_out1,x_sym1];end
new_out=new_out'; %CP added OFDM symbol
new_out1=new_out1'; %CP added OFDM-CDM symbol
% Setting noise power, Average symbol signal power is unity, bit SNR is used %
E_stn = 1;E_st = E_stn/log2(4);
SNR_db = 0:15;
dblen = length(SNR_db);
set_ntp = 10*log10(E_st) - SNR_db - 3.0103;
SNRarr = 10.^(0.2*SNR_db);
% Setting Rician channel Parameters%
Fd = 1;Fs = 1;Es = 1;
K = '100';Tss = 'n1*1e-0';
Fddc = '5e-2';gdB = '0';dVec = '0';
set_param('Ricchan/Rician Fading
Channel','K',K,'Fd',Fddc,'gainVecdB',gdB,'delayVec',dVec);
   sim('Ricchan');
set_param('Ricchan/Rician Fading
Channel1','K',K,'Fd',Fddc,'gainVecdB',gdB,'delayVec',dVec);
   sim('Ricchan');
   P_exp=[];P_exp1=[];
for iSNR = 1:dblen
      nt = wgn(length(new_out),1,set_ntp(iSNR));
      nt1 = wgn(length(new_out1),1,set_ntp(iSNR));
      xt=stc+nt;      % OFDM passing through the rician channel
      xt1=gtc+nt1;    % OFDM-CDM passing through the rician channel
% QPSK receiverv for OFDM
bits_out1=[];bits_out=[];
for a=1:num
   y_rmCP = xt((a-1)*(N+L)+1+L:a*(N+L)); % Get current OFDM symbol, strip
CP
   X_hat = 1/sqrt(N)*fft(y_rmCP);% FEQ Channel and noise
   X_hat = X_hat(1:N/2);
```

```
real_index = 1:2:N-2-1;
    imag_index = 2:2:N-2;
    bits_out_cur(real_index) = sign(real(X_hat(2:length(X_hat))));
    bits_out_cur(imag_index) = sign(imag(X_hat(2:length(X_hat))));
    bits_out=[bits_out,bits_out_cur]; % u(t)
end
bits_out=(bits_out+1)/2;%convert -1 to 0 in order to comparion at bit error
P_expt = biterr(input,bits_out)/n ;
P_exp = [P_exp P_expt];
for b=1:(num*T)
    y_rmCP1 = xt1((b-1)*(N+L)+1+L:b*(N+L)); % Get current OFDM symbol,
strip CP
    X_hat1 = 1/sqrt(N)*fft(y_rmCP1);% FEQ Channel and noise
    X_hat1 = X_hat1(1:N/2);
    real_index1 = 1:2:N-2-1;
    imag_index1 = 2:2:N-2;
    bits_out_cur1(real_index1) = sign(real(X_hat1(2:length(X_hat1))));
    bits_out_cur1(imag_index1) = sign(imag(X_hat1(2:length(X_hat1))));
    bits_out1=[bits_out1,bits_out_cur1]; % u(t)
end
bits_out2=(bits_out1+1)/2;%convert -1 to 0 in order to comparion at bit error
P_expt1 = biterr(input1,bits_out2)/n1 ;
P_exp1 = [P_exp1 P_expt1];
end
semilogy(SNR_db,P_exp,'-ok','LineWidth',2);hold on;gtext('OFDM');
semilogy(SNR_db,P_exp1,'-.sk ','LineWidth',2);hold on;gtext('OFDM-
CDM');grid on;gtext('K=100');
set(gcf,'Color','w');set(gca,'FontSize',12);toc;
xlabel('\it\gamma_b \rm\bf( bit SNR ) in dB','FontSize',12,'FontWeight','bold');
ylabel('\itQPSK-OFDM/OFDM-CDM \rm\bf(
BER)','FontSize',12,'FontWeight','bold');
diffx = max(SNR_db)-min(SNR_db);diffy = max(P_exp)-min(P_exp);
```