Studies on Multiple Access for Aeronautical Wireless Network

航空無線ネットワークにおける多元アクセスに関する研究

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Doctoral Dissertation

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Summary

There are two major studies presented in this dissertation. The first study concentrates on the communications between commercial aircraft and ground air traffic controller (ATC) system. The second study is about the communication between an unmanned aerial vehicle (UAV) and a wide area wireless sensor network (WSN) on the ground. Regarding to the former study, it aims to provide a revolution in communications between aircraft and air traffic controller as well as the communication between aircraft and aircraft. For the case of communication between aircraft and ATC system at the areas near the airport since from the aircraft, the study has deeply conducted an empirical study for a new wideband, 5 GHz band, in chapter 3. This study has also provided a novel solution for improving the received signal power at the area located above the dimensional transmitting antenna. The feasibility of this 5 GHz band is that at least validated by a system performance comparison with VDL-2 system and under the same conditions of communication at each phase of the flight. The valuable achievement of this band comparing to the conventional VHF band is its wide spectrum. The abundant spectrum is also a fundamental condition to deploy a multi carrier transmission technique for a high bit rate communication between an aircraft and an ATC system. A preliminary evaluation of multi carrier transmission technique has been carried out. This is one of the most important requirements for building communication systems at advanced airport in the near future. Chapter 4 provides another breakthrough to the aeronautical communication system where a direct communication among the aircraft has first been proposed. In this case, each aircraft is not only a human carrier but also a data information carrier and forwarder in a multi hop relay network. This concept does not exist in the current aeronautical communication network yet. Our proposal has shown the benefits of a TDMA based multi hop ad hoc data relay network built among the aircrafts on the ocean with the control functions at ground stations. It has significantly improved the situational awareness for the oceanic flights which is now very limited in avionic communication. This is the essential condition for the airlines authority to reduce the separation distance between the two aircrafts in order to use airspace more efficiently. The designed system is mainly based on an experimental study that has determined the most effective communication distance between

an aircraft and an aircraft on the ocean. In addition to the proposal in chapter 4, the next chapter has added another novel S-TDMA based access scheme that is more autonomous than the prior access scheme. For this system, the aircrafts in a sub space are able to autonomously reorganize if an aircraft enters or leaves the sub space. In addition, a model of a multi channel is provided in order to increase the ability of data transmission at each aircraft. With three supporting schemes of IB-NS (Interference Based Node Selection), DBTA (Distance Based Timeslot Assignment) and PATR (Position Aid Timeslot Reuse), system performance has obtained a high capability of relaying packet even system suffers a high number of relaying hops. More interestingly, chapter 6 introduces a new communication model with another aerial vehicle that operates at a lower altitude comparing to commercial aircraft's altitude. In this system, an UAV (Unmanned Aerial Vehicle) is employed for collecting information from a large area WSN (Wireless Sensor Network). The proposed FRA (Frame Based Random Access and PFS (Prioritized Frame Selection) schemes are the core of the proposed communication protocol. FRA is efficiently used for quickly access to the channel, which is much faster than the common methods in conventional WSNs. PFS is the scheme to manage and adjust the number of priority groups that enables systems obtain a PER that is better than the requirement. With the ability of quick accessing to channel (FRA scheme) and well managing the priority of sensor groups as well as properly selecting the number of priority groups (PFS scheme), this communication protocol is able to maximize the number of sensors communicating with UAV at the same time. This communication model is potential in a list of applications where the proposed communication protocol could still be used with a minor modification. Moreover, further discussions for each study are also proposed and illustrated in chapter 7.

To my parents,

To my wife,

To my son.

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1

INTRODUCTION

This chapter briefly explains the outline of the dissertation. The beginning of the chapter describes the current state of the art in aeronautical communication. This part has also mentioned the future requirements that the current systems might not afford to. From these opening issues, we confidently show our two major studies which cover entirely aeronautical communication. They include air to ground communication and air to air communication systems. With the achievements of communication protocols studied in aeronautical communications for commercial aircrafts, we believe that they are suitable to apply for lower altitude air vehicles such as helicopter, UAV (Unmanned Aerial Vehicle) in the future. Our studies will contribute to the development of new standards in aeronautical communications because they have searched for those revolutions to prepare for future ATN (Aeronautical Telecommunication Network). Besides the communication used for aeronautical communication, we have also proposed a novel communication system that employs UAV and wide area wireless sensor network (WSN). This proposal is promising to be utilized in a variety of applications in both society and academia. It also strongly recommended to be used for urgent situations or difficult missions that may be harmful to the human lives.

1.1 State of the art in Aeronautical Communications

Nowadays, the air transportation has become an indispensable mean for the people who move between the two distant places. These aircrafts belong to both domestic and international flights groups.

The former group usually includes the flights passing through the continental areas (Fig. 1.1). For these continental flights, a direct communication between aircraft and ground air traffic controller (ATC) usually exists at all the time of flight [1]. For the direct communication between the aircraft and the ground station, the VHF (Very High Frequency) band based systems are commonly used. Also, the radar systems at ATCT, TRACON, and ARTCC are actively used for detecting the aircrafts' positions. The position information of all the aircrafts supplement to the air traffic controllers for mastering the aircrafts.

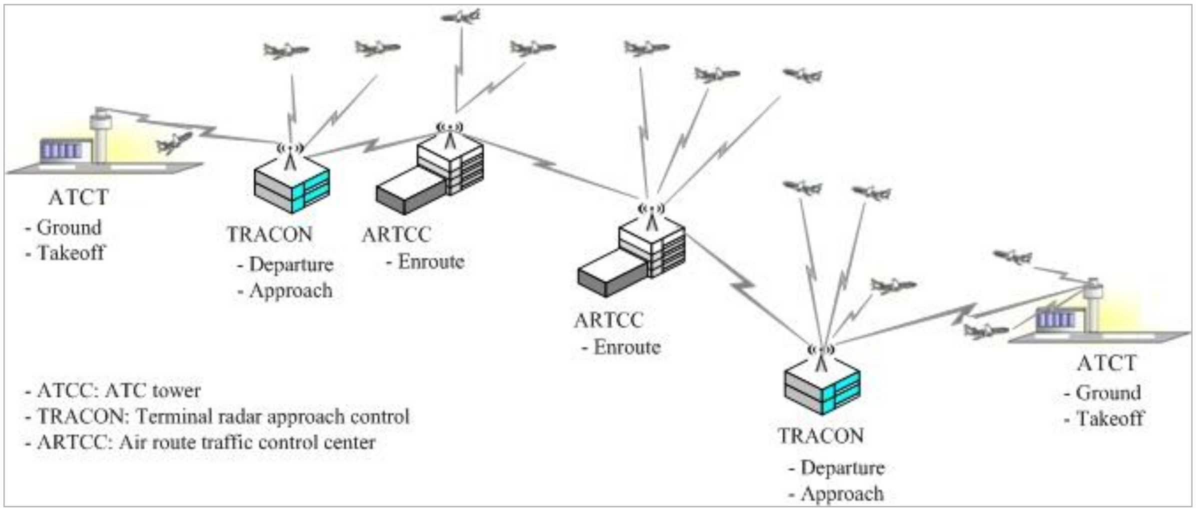

Figure 1.1 The current continental air traffic control communication systems

The latter group contains the flights which usually pass through the oceanic areas. In these cases, the distance between the aircraft and the ground system is large and it might be larger than the communication distance of VHF system. Therefore, to oceanic flight routes, VHF based communication system is not suitable anymore. A long distance communication such as HF radio or SATCOM (Satellite Communication) system is used instead of VHF system. HF radio based system is especially used for the flights across the polar areas as SATCOM is not available at these areas. As a result, at the most favorable radio frequency spectrum, an aircraft needs to setup both voice and data communications with air traffic controller. Figure 1.2 shows the current situation of oceanic air traffic control communication.

Figure 1.2 The current oceanic air traffic control communication systems

Regarding to the history of current aeronautical communication systems, in the early eighties worldwide data networks were developed as an addressable, digital data link for commercial and business aircrafts. This system is known as ACARS (Aircraft Communications Addressing and Reporting System) [2]. It is introduced to reduce the flight crew's workload by using modern computer technology to exchange many routine reports and messages. Also, ACARS enhances the conventional VHF based voice services, which were claimed with several limitations. ACARS system has therefore improved the safety and efficiency of modern air transportation. However, ACARS system is only suitable for transmissions of short and simple messages between aircrafts and ground stations via HF, VHF or satellite system. As a result, a requirement of adding another high capability radio system has been emerged. Long after 20 years, a much faster and higher capacity than ACARS system was developed called VDL-2 (VHF Data Link Mode 2) [3]. This system works on VHF frequency band and provides a transmission of text messages between aircraft and ATC system on the ground. VDL-2 system can provide communication with a maximum bit rate of 31.5 kbps for a distance up to 370 km (200 nautical miles). This system has enabled the airport to accommodate communication for a larger number of aircrafts compared to ACARS's system. This is because VDL-2 uses the spectrum more efficiently than the ACARS system [4]. However, VDL-2 system uses CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) for multiple aircraft access; hence, the delay is not guaranteed to implement a critical time service. This is more serious when the communication distance is as large as 200 NM. Correspondingly, a newer version of VDL-2 system has been required for development. This system has been trialed recently which named VDL-3 (VHF Data Link Mode 3). VDL-3 system uses TDMA scheme for multiple access among the aircraft, therefore the delay is guaranteed. Moreover, the services in VDL-3 system include not only data but also voice communications [5]. However, VDL-3 system does not improve the capacity of air to ground communication system. In addition, the requirement of exchanging more advanced information between aircraft and ground station has always increased. Therefore, the serious requirement has forced the researchers and related organizations, such as ICAO (International Civil Aviation Organization), FAA (Federal Aviation Administration) to prepare for a next generation air to ground system [6]. The future system is required to have ability to accommodate much larger air traffic comparing to the current system's capability. As the typical features of security for the aircraft during its taking off and landing, another concern is an ability to provide a high speed communication between the aircraft and air traffic controllers at the airport as well as the areas nearby the airport.

Following more specific demands for the communication between the aircraft and the air traffic controller, there are three distinct portions of the future air to ground system that it must satisfy the respective operational requirements. The air to ground communication system needs to provide following capabilities:

- ❖ High system capacity for the communication between the ATC station and the aircraft when a direct air to ground data link is available. This situation must be qualified for the service in these two areas: the area near the airport and the area distant from the airport.
- ❖ High frequently position reporting for the aircrafts located in remote and oceanic areas.

For the high bit rate communication system between the aircraft and the ATC station in such a case that a direct connection is available and the aircraft is far from the ground, there has been one study that tries to utilize all the available VHF frequency channels. This system therefore might provide a wideband communication by selecting idle frequencies to use for its communication. This system is called as B-VHF (Broad-VHF) [7]. Regarding to the ability of providing high frequent routine reports from distant aircrafts, the solution is to use satellite system for relaying the reports to the related ground station. However, at the estimated increase in aircraft number, the installation of the new aeronautical satellites for this mission is unavoidable. In addition, this system still does not improve the situational awareness of each aircraft on the airspace because satellite is only used as a data relay station. The next section 1.2 presents our interest on the status of communication systems that employ the Unmanned Aerial Vehicle (UAV). This aerial vehicle is expecting to be a new dimension of the aeronautical communication sector.

1.2 Current Status and UAV Based Communication

According to the studies on air to ground and air to air communications for commercial aircrafts which usually fly at an average altitude of 10 km, these systems are also applicable to the lower altitude air vehicles, such as UAV (Unmanned Aerial Vehicle) [8]. At present, UAVs have not been involved in ATM (Air Traffic Management) system yet [9]. However, the range and height of UAV's flight are improving which might be harmful to commercial aircrafts in the current air transportation service. In addition, the interest of this promising unmanned aircraft has been increased recently, which is not only a hobby but also its usages in commerce and academia. As a result, UAV has been significantly considered to integrate with the current controlled airspace by ICAO and other related organizations. This action indicates the importance and benefit of UAV in future aerial vehicles applications. Assuming that UAV is added to ATN (Aeronautical Telecommunication Network) [10] for a safe air transportation service, UAV platform must be transparent to ATN system. Therefore, we highly expect that ATN will be appended with UAV platform and our studies for commercial aircrafts will be applicable. For systematic organization, there are some methods can be applied in case of integrating UAV. Altitude based communication system can be one of the candidates. It is originated from the significant difference in altitude of an UAV and a manned aircraft. Also, the operating conditions of these two vehicles are also different, so the technical features for respective systems are different. In this dissertation, we do not evaluate our proposals in the case that UAV is integrated with ATN. Actually, this evaluation is similar to the evaluations in our presented studies. We further concern another aspect of the communication relating to UAV but not for air traffic management. It is the communication between UAVs and network systems on the ground. For this purpose, we do concern the communication system employing UAV, in which the communication protocol used by the UAV and the ground system is a major contribution.

The motivation of this study comes from the potential applications that employ UAVs. At present, UAVs have soon become a new component of aeronautical field because of its attractive features comparing to those in conventional helicopters. However, UAVs have been mainly used to collect the negative information from ground (i.e. remote sensing by using camera/video recorder or using onboard sensors), which is similar to the current helicopter's role. Hence, the communication protocol between the UAV (in the air) and a WSN (on the ground) has not been studied or academically reported much. This kind of air to ground communication protocol will become more challenging in the cases of urgent deployment (i.e. emergencies) or harmful to the human lives (i.e. natural and human-made disasters). In the cases that the received data by UAV might lead to a difference between death and life; the more exact and more stable information we get from the ground system the higher possibility we can save more lives.

In our proposed system model, a UAV carries a receiving system and a beacon generator. The receiving system will communicate with the system on the ground. For instance, in the case of monitoring an area, the deployment of a WSN (Wireless Sensor Network) is needed. The sensors sense the surrounding environment and periodically send data to the UAV. The target is to find a stable and effective protocol for the communication between the UAV and the ground system. The performance of system might vary at different operational conditions of the UAV, such as ground speed, altitude, and the density of users communicating with the UAV.

1.3 Contribution of the Dissertation

According to the current state of the art in aeronautical communications and the future requirements of its systems as we have just discussed above, this dissertation have tried to solve the opening issues of this challenging communication by proposing following major novel contents:

1) A wide frequency spectrum for air to ground communication at the areas near the airport. This is fundamental for deploying a wideband communication at advanced airports that it will also be evaluated.
2) A multi hop ad hoc network for relaying data from any distant aircraft (such as oceanic flight) to its relevant ground station. This solution provides the essential conditions for the aircrafts to be near to each other, or means the airspace is used more efficiently.
3) A novel MAC protocol for communication between the UAV and a large area WSN on the ground.

In the third study of 3), we do focus on the UAV based communication system which be used in several kinds of applications, from academia to society. Especially, UAV is much suitable than helicopter in serious cases of urgency such as natural disasters, toxic plume, and so on. In these cases, a network of sensors is necessary for collecting all needed information where the environment is harmful to human lives. In this research, we have introduced a novel communication model and our contribution is to propose:

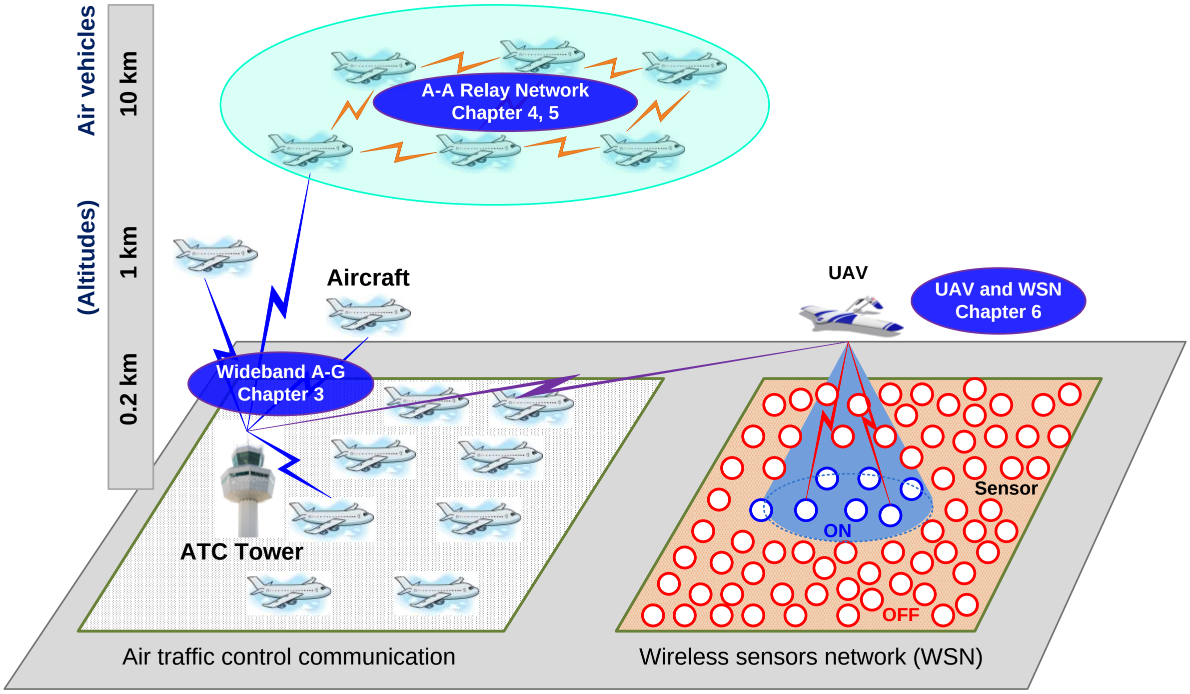

Figure 1.3 The panorama of aeronautical wireless systems in the dissertation

Figure 1.3 briefly expresses our major studies whose detail contents are described above. In this figure, A-G stands for the air to ground communication system, and A-A is for the air to air communication system. More specifically, the A-G communication system that we are going to demonstrate will primarily concern the aircraft located near the ATC tower. Also, in this figure, the vertical column describes not only the type of air vehicles but also the altitude of the respective vehicle. For instance, commercial aircrafts always approach to a height of 10 km during its en-route phase, and its altitude is much lower when it prepare for landing to the destination airport or it was just after the taking-off from the departure airport. Regarding to the altitude of the UAV, it is now always lower than the common altitude of the commercial aircrafts. At present, UAV is not officially controlled by the aeronautical air traffic controllers; but it is considered to be integrated with the aeronautical telecommunication network in the future. The next sections start to clearly describe the full contents of each study.

1.4 Air to Ground Communication at Advanced Airports

For the air to ground communication at future airports, it is difficult to think about the VHF band because the VHF spectrum assigned for each airport is determined. In addition, the aeronautical VHF band becomes saturated soon; and it is difficult to find even a vacant frequency [11], [12]. Therefore, two approaches have been discussed in order to solve this issue. The first solution is to use satellite system for supplementing to the capacity of the current communication systems such as between the aircraft and the ATC controller. The second one is to discover a new wideband spectrum that is feasible to the communication between such aircrafts and ground air traffic controller. However, communication service via satellite system is still relatively expensive; and additional satellites are needed for a global coverage service. As a result, the solution for advanced airport communication only lies on the finding of a new and wide applicable spectrum. There has been a controversy on the capability of using the frequency spectrum of MLS (Microwave Landing System) for airport communications service. The argument originates from the high path loss and high Doppler shift effect that may both affect the system. This band, MLS, is a wide band that ranges from 5030 to 5150 MHz, but the later part of 5091-5150 MHz has not been used. MLS band is just below the 5 GHz wireless local area network (WLAN) band, and hence it could be a benefit if requesting for WLAN manufactures about a new system production for aeronautical communication. Since that meaning, this band is proposed by the representative organizations, such as ICAO (International Civil Aviation Organization) [13], and the ITU (International Telecommunication Union) World Radio Conference [14].

On the top of these attractions, Waseda University and ENRI (Electronics Navigation Research Institute, Japan) have conducted this study during the period of 2004-2005. There were also another study collaboratively executed by Ohio University and NASA [15]. However, this project only focuses on the airport surface communication while our research did concern both airport surfaces and airport nearby areas [16]. For the overlapped research content, the results are quite close to each other. Our experiments and system performance evaluations at this band for advanced airport's communication will be explained and described in chapter 3.

In aeronautical communication, the two primary communication sectors are air to ground and air to air communications. This section already demonstrated the studies in air to ground communication; the next section is for our studies in air to air communication.

1.5 Air To Air Communication

Regarding to the second content which is about a multi hop ad hoc relay network for distant aircrafts, none of previous studies is existing. However, there is a reason why we did not concern about this relay network for continental and polar aircrafts. For continental aircrafts, it is because availability of direct data link between continental flights and ground stations is high; hence, the effect of adding this relay network is not considerable. The reason is different to the polar aircrafts which are not usually crowded, so the capability of establishing an ad hoc network is low. Therefore, our proposals only concern the benefits of doing multi hop data relay for oceanic aircrafts.

Actually, the current aeronautical communication systems for oceanic flights allow the aircraft to send its reports to ground station via HF radio or satellite based systems. In addition, the pilots still can verbally communicate with ground controllers via these systems. The HF and Satellite based systems will be clearly described in chapter 2. As we have mentioned above, the communication services through satellite system are still expensive and long delay so HF based voice communication is the main method for communication between an oceanic aircraft and the ground station. However, it has been reported to be complex in the operation and unstable in system performance. This limitation also applies for the worldwide data communication system that base on HF radio, named HFDL (High Frequency Data Link) [17].

In addition to the existing HF and satellite based communication systems, from the point of view of allowing other aircrafts to know an aircraft's position report, we must mention a recently trailed system, the ADS-B (Automatic Dependent Surveillance-Broadcast) [18]. The aircraft equipped with an appropriate ADS-B transceiver will be able to broadcast its own reports to nearby aircrafts or receive its neighbors' position report. However, there are different kinds of transceivers which are assigned for aircraft type, region, location, etc. Therefore, only the aircrafts equipped with same type of transceiver can exchange their position reports. Also, in an ADS-B system, at the receiving aircraft, there is no further broadcast; hence, the fact that the ground station will receive an aircraft's report is not guaranteed and situational awareness is not high.

Our proposal is to develop a multi hop ad hoc network that uses VHF frequency band for oceanic aircrafts. This network allows each aircraft's position report to be relayed via intermediate aircrafts to the ground station. These intermediate aircrafts are nearer to that station than the transmitting aircraft is. VHF band is the most preferable because its attraction in aeronautical communication field. Also, a wide spectrum allocation in the airspace above the oceans is easier than that in the continental areas. We call this relay network as the air to air communication system that is used for future oceanic aircraft's communication. The details of this content will be described in chapter 4 and chapter 5 which are according to our two proposals.

1.6 Structure of the Dissertation

According to the motivations of the opening issues that we have just described for aircrafts and UAVs, the dissertation will gradually solve each of them. The contents are described in details as the following organization:

- Chapter 1 introduces the research and plan in this dissertation.

- Chapter 2 presents the current air to ground communication systems in aeronautical field. Because the major frequency spectrum used in this sector is HF and VHF, this chapter mainly describes the HF and VHF based radio/data communication systems. In addition to these two bands, the description about satellite based communication system is also presented. The brief introduction of UAV and its potential will finalize the content in chapter 2.

- Chapter 3 introduces our studies on the new frequency band, the MLS band, for aeronautical communications. This chapter starts with a description of a novel experiment for the two communication systems installed on ground and airplanes. Then, our evaluation on radio channel characteristic at this band is demonstrated in details. More specifically, Rice factor and propagation model are derived from the measurements. Another supplemental experiment has also been conducted to improve the signal strength at the areas right above the ground system which uses the directional antenna. Finally, our estimation in terms of system performance has shown that this band is suitable for employing a wideband service air to ground communication at the airport surfaces or the areas near the airport. The reasons that eliminate its applicability to further distant aircrafts include a strong Doppler shift effect and a large transmitting power at such high frequency signal [19], [20].

- Chapter 4 describes in details our proposal of a data relaying system which bases on mobile ad hoc network used for oceanic flight routes in aeronautical communication. This system uses only one VHF channel that is designed to accommodate all the flights i.e. the aircrafts pass through the North Pacific Ocean between Japan and North America. Before demonstrating the communication protocol, we explain in details our novel experiment on air to air communication between the two practical aircrafts and both of them are during the en-route phase of flight. From this experiment, we have found the two major results. The first one is the formula to express the relationship between signal receiving power and relative distance between transmitting and receiving aircraft. The second thing that has been found is the effective distance for air-air communication between the two en-route aircrafts. We also introduce our proposed mechanism in terms of SNR (Signal to Noise Ratio) adjustment in order to increase the successful packet relayed ratio in case many aircrafts join the TDMA multiple access scheme. This mechanism is called IB-NS (Interference Based Node Selection). Another scheme for improving packet error rate during the sparse aircraft situations has also been illustrated, named NADA (Node Additional Delay Allowance). The evaluation of the system performance in terms of the packet repayable rate at the actual air traffic between Japan and North America finalizes this chapter. The actual air traffic in the simulation is the one after applying an increasing rate to the actual air traffic on that oceanic route [21], [22].

- Chapter 5 adds another proposal which also provides a multi hop ad hoc relay network for oceanic aircrafts by not using a single channel system but using a multi channels system in VHF frequency band instead. The communication protocol of this system will be explained in details in both single channel and multi channel cases. The obtained results in air to air communication channel from chapter 4 and the proposed IB-NS scheme are all applied to the system in this chapter. In connection with the proposal in chapter 4, this communication system is a fully autonomous multi hop ad hoc network which is based on Space Time Division Multiple Access (S-TDMA). After the aircrafts joins this system, it still can work autonomously even when there is a loss in connection with the ground station. Furthermore, other two additional schemes are proposed for autonomous operating aircrafts in order to utilize and allocate timeslot more efficiently. These schemes are PATR (Position Aid Timeslot Reuse) and DBTA (Distance - Based Timeslot Assignment) [23], [24], [25]. The evaluation of the system performance has shown the benefits of using this system for oceanic flight routes. This system can save cost for airlines companies, and also increase the safety of each flight even the safe distance between those flights has much been reduced.

- Chapter 6 introduces another lower altitude aerial vehicle, the unmanned aerial vehicle (UAV). This new vehicle is expected to be a new dimension of aeronautics sector, which might be integrated into current aeronautical telecommunication network. For that integration, our studies in chapter 4, and 5 are able to cover. The content in this chapter further concerns a study for the communication between a ground communication system, such as wireless sensor network (WSN), and the UAV. In which it provides a novel model for the communication between the UAV and the system on the ground. In this case, it is assumed that the ground system is a WSN which includes a large number of sensors randomly distributed on an area of the interest. This kind of communication is expected to become a new direction in several kinds of systems used for data collection, area monitoring, disaster aids, and so on. This chapter mainly focuses on describing in details of our proposal on a novel access scheme that is used for communications between many sensors on the ground and a UAV in the air. The core of this method includes a novel PFS (Priority Frame Selection) and FRA (Frame Based Random Access) schemes. The purpose of PFS scheme is to control the priority for channel access and data transmission of each priority group. There are three kinds of PFS schemes that are introduced in this dissertation. They are High Power High Priority (HH), High Power Low Priority (HL), and Dimensional- HHHL (D-HHHL). The simulation results and its evaluation in terms of Packet Error Rate (PER) will end this chapter [26], [26], [28]. The results have shown the promising application of this simple access scheme when the communication between a UAV and the ground WSN is maximized.

- Chapter 7 presents our conclusions on the achieved studies. Moreover, this chapter also illustrates our discussions for future studies which relate to air to ground communication, air to air communication, and the communication between UAV and ground system.

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2

THE CURRENT AERONAUTICAL COMMUNICATION SYSTEM AND APPLICATION OF THE UAV

This chapter provides the updated information about the communication system which has been used in aeronautics field. These systems are primarily based on the aeronautical HF and VHF bands whose operations are all regulated by ICAO (International Civil Aviation Organization). We also provide the description of the technical specifications of each system which is reused in the next chapters for the simulations and evaluations. We briefly introduce the potential applications of the UAV (Unmanned Aerial Vehicle) which could be employed in future scenarios, especially in the supporting communication before, in, and after the disasters.

2.1 Radio Communication Systems on an Aircraft

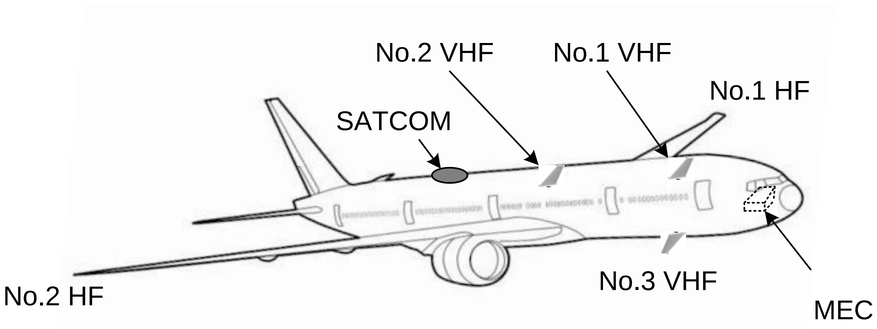
It is common that a commercial aircraft is equipped with two communication systems in both VHF and HF bands. In some new aircraft types, it is additionally equipped with a transceiver in order to communicate with INMARSAT (International Maritime Satellite). This system aims to provide the global services in aeronautical sector that base on satellite communication. It is usually called SATCOM system, which ensures the capability of the communication between distant aircrafts and air traffic controllers on the ground. In addition, SATCOM system can provide both data and voice communication.

The operating conditions of the radio equipments on the aircraft are usually from -15^{o}C to $+70^{o}$C for temperature, and about 95% in terms of humidity. In addition, the conditions of the system operation are quite strict. These requirements include the signal reflection and the noise generation that are clearly stated in [1]. As a result of those requests, the MEC

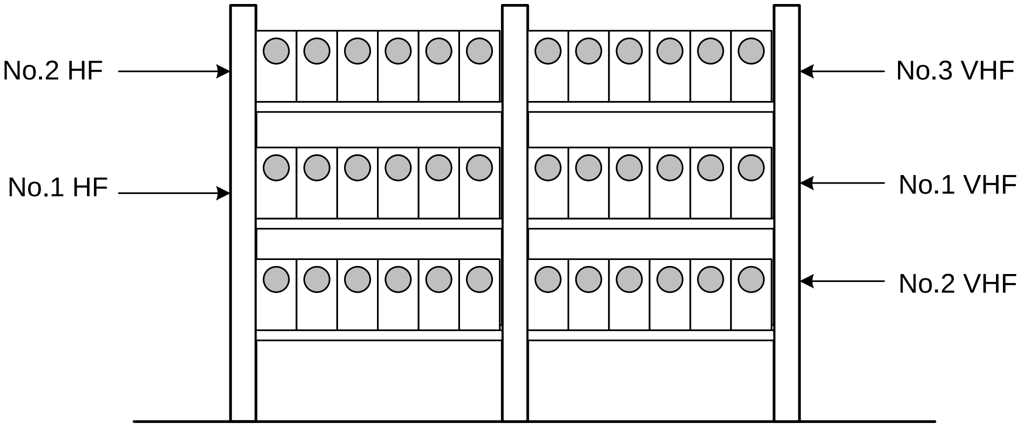
(Main Equipment Center) is located at the head of the aircraft. Figure 2.1 a) shows the common position of MEC in the 747 aircraft type which is popular all over the world. The status of MEC is managed and presented in another systematic rack in the aircraft as in Fig. 2.1 b). Also, the equipments in MEC are maintained in a proper working condition by air conditioner and other special systems. This is also to ensure that MEC is in the best condition for the most stable system performance. In those equipped systems, VHF and HF based radio systems are always primary in communication for an aircraft. The next sections will provide detail information of each system.

2.1.1 VHF Based Radio Systems

In the air transportation systems, all of the aircrafts are equipped with VHF radio based systems. There are up to three VHF systems installed inside an aircraft, as shown in Fig. 2.1. As the communication feature in VHF band, the signal transmission in this band is usually in line of sight (LOS) range. Therefore, the communication distance in VHF based system is approximate 200 nautical miles (NM). However, the requirement in the communication for air transportation is critical, so a smaller value is preferred. The common communication distance in VHF band is about 162 NM (300 km), which is to ensure the good communication conditions even in the unfavorable communication conditions. This distance is worldwide applied for geographical designs of airports and ground systems in each country. The VHF based radio system is always the major and essential method for the communication between aircraft and air traffic controllers. The information transmitted via this system needs to ensure the full information reported from the pilot to the air traffic controller. VHF system is also the main way to guarantee an adequate command from the ground controller to the aircraft. Therefore, the behaviors and operations of the aircraft are fully managed and predicted by the air traffic controller. At the nearby airport areas, there are other supplemental systems that could be used for a communication between the air traffic controller and the aircraft. However, the VHF system is still the most frequently used because its favorable features in communication specially used in taking off and landing of the aircraft. Therefore, the VHF radio system is indispensable in any aircraft.



a) The position of radio system on the aircraft



b) Main equipment center (with rack systems for all radio system)

Figure 2.1: Radio system on a common aircraft

Regarding to the technical specifications, this system may use different radio channels in VHF band, which ranges from 118 to 137 MHz. The separation between these channels is usually 25 KHz. Nevertheless, in European airspace, a new standard has been implemented where the separation is reduced to only at 8.33 KHz. This is because of the different modulations applied for the system. The modulation schemes are also different in voice and data transmissions. For voice communication, the AM (Amplitude Modulation) is used; and for data communication, the D-8PSK (Differential-8 Phase Shift Keying) is used. The data bit rate is usually at 31.5 kbps [2].

The number of VHF systems installed on an aircraft is dependent on the aircraft type and the flight route where that aircraft involves. For the big aircraft type, there are usually three VHF communication systems (Fig. 2.1 a). The first (No. 1) VHF system is used by the pilot, the second one is used by the second pilot, and the third one is used for transmitting the aircrafts and the airlines information. The information in the third VHF system is used for managing issues of the airlines. Actually, there are several kinds of information transmitted through the third VHF system. For instance, the information includes the flight schedule, the current and next estimated aircraft positions, and the number of passengers and so on. The conceptual figure of the VHF system is shown in Fig. 2.2.

A VHF communication system on an aircraft include following sub items:

- A signal transceiver installed inside the MEC.
- Two equipments used for frequency selector. They will set the frequency for operating the system. The information of the selected frequency is then transferred to the above VHF transceiver.
- Two audio selectors used to adjust the received voice volume.

The frequency and audio selectors are in the cockpit room. The signal transmitted by the cockpits goes to the VHF transceiver. This signal will be processed based on the setting information for the system by this transceiver. Then, it is transited to the installed antenna on the aircraft’s body. There are two VHF antennas (No. 1 VHF and No. 2 VHF), which are separating at 15 meters.

It is noticeable that the No. 1 VHF system is only used by the pilot, and almost used for the emergent cases. Therefore, it is always connected with both the DC battery and the electrical sources. Table 2.1 shows the technical specifications of the VHF communication system [3], [4].

TABLE 2.1: VHF COMMUNICATION SYSTEM SPECIFICATIONS

Parameters	Value
Frequency	118.000-136.975 MHz
Channel separation	25 KHz, 8.33 KHz
Transmitting power	30 W
Modulation	AM (Voice); MSK (ACARS); D-8PSK (Data, in VDL-2)
Minimum receiving power	-98 dBm (6 dB for S/N)

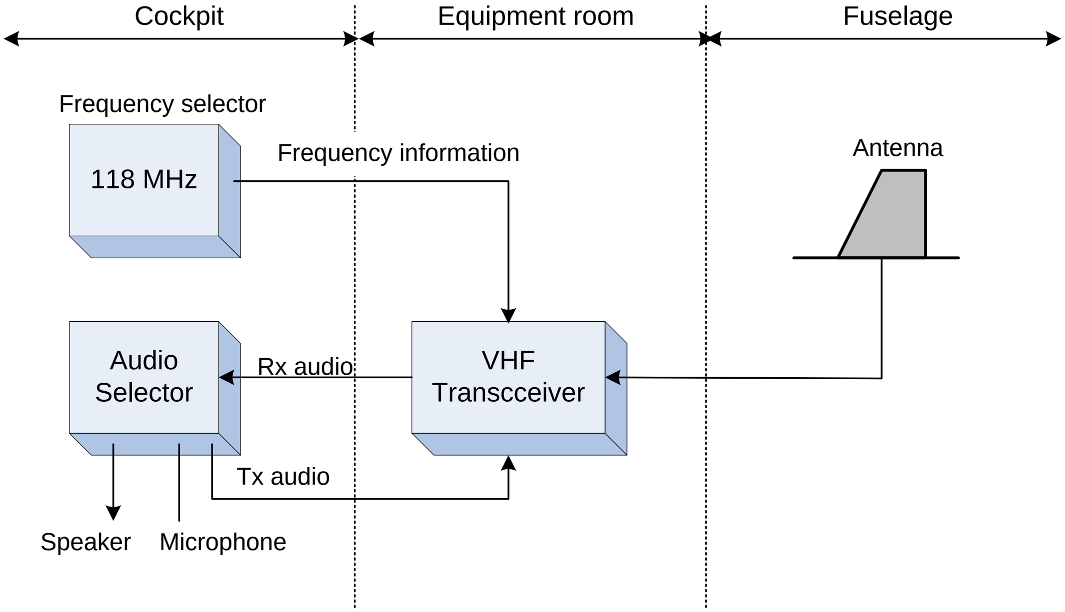


Figure 2.2: The conceptual description of a VHF system on the aircraft

2.1.2 HF Based Radio Systems

Normally the communication between distant aircraft and ground air traffic controller could be out of the communication range in VHF band even though the maximal transmission distance for VHF system is applied at 200 NM.

Generally, the long flights will pass through the oceanic or polar regions where there are no VHF infrastructures. In that case, a longer distance communication system must be used instead of VHF system. The most popular system in aeronautical communication that provides such long distance communication is the HF based system [5]. So far, this radio system provides the communication between the pilot and the ground station via the SSB (Single Side Band) in voice communication. Because the nature of the HF band communication is reflecting the radio signal from the ion layer, hence, the stability depends on several factors such as time, location, weather condition, etc. As a result, it requires the system to adjust the frequency to obtain the best system performance. This change needs to be according to each of specific situation. Also, the selection of this frequency sometimes depends on the experience of the pilots. Hence, it usually takes time to select the most suitable frequency when the situation of communication always changes. Furthermore, the noise and the interference also affect to the HF based system performance. From these operating conditions, the stability and performance of an HF based communication system are not high.

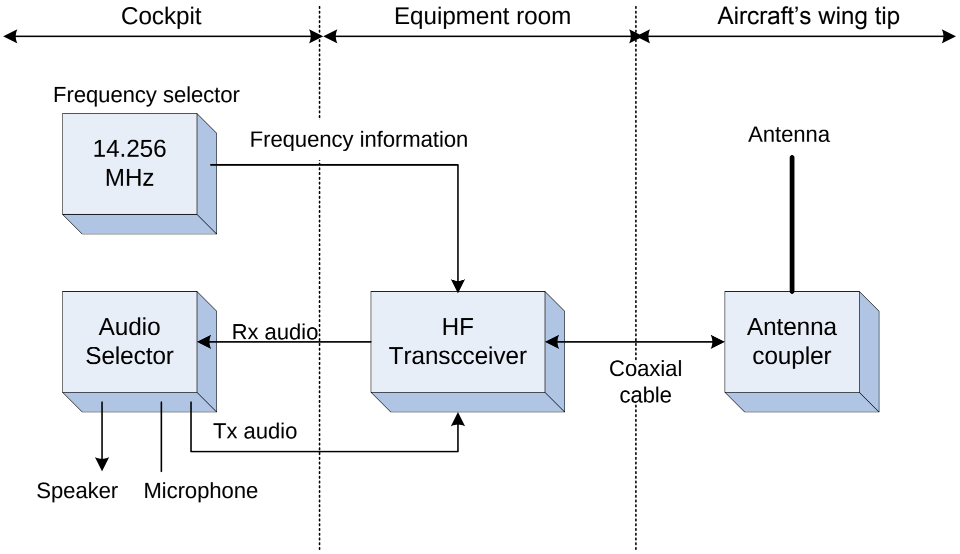


Figure 2.3: The conceptual description of an HF system on the aircraft

Usually, the large aircraft type contains two HF systems. The conceptual operation of an HF system is described in Fig. 2.3. Theoretically, the HF radio based system has a similar structure with the VHF based one but different antenna system. For the HF system, an antenna coupler is installed underneath the main HF antenna. This coupler is used for automatic matching of the impedance and the antenna. Besides, a lightening arrester is also used to protect the antenna coupler. This antenna coupler has a significant effect in improving the HF system performance. However, to install an effective HF antenna on an aircraft is not easy because of the constraint of aircraft design. It is impossible to change the design of an aircraft just because of the antenna structure. That is why a high performance HF system is not expected. The technical parameters of an HF system are presented in Table 2.2.

As similar to the VHF radio system, HF system is also installed in MEC. A HF system is more complex than a VHF system. Therefore, the risks caused by using HF radio based system are also higher than that in a VHF system.

In addition to HF based voice communication described above, there is also the data communication at this band. For HF based data system, HFDL (HF Data Link) is usually used by the air transportation companies that have flights to the North Pole [6]. At those areas, they are not covered by the satellite based communication system. Consequently, the HF based system is used instead of the SATCOM system. For the HFDL system, an automatic matching method is also applied. The system will select the optimal operating frequency to apply for the data communication, which is dependent on the actual situations (i.e. the temperature, weather, etc.).

TABLE 2.2: TECHNICAL INFORMATION OF HF RADIO BASED SYSTEM

Parameter	Value
Frequency	2.000-29.999 MHz
Spectrum separation between channels	1 KHz
Transmitting power	400 W
Modulation scheme	Voice: SSB (Single Side Band) Data: BPSK, QPSK, 8-PSK
Data bit rate	300 bps, 600 bps, 1200 bps, 1800 bps
Receiving threshold	1E-6 V (10 dB SNR)
Frequency selectivity	2.15 kHz (Above)
Allowable deviation of frequency	20 Hz (Maximum)
Antenna	3.5 m (Probe)

2.1.3 Satellite Based Communication Systems

For the aircrafts produced after 1990, another system is installed to supplement the aircraft’s communication. This system is called SATCOM which is possible to communicate with the INMARSAT [7]. This international marine satellite is launched to provide the public telephone services to the airline passengers and other satellite based communication services. Therefore, it is not usually used for the air traffic control communication. In fact, another satellite based communication system called CPDLC (Controller Pilot Data Link Communication) is used for air traffic control. However, this system is not popularly used because of its high cost.

Regarding to the air traffic communication for Japanese oceanic areas, another new satellite called MTSAT (Multi-functional Transport Satellite) was launched and it is used for full air traffic control communication. Since that time, the aircraft position will be transmitted to the air traffic controller on the ground through MTSAT system. In addition, the position of aircraft is highly accurate with the usage of GPS (Global Positioning System) receiver. These applied systems have enabled the air transportation companies to reduce the safe distance between the two aircrafts in the airspace. This is meaningful because it allows increasing the number of aircrafts in the airspace or increasing the airspace usage.

Regarding to the satellite based systems; some airlines have installed another satellite communication system that can be used for emergent situations, especially after the event on 11th of September, 2001.

TABLE 2.3: TECHNICAL INFORMATION OF SATCOM SYSTEM

Parameter	Value
Transmitting power	+ 48 dBm
Frequency	1.6 GHz (Transmitting); 1.5 GHz (Receiving)
Multiple Access Scheme	Data: Slotted ALOHA, Reserved TDMA Voice: Reserved 1-channel
Data bit rate	600 bps
Modulation	Data: BPSK Voice: Offset QPSK
Antenna	Phase array antenna Gain: 12 dBi, 0 dBi

For the systematic structure of a satellite based system, a conceptual satellite communication system includes following fundamental elements: SDU (Satellite Data Unit), HPA (High Power Amplifier), Diplexer, LNA (Low Noise Amplifier), BFU (Beam Forming Unit), and phase array antenna. In which, SDU is the essential part of the system, takes the responsibility of processing the communication protocol, digital signal processing, data processing, channel selection, and frequency selection. HPA is used to amplify the received signal from SDU. Diplexer is in charge of multiplexing the transmitting signal and receiving signal. BFU is used for creating a proper beam which depends on the actual positions of the aircraft and the satellites. The SATCOM system is usually installed on the ceiling of the cabinet and underneath the antenna.

2.2 UAV and Its Potential

The motivation of this study on the communication between a UAV and a ground network comes from a series of potential UAV's applications in the near future [8]. So far, the most popular applications employing UAV is in order to extend the communication range of multi hop ad hoc network. In this study, some isolated small network will be periodically connected to other networks by the UAV [9]. Besides, there are many of other potential applications employing UAVs which are well-known in capability of disaster discovery, aid, and recovery (i.e. [8], [9], [10]).

Nowadays, people are suffering from many kinds of disasters which might happen anywhere and anytime [11]. This information shows that the related communication technology must play an essential role in deploying autonomous monitoring and detecting those disasters. In which, the unmanned aerial vehicle (UAV) is the best selection because the manned aircraft is limited with flight stability and high risk to human. As well as, other activities such as disaster aid and recovery are also not less important than the functions of its detection. In those cases, a communication between a UAV and a ground system network is the most essential in succeeding the mission. For example, after being damaged by a strong earthquake or flood, some local areas are totally isolated from outside. Therefore, there is no possible communication infrastructure in the area; and an urgent communication system is needed. The current method is to deploy a helicopter or a manned aircraft in order to take photos or record videos from the distance. Then the data is processed (i.e. by a data management agency) to provide more information for the rescue mission. However, in some certain cases, the deployment of an aircraft or a helicopter is not effective because it is expensive and even not safe to the human. Therefore, the current methods may lead to some unexpected results, such as some compromise between the death, the life, and the cost.

A communication system may be quickly established with the usage of UAV. First of all, a system on the ground is deployed. This system can be a connected network or unconnected network. Additionally, the ground system might be constructed from a variety of elements. These elements can be randomly deployed or already exist. Furthermore, they can also be the small BTS (Base Transceiver Stations), static/mobile sensor nodes, mobile sinks, or robots, and so on. The purpose of the ground system is to collect or relay necessary information/data from other communicable objects in the environment of our interest. This environment should be different according to the specific application scenarios. Then, one or several UAV will be launched for collecting the information/data transmitted from the elements of the system on the ground. Following this method, the way of retrieving data from the ground is different from the existing ways employing the manned aircrafts in which the passive information is obtained from the ground. However, in this case, with the UAV, the positive information is directly obtained from the ground network's elements instead of recording passive information from a distance. With the system features explained above, the applications based on UAV requires a stable communication between the UAV and the ground network. This issue does not exist in the conventional ways, and it is a challenge to the system design. Chapter 6 is going to describe the detail information solution in which the major content is a novel communication protocol that guarantees and satisfies the above issues.

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3

WIDEBAND COMMUNICATION FOR ADVANCED AIRPORTS

This chapter introduces how we have developed and evaluated a new wideband frequency spectrum at 5 GHz for aeronautical communication. From our analysis and evaluation, this frequency band is suitable for the communication between an aircraft and an airport rather than the longer distance communication. It is promising to use for the advanced airport communication where the aircraft is not far from the airport. More specifically, a wideband communication based on this new frequency band is a target of advanced airport's communication.

3.1 Introduction

In the current air traffic control, the communication between an aircraft and a ground ATC controller usually uses VHF based systems [1]. These systems can provide both voice and data services as a fundamental requirement for an aeronautical communication. This requirement has been mentioned in chapter 1, in the introduction part. However, the VHF based voice communication system has been used for more than 50 years with Amplitude Modulation (AM) scheme [2]. This voice communication is therefore easily affected by other noise or interference. In addition, other limitations have also been reported. Therefore, researchers need to develop a VHF based data communication for ATC such as VDL-2 and VDL-3 systems [3], [4]. However, according to the estimation of the number of aircrafts at busy airports in the near future, it will be larger than system capacity in the next decade [5], [6]. In addition, the situation of full VHF frequency spectrum occupancy has been warned by ICAO and related organizations in aeronautical field. For instance, at large airports in Europe, America or Asia, it is not possible to find an additional VHF frequency in order to use for the air traffic control even if the number of aircrafts is over the system capacity. This situation certainly leads to an unavoidable delay because many aircrafts must wait for the ATC controller to guide them for taking-off or landing. Furthermore, the requirement of better service for an advanced airport in the near future additionally makes the situation worse.

Based on the situation of the current air to ground systems and future requirements on communication at advanced airports, a possible innovation is to find a new wideband spectrum for ATC communications. There are controversies on the spectrum that could be used for a wideband air to ground communication. The top of these controversies is 5 GHz in MLS band that is assigned for aeronautical communication. This MLS spectrum has a wide range starts from 5030 to 5150 MHz [1]. Fortunately, a half of this range, from 5090 to 5150 MHz is still unused and could be requested for other application in aeronautical communications.

Historically, the aeronautical channel usually refers to the air to ground channel and sometimes, to the aircraft to satellite channel [7], [8], [9], [10], [11]. Our studies is specific to the outdoor air to ground channel between an air traffic control tower and an aircraft that the future airport surface networks will extend to include this communication system in the terminal area (approximately within a distance of about 90 km from the airport). In fact, there is no practical evaluations of this band for the outdoor communication between the aircraft and the ATC station so far. In order to validate the ability of this band for the air to ground communication, a practical evaluation is necessary. This chapter provides our studies on this 5 GHz band by doing practical air to ground experiments. There are several factors derived from these measurements such as Rice (K) factor, propagation path loss model, receiving power, etc. at each period of flight (i.e. en-route, taking-off/landing, taxing, and parking) when aircraft is near the airport. From the air to ground measurement data analysis in the case of using directional antenna, the receiving power at the airspace located above the transmitting antenna is fluctuated and unstable. We have proposed a scheme of installing two reflection boards at the two sides of the transmitting antenna. The measurements show that the receiving power is much improved and the K factor is also increased.

Based on such analytical results, the computer simulations with VDL-2’s technical specification have been executed in order to evaluate the BER of the end to end system. In addition, another simulation that applies QPSK modulation has also been done. The simulation results showed the ability of using this band for an airport communication; and the capability to replace the current saturated VHF band for the air traffic control communication and other supplemental services.

The rest of chapter is organized as following order. Section 3.2 describes the air to ground experiment, measurement and data analysis. Section 3.3 discusses on simulation parameters and numerical results. Section 3.4 illustrates the evaluations on system performance that uses 5 GHz band in both single carrier and multi carrier transmission techniques. The last section 3.5 provides concluding remarks regarding to this new frequency spectrum.

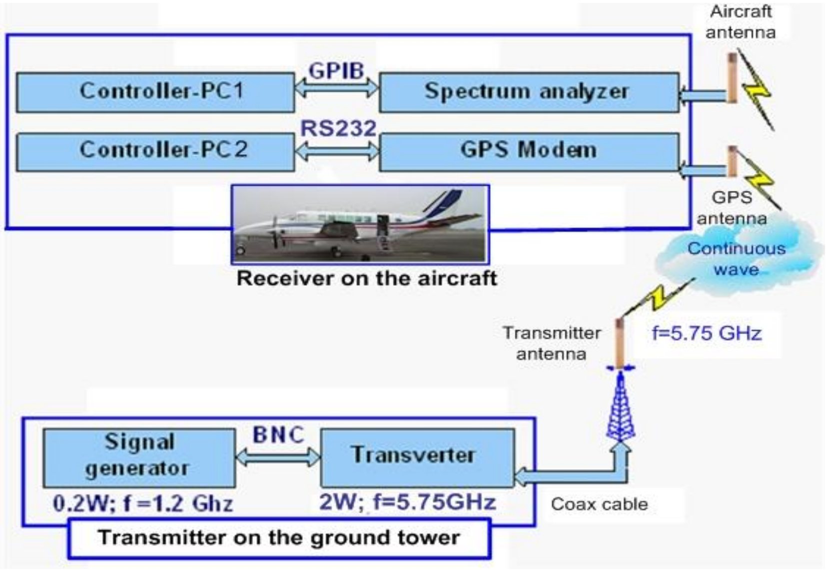

Figure 3.1: Experiment model for an air to ground communication at 5 GHz band

3.2 Studies on Channel Characterisitcs of 5 GHz Band in Aeronautical Communications

3.2.1 Experiment Model

Figure 3.2: The experimental aircraft – B99

Figure 3.3: Transmitting system on the ground

Figure 3.4: Receiving system on the aircraft

TABLE 3.1: TECHNICAL PARAMETERS OF AIR TO GROUND EXPERIMENT

Transmitter system (ground station)	
Frequency	5.740 - 5.780 GHz
Signal Power	2 W
Signal Type	Continuous wave
Antenna	On the top of a 20 m high building.
	Directional, Gain =11 dBi
Receiver system (aircraft)	
Experiment Aircraft	Beech-craft B-99
GPS modem	Capture geographical location of the aircraft
Antenna	Installed at the bottom of aircraft body
	Mono pole, Gain =0 dBi

All the parameters of the transmitting and receiving systems are presented in Table 3.1. Before explaining about the experiment model, it is noticeable that 5 GHz band is not significantly different from 5.8 GHz in terms of radio propagation; therefore we have selected 5.8 GHz for our experiment in order to avoid any interference to the existing MLS systems. Our experiment is an air to ground communication system with the aim to study channel characteristics of 5-GHz band in aeronautical communication especially for the areas near the airport. Figure 3.1 shows the conceptual system of our experiment. The venue of this experiment is Sendai airport, a general airport, located in the northern part of Japan. For conducting this study, Waseda University and Electronic Navigation Research Institute (ENRI) of Japan have collaborated during the period of 2003-2005.

According to Fig. 3.1, the transmitting system is installed at the top of the highest building nearby Sendai airport, at a height of 20 meters. The receiving system is installed on the experimental aircraft. The experiment aircraft is a Beech-craft B-99, which is owned by ENRI. B-99 has been used for several kinds of studies on experiment-based air traffic control communication conducted by ENRI. Regarding to the transmitting system, fist of all, a generator, GSV-3000, generates a signal at frequency of 1.2 GHz. This signal goes to a converter where it will be converted into 5.8 GHz output signal with a higher power at 2 W. The converted signal is connected with a directional transmitting antenna as in Fig. 3.1. This signal will be transmitted into the airspace. For the receiving system on the aircraft, signal has been received by the aircraft's antenna connecting with a spectrum analyzer, HP-856, which was controlled by a program installed in PC-1. This PC mainly stores all the measured data in terms of the receiving signal power and according time which is used for further analysis later on. The PC-2 is another computer that is connected with the aircraft's GPS receiver. The recorded data in PC-2 is the respective geographical positions of the aircraft during the measurement for receiving signal (Fig. 3.1). The frequency of measurement is 1 Hz, which means the receiving signal power has been recorded at every second. The experiment is prepared to start all recordings from the first movement of the aircraft. The measurements have lasted until the aircraft comes back and parks at the departure airport (Sendai airport). For checking the stability and reliability of the system and the measurement, the experiment has been done at two times. During these measurements, weather condition was quite different. In the first time, the sky was clear and blue, but it was cloudy in the second time. However, the flight route in the two times was kept the same. From the analysis for the results, the measurements in these two times have provided similar results. Therefore, any one of the measurements could be used for further analysis in terms of Rice factor and the relation between transmitting and receiving powers described in the next section 3.2.2.

For more specific imagination of the experiment, the flight contour is located inside the area limited by these coordinates: longitude of 141°-141.5° and latitude of 38°-38.5°. Due to the limitation in altitude of the aircraft B-99, the experimental aircraft has only increased its altitude up to 3000 feet. In fact, that altitude satisfies the requirement of an air to ground communication for the area near the airport. According to the measurement, the maximal distance from aircraft to the Sendai airport's building is about 45 nautical miles (NM). That is also the location when the aircraft starts to turns back to its departure. The entire flight path during the experiment is fully displayed in Fig. 3.5.

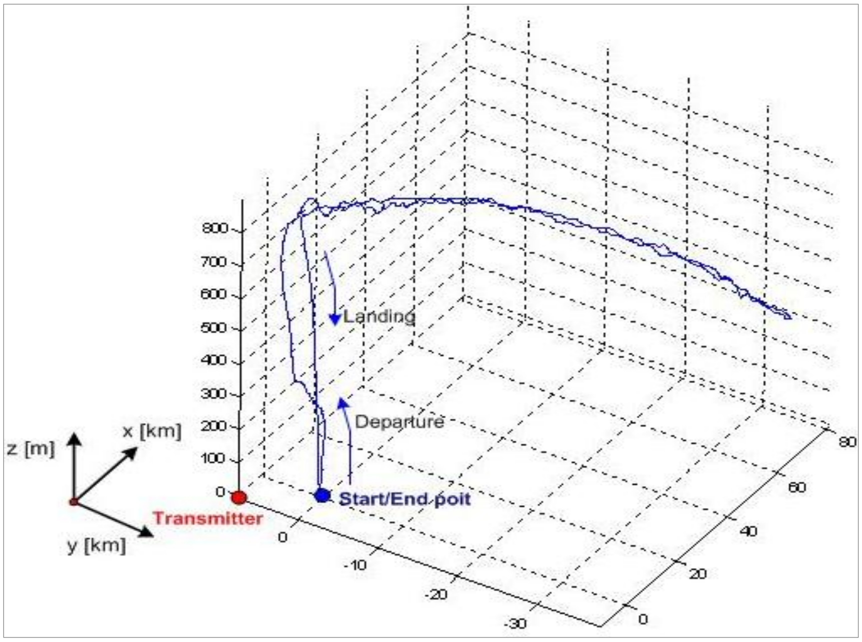

Figure 3.5: Flight contour of the experimental flight B-99

3.2.2 Measurement and Data Analysis

3.2.2.1 Rice (K) Factor

In this experiment condition, the receiving system on the aircraft and the transmitting system on the ground can usually see each other, or the transmission is almost in line of sight (LOS). The receiving power values therefore follow a well-known Nakagami-Rice distribution as same as the explanation in [12]. Therefore, to extract Rice factor; firstly, we need to select a large group which result is representative for a concerned area. For instance, the areas where the aircrafts belong to its parking/taxing, taking-off/landing or en-route phase. For each of those major groups, the respective data measurements are divided into several sub data groups which contain 20 measured data points each. This selection is because the aircraft moves at a quite high speed; hence, it is impossible to select more measured points for the calculations of a sub data group. In addition, to increase the number of sub groups or increase the number of plotted points, these sub groups are considerably overlapped. There is one measured point that makes the two consecutive sub groups different. As a result, we have created many consecutively overlapped sub groups. There are three steps applied for finding K factor representative for a large group. First of all, we need to make the graph connecting all the points stand for the sub groups belong to the large group. This point is representative to one sub group which is created by two values of relative power in the horizontal axis and cumulative probability in vertical axis. The relative power is estimated by finding the difference between the average powers of that sub group and the large group. It is obvious that the original point of the graphs is the average power of the large group. The absolute value of the average power of the large group is not zero but it is zero at relative value (Fig. 3.6). The second step is to calculate the fading depth of all the points standing for the measured data in the respective large group. The fading depth is the gap between two relative power values at which their cumulative probabilities are 1% and 50%, respectively. In the last step, after finding the fading-depth of its large group, fitting this value to the vertical axis in Fig. 3.7, and a respective value on horizontal axis is obtained. This achieved value shows the ratio in signal powers which is defined as the ratio between the direct-path power and other reflected-paths power. It is also called Rice-factor or K factor. The high value of K factor the stronger LOS signal; hence, the better communication condition. An example is given in Fig. 3.7 where the four lines are for typical phases of the flights such as parking, taxing, taking-off/landing, or en-route. The K factors in those situations are at 1.7, 4.5, 6, and 15 dB. Also, in this figure, the fading-depth is smaller if the line is sloppier. The small fading-depth means that the receiving power values are quite stable and there is less fluctuation in the signal receiving power. As a result, the channel condition is good and the K factor is therefore large.

By demonstrating all the measured data from the experiment, all K factors are described with a relation to the actual position of the aircraft as in Fig. 3.8. The flight route is known, so the aircraft position in the flight route could be determined if the distance from aircraft to the airport (transmitting system) is known. Figure 3.8 indicates that K factors in nearby airport area (i.e. $d \leq 3$ km) are low and sometimes even lower than zero, which means that the channel fading is close to Rayleigh fading. However, in further distance areas (i.e. $d \geq 3$ km), K factors increase and become relatively high, which means that the channel at those area is close to Rice fading. There are some typical statistical values extracted from Fig. 3.8 and denoted in Table 3.2. These values are useful references in designing aeronautical radio channel for this 5 GHz band which has not been much published yet.

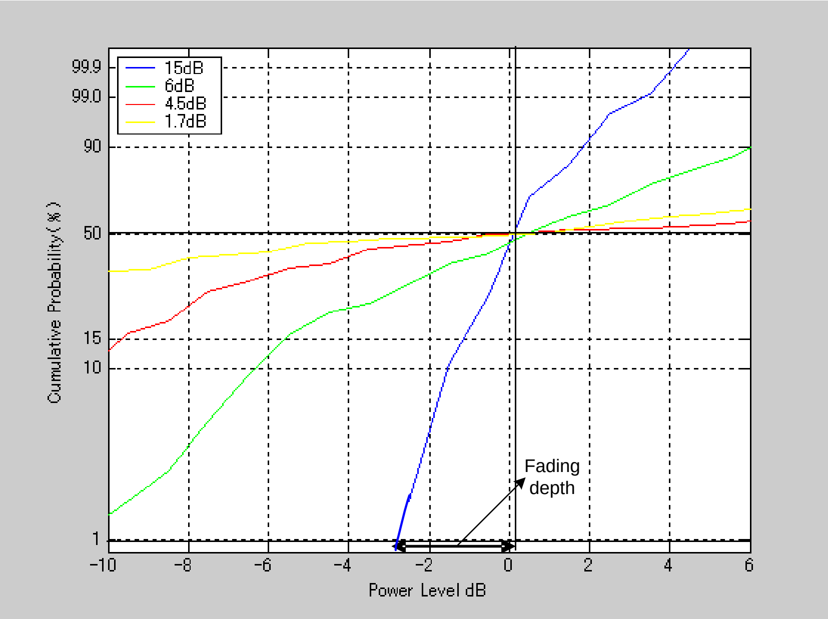

Figure 3.6: A description of cumulative probability and relative power values (i.e. at four values of K factors: 1.7, 4.5, 6, and 15 dB).

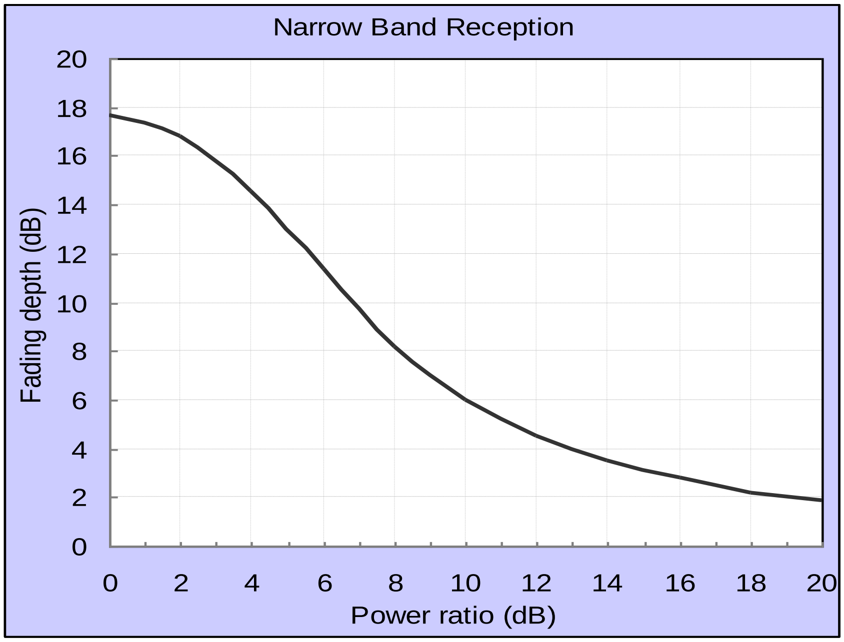

Figure 3.7: Relation between fading-depth and power-ratio in narrow band case

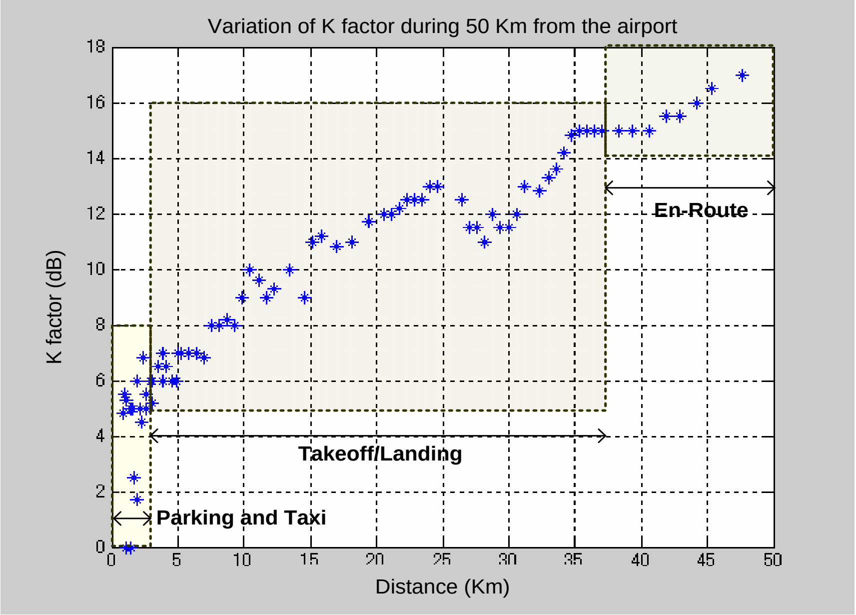

Figure 3.8: Rice factor versus the distance between transmitter and receiver

TABLE 3.2: TYPICAL VALUES OF K FACTOR AT DIFFERENT PHASES OF FLIGHT

Phase of flight	Minimum	Maximum	Mean
Parking	-2 dB	5 dB	-1 dB
Taxi	5 dB	7 dB	5 dB
Taking-off/landing	5 dB	15 dB	10 dB
En-Route	15 dB	≥ 20 dB	≥ 15 dB

The K factor in Table 3.2 shows that, at parking area, where aircraft is parking at a terminal, due to the existence of many other objects on the airport, the radio channel suffers a heavy reflection, and therefore it is close to a Rayleigh fading channel. Meanwhile, in other phases of flight, the channel is a Rice fading channel with K factor increases gradually from taxing to taking-off/landing, and gets maximum at en-route phase. These phases could be known by calculating actual distance from aircraft to ground station or the actual altitude of the aircraft, which is roughly assumed in [6].

3.2.2.2 Relation between Receiving Power and T-R Distance

During the experiment, the transmitting system and receiving system usually see each other, or they regularly communicate in line of sight (LOS) condition. When the aircraft is far from the airport, the altitude of aircraft is quite small compared to the distance between the aircraft and the airport. In this case, the single reflection from ground may dominant the other reflections; hence, the received signal consists of two components: a direct component (LOS); and a reflected component from the ground. As a result, in this experiment, the received signal may follow one of the following two kinds of signal propagation model:

- Line of sight (LOS) model
- Two-ray model.

A. Line of sight model

In this case, there is only one line connecting the transmitting and receiving system (the aircraft). There is also no obstruction between them. Assuming the *d* is the distance between the transmitting systems and receiving aircraft system, the received signal in case of LOS will be:

$$r(t) = \frac{\lambda\sqrt{G_l}e^{j(2\pi d/\lambda)}}{4\pi d}s(t) = \frac{\lambda\sqrt{G_l}e^{j(2\pi d/\lambda)}}{4\pi d}u(t)\cos(2\pi f_c t + \phi_0) \tag{3.1}$$

where *f* is the carrier frequency; $G_l = \sqrt{G_t G_r}$ is the product of the field radiation patterns of the transmitting and receiving antennas in the direction of LOS, respectively. ϕ_0 is an arbitrary initial phase of the carrier; *u(t)* is the complex base band of transmitted signal. This formula is also partially used for building the formula of two-ray model in the next part.

B. Two-ray model

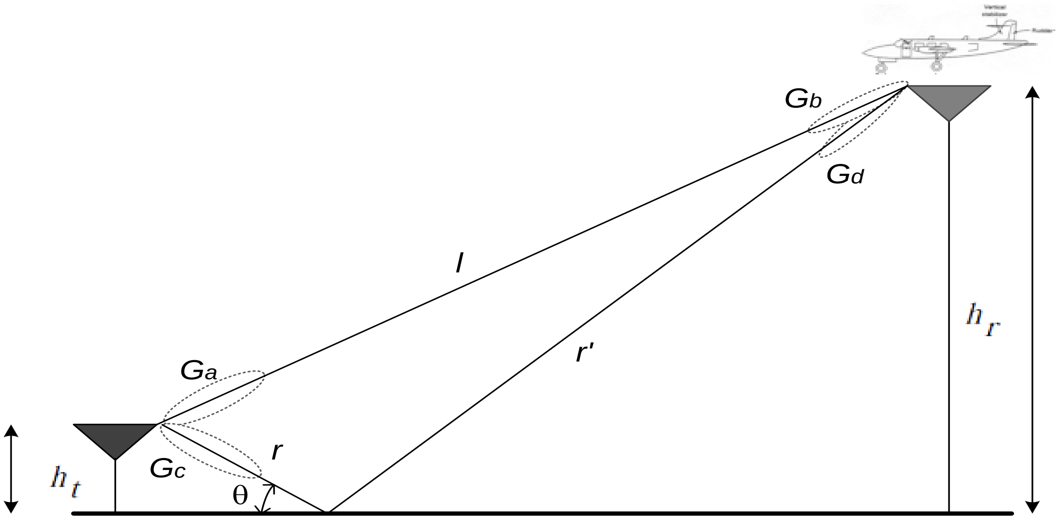

Figure 3.9: Two-ray model between transmitting system and aircraft

If we ignore the effect of the surface's wave attenuation, the received signal for the two-ray model will be described as following:

$$r_{2ray}(t) = \frac{\lambda}{4\pi}\left[\frac{\sqrt{G_l}u(t)e^{j(2\pi l/\lambda)}}{l} + \frac{R\sqrt{G}_r u(t-\tau)e^{j2\pi(r+r')/\lambda}}{r+r'}\right]\cos(2\pi f_c t + \phi_0)$$

(3.2)

where $\tau = (r + r' - l)/c$ is the relative time delay of the reflected and the direct component. $G_l = \sqrt{G_a G_b}$, is product of the two field radiation patterns of transmitting and receiving antennas in the LOS direction. Similarly, $G_r = \sqrt{G_c G_d}$ is the product of the two field radiation patterns of transmitting and receiving antennas in the two directions *r* and *r'* (Fig. 3.8).

In Eq. (3.2), R is the ground reflection coefficient, which is given by:

$$R = \frac{\sin\theta - Z}{\sin\theta + Z}$$

$$\text{where} \quad Z = \begin{cases} \sqrt{\varepsilon_r - \cos^2\theta}\,/\,\varepsilon_r \\ \sqrt{\varepsilon_r - \cos^2\theta} \end{cases} \tag{3.3}$$

In Eq. (3.3), the first condition is occurred in case of vertical polarization; and the second one is for the horizontal polarization; ε_r is the dielectric constant of the ground. If pure dielectric is applied for the ground surface, we have ε_r =15.

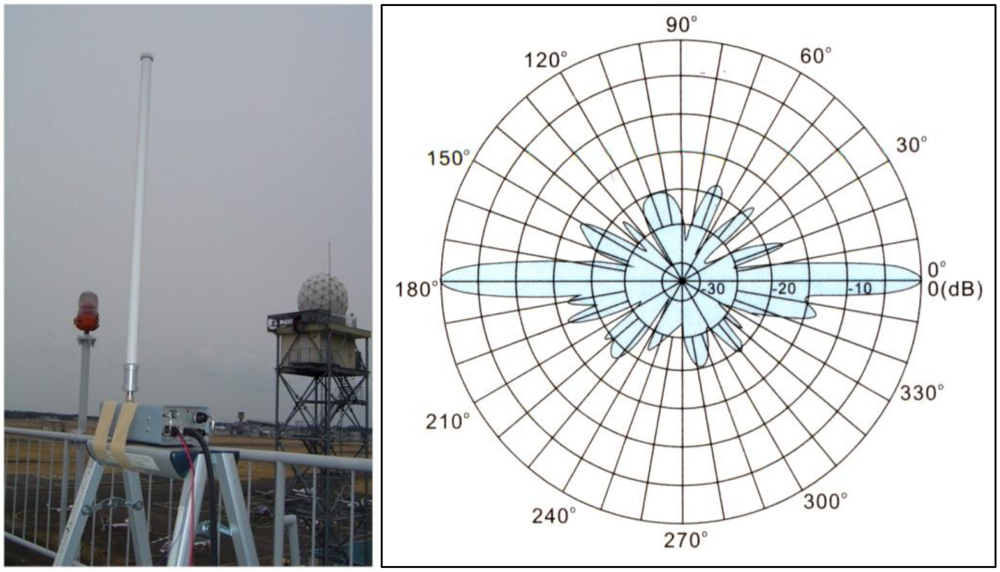

Figure 3.10: The transmitting antenna and its radiation pattern

Before describing the received signal in the three cases of: measurement, LOS, and two-ray model; it is noticeable to explain more about the gain applied to transmitting antenna.

This is because there is a significant difference in antenna gain when the angle varies. This gain will get its maximal value if the angle is at 0^o or 180^o.

According to the transmitting antenna that we have used in the experiment, Fig. 3.10, the dependence of antenna gain on the variation of angle is described as in Fig. 3.11. In order to show the similarity between the two propagation models of LOS and two-ray applied to the propagation in experiment system, it is necessary to estimate the practical transmitting antenna gain at each position of measurement. By using the recorded GPS data during the experiment, the actual angle is found and therefore the respective antenna gain is calculated by fitting the angle to the horizontal axis in Fig. 3.11.

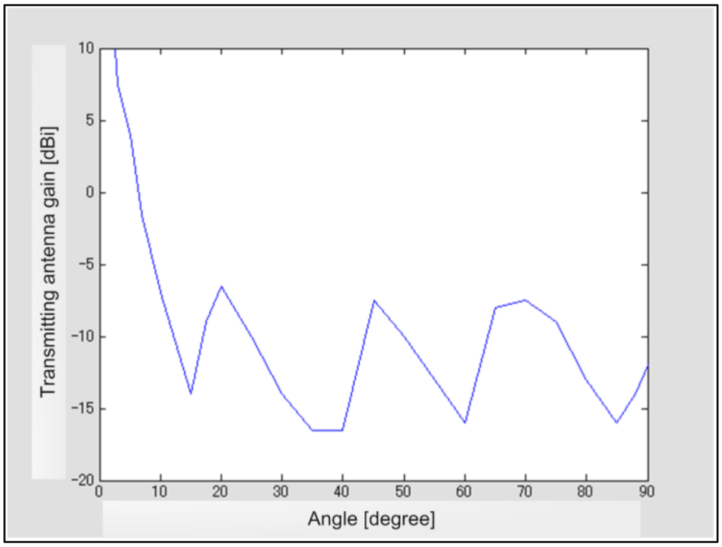

Figure 3.11: Relation between the transmitting antenna gain and elevation angle

Actually, the first element in Eq. (3.2) reflects the LOS received signal, which has been described in Eq. (3.1). The results in Fig. 3.12 show that at the area where $d \leq 10$ km, the LOS model is close to the measurement data than the two-ray model's. However, at further distance i.e. $d > 10$ km, the two-ray model is close to the measurement's description.

From the measured data that is described in Fig. 3.12, there is a notice that the receiving signal power at the distance $2.5 \text{ km} \leq d \leq 5$ km has been considerably fluctuated. For instance, the receiving signal power has decreased sharply and then quickly increased when the aircrafts passes through this area. These phenomena may affect to the practical communication system if this new spectrum is applied for avionics systems. For example, the receiving power may become lower than the receiving signal threshold if the distance increases. As a result, the data packet could be lost and hence PER is high in the case of long distance communication.

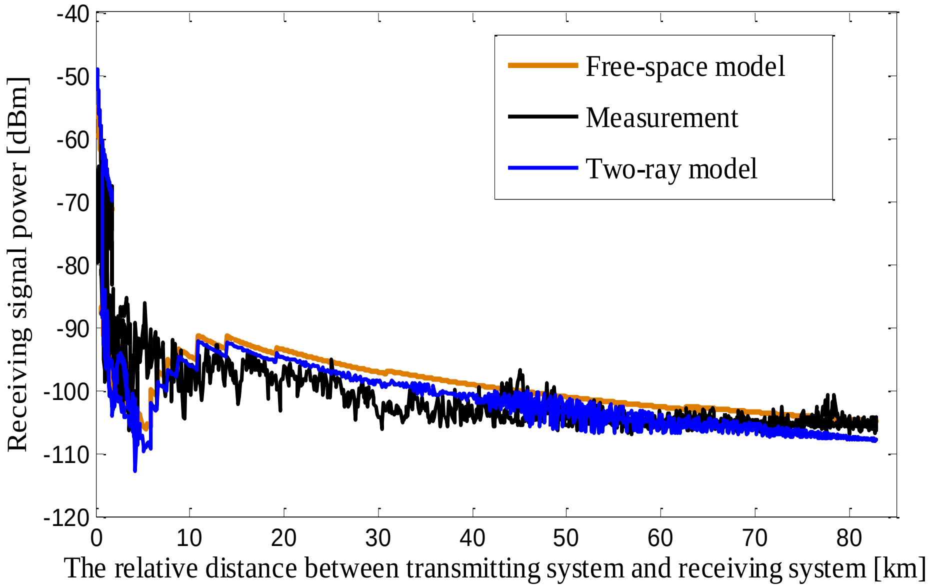

Figure 3.12: Comparisons of measured data with the two LOS and two-ray models

To have more specific evaluation about this issue, we have conducted additional analysis which expresses the relation between receiving power and respective incident angle. Incident angle is the angle between one line and the horizontal plane. In which, this line connects the experimental aircraft and the transmitting system. The entire flight route of the experiment is fully displayed in Fig. 3.13. It shows that at the range of the above mentioned distance (2.5 km $\leq d \leq$ 5 km), the incident angles are almost maximal. This means that at those moments, the aircraft located fairly above the transmitting antenna with incident angle between 80^0 and 90^0. According to the radiation pattern of transmitting antenna in Fig. 3.10-3.11, the antenna gains at those angles are quite small and significantly fluctuated. Also, Fig. 3.13 shows that the receiving power and incident angle of the two periods when the aircraft leaves the airport and comes back the airport are quite symmetrical. The incident angles are quite small at the two extreme cases. They are the cases when the aircraft is near or far from the airport. However, at the former case, the receiving power is high but fluctuated due to that fact that the incident angles are increasing sharply. At the latter case, the receiving power is lower but stable. From this result, in order to have a stable communication for this frequency band, it is necessary to stabilize the receiving signal power at the areas right above the transmitting antenna at the airport.

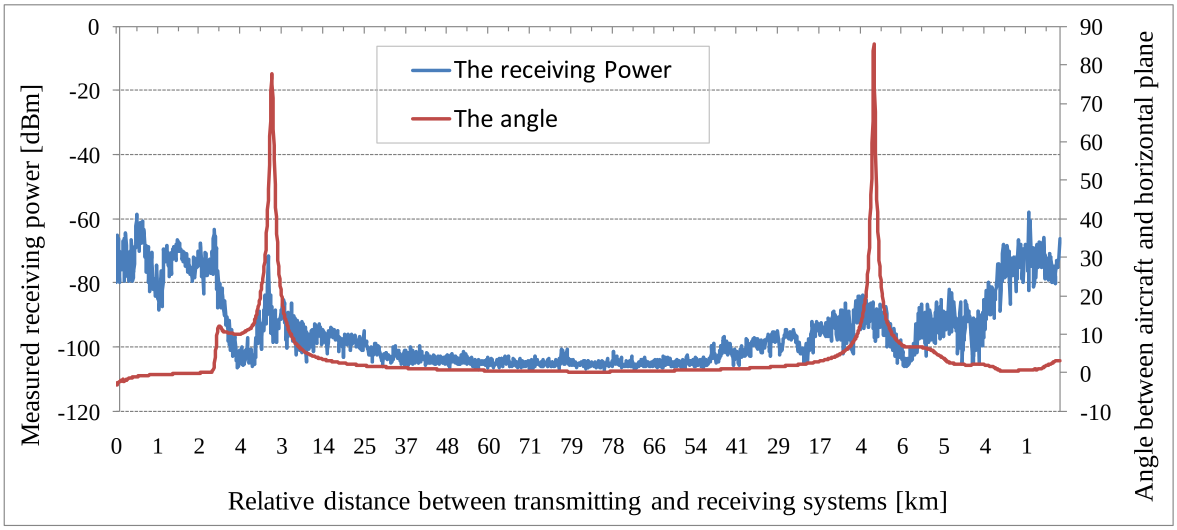

Figure 3.13: The relation between receiving power and incident angle versus distance

3.3 Proposal of Ground Antenna with Reflection Board for 5 GHz Band in Aeronautical Communications

3.3.1 Experiment Model

In order to against the situation of low and fluctuated receiving signal power at the areas above the transmitting antenna, we continuously propose an additional scheme for transmitting antenna side. This scheme is described in Fig. 3.14. In theoretically, experiment in Fig. 3.1 could be described in a vertical 2-D as in below Fig. 3.14. However, there are two additional two square reflection boards installed at the two sides of ground antenna. For obtaining the similar receiving signal power as we have done in prior outdoor experiment, this time we have conducted an indoor experiment in which the model is displayed in Fig. 3.15. This system model is to implement the idea of using two reflection boards presented in Fig. 3.14.

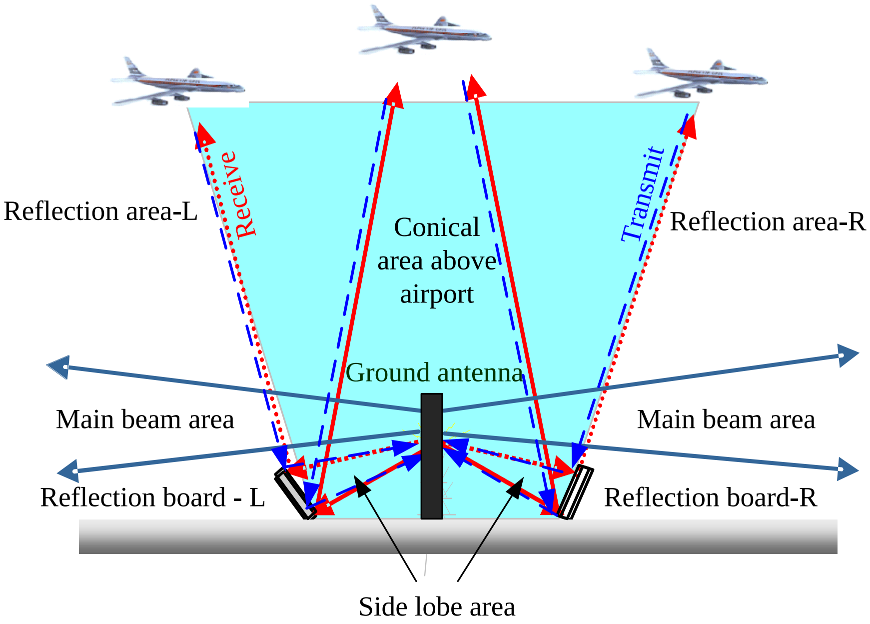

Figure 3.14: Proposed models for transmitting antenna with 2-side reflection boards

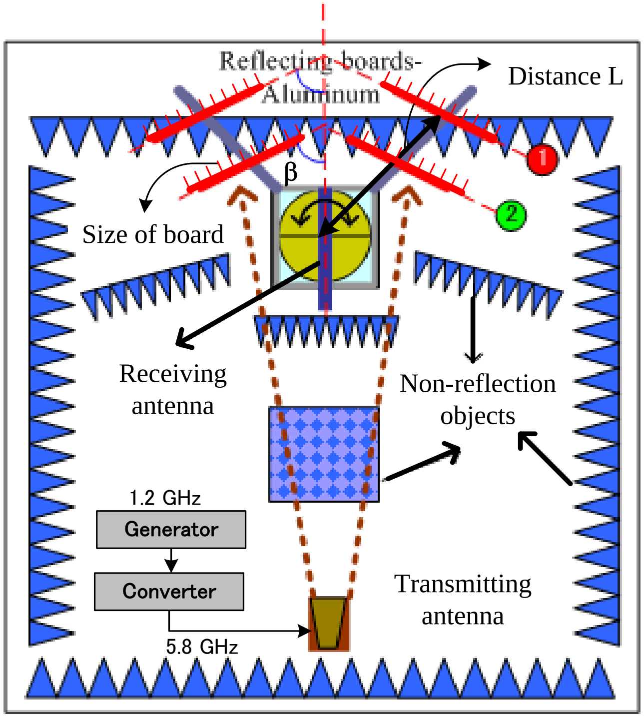

Figure 3.15: Indoor measurement with 2-side reflection boards

First of all, in order to stimulate the real radio propagation medium, we have attached the receiving antenna on a rotator and transmitting antenna fixed on a distant shelf that they can see each other and be parallel to the floor (Fig. 3.15). Then, rotating the receiving antenna by an electric system for which the angle changed from -180^{o} to 180^{o}. During the rotation, both reflection boards were also rotating together. It is noticeable that, this receiving antenna is actually the transmitting antenna that has been used in prior experiment. In the previous experiment, the transmitting antenna was fixed on the ground and the receiving antenna (on the aircraft) was moving. The roles of these antennas have been swapped each other because it is difficult to install the aircraft's receiving antenna in this indoor experiment. In addition, this exchange does not make any change in the propagation path between the new transmitting and receiving antenna compared to the prior experiment. Fig. 3.15 shows the indoor experiment system in horizontal 2-D plane from the above high view. Furthermore, instead of using the receiving aircraft antenna which now is the transmitting antenna, we have used a sharp beam antenna, called horn antenna, which is fixed on the shelf that is in LOS with the rotating receiving antenna. Another factor should be concerned is in the outdoor environment (Fig. 3.1), there will be few reflections from the ground or other objects. Therefore, in order to avoid multiple reflection rays from different dimensions in the indoor experiment, non-reflection objects are installed at the edges of the communication room.

Regarding to the experiment configurations, in the experiment model with Fig. 3.15, two kinds of reflection-boards are used which sizes at 30 cm^{2} and 50 cm^{2}. In addition, the distance from the reflection-boards to the receiving antenna, L, are selected at 60 cm (❶) and 20 cm (❷). At each size of reflection-board and each value of L, four measurements have been conducted at various values of angle β at 30^{0}, 45^{0}, 60^{0}, and 75^{0}. Furthermore, each measurement has been carried out with three scenarios: no reflection board, one and two reflection-boards are installed.

3.3.2 Experiment Results

From our measurements, the reflection signal is strongest in the case that the distance between reflection boards and antenna is L_0 = 20 cm. This value is dependent on the characteristics of the antenna (receiving antenna). In addition, the angle between the reflection board and the receiving antenna does also factor the receiving power. Therefore, at the distance of

L_0, measurements are described at different values of the β angle. In each description, the receiving antenna fully circulates from -180° to 180°. During the moving of the receiving antenna, a similar system as in the prior experiment will connect with this antenna in order to record all the related data. These measurements will be used for further analysis that the results are to be shown in Fig. 3.16. This figure shows the results in the four selective cases according to the three values of β at 45°, 75°, 60^0, and the case without any of reflection boards. In those three cases of β, two reflection boards were always installed at the both sides of the receiving antenna. From the result Fig. 3.16, the light red curve which is drawn at angle $\beta = 60°$ has shown to be the best case compared with other cases. In this case, the signal is better than that in other cases. Averagely, an amount of 15 dBm has been improved compared to the case of none reflection board. Also, the brown line, at $\beta = 45°$ seems better than the red one if the angle varies between -15^0 and $+15^0$. However, the receiving signal in the former case (*brown line*) changes faster and sharper than that in the latter case (*red line*); hence, it is not preferred to use. By using a similar method for calculating K factor as we have mentioned in the above previous experiment, we also applied to the measured data this time. It results to an increase for the K factor. The averaging value of K factor is 5 dB increased compared to the case without the reflection boards.

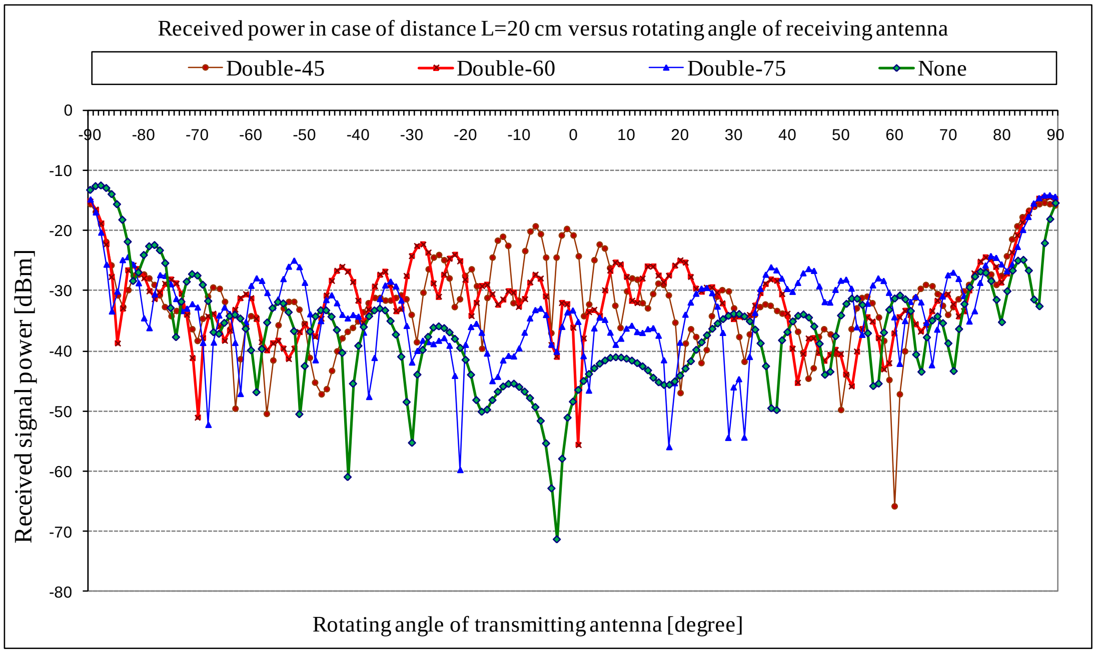

Figure 3.16: Measurements in case of L_0 and varying angle of β

From all of the measured results, we could state that our proposed model applied to the transmitting directional antenna in 5 GHz band has shown a considerable improvement in the receiving signal power at its above area. This issue does not happen in the case of using Omni-directional antenna. However, it is not practical to use it in such high frequency band because the system requires a much higher transmitting power. This solution does improve not only the receiving signal strength but also increase the channel fading condition. The signal strength is not as fluctuated as it was in the case of without the reflection board. This solution has enabled us to use the directional antenna for 5 GHz band in aeronautical communication where the bad receiving signal power is cleared.

If we concern about the configuration in practical system, the reflection board's positions are around the transmitting antenna on the ground system. In practice, the flight routes of aircraft are multi dimensions, therefore, it is necessary to install more reflection boards surrounding the transmitting antenna. The number of reflection boards should be an even number and symmetrically installed around the antenna.

3.4 Performance Evaluation of 5 GHz Band

3.4.1 Comparison with VDL-2 System

This section introduces the evaluation of the channel performance of C band system in QPSK modulation under the same operating conditions of a popular system, so called VDL-2. This system has been mentioned and described in details in chapter 2.

3.4.1.1 Simulation Parameters

For the system performance comparison, specifically in BER, Table 3.3 shows typical parameters for the both simulations for VDL-2 and C band based systems.

VDL-2 is a spectrum limited system because of bandwidth limitation in VHF band for ATC. In addition, transmitting power in ATC is also very carefully designed in order to avoid any interference to existing systems in the same band. Furthermore, system cost and size are also high concerns because avionics system is a worldwide communication system. As a result, the modulation of D-8PSK is the most suitable one for VDL2 system. Regarding to the new C band, frequency spectrum is much wider and higher than the VHF's band; we therefore decide to choose a lower modulation-rate scheme, such as QPSK, to estimate channel performance.

TABLE 3.3: SIMULATION PARAMETERS FOR VHF/5 GHZ BAND BASED SYSYEMS

Parameter	Value
VHF – Mode 2(VDL-2) technical specification	
Frequency	125 MHz
Modulation	D-8PSK
Bit rate	31.5 kbps
Channel fading	Rayleigh fading and Rice fading channel (*K*=5, 10, 15 dB)
Aircraft speed	Maximum at 400 km/h
5 GHz band (Estimating System) technical parameters	
Frequency	5.1 GHz
Modulation	QPSK
Bit rate	31.5 kbps
Aircraft speed	Maximum at 400 km/h
Channel fading	Rayleigh fading and Rice fading channel (*K*=5, 10, 15 dB)

3.4.1.2 Evaluation of System Performance

Figures 3.17 and 3.18 show the channel performance at the same bit rate of 31.5 kbps under the same channel propagation conditions applied for the VDL-2 and C band system, respectively.

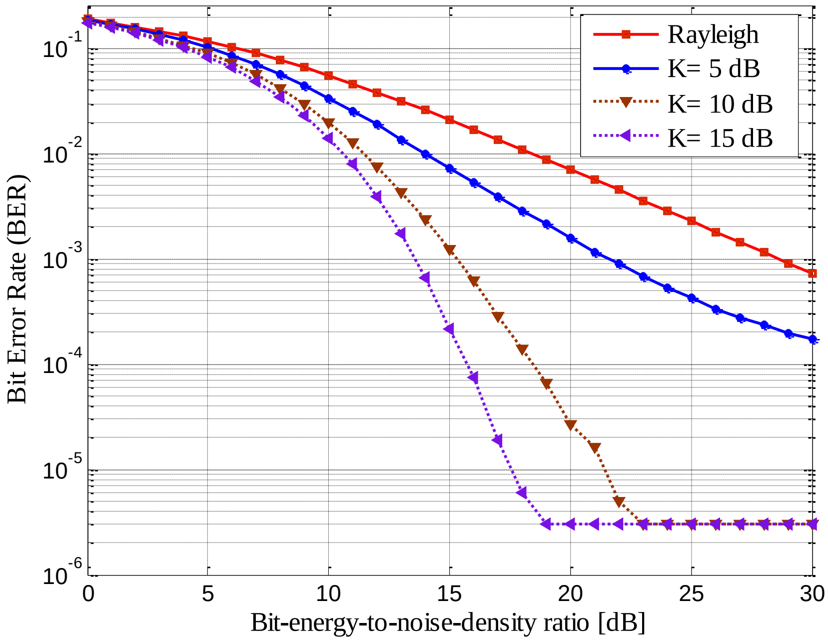

Figure 3.17: BER performance of D-8PSK for VHF band based VDL-2 system

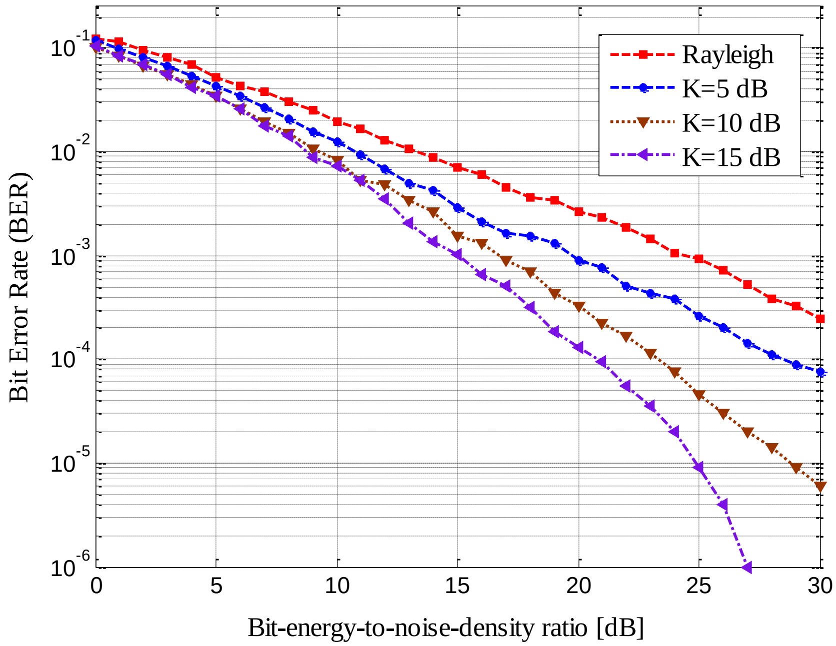

Figure 3.18: BER performance of QPSK for 5 GHz band based system

Assume that a signal-to-noise (SNR) ratio of 10^{-3} is required for a stable service in ATC when coding technique was not applied to improve BER yet. Look at Figs. 3.17-3.18 we can summarize some typical values of BER at K factors of 5, 10, and 15 dB. These values also correspond to typical phases during the experimental flight if we fit them with the Fig. 3.8. These phases are according to taxing, taking-off/landing, and en-route which have been mentioned above.

TABLE 3.4: TYPICAL REQUIRED SNR FOR VDL2 & 5 GHz BAND SYSTEMS

Parameter		Required SNR (dB)	
Channel fading	Phase of flight	VDL-2 system	5 GHz band system
Rayleigh	Parking	28	25
K=5 (Rice fading)	Taxing	22	20
K=10 (Rice fading)	Taking-off/landing	15.5	16.5
K=15 (Rice fading)	En-route	13.5	15

Table 3.4 shows that, system performances at 5 GHz band in two phases of parking and taxing are better than that in VDL-2 system under the same conditions of simulation. However, in other phases, such as taking-off/landing or en-route, VDL-2 system is a little better than that in 5 GHz band based system. This is because in the latter cases, the ground speed of aircraft starts to be considerably high, the Doppler shift therefore does affect to the system performance. This means the wideband, 5 GHz band, is very promising to be used in the communications between aircraft and airport especially at the area on the airport or near to the airport because in those cases, the speed of aircraft is more preferable to the 5 GHz band system.

3.4.2 Evaluation of MC-CDMA in 5 GHz Band

To show the valuable feature of implementing this wideband in aeronautical communication, it is meaningful to evaluate system performance in a multi carrier based system. The reason of selecting multi carrier based transmission in this field because of the two major reasons. They are the high Doppler shift effect due to relative high speed of the aircraft during its flight phases; and the multi reflection of propagation paths due to the existing of several objects especially at the airport area. CDMA is well-known with the ability to against the fading channel; and OFDM is popular with the ability to transmit high bit rate and overcome the high Doppler shift communication situations. In OFDM system, by properly setting the sub carrier spacing, the Doppler shift effect is almost eliminated. Moreover, OFDM can combat selective fading channel by simple equalization techniques. With these advantages, their combination, MC-CDMA, is expected to perform well in aeronautical communication channels compared with current single-carrier techniques. Furthermore, MC-CDMA is simple in allocating a number of sub carriers for specific users. This flexibility is necessary to provide on-demand services for air traffic control communication at advanced airports in the near future [14].

3.4.2.1 Simulation Parameters

In our simulations, we have assumed that the ground antenna is a directional antenna with the gain of 20 dBi. The RMS (Root Mean Square) delay spread values are according to the case of 20 dBi antenna gain at different periods of flight [15]. The guard length is set at least 4 times larger than the RMS delay spread as reported in [16] and [17]. Sub carrier spacing is always ensured to be wider than the maximum of Doppler shift frequency to avoid ISI (Inter Symbol Interference).

Simulations are to evaluate BER of MC-CDMA system during three periods of taking-off/landing, taxing and parking. In each period, two cases according to two system designs are simulated and compared. They are respective to the cases of data bit rates are at 256 kbps and 1024 kbps. Assuming the applied modulation scheme to the both cases is QPSK. All of other parameters are shown in Table 3.5.

TABLE 3.5: SIMULATION PARAMETERS FOR MC-CDMA SYSTEM IN 5 GHZ BAND

Parameter	1024 kbps	256 kbps
Rice factor (*K factor*)		
▪ Taking-off	10 dB	10 dB
▪ Taxing	5 dB	5 dB
▪ Parking	- 5 dB	- 5 dB
RMS delay spread		
▪ Taking-off	1.5 μs	1.5 μs
▪ Taxing	0.85 μs	0.85 μs
▪ Parking	0.45 μs	0.45 μs
Maximum of Doppler shift		
▪ Taking-off	1400 Hz	1400 Hz
▪ Taxing	235 Hz	235 Hz
▪ Parking	70 Hz	70 Hz
Number of paths for echo effect		
▪ Taking-off	6 paths	6 paths
▪ Taxing	10 paths	10 paths
▪ Parking	15 paths	15 paths
Modulation	QPSK	QPSK
Ground antenna gain (directional)	20 dBi	20 dBi
Aircraft antenna gain (Omni-directional)	0 dBi	0 dBi
Frequency	5.1 GHz	5.1 GHz
Bandwidth	4.096 MHz	4.096 MHz
Spreading code length (Wash code)	32	32
Sub carrier space	33 KHz	33 KHz
Total no. of sub carriers	124	124
Symbol length	36 μs	36 μs
Guard length	6 μs	6 μs
No. of sub carrier per user	19	5

3.4.2.2 Evaluation of System Performance

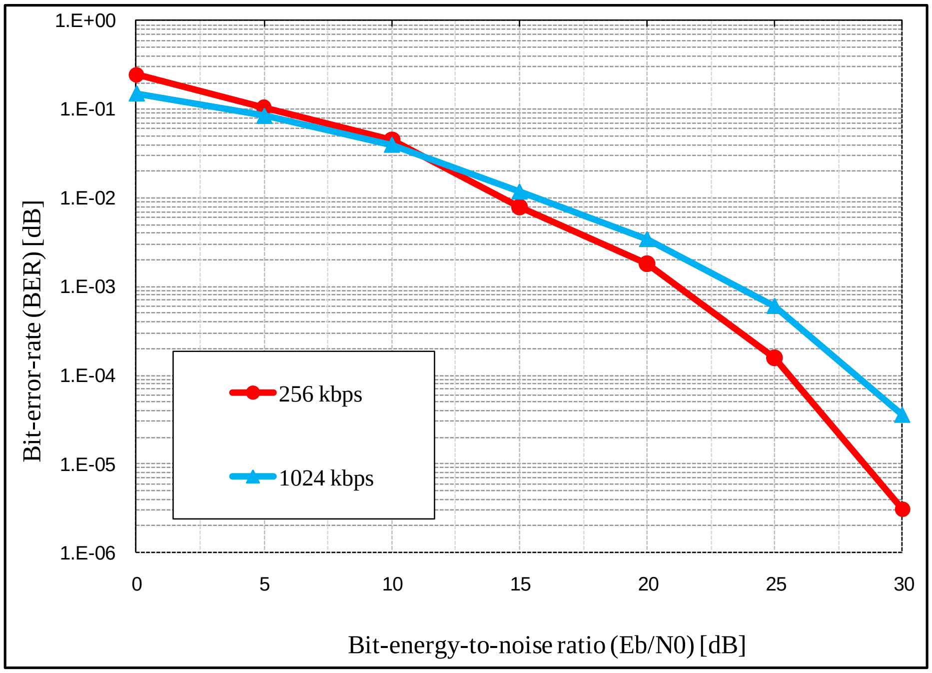

Figure 3.19: System performance of MC-CDMA at 5 GHz band in parking period

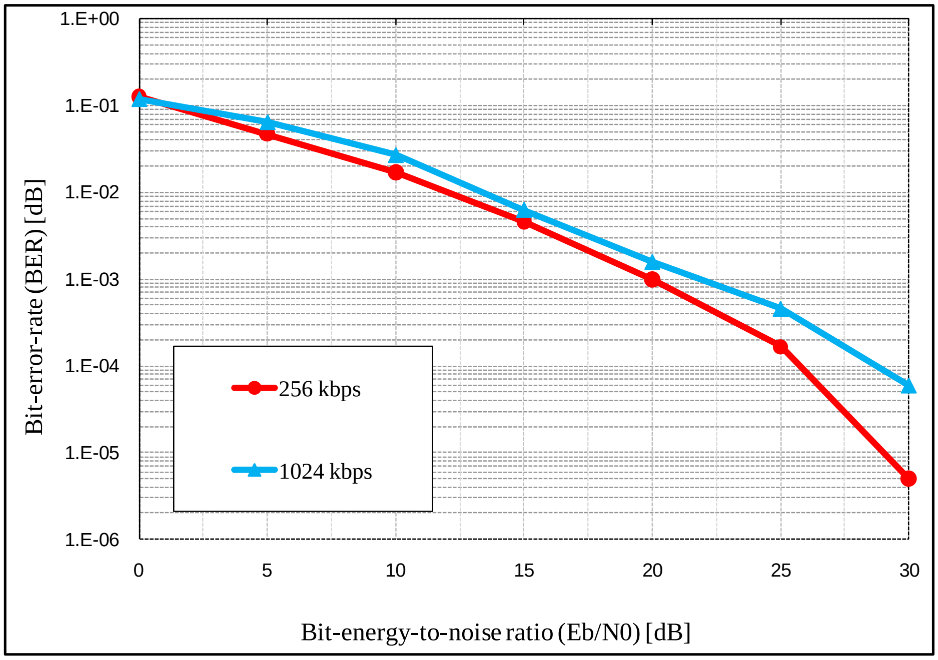

Figure 3.20: System performance of MC-CDMA at 5 GHz band in taxing period

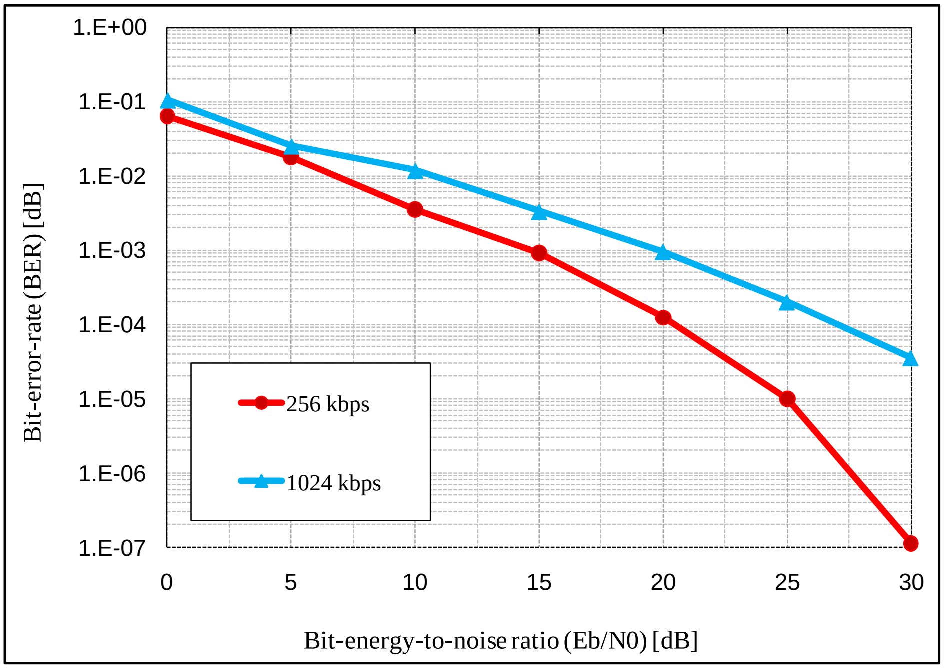

Figure 3.21: System performance of MC-CDMA at 5 GHz band in both taking-off and landing periods

In all simulations, the systems were assumed with a simple MC-CDMA model and a perfect channel estimation function. Also, channel coding was not applied yet for simulation. The total bandwidth is supposed to be about 4.096 MHz in all the cases. In practice, the bandwidth is determined if the number of users in the system is known. In CDMA part, Wash codes are used to spread symbols in frequency domain. All other parameters are shown in Table 3.5.

In Figs. 3.19-3.21, the horizontal axis describes the bit-energy-to-noise ratio (E_b/N_0) and the vertical axis is the BER of system. In all three phases of the flight, within 30 dB of E_b/N_0, BER can reach to 10^{-4} or better depending on each period and the case of situation. This E_b/N_0 is assumed to be quite large because the aircraft and ground station are not far from each other, so by increasing transmitting power, we can obtain large values for this ratio.

In addition, from these figures, there is no significant difference in BER performance of the systems in the two periods of taxing and parking even the respective channels are not similar. In fact, from our experimental studies, K factor in taxing phase is better than that in the parking phase. And in the parameter set for these phases, the aircraft speed in taxing phase is higher than that in parking phase. Therefore, the channel may suffer from a heavier

Doppler-shift effect during taxing phase compared with that in parking phase. From these main reasons, the channel characteristic in each of those two phases has advantage and disadvantage, which may lead to a similar result in terms of channel performance.

In taking-off/landing phase, aircraft always moves at higher speed compared with its speed in the other two periods and therefore suffers a heavier Doppler shift effect; however, the channel condition is much better than other cases because it was almost in LOS. Consequently, the BER performance was improved considerably, especially at areas with large values of E_b/N_0 (Fig. 3.21). Moreover, from Figs. 3.19-3.21, we have an additional conclusion as following: if $E_b/N_0 \geq 25$ dB, BER obtained in parking period is even a little better than that in taxing period and it is close to BER in takeoff/landing period displayed in Fig. 3.21.

From the simulation results, when aircrafts are near the airport, it is simple to increase the transmitting power from the ground system and ensure that the receiving systems on the aircrafts can catch the information signal with large enough E_b/N_0 ratio i.e. at least 25 dB to get good performance with our system. This is an advantage of implementing this system.

3.5 Conclusion

This chapter has provides the details of studies on the new and wide spectrum, the 5 GHz band (5090-5150 MHz). Before this study, there have been a lot of arguments and controversies on the feasibility of this band for aeronautical communication systems. The crucial questions raised to this band are its high Doppler shift may significantly affect to system performance; and high transmitting power issue. These issues are due to the extremely high frequency in the new band comparing with the VHF band in aeronautical communication.

Our studies in this chapter have answered the most serious wonder by showing the capability and suitability that this band could be effectively utilized for avionics communications. In addition, the following doubt is also cleared by applying our proposed novel scheme with the reflection boards. This technique has improved the receiving signal strength in case of using directional antenna in aeronautical communication. This innovation is a contribution to facilitate this wide band for practical systems. From the experimental based channel characteristics studies, we have conducted a preliminary evaluation on the capability of a communication system. This analysis is comparable with the most popular VDL-2 system in the aeronautical communications. From valuation results, it is possible to state that this new spectrum is possible to use for the communication at the airport or for the nearby airport areas. The simulated results show that the system performance of a 5 GHz band based system is not significantly different from that in the case of VDL-2's system.

Another valuable thing from this study is the ability to provide an enormous spectrum for communications; which should be evaluated and deployed more. Specifically, a wideband services based on multi-carrier transmission technology is a promising candidate [15], which has been evaluated above. In practice, it is always necessary to provide an on-demand service between an aircraft and an ATC controller. This requirement is especially high for the communication at the areas nearby airport. With the applicability of multi-carrier based transmission, this requirement has become true and the feasibility is high.

This new spectrum has opened a new era for the wideband communication at the airport. It has also fulfilled the general requirements for the future air to ground communication systems in avionics area that we have mentioned in chapter 1. In the next chapter, we describe the proposals that how to satisfy the future requirements on the air to air communications. In aeronautical network, air to air communication is the other important communication sector that is connecting with air to ground communication in this study. These communication systems basically complete the entire communications for any flight in the airspace.

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4

TDMA BASED AIR TO AIR COMMUNICATION SYSTEM FOR OCEANIC FLIGHT ROUTES

A study for wideband communication has been proposed for the air to ground communication in previous chapter. This chapter intends to provide a novel proposal for the air to air communication in VHF band. The experimental study results mainly include the propagation path loss and effective communication distance between oceanic aircrafts. These results are also applied to the computer simulation for evaluating the system performance of a multi hop ad hoc data relay network among oceanic flight routes.

4.1 Introduction

As the number of flights on ocean routes has increased, putting more aircraft on the existing flight routes has emerged as a topic in future avionics communication. For example, the air traffic between Japan and America on the North Pacific Oceanic routes in the year 2000 increased by 50 percent, compared with that in 1993 [1], [2]. Between 2000 and 2010, air traffic between Japan and North America is to be double [3]. An even larger increase in the number of aircraft in Europe and America airspaces is reviewed in [4], [5].

In order to provide an effective and safe service in air transportation over the oceanic areas, air traffic control systems are used as it is in continental areas. These systems aim to setup a possible communication between pilot and air traffic controller for periodical reporting of the aircraft position. As described in chapter 2, air traffic control systems for oceanic flight routes also include two major bands of VHF (118-137 MHz) and HF (2.85-22.99 MHz). A common communication system currently used in oceanic air traffic control is displayed in Fig. 4.1.

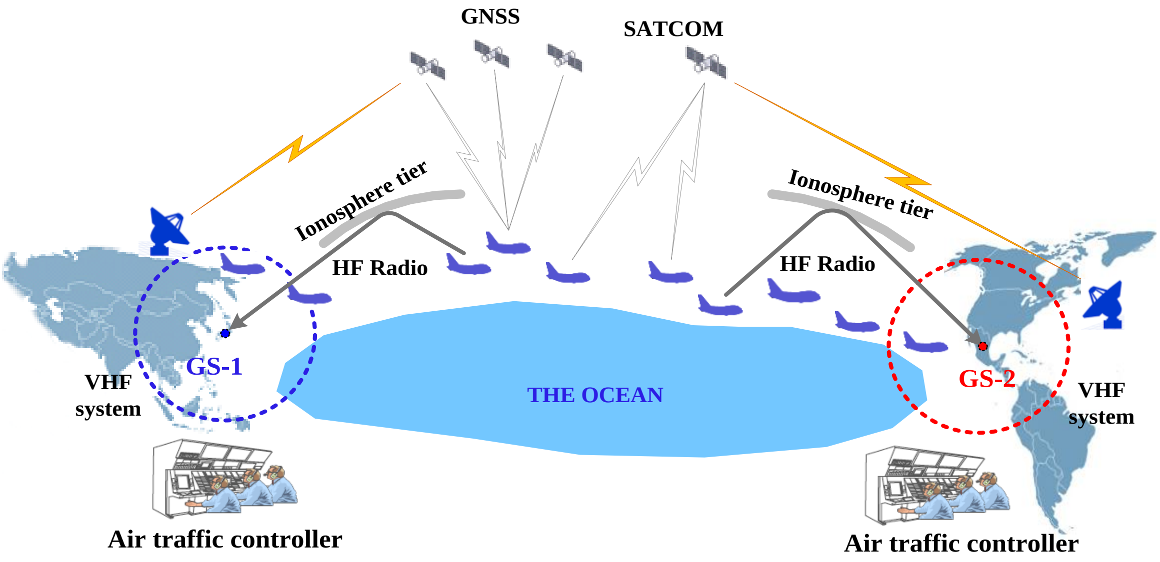


Figure 4.1: Current aeronautical communication systems for oceanic flights

The VHF radio based system is used for a communication range up to 300 km between aircraft and ground station. The HF radio based system could be used for longer ranges of communication such as the cases of oceanic and polar aircraft. However, the performance of HF system depends on solar physics. As a result, it normally takes about 2 minutes to setup a communication, and the successful rate is around 80% or lower [6], [7]. In addition, oceanic aircraft are equipped with a satellite based SATCOM (Satellite Communication) system. However, the SATCOM is often used for airline operational communication services, and is not widely used for ATC due to the high cost compared to the HF based system. That is why the current oceanic ATC mainly uses HF radio based communication with SATCOM system used only as a backup when the HF system cannot be utilized. Similarly, our proposed system will use SATCOM as a backup when the main mode of communication (relay network) cannot be established.

Because of the increase in air traffic, two concerns are raised. One is the increasing burden on the aeronautical satellite system if all aircraft use SATCOM system; the other concern is that the HF radio based communication system cannot support aircraft reporting their position at a high rate for the predicted increase in air traffic [8].

Regarding the issue of the rising burden on the aeronautical satellite system, specifically in the number of satellite links, there were studies which partially solve this issue. These studies have proposed to collect data from several aircraft and add it into one satellite link. This one satellite link would be used instead of several individual links between the aircraft and the satellite [9], [10]. There was another proposal that enables the ATC load on satellite system to be reduced by routing the data from the aircraft to the ground station via HAPS (High Altitude Platform System), which was studied in [11], [12]. However, this requires the existence of HAPS in the flight-route airspaces. In addition, there were studies that regarded only the feasibility of multi hop communication system and the connectivity of ad hoc networks used for air traffic management in [13], [14] and [15], respectively.

There are also concerns regarding the limitations of the HF radio communication system in high air traffic routes. Due to the limitations of an HF-based system in reliability and interval of position reports, ATC authorities require that any two consecutive oceanic aircraft must be separated by a large distance (i.e., 93 km [9], [10]). This regulation prevents significantly increasing aircraft density on a given route, and hence is inefficient in using airspace. Since all oceanic aircraft must follow specific flight routes, this issue is of particularly high concern when the number of aircraft is sharply increasing.

This chapter represents our studies that we have proposed for enhancing the communication between aircraft and aircraft as well as between aircraft and ground station. In these studies, in addition to broadcasting of aircraft's own position report, it needs to receive and forward information of other aircrafts. As a result, the situational awareness is significantly improved in the entire region. Also, the high rate of aircraft position reporting is another issue to be solved in this study, which must satisfy the future requirement of surveillance for oceanic aircraft.

This study therefore provides following contents:

(1) Extract and validate the received signal power equation in the space between two aircrafts. This allows for finding the most effective air-to-air transmission distance in VHF band; exactly calculating the received signal power and accurately calculating the interference power for the communications among the aircrafts.

(2) Propose the TDMA (Time Division Multiple Access) based scheme, which enables all the aircrafts in the flight-route airspace to work autonomously with the support of ground stations [16].

(3) Propose additional mechanisms allowing system to improve the ability of relaying data packet such as adding more delay to each aircraft or changing the routing-path

which is dependent on the flight schedules. This scheme is effective to the studies in (2) [17].

(4) Moreover, another IB-NS (Interference Based Node Selection) scheme has also contributed to these communication systems in terms of improving the Packet Error Rate (PER) by flexibly adjusting the transmission distance in the system in (2) [18].

4.2 Air to Air Experiment for Oceanic Flights

4.2.1 Experiment Model

In our proposal, the system is based on TDMA in which the estimating exactly receiving power or interference power of signal from one transmitter or an interference source is important for an optimal system design. Theoretically, the receiving signal power can be calculated by using the free-space path loss equation if the transmitter and receiver are in line of sight (LOS) range [19]:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{4.1}$$

According to Fig. 4.2, the segment A_1A_2 is the LOS distance of the two oceanic aircrafts which could be theoretically calculated as follows:

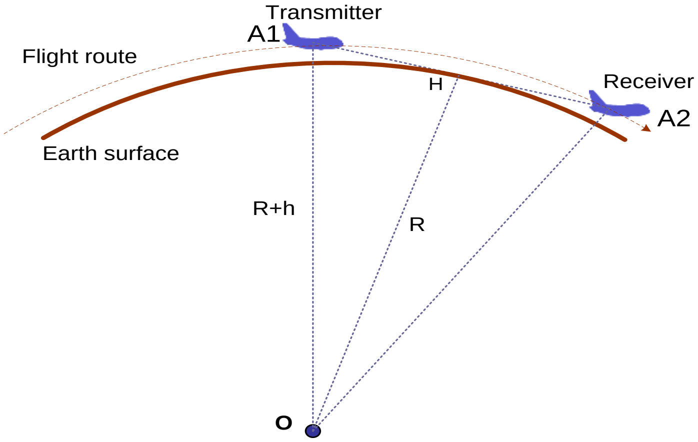


Figure 4.2: Theoretical LOS distance between the two aircrafts

$$d_{LOS} = 2\sqrt{(R+h)^2 - R^2} \tag{4.2}$$

where R is the Earth radius and h is the aircraft altitude.

By applying typical conditions of oceanic flights with h= 9-11 km, and R = 6378 km, d_{LOS} is varied between the minimum at 678 km and maximum at 750 km; and the average value at 714 km.

TABLE 4.1: TECHNICAL PARAMETERS FOR AIR TO AIR EXPERIMENT IN VHF BAND

Parameter		Value
Frequency		123 MHz
Transmitted RF power		+ 45 dBm
Modulation method		D-8PSK
Receiver sensitivity		- 98 dBm
Transmitting and receiving antennas	Gain	0 dBi
	Direction	None (Horizontal plane)
	Polarization	Vertical
Aircraft speed		250 m/s
Aircraft altitude		10 km
T-R (Transmitter-Receiver) distance		280 - 800 km
Recording data frequency		1 Hz

When the distance between them becomes large and near the upper bounds of the LOS range, the received signal power could be diffracted by the Earth surface. This diffraction effect will be complex as described in [20]. This chapter provides a practical experiment that has been carried out to examine the characteristics of the receiving signal in both scenarios. These scenarios are for the cases that the distance between the two oceanic aircrafts is smaller or larger than the theoretical LOS range (Fig. 4.2). The measurement was done with the following criterions: both aircrafts were in the en-route phase of flight, at an altitude of approximately 10 km, the location was the airspace of Japanese ocean, and the two aircraft flew almost parallel while slightly diverging. The aircraft were slightly diverging because we intended to imitate the actual flights but a range of distance values was desired. The technical parameters of the experiment are described in Table 4.1 and typically used in current ATC systems.

4.2.2 Measurement and Analysis

Each aircraft contained an onboard GNSS (Global Navigation Satellite System) receiver to record the instantaneous position and time, and an onboard computer to save the processed position information. In addition, the receiving aircraft contained a spectrum analyzer and an extra onboard computer to analyze the received signal and store it, respectively.

The analysis of the measured data includes two steps. First, we synchronize the temporal information from data that was recorded in both aircrafts. This step provides a series of outputs, each of which contains the received power, the two aircraft's positions, and the time of measurement. Second, we calculated the relative distance between the two aircrafts based on their position information. We can get the relationship between the received power and the respective transmitter-receiver distance. The formula that describes the average approximation of measured power is derived by using with the SPSS program [21], and is shown as follows:

$$P_r(d) = P_0 + P_1 * d + P_2 * d^2 + P_3 * d^3 \tag{4.3}$$

$$\text{where} \quad \begin{cases} P_0 = -45.395697; P_1 = -0.253725201 \\ \\ P_2 = 5.5997941\text{E-}4; P_3 = -4.3484527\text{E}-7 \end{cases}$$

and $P_r(d)$ is the average received power in dBm, d is the relative distance between the transmitting aircraft and receiving aircraft in km.

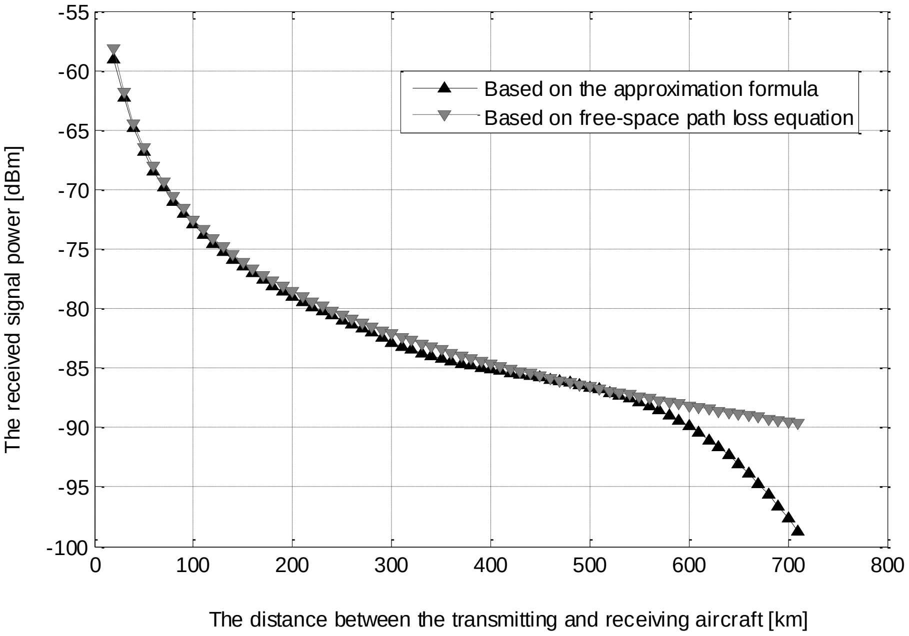


Figure 4.3: Comparison of received powers calculated by equations (1) and (3)

As can be seen from Fig. 4.3, when the aircraft are not near the edge of the LOS (d < 590 km), our approximation in Eq. (4.3) is very close to the free-space path loss in Eq. (4.1). However, our measurements show that near the edge of the LOS range, Eq. (4.1) is no longer valid. Therefore, Eq. (4.3) is more adept for modeling received power, especially for the range beyond the theoretical LOS range (d > 714 km). It should be noted that our measurement did not involve any distances less than 280 km. However, if d < 280 km, the two aircraft are within LOS range. Therefore, the receiving power calculated by using Eq. (4.1), should be similar to the receiving power calculated by using Eq. (4.3) (Fig. 4.3).

The theoretical d_{LOS} from Eq. (4.2) is approximately 714 km. However, our measurements show that the practical d_{LOS} is approximately 124 km shorter. This is due to the diffraction effect of the ocean surface at distances near the LOS range. This effect was not considered in the free-space model shown in Eq. (4.1), while our measurement result in Eq. (4.3) does factor for this effect.

Since our experiment conditions are similar to actual oceanic flights, the results of Eq. (4.3) are important in finding the optimal design values of the proposed system described in the next sections 4.3 and 4.4. It also plays an essential role in applying another proposed scheme to multi-hop ad-hoc relay network for oceanic aircrafts, IB-NS, will be described in

Sect. 4.4. The mentioned result is the most effective transmission distance which the system should use for communication between an aircraft and an aircraft in the airspace. There are several experimental-based studies on the effective transmission distance in VHF band for the air to ground communication, which is maximal at 370 km [22]-[25]. However, there is no such result for the air to air communication except the principal estimation. Theoretically, the effective communication distance or the communication range of interest is the maximal separation between the transmitting and receiving systems in the case the receiving power is still larger than a certain level. This level is constrained by applying a certain value for the transmitting power. For instance, in an aeronautical communication system, the standard transmitting power applied for VHF system is 45 dBm; and the common value of the receiving power is -95 dBm [23]. In addition, for a safe communication, a margin of 3 dB is also common applied.

By taking all of those values in aeronautical VHF system, and fitting them with the receiving power measured and described in Fig. 4.3, the effective distance for an air to air communication in VHF band is 650 km. At this value, the receiving power is -92 dBm which is 3 dB larger than the minimum requirement of -95 dBm.

Finally, Eq. (3) does not only apply to the specific flight conditions used in the experiment, but can also be used for other conditions. In those cases, only the P_0 parameter needs to change accordingly to the total of transmitting power and antenna gain values.

The parameters we have derived from experiment are important in terms of highlight the practical design in multi hop ad hoc network we will describe. These results contribute to the implementation in physical layer of the two communication protocols appear in the sections 4.4 and 4.5.

4.3 Multi Hop Mobile Ad Hoc Data Relay Network Proposed for Oceanic Flight Routes

In current state-of-the-art of avionics communication, aeronautical telecommunication network (ATN) has several shortcomings including the usage of aircrafts only as end nodes. Therefore, all data from aircrafts must be transmitted via ground stations or satellite system. This leads to one of the bottlenecks for future expansion of aeronautic networks; and the free flight concept in [26] is difficult to carry out. This also makes it impossible for a new concept of networking the sky as shown in [27]. However, with mobile ad hoc networks, both intermediate and end systems can be provided, thus bypassing current ATN limitations. On those considerations, we propose to use local mobile ad hoc networks which are represented by the circles in described in Fig. 4.4.

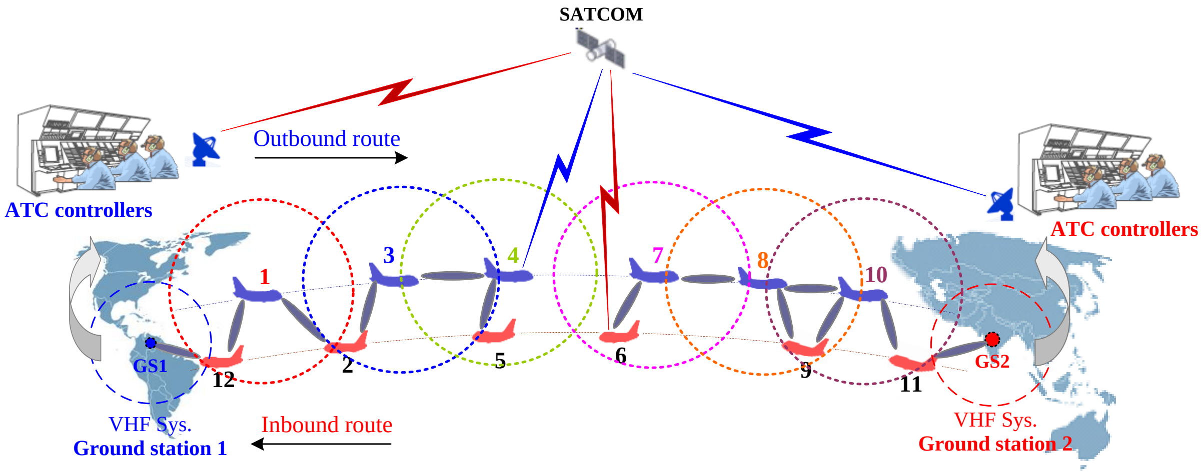


Figure 4.4: System model of multi hop ad hoc relay data network for oceanic flights

Our proposals in this chapter are the forms of “Data Relay System” that is for relaying position reports of aircrafts passing through the ocean routes. In this system, an aircraft transmits its data periodically, as well as relays other aircraft’s data. The final destination for the data relayed between the aircrafts is the most relevant ground station. This relay between the transmitting aircraft and the ground station is based on local ad-hoc networks. The local ad-hoc network at each aircraft is established by using all the air to air connections between the aircraft and other aircraft that are located within its communication range. In the case of no other aircraft within the aircraft’s communication range to relay its data, the load will stay at the aircraft for an allowable delay period as we will explain more in the later part. This delaying permits the aircraft having more capability to find the next destination aircraft to relay the data. We will describe in detail this mechanism in the next section. In the case of waiting time starts to be greater than the allowable delay, we assume that the load will be relayed to the relevant ground station via SATCOM system. Figure 4.4 presents a general mode of this “Data Relay System” for oceanic aircrafts in both inbound and outbound flights routes. This is an example given from Fig. 4.4. The aircraft No. 4 could successfully receive data from other behind aircrafts, but aircraft No. 4 cannot find any other aircrafts for forwardly relaying the data to ground station No. 2 (GS-2) located in front of its flight route. In that case, this aircraft may use SATCOM system to relay its data to GS-2. Similarly, aircraft No. 6 also uses SATCOM system to relay its data to GS-1. Assuming that, there is no additional delay due to activating SATCOM system, so there is no concern of this kind of delay in our simulation and evaluation.

An important notice to this data relay system is the relaying between aircraft and ground station. If an aircraft locates inside the air to ground communication range of VHF based system (300 km), the existing VHF data link will be used for the communication between the aircraft and the ground station. We also assume that all the aircrafts have equipped with VDL-2 system, hence, it is possible to use this data link for our proposed system. This assumption is suitable because the popularity of VDL-2 system in aeronautical communication.

Regarding to the information each aircraft in this relay system will broadcast or report to its relevant ground station, all the aircrafts will use the same data format. This format may be changed as the difference in the depth of information exchanged between the aircraft or the different requirement in aircraft position reporting. For instance, this data may only contain the actual position, status, next destination, etc. of the aircraft in the case of simple requirement by ATC. However, since the requirement on position report to ATC has always increased, it requires additional information such as 4-D strategy of aircraft, the weather condition, high accurate aircraft position, and so on. With this proposal, in any of the situations, an intermediate aircraft is able to update the position information of other aircraft during the relay. This enables the air traffic controller to manage all aircraft’s position, and allows the pilot to monitor other aircraft’s status. In addition to the position report [28], the data load at the aircraft and other information are also included in the packet format. Other aircraft’s data are stored and updated in local memory at each aircraft. This information is used to find the most appropriate aircraft for forwarding the data to in the relay process. The selected aircraft is the one with the lowest data load and the furthest from the transmitting aircraft. It is important to factor an aircraft’s data load in the selection process, as it is proportional to the data-processing delay for that aircraft. It is necessary to transmit as far as possible between each aircraft to minimize the number of relay hops, which is inversely proportional to transmission distance.

By using this relay system, the aircraft's position report will be frequently and reliably relayed to the relevant ground station. As a consequence, the ground air traffic controller can exactly trace and guide the oceanic aircraft. In addition, the relay enables other aircraft to recognize the aircraft's availability; hence, the situational awareness of an aircraft is significantly improved.

In conclusion, this data relay system not only reduces the load over current ATC systems, it also increases the situational awareness of all the aircraft in the airspace. These factors are highly concerned in aeronautical communication as the conditions to modernize air traffic management systems.

4.4 TDMA Based Multi Hop Ad Hoc Data Relay Network for Oceanic Flight Routes

4.4.1 System Description

For this data relay system, the communication between the aircrafts will be done with a TDMA based broadcasting scheme. There are several broadcasting schemes that are not TDMA based, but for various reasons these other systems were not chosen. For example, IEEE 802.11 CSMA/CA is widely used in WLAN (Wireless Local Area Network). However, there is too much overhead such as RTS/CTS, which is long for such a wide range communication system (i.e. 300 km or larger). In addition, the data transmitted in this system is small compared with the data in WLAN, so the CSMA/CA's strengths, such as high bit rate transmission, are not used. Also, the hidden terminal and exposed node issues may become more serious due to the long communication range. Another well-known scheme, CDMA, is well robust in fading channels. However, the channel between two oceanic aircrafts is always in LOS condition and good compared to that in terrestrial cellular system; so the outstanding feature of spreading spectrum technique in CDMA is not used. In addition, to be applied in this system, all the aircrafts need to use the same PN code. This code is predefined in the system, and all the aircrafts know this code. However, multi-aircraft interference will become another issue because many of aircrafts join the system and their data transmission could be the interference to any of other aircraft's transmission. Another issue which is disadvantage to CDMA system, it always requires wide band that may not be suitable for VHF/L and even higher-frequency bands. This is because the VHF/L band is already occupied with several applications and services [29]. As for higher-frequency bands in aeronautical communications, our previous study has analyzed the 5-GHz band [30], showed that it could be only exploited close to an airport [31], [32]. From those issues emerged from other well-known access schemes, the TDMA based access scheme can avoid the issues just mentioned, and as soon will be described, has several advantages of its' own.

Considering these criterions, we propose a single TDMA channel that accommodates all aircrafts in a certain oceanic flights route which is always worldwide recognized. The structure of a frame and timeslot for this communication protocol is described in Fig. 4.5.

In this TDMA system, time is divided into frames, called frame periods (FP). Each FP includes two parts: random access slots and reserved access slots. Random access is the period for an aircraft tries to access to radio channel of the system. After accessing the channel, system will assign each aircraft with an appropriate timeslot. We assume that ground stations must manage and control the entrance of any aircraft in the system. This means all of the aircrafts will join the system at one ground station (i.e. GS-1 or GS-2) and leave the system at another ground station in the other side (i.e. GS-2 or GS-1).

For accessing to the system, if an aircraft first joins the system, it listens to all neighbor transmissions within a FP. After getting necessary information such as the neighbor's aircraft position, the number of available timeslots in the FP, it sends a request to the nearest ground station (GS). This request is for accessing to the system which usually contains a selected timeslot. The aircraft uses a timeslot in random access part to send this request. There are not many aircrafts join the system at the same time, so a simple scheme such as slotted-aloha could be used in this period. After sending the request, this aircraft also needs to wait until related ground station properly assigns with a time slot. In the case of leaving the system, a similar but simpler process is also needed. The leaving aircraft sends a message to the nearest ground station in order to inform about its leaving. The ground station will release the timeslot that is assigned for the aircraft, and wait for a confirmation from that aircraft. The timeslot assigned for each aircraft is unchanged during the period it joins the system.

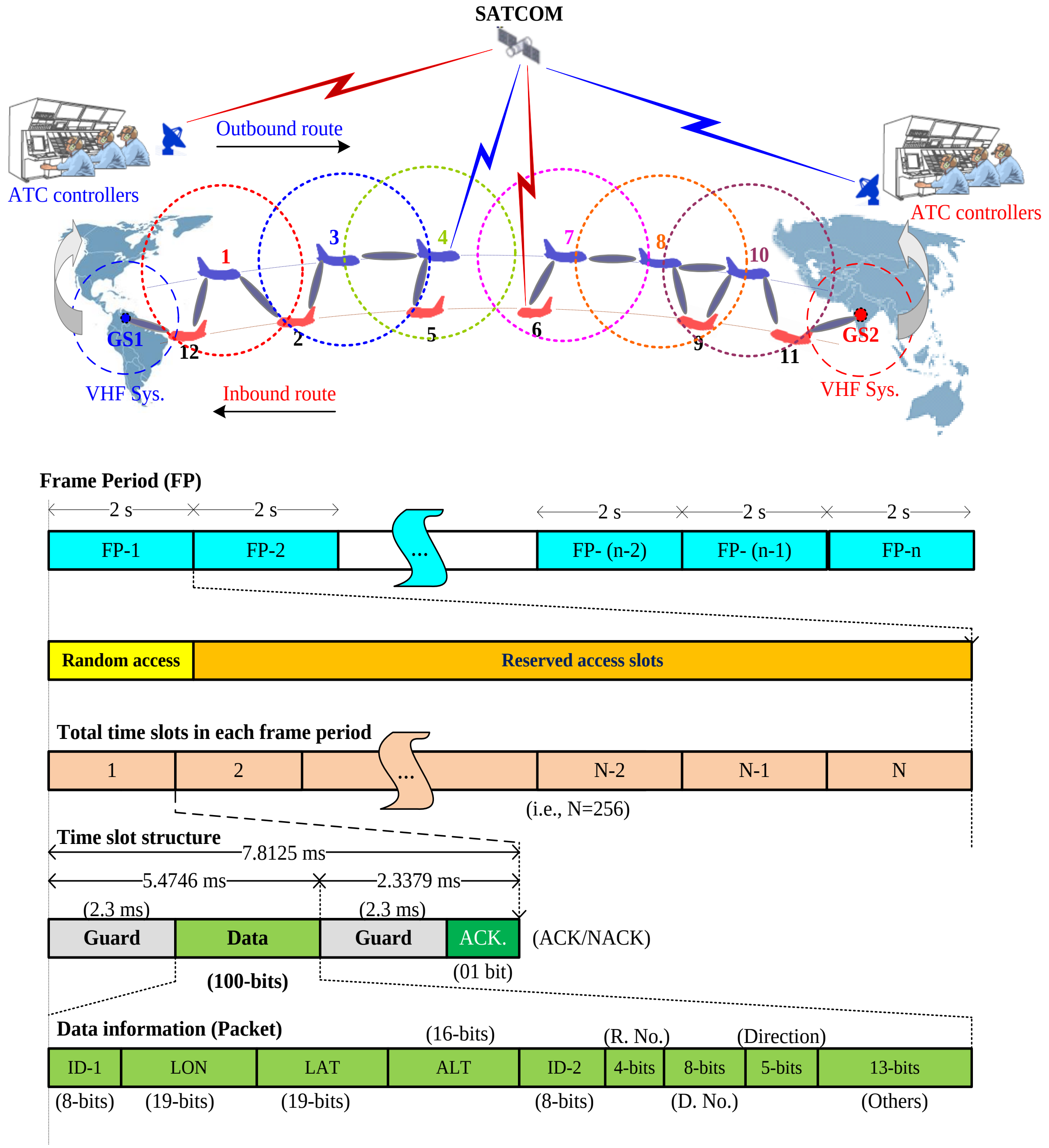


Figure 4.5: TDMA-based communication protocol for oceanic flight routes

Regarding to timeslot structure, there are two parts each of which are used for data communication and acknowledgement. Regarding to the data transmission part, it contains two sub parts. The first sub part includes a guard time (i.e. 2.5 ms for the signal to propagate through a distance of 650 km) to compensate the propagation delay; and the second sub part is for data transmission (i.e. 2.78 ms for accommodating 100 bits at transmission rate of 31.5 kbps). In this system, the data part is the major part for communicating and exchanging the necessary information between the aircrafts as well as for reporting to air traffic controller. Therefore, the data part must contain at least the following sub contents: aircraft ID, aircraft position (i.e. longitude, latitude and attitude); and some other information that could be shared with other aircrafts. For the acknowledgment part, its length must be wide enough to accommodate both guard time (i.e. 2.5 ms) and acknowledgment information. We also assume that the data bit rate possible for communication between aircraft and between aircraft and ground station is at 31.5 kbps, which is exactly same with the bit rate in VDL-2 system (see chapter 2, section 2.1.1).

According to these system design criteria, if we assume a frame period of 2 s, this system can provide a maximum of 256 aircrafts. This number of aircrafts is three times larger than the maximum number of flights on North Pacific Ocean routes or two times larger than total flights on North Atlantic Ocean routes at any time. The ground stations i.e. GS-1 and GS-2 are always kept synchronized with Global Positioning System (GPS), and of course all the aircrafts in the system also ensure its synchronization with the GPS. These ground systems are also connecting each other and able to share the information for controlling this communication protocol by a wired network system.

Theoretically, the guard time length is proportional to the communication distance and it is also considered as a dead time. However, the larger transmission distance the higher the probability of establishing a local ad hoc network. This enlargement in communication distance enables the system to increase the ability of relaying more packets. Based on both theoretical and experimental evaluations, an initial value of transmission distance is at 650 km (section 4.2.2).

4.4.2 Data Format and Aircraft Position Reporting

According to Fig. 4.5, each aircraft in the system is always assigned with a unique time slot when it enters the system. Also, at this timeslot order in any frame period, the aircraft's packets are processed. This process usually contains other two sub processes. First, the aircraft generates a new packet and firstly transmits this packet by itself. Second, its packets are processed by other aircrafts when they are staying at those aircrafts. It depends on the interval set for the system, there will be only one or two sub processes occurred. The packet of each aircraft is regenerated after an interval which is predefined. This interval usually has a length of at least several frame periods. After this interval, packet regeneration aims to keep the aircraft positions updated to other aircrafts and air traffic controller on the ground.

Because each position report at least includes ID of both transmitting and receiving aircrafts, at the receiving side, the receiver will send a feedback to the sending aircraft. The feedback could be ACK or NACK which depends on the correction of receiving the packet. If the acknowledgment is ACK, the receiving aircraft continues to relay the received packet to the next appropriate aircraft. This relay will happen at the same time slot that it received the packet but it must be in the next FP. In the case of NACK, the sending aircraft needs to try its own position report retransmission after the mentioned interval. This relaying process is repeated until a packet reaches its final destination, which will be one of the ground stations.

As we have mentioned the probability of existing concurrent transmission at the same time is high because each aircraft usually has many packets in relaying process. That is why the interference due to simultaneous transmissions needs to be concerned. To describe this interference, we divide the neighbors of an aircraft into two groups, called adjacent-relay aircrafts (ARA) and distant-relay aircrafts (DRA). ARA is the group of aircrafts where their data transmission is affected by each other. DRA is the group of aircrafts where their transmissions are not affected each other because they are separated at a long enough distance. At the assigned timeslot order of an aircraft, after some intervals, the aircraft’s packets are processed by one or several neighbor aircrafts. These aircrafts belong to ARA or DRA group of that aircraft which is determined by the number of FPs in this interval. The shorter the interval is, the more often the aircraft can transmit its position report, and the more often its position reports are relayed by others. However, the shorter interval value means that after a short period, the aircraft can regenerate its own position report. However, this frequent regeneration of position report may cause to unexpected interference to other aircrafts that are relaying position report of that aircraft. The importance we need to find is the optimal value of this interval at a specific air traffic situation. This will be detailed discussed in the later sections.

4.5 Interference Based Node Selection (IB-NS) Scheme

In this system, the aircraft generates its position report after a specific interval. In other way, at the aircraft's timeslot, its position reports will be generated or relayed by other different aircrafts. These aircraft are far from each other at a distance because the packet is relayed or regenerated only after an interval. And this interval usually contains several FPs. However, it is possible for these aircrafts to cause interference to each other as it depends on the distance of separation between them.

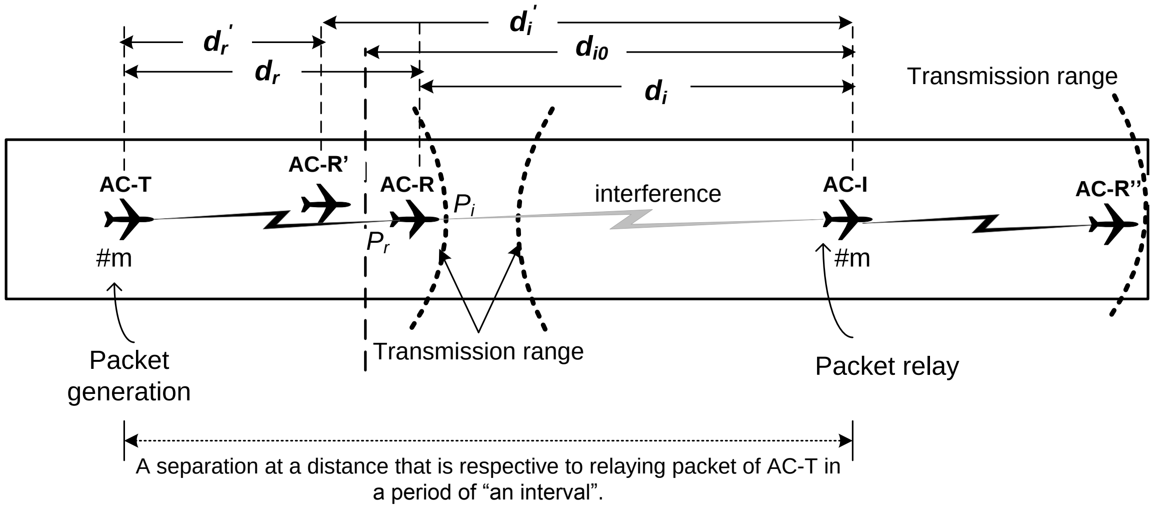


Figure 4.6: Description of the interference based node selection (IB-NS) scheme

Figure 4.6 shows an example of radio interference that could be high in the TDMA system due to a short separation in distance of concurrent transmitting aircrafts. The transmitting, receiving and interfering aircraft are named as AC-T, AC-R, and AC-I, respectively. The AC-T will generate a position report for itself; while AC-I relays another position report of AC-T. The packet generation and packet relay done by AC-T and AC-I are at the same timeslot order (i.e., #m). Actually, the relaying packet is originated by AC-T at timeslot i.e. #m but it was an interval ago. The packet reception at AC-R will be successful if the two conditions of SNR and NIR are satisfied: ($P_r - N_0 \geq \gamma_c$) and ($P_i - N_0 \leq I_0$) [33]. In which, γ_c is the communication threshold; I_0 is the interference threshold; N_0 is the noise power at the reception; P_r is the received signal power and P_i is the strongest interference power. P_r and P_i are calculated based on Eq. (4.3). The first condition is satisfied, but the second condition might be not guaranteed if ($P_i > N_0 + I_0$). This is because AC-R may be located in the affected area of the AC-I transmission. However, AC-T might not have enough information about AC-I, so the high interference at AC-R could not be avoided in advance.

In order to solve this issue, we proposed that the aircraft with failed reception (AC-R) include the maximal interference power P_i in the feedback. Based on the feedback information, the transmitting aircraft, AC-T, can estimate the practical distance d_i from AC-T to AC-R. In addition, to ensure the condition of ($P_i - N_0 \leq I_0$), we find the minimum distance d_{i0} from the interference source AC-I by using Eq. (4.3) explained in Sect. 4.3. From d_i and d_{i0}, the minimum distance that the receiving aircraft needs to be separated from AC-I, is also found. According to this value and the information in the routing table of AC-T, it can find the most appropriate aircraft for forwarding the data again. In Fig. 4.6, this aircraft is AC-R' which has distance $d_{i'}$ to AC-I. In this scenario, the NIR condition is satisfied because ($d_i' > d_{i0}$).As a result, the two conditions above is satisfied even if the transmission range is maximal. By this way, we can minimize the transmission interval, which enables the system to have more frequent aircraft position report. We named this scheme as Interference-Based Node Selection (IB-NS).

4.6 Routing Table and Packet Relaying Algorithms

This part explains about routing algorithms for the aircrafts which describes how an aircraft finds the next aircraft to relay its packet to. There are a few routing protocols have been proposed in aeronautical communication which is used with a satellite communication system [12]. The second one is for internet services where the addition of new gateways is unavoidable [13]. Also, these two protocols discuss on internet services for oceanic flight routes which are not used for general air traffic control. We propose a communication system in order to provide frequent position reports of all aircrafts on specific ocean routes. This system does not require any additional infrastructure except the Global Positioning System (GPS) system which is available on any aircrafts.

For building a routing table, each aircraft must listen to its neighbor aircraft's position reports at least in the first FP. This is possible because these aircrafts will transmit their information at their own timeslot within a FP. By using such information, the aircraft can build a routing table for selecting its routing paths. In this table, we use these two factors with lowering priorities. They are the relative distance between an aircraft and its neighboring aircraft; and the amount of data load at the aircraft. It is noticeable that, each position report usually includes aircraft ID, aircraft position and aircraft direction. Therefore, in addition to the information in each neighbor aircraft, the routing table must include the relative distance and relative direction.

In regarding to the distribution of air traffic on oceanic routes at different period of the day, it has shown that the air traffic is unequal in almost of typical oceanic routes. For example, the air traffic in the Northern Atlantic Ocean (NOA) and in the Northern Pacific Ocean (NOPAC) routes. To be adaptive with these air traffic situations, we propose the following packet relaying algorithms in order to find out the most effective method:

1) *Algorithm 1*: each aircraft insists on relaying packets to the aircraft ahead and furthermost. In addition, only the same direction aircrafts are selected for routing.
2) *Algorithm 2*: each aircraft insists on relaying packets to the aircraft ahead and furthermost. However, the opposite direction aircraft is still being selected in case of no the same direction aircraft in the communication range.
3) *Algorithm 3*: the valid airspace is equally divided into several parts where each part is assigned with a ground station. If an aircraft belongs to a part, its packets will be relayed to the next aircraft in the same part which is close to its ground station. If there are no same direction aircrafts, it selects opposite direction aircrafts.

4.7 Node Additional Delay Allowance (NADA) Mechanism

The air traffic in most of the ocean routes are not equally distributed in different zones, therefore there will be few aircrafts at some areas or locations. In that case, the possibility to find an aircraft in the communication range is low; hence, the packet relaying capability is also low. In order to increase the possibility of finding an aircraft to relay data, we propose a scheme in which we allow the packet to stay at the aircraft for some certain waiting time (wt). We named this scheme as Node Additional Delay Allowance (NADA).

It is noticeable that the additional delay does not affect to the aircraft's packets arrival interval in this end-to-end relay system. Because the interval of regenerating new packet of the aircraft is fixed and all the packets experience the same delay on each aircraft, the delivery time of these packets at the final destination is also not changed significantly. It does factor to only the first packet delivery. However, the interval for aircraft position report at present aeronautical communication is quite large, i.e. 5-10 minutes, so the delay of the first packet does not affect to the air traffic control tasks.

The working process of this mechanism is additionally explained as following:

1) The delay process is only applied to the packets after their arrival at the aircraft.
2) Packets are allowed to stay at the aircraft for the waiting-time (wt) before the aircraft relays to the next aircraft. This waiting time is activated for the first time once this aircraft cannot find the route to relay the packet.
3) The value of waiting time is assumed to be a multiple of FPs since FP is relative small compared to total delay allowed.
4) As explained above, after an interval, another updated position packet of an aircraft will arrive. If the some packet of this aircraft is still waiting at an aircraft, the newer packet will replace the older one and continue to wait until the allowed wt. The process for the prior packet is deleted.
5) During waiting at an aircraft, if this aircraft can find a route to relay the packet, the packet is relayed to the next aircraft immediately and waiting process is reset.
6) If the waiting time is up and the aircraft still cannot find any suitable route to relay the packet, this packet is counted as failed and packet loss counter is incremented '1'; also the waiting process is reset.

Both relaying-packet algorithms and NADA mechanism will be simulated and evaluated in the next section 4.8.

4.8 Simulation Numerical Result

4.8.1 Input Data and Simulation Assumption

As explained about the air traffic scenario on oceanic routes, it is impractical to assume a fixed air traffic model in the whole day and use that for simulation. In our end-to-end system, the packet-loss-ratio is expected to be lower in higher air traffic routes because of the high availability of aircrafts to relay. In addition, the reports in [9] and [10] express that the air traffic density on NOA routes is higher than that in NOPAC routes. Therefore, the air traffic model in NOPAC routes is selected for initial input data in our simulation. After analyzing data that are collected on the inbound, outbound of NOPAC routes between Japan and America from March 2000 to February 2001 using Flight Data Processing System described in [2], aircraft arrival and departure distributions in a day on NOPAC routes were obtained in Japan standard time (JST). Based on [3], it is possible to assume that the current number of aircrafts is 1.5 times larger than that in 2000. Therefore, the input data for our simulation is described as in Fig. 4.7.

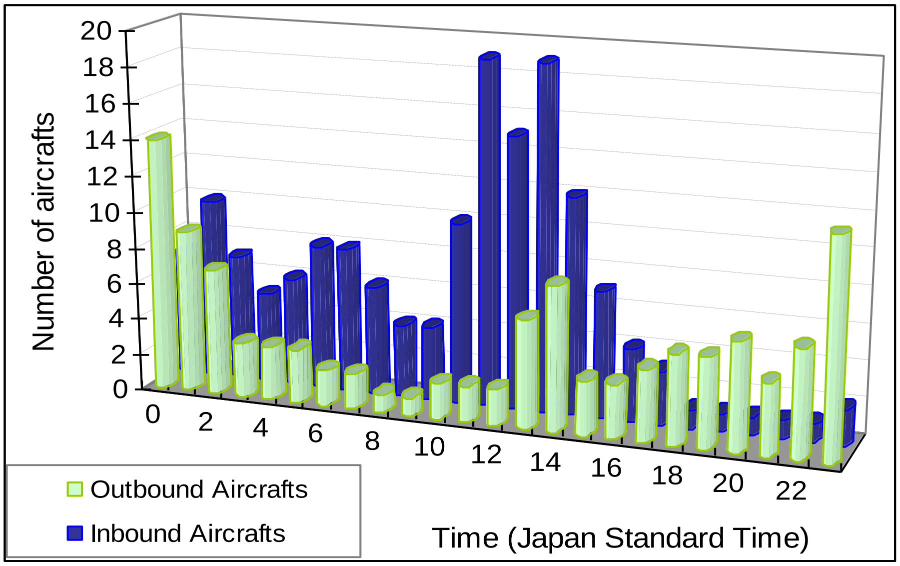


Figure 4.7: The number of outbound and inbound aircrafts on NOPAC route

Before discussing on numerical results, the following conditions are explained in greater detail:

1) The average interval time of arrival/departure aircrafts is calculated based on average hourly-aircraft distribution (Fig. 4.7). Based on the interval time, the aircrafts in each hour are generated randomly but ensured that the minimum time interval between any two aircrafts is always kept at least 3 minutes for both outbound and inbound flights.
2) The maximum radius for the air to air transmission between aircraft to aircraft is set to 650 km; for the case of the air to ground between aircraft and ground station, this value is set to 300 km (same as regulation for VDL-2 system).
3) When a packet arrives at a relay aircraft, based on the routing table at this aircraft, an optimal destination aircraft is decided to relay the packet to. If no aircraft is founded, the number of packet error is incremented ‘1’.
4) When a packet arrives at an ATC station successfully, the final destination, the number of successful packets is incremented ‘1’.
5) Three packet relaying algorithms (Sect. 4.6) were applied to the simulations in order to validate our system proposal. Each simulation is conducted in 25 days, or in 600 hours of flying, to evaluate the packet error rate.
6) The distance between ground stations i.e. GS1 and GS2 in our end-to-end system is assumed of 8100 km. The average ground speed of the aircrafts is 1000 km/h.

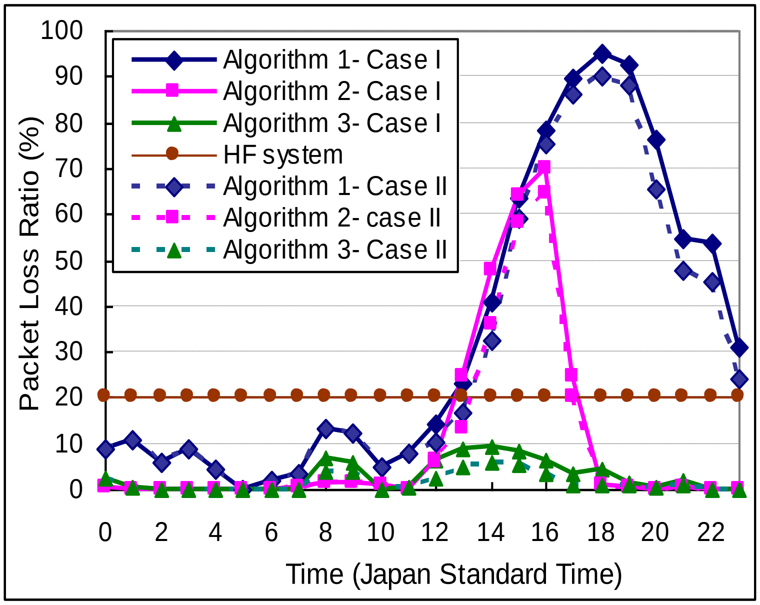
4.8.2 Numerical Results without NADA Scheme

Fig. 4.8 shows the packet loss rate that occurred during relaying packets from all aircrafts in the end-to-end system to their relevant ground stations. Assuming the channel condition between the aircraft is always good; therefore there is no additional packet error during the transmitting or relaying. As a result, the packet error rate (PER) is equal to the packet loss ratio, which is caused by the loss of packet during those processes. In this chapter, the concepts of packet error ate and packet loss rate are same. This ratio is defined as the ratio between the total number of lost packets and the number of generated packets. This ratio is also the most important factor in a multi hop relay network; hence, it is evaluated for the end-to-end system at every hour in the day in Japan Standard Time (JST).

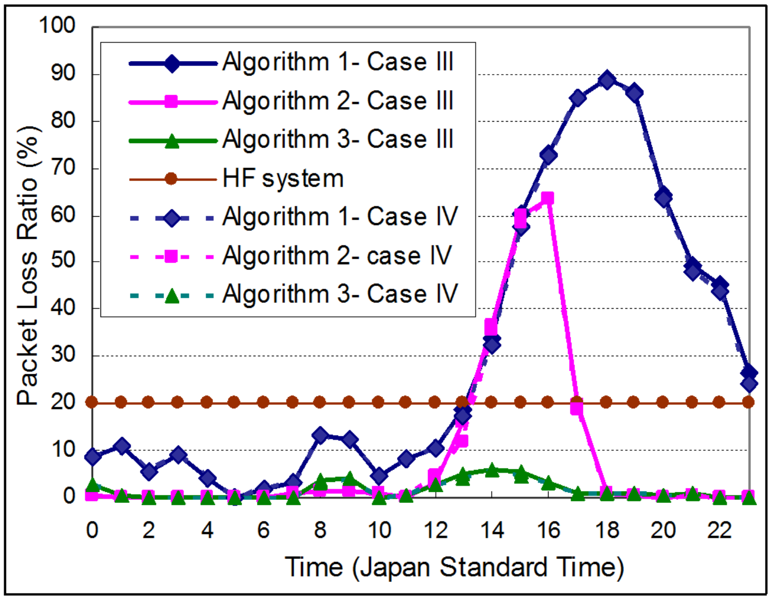
In Fig. 4.8 a), case I and case II are according to the two situations that the intervals are 3 and 4 FPs, respectively. In addition, all the results in Fig. 4.8 a) are without applying the proposed scheme of IB-NS. However, in Fig. 4.8 b), cases III and case IV are according to the intervals of 3 and 4 FPs, respectively, and with the IB-NS scheme. In Fig. 4.8 a), the packet loss rate in the case II is better than that in the case I. This is because, in the case II, the aircraft that transmit packets at the same timeslot order are more separated than the aircrafts in the case I. This enables the system to avoid packet loss due to strong interference effect that is caused by the neighboring aircraft's transmission. In Fig. 4.8 b), packet error rate in the case III and IV are almost the same which is similar to that in the case II (Fig. 4.8 a). This means that at the interval of 4 FPs, packet error caused by the interference of neighboring aircraft's interference is ignorable; hence, IB-NS is not necessary. However, at the interval of 3 FPs, the IB-NS scheme was useful and has significantly improved the packet loss ratio.

Regarding to the effect of packet relaying and routing algorithms, from those results, the packet error rate in case of applying algorithms 1 or 2 are relatively high in some periods of time compared to that in case of using algorithm 3. The possible reason is, the aircraft distribution is not actually equal in hours of the day for both inbound and outbound flight routes. In the first two algorithms 1 and 2, they do not allow a flexibility to find the next aircraft. However, in algorithm 3, the sparseness of inbound flights should be reduced by the density of outbound flights or inversely, which could improve the performance in overall. In practice, the departure time of oceanic flights is usually set for the convenience of local time. But due to the difference in time zone of those places, the departures of outbound at those places are quite different. Hence, the departure and arrival time at a local place are different. Therefore, the aircraft densities of inbound and outbound flight routes are not equal. That is why algorithm 3 has shown its advantages compared to other algorithms 1 and 2.

From those discussions on the obtained results we mentioned above, the optimal interval values should be 4 FPs if IB-NS scheme is not used; or only 3 FPs if IB-NS scheme is applied. Therefore, the latter option which is with algorithm 2 and 3 will be further analyzed when considering the NADA scheme in the next part.



a) Without IB-NS scheme



b) With IB-NS scheme

Figure 4.8: Packet loss rate of end-to-end system in the day

4.8.3 Numerical Results with NADA Scheme

From the results we show above, in the system with algorithm 3 for relaying packet, the packet loss ratio is minimal. This value is even much lower than the packet loss ratio in the current HF system (i.e. it is now about 20%). However, to make this ratio lower is essential in this relaying system. This part describes the results of simulations when we apply the algorithms 2 or 3, both the IB-NS and NADA schemes. Typical values of waiting time are used in each case, for example:

1) In algorithm 2, waiting time values are selected at: 10, 20, 40, 60, 80 and 100 s.
2) In algorithm 3, waiting time values are selected at: 10, 20, 40, 60 and 80 s.
3) Each simulation has been conducted 600-hour flying time, as long as in prior simulation.
4) Other conditions such as end-to-end system and air traffic scenarios are the same as in previous simulations.

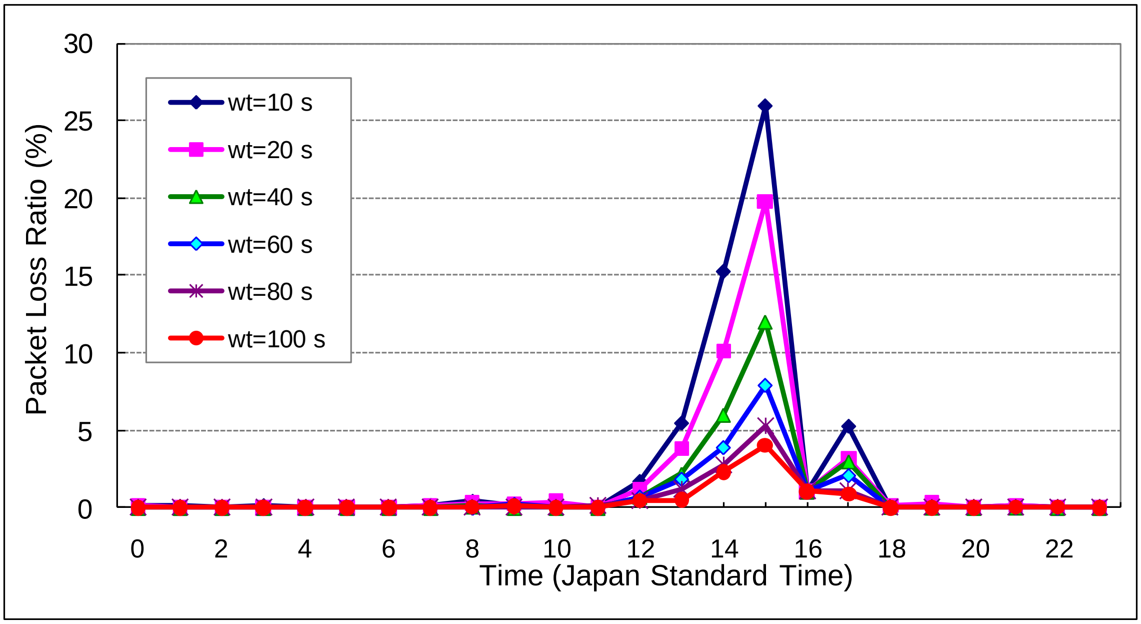


Figure 4.9: PER in case of applying algorithm 2 and both IB-NS, NADA schemes

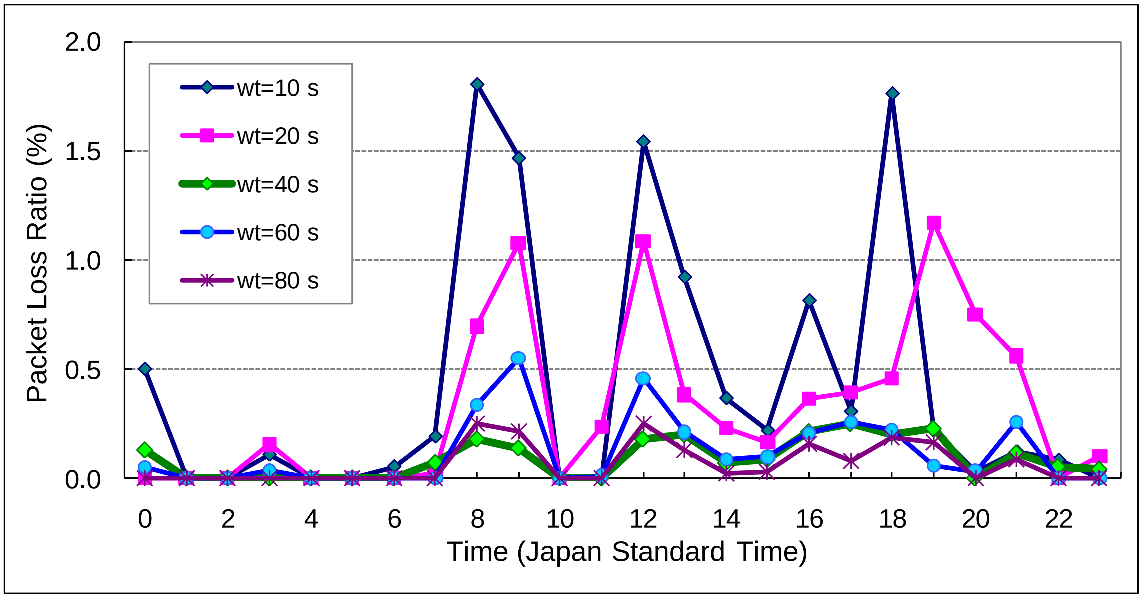


Figure 4.10: PER in case of applying algorithm 3 and both IB-NS, NADA schemes

By using the IB-NS scheme for improving the packet loss ratio and NADA scheme where an additional delay allowed the packet to stay at each aircraft for wt, packet loss ratio has been significantly improved, especially at some peaks that we just mentioned in case of without using DANA scheme.

In addition, from Figs. 4.9-10, the mechanism of allowing a waiting time (wt) will be only activated at the periods or the locations that there are few aircrafts and they are sparsely distributed. This means that the packets are additionally delayed only in those periods. Also, in other periods, the packets are relayed without any additional delay for the packet at the aircraft. For example, at some periods such as [7H-9H] and [13H-17H] in JST, the packet loss ratio in the case of applying algorithm 2 and 3 already reached the peak (Fig. 4.8).However, the results are much better in case of applying this DANA scheme (Fig. 4.10). From the results described in Fig. 4.9 and Fig. 4.10, we have the larger value of waiting time the lower obtained packet error rate in both algorithms 2 and 3. In addition, the result in the case of applying algorithm 3 is always better than that in the case of applying algorithm 2. For instance, with wt of 40 s, the packet loss ratio is much improved and it can reach a quite low rate which is even smaller than 0.2%.

4.9 Conclusion

In this chapter, a highly reliable communication system using a single aeronautical VHF channel has been proposed for oceanic flight routes. This system mainly uses the air to air links among the aircrafts to create the local mobile ad hoc networks. In addition, a TDMA based access scheme has introduced its advantages in terms of allowing the aircraft access and transmit their data. The system provides only one channel digital data link connecting aircrafts in a specific oceanic area and relays position reports of any aircraft in system to the relevant ground station. The system also makes aircraft position reporting more frequent and more stable than current systems. Moreover, this proposal system does not require any additional infrastructure except the existing VDL-2 system and VHF channel.

The numerical results show that the best system performance is achieved when applying an interval at 3 FPs combined with IB-NS scheme and packet relaying algorithm 3. In addition, with an allowed maximal waiting time i.e. wt of 40 s (Fig. 4.10), the packet loss ratio is improved significantly compared with non-waiting time case (Fig. 4.8) and the packet loss ratio is always below 0.2% in all the cases of air traffic on NOPAC routes (Fig. 4.10). Therefore, all flights on the ocean are controlled easily via exact and frequent position reports by relaying from this system. With such achievement, air traffic controller can also trace any of oceanic flights in the managing region.

This feature allows aeronautical authority (ATC centre) to confidently reduce the safe separation in time or distance between consecutive flights since their situational awareness has been greatly improved. This can increase the number of coexisting aircrafts on the ocean routes and therefore improve the efficiency of airspace usage.

The system can be used independently with current systems or to supplement to the current existing HF/SATCOM systems. With this proposal system, the aircraft position reporting system is completed and it is essential to any oceanic flight routes. However, satellite communication is still recommended to use as a backup for this system in case some position reports are not reachable to ATC centers in time or for some emergency cases where data and verbal communication with ATC controllers are necessary.

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5

S-TDMA BASED AIR TO AIR COMMUNICATION SYSTEM FOR OCEANIC FLIGHT ROUTES

This chapter introduces another communication protocol between aircraft and aircraft. This protocol also uses multi hop ad hoc network for relaying aircraft position report from any oceanic flight. However, this system is more autonomous than the system described in previous chapter. This chapter also provides both single and multi radio frequencies based system for oceanic communication system. For more practical system design, all the experiment based results in chapter 4 are fully applied.

5.1 Introduction

In section 4.4 of chapter 4, we have proposed a multi hop ad hoc data relay network that tries to overcome the issues of future air traffic on the typical oceanic flight routes. However, this system's features may lead to some of following limitations. First of all, at a very high aircraft density situation, the frame period will become too large because this period is directly proportional to the number of aircraft. Secondly, the highly frequent position reporting may be difficult because the frame period is reversely proportional to the interference of co-transmissions. In addition, it is difficult for this system to apply different position report rates for different groups of aircrafts. Another limitation of the proposed system is its requirement on using ground stations at the two sides of flight routes. These ground stations are responsible for adding or removing aircraft to or from the system when an aircraft enters or leaves the airspace contains flight routes [1], [2], [3]. These features have shown that this system is not a fully autonomous one. In order to overcome those situations, we have proposed another scheme which only uses one VHF channel but the system is fully autonomous [4]. In this part, we further introduce a multi channel multi hop ad hoc data relay network that is estimated to fulfill the future requirement for both the communications among the aircraft and between the aircraft and ground station [5]. This proposal also supplements to previous proposal in the case of many aircrafts come from diverging flight routes on the ocean and they may not join the system by communicating with one of the ground stations.

In this proposal, we will apply the experimental results for air to air communication; and the IB-NS scheme described in sect. 4.4.3, chapter 4. In addition, two additional mechanisms, named Position Aided Timeslot Reuse (PATR) and Distance Based Timeslot Assignment (DBTA) will be illustrated in this chapter. They aim to improve the timeslots usage and efficient timeslots assignment in the cases of low air traffic that commonly occurred at some areas or locations in the oceanic airspace.

5.2 System Description

In the prior chapter, the section 4.4, we have discussed in details the suitability of a TDMA-based multi hop ad hoc relay network used for air traffic control communication over a certain oceanic flight route. However, in this chapter, we propose another protocol that provides more flexibility to the system. This system is expected to fulfill the requirements of a future communication for oceanic flights, which requires a high rate of aircraft's position information reporting. The major difference with the previous protocol is that this protocol combines both space domain and time domain. As a result, this system can organize a Space-Time Division Multiple Access (S-TDMA) based communication for diversified oceanic flight routes in a valid region [6]. This fully autonomous feature cannot be supported by the previous protocol which only bases on TDMA. This proposal partially utilizes the Time Division Multiple Access which is a part of the S-TDMA system. The reason of this selection which bases on time division approach comes from the unsuitability of other schemes (i.e. CSMA/CA, CDMA). The theoretical evaluation of those schemes have been clearly described and illustrated in section 4.4.1 of chapter 4.

The SATCOM system in Fig. 5.1 also plays the role of a system that backup the proposed air to air network. This function of SATCOM is as the same as its role in the TDMA based system that was described in section 4.3. Consequently, in the case that an aircraft cannot find a destination for relaying its data to, the SATCOM system will be used to relay this data to the aircraft's relevant ground station.

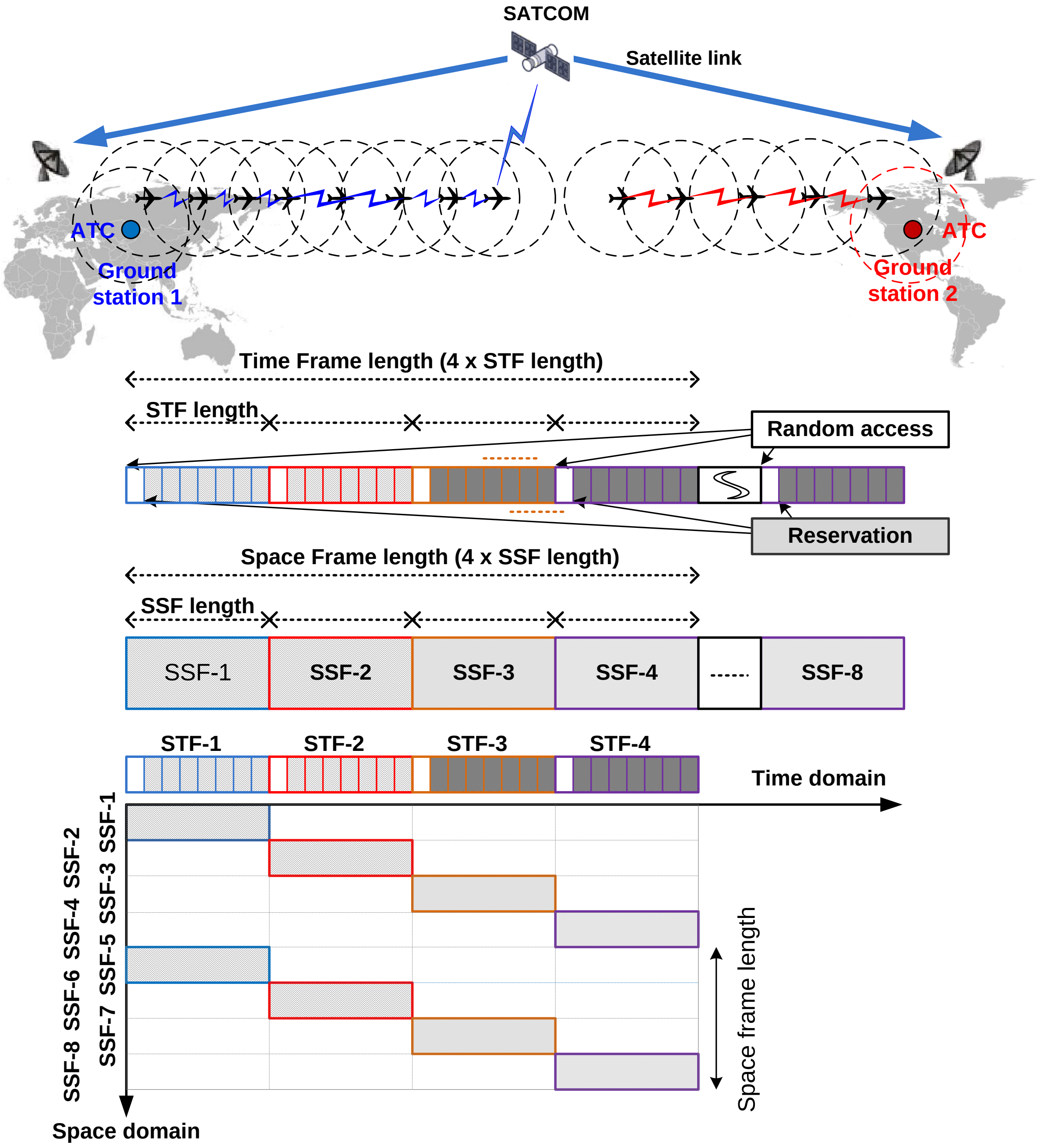


Figure 5.1: The S-TDMA based communication protocol for oceanic flight routes

In this S-TDMA system, the flight-route airspace is divided into consecutive space frames. All of the space frames are the same length and divided into sub space frames (SSF). The length of each space frame is basically proportional to the communication range of each aircraft which is commonly designed for all the aircrafts. This length is designed to be large enough in order to guarantee an ignorable interference could be occurred by the transmissions of the aircrafts located in those space frames. Following the approximation of describing the relation between the receiving power strength and the distance between these two aircrafts, it is possible to obtain a possible space frame length with the condition of getting an ignorable interference level. Generally, the length of the entire airspace containing the flight routes is predefined, and the communication distance is also known. Therefore, the space frame length and the number of space frames are to be determined. The sub space frames of each space frame are also defined and the system design in terms of space domain is therefore completed.

Similarly, the time domain is divided into time frames, one time frame for each space frame. Because each time frame needs to provide enough timeslots to all the aircrafts locating in each space frame, the time frame length is therefore proportional to the communication distance and the maximal number of aircrafts in one space frame. Regarding to the further division for the time domain, each time frame contains a number of sub time frames (STF), where the number of sub time frames per time frame equals the number of sub space frames per space frame. Each STF has an associated SSF. Each STF is subsequently divided into two parts: random access (RA), and reservation access (RE). Both parts are further divided into timeslots whose structure is represented in Table 5.1. The purpose of the RA's timeslot is for the aircraft to access the new STF (channel access) when it first enters the respective new SSF. The RE's timeslot is allocated for data transmission for the aircraft located in the SSF.

For the aircraft access to the new STF, a slotted-aloha scheme is used because only a few aircrafts will ever enter a SSF at the same time, and the scheme is simple to use. During the RA timeslot, the aircraft sends a timeslot request message to all the aircraft in the new SSF. In addition to the aircraft's position report, this message also includes the data load, requested timeslot, and other information as shown in Table 5.1. In order to recognize the requested timeslot, the aircraft needs to listen to the data transmission of all the aircraft in the new SSF before it enters. By doing this, the entering aircraft can find the available timeslots in the new STF. The aircraft then randomly selects a timeslot from the group of available timeslots and requests to use it.

In order to be allocated with the requested timeslot, the entering aircraft needs to receive the confirmation from the new SSF's aircraft. From the first frame after completing the confirmation process, the aircraft will start to officially use that timeslot for data transmission. In addition, an autonomous network of the aircraft in the new SSF is also established. In theory, both the timeslot request and confirmation processes are not necessary; however, these processes enable the system to avoid a disturbance in data transmission. Also, these two processes are necessary if two schemes of PATR and DBTA (Sects. 5.6.1 and 5.6.2) are applied to this system.

The number of timeslots in each STF is enough for accommodating the communication of all the aircrafts within its respective SSF as being mentioned above. However, in the case that an aircraft could not find an available timeslot in the new STF due to a shortage of available timeslots, it may temporarily use a timeslot in the RA part to keep its communication uninterrupted. This aircraft needs to release this timeslot after successfully obtaining a timeslot in the RE part, and the released timeslot is available for other coming aircrafts to randomly access to the channel of the system.

When the aircraft leaves the SSF, the aircraft needs to release its assigned timeslot. The timeslot will be released when the aircraft sends a timeslot release message to all the aircraft located in the SSF it has left. Similar to the allocation process, a confirmation is also necessary to prevent data disturbance. With this system, other aircraft in the SSF are not only aware that the aircraft left the SSF through the timeslot release message, they are also aware the time the aircraft left by using their storing data as described in Sect. 5.1.

Several SSF are simultaneously able to utilize the same STF, with the condition that each SSF must be separated by at least one space frame length to prevent interference, hence increasing spectrum usage. For example, in Fig. 5.1, the STF-1 is simultaneously assigned to SSF-1 and SSF-5, STF-2 is assigned to SSF-2 and SSF-6, etc.

Regarding to the time division in this S-TDMA system, an important requirement is to maintain the synchronization among those oceanic aircrafts. However, these aircrafts are far from each other, which might be outside of the communication range. In this case, the system enables the synchronization between the local time at each aircraft and a high precision time source such as the GNSS (Global Navigation Satellite System). In such flight routes, each aircraft is always equipped with a receiving system for getting the signal from the GNSS; hence, the synchronization is not an issue any more. In addition, this system is usually valid in a predefined region or area which contains those oceanic flight routes; hence, by detecting the passing geographical information, each aircraft can simply know when it starts to join this relay system. That is also the time for the aircraft to start the synchronization with GNSS time for following the time division in the system design. With this synchronization, each aircraft can easily follow all the STFs in each time frame, and all the timeslots in each STF in order to avoid the communication's turbulence or collision among these aircrafts' transmissions. Also, each aircraft can access to the channel at the exact timeslots (RA timeslots) or transmit at its assigned timeslots (reservation timeslots). Furthermore, the time synchronization is also important for the aircrafts that are quite separated from each other, which are locating in different space frames. This is because these distant aircrafts' transmissions are required to be listened by other aircrafts belonging to its neighbor SSFs. This is one requirement of the proposed system which enables all the aircrafts to fully listen to other aircraft's transmission. Consequently, without the time synchronization for all the aircrafts, it is not guaranteed that all the aircrafts can adequately get the information from its nearby aircraft's.

There are several advantages to this system. Since the aircraft in each SSF can observe other aircraft' transmission, the aircraft are able to operate autonomously. In addition, the system can easily be adapted to any configuration or any oceanic flight route that are managed via geographical coordinates. Furthermore, the issues such as hidden terminal and exposed terminal are avoided in this S-TDMA based system because the aircraft always transmit data on different timeslots within one frame.

5.3 Data Format and Aircraft Position Reporting

In this system all the aircraft will use the same data format as the prior protocol. However, this case, the format of position report is more advanced than the previous one because it contains more additional information used for oceanic ATC. The data format of a packet is described in Table 5.1 [6], [7]. Another difference comparing to the previous one is the frequency of aircraft position generation. In the TDMA-based protocol, after each frame period (FP), an aircraft will regenerate its position report and start to relay to other aircraft. This period is the time interval that each aircraft broadcast its actual position to the neighboring aircrafts. In this system, the frequency of generating an aircraft's position report is dependent on its actual phase of the flight. The phase of flight is determined by calculating the relative position of the aircraft with the nearest ground station, which includes 4 main types of phases (Table 5.2). However, in order to increase the ability of exchanging the position information among the aircrafts, this system enables the aircraft to broadcast its own position report in case it found any of idle radio resource. Therefore, the interval time that an aircraft broadcast its actual position report is high; hence, it increases the situation awareness for the aircraft in the entire system.

TABLE 5.1: STRUCTURE OF TIMESLOT USED FOR S-TDMA BASED PROTOCOL

Purpose	Content	Requirement on data	
		Advanced	Basic
Guard time	At the front & end	(Table 5.4)	
Total length of part I [ms]		2 x Guard time	
Transmit, broadcast, timeslot request or release	Aircraft data	640	152
	Type of trans.	2	2
	Load of Tx	8	8
Transmit, broadcast, timeslot request and release	ID of the Tx	48	48
	ID of the Rx	48	48
Feedback information	Load of the Rx	8	8
	ID of the Tx & Rx	48 & 48	48 & 48
	Acknowledgement	1	1
Total length of part II [bits]		851	363

TABLE 5.2: AIRCRAFT DATA UPDATE INTERVALS AT MINIMUM SEPARATION OF 18.52 km

Phase	Interval of position update
Parking	15 [s]
Runway or Departure	2 [s]
Terminal area	5 [s]
En-route	10 [s]

Regarding to packet relaying mechanism, each aircraft in a SSF will be assigned at least one timeslot which allocate inside the respective STF. The aircraft use this timeslot for transmitting its own position report, with the highest priority. The lower priorities are for relaying data of other aircraft and broadcasting its own position.

5.4 Interference Based Node Selection (IB-NS) Scheme

The IB-NS scheme has been clearly described in Sect. 4.4.3, chapter 4. This scheme is also applied in this S-TDMA based communication system to increase the ability of transmitting data with a feedback of the maximal interference from other co-transmissions. There is some major difference of IB-NS scheme for this system and previous system (Fig. 5.2). The utilization of IB-NS in the later part will be explained in details.

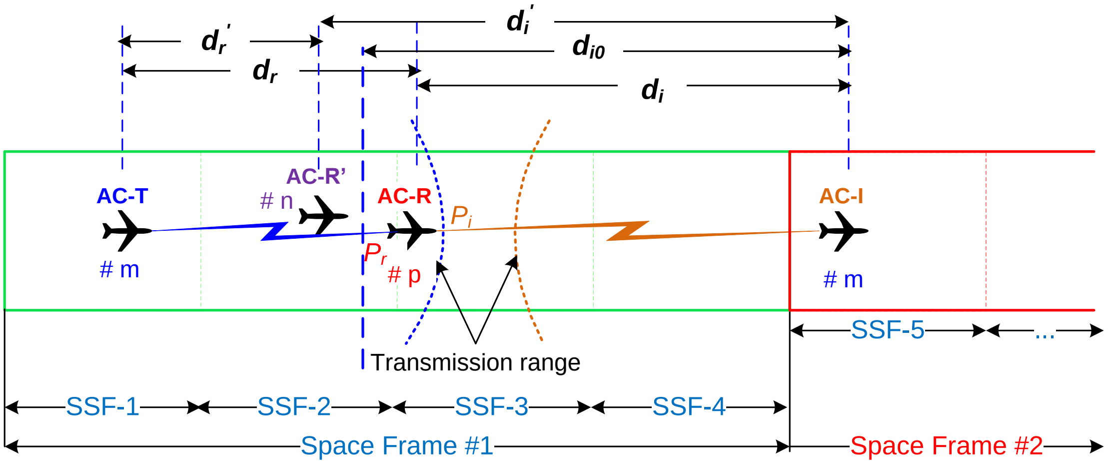


Figure 5.2: Description of the interference based node selection (IB-NS) scheme

5.5 Routing Table and Packet Relaying Algorithm

In this S-TDMA based system, an aircraft's will generate its actual position report at its own timeslot or at another idle timeslot that is possible to use. In the case with idle timeslot, the aircraft can generate its own position report if it is time for its periodical report. In other cases, it relays other aircraft's data or broadcasts its own position at lowering priorities. From this process, other nearby aircraft and even the distant aircraft can catch an aircraft's position frequently. This information is used to build a routing table for each aircraft as in the previous protocol. Base on this table, the aircraft can find the most appropriate aircraft for forwarding the data to in the relay process. In this system, the selected aircraft is the one with the lowest data load and the furthest from the transmitting aircraft.

5.6 Enhanced Mechanism of Timeslot Usage

5.6.1 PATR (Position Aided Timeslot Reuse)

In any TDMA-based system, the number of timeslots is always larger than the maximal number of users. Our proposed system, the S-TDMA based system, is also not exceptional. Specifically, in each SSF, the respective STF must contain enough timeslots to assign timeslots to each aircraft located within the SSF. However, in practice, the distribution of the aircraft in oceanic airspaces is unequal. Therefore, there are several SSF that are at low aircraft density. In these cases, the timeslot utilization is not desirable due to many unused timeslots occurred. Figure 5.3 shows an example in the case of 4 aircrafts in the SSF and 12 RE timeslots in the respective STF. The timeslot allocation in this figure is the result of following the timeslot assignment algorithm described in section 5.2 for the S-TDMA system.

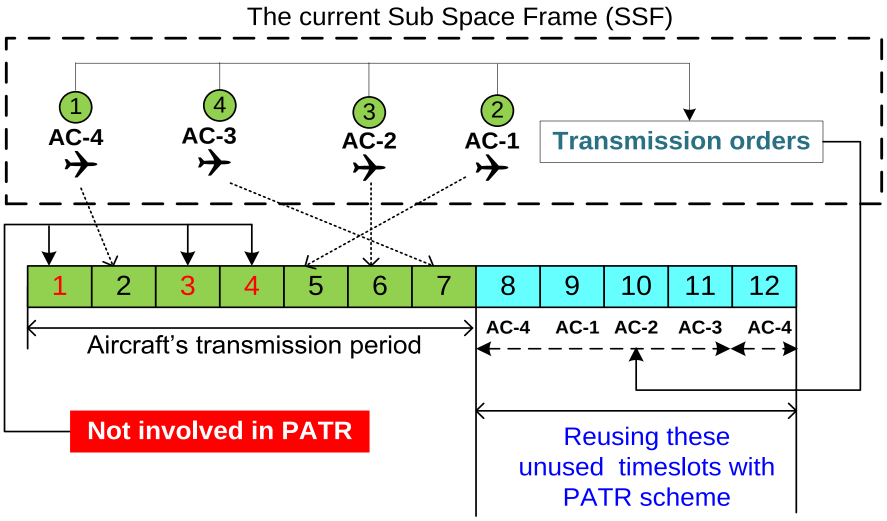


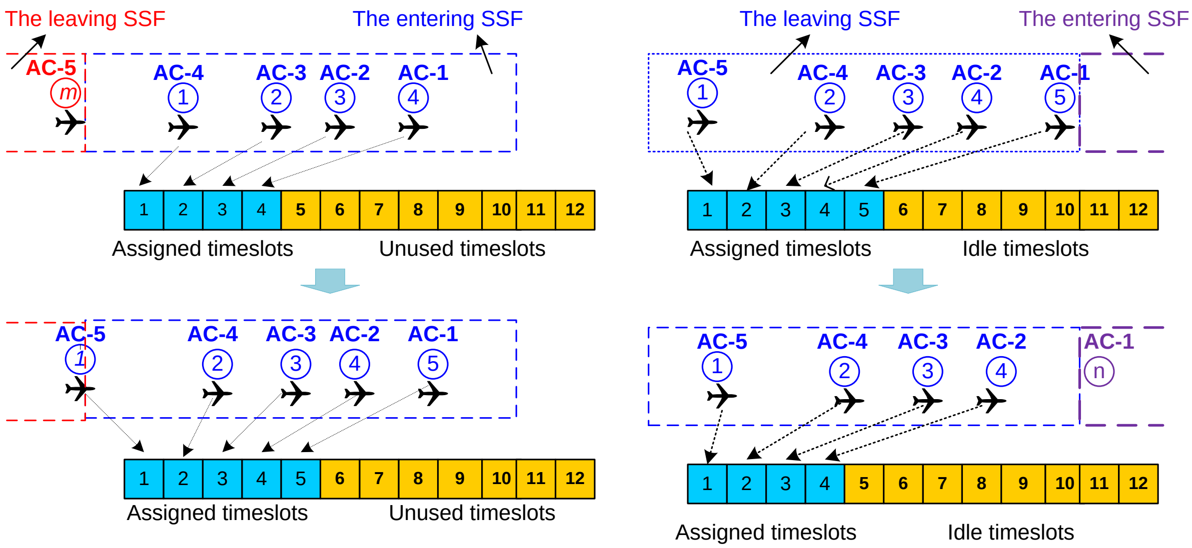
Figure 5.3: The concept of reusing unused timeslots in the PATR scheme.

The PATR scheme is proposed to reuse the unused timeslots in the STF. This scheme utilizes the timeslots greater than the maximum timeslot currently being used. PATR allocates these unused timeslots to the SSF aircraft according to their transmission order, i.e. the aircraft with the lowest transmission order uses the first available time slot, the aircraft with the second lowest transmission order uses the second available timeslot, etc. The aircraft will still also transmit on their original time slots as well as the newly allocated timeslots. Because the aircraft in the SSF can observe the neighboring aircraft and operate autonomously, this PATR scheme is autonomous and independent in each SSF.

From the example shown in Fig. 5.3, the aircraft AC-4, AC-3, AC-2, and AC-1 are assigned the timeslots #2, #7, #6, and #5, respectively. Therefore, the data transmission orders of these aircrafts are as follows: AC-4, AC-1, AC-2, and AC-3. As described above, the PATR scheme will only utilize the timeslots starting from timeslot #8. Based on the transmission orders of these 4 aircrafts, they will successively use the unused timeslots until there are no available timeslots. The sequence of using these timeslots is displayed as in Fig. 5.3.
By using the PATR scheme, aircraft may have several timeslots available for data transmission, and therefore aircraft position report broadcasting is significantly increased. However, in this scheme there may be several timeslots which are not used due to the original timeslot assignment algorithm. For instance, in Fig. 5.3, 7 timeslots are used by only 4 aircrafts, leaving 3 unused timeslots.

5.6.2 DBTA (Distance Based Timeslot Assignment)

In order to improve the PATR scheme, the DBTA scheme is proposed to minimize the maximum timeslot allocated for an aircraft based on distance. In fact, the DBTA scheme is an enhanced timeslot allocation method that should be jointly used with the S-TDMA system (Sect. 5.1). In DBTA scheme, the timeslots are assigned in a sequence identical to the order of the distance value of the aircraft. For example, in Fig. 5.4, the timeslots are assigned to the aircraft according to their distance from the ground station 1 described in 5.1. With this scheme, the highest timeslot used is always equal to the number of aircraft, and the highest timeslot is always assigned to the furthest aircraft. Also, the lowest timeslot is always assigned to the nearest aircraft. To achieve and maintain such timeslot assignment, two important processes need to be executed when the aircraft enters a new SSF or leaves its current SSF.



a) AC-5 enters the new SSF b) AC-1 leaves its current SSF

Figure 5.4: The two major processes of the DBTA scheme.

At the time the aircraft enters a new SSF, if it does not recognize any aircraft in this SSF, it will use the minimum timeslot in the RE part of the new SFT. Otherwise, it needs to send a timeslot request message to the aircraft in the new SSF. After receiving this message, each aircraft shifts their timeslot order up by 1 after sending a confirmation to the other aircraft, including the entering aircraft. The minimum timeslot therefore becomes available. This timeslot will be officially assigned to the entering aircraft after the confirmation process is done. Figure 5.3 and the upper part of Fig. 5.4 a) show the difference in timeslot assignment of AC-1 - AC-4 in the two cases: S-TDMA without DBTA and S-TDMA with DBTA. The lower part of Fig. 5.4 a) shows the behavior of the DBTA scheme when AC-5 enters the SSF of with the aircrafts AC-1 - AC-4.

When leaving the SSF, the aircraft needs to send a timeslot release message to other aircraft in the SSF. The timeslot will be released and confirmed by all other aircraft with a confirmation process as described in Sect. 5.2. If this aircraft further enters another new SSF, the entering SSF process will be repeated as we have mentioned above. Figure 5.4 b) shows an example of DBTA scheme when AC-1 leaves its SSF.

5.7 Simulation and Numerical Results

5.7.1 Assumptions and Parameters

TABLE 5.3: COMPUTER SIMULATION PARAMETERS

Parameter	Values		
Communication range [km]	300	500	650
# sub areas in the region	12	9	8
Sub space frame (SSF) length [km]	300	400	450
Data bit rate [kbps]	31.5 [8]		
# sub space frame in one space frame	4		
# RFs	1, 2		
Transmitting power [dBm]	+ 36	+ 42	+ 45
Noise at reception [dBm]	-98		
Communication threshold, γ_c [dB]	10		
Interference threshold, I_0 [dB]	6		
Aircraft speed [km/h]	1000		
Aircraft altitude [ft]	30000		
The aircraft density unit, A_0	1/650 [aircraft/km]		
Density of the aircraft [A_0]	1, 5, 10 … 35		
# aircraft per sub space frame (maximum)	17	22	25
Time frame length in cases of advanced and (basic) requirement on data [ms]	2090 (972)	2790 (1363)	3260 (1642)
Guard time [ms]	1.0	1.7	2.2
# of timeslots in RA part	1		
Allowable delay at each aircraft [ms]	#RFs x Frame length		
Aircraft to ground communication link	Two-ray model [9]		

For air traffic control, the aircraft's data must contain its position, intent trajectory, flight level, measurement time and other management information. Airlines, authorities, and other institutions have various requirements regarding the depth of this data. For this paper, the aircraft data follows the basic and advanced requirements, as shown in Table 5.1. The advanced data includes more additional information such as sensed meteorology, highly accurate aircraft position, magnetic heading and so on. Based on Table 5.1, the length of timeslots in part II is known; hence, the total timeslot period is determined if only guard time value is known. The guard time is proportional to the communication distance value, which is at minimum

300 km and as same as the current ATC system's regulation. In addition, the minimum receiving power in aeronautical condition is usually requested at least at -95 dBm [8], so the maximal and effective communication range is at 650 km, according to Fig. 4.3 in chapter 4. For each value of the communication range, the number of channels and the data requirement are also factored into the simulations. Other parameters that we have used in the simulations are shown in Table 5.3.

5.7.2 Simulation Results with One Radio Frequency

The proposed system is a multi hop relay network; hence, we will evaluate the end to end system performance with the following three factors: achievable relayed packet rate, average total delay, and number of hops. Achievable relayed packet rate is the ratio between the number of successfully relayed packets and the number of total transmitted packets. The packet is counted as successfully relayed if it was relayed to its relevant ground station via the proposed system. Otherwise, the packet will be relayed via the SATCOM system mentioned in Sect. 5.2. Average total delay is the average of the total delay of all the packets that have successfully relayed through the system. Number of hops is the average number of times that each packet has been relayed through our system in the case it was successfully relayed.

Three configurations are used in simulations to compare system performances of the proposed scheme: S-TDMA, S-TDMA with PATR, and S-TDMA with both PATR and DBTA. The results are shown in the following figures where C1 corresponds to the S-TDMA only system, C2 is the case where S-TDMA system only implements PATR, and C3 is the case when S-TDMA system uses both PATR and DBTA.

Figure 5.5 show that system performance obtained the best results in terms of achievable relayed packet rate if we apply the combination of C3 and at the communication range of 300 km. At these conditions, the number of hops used in relaying data and total delay (Figs. 5.6-5.7) may be higher than other cases. However, the number of hops does not considerably affect the system performance because of the good channel situation between oceanic aircraft. The average accumulated delay also does not affect on the oceanic ATC operation that will be explained in Sect. 4.4 of chapter 4.

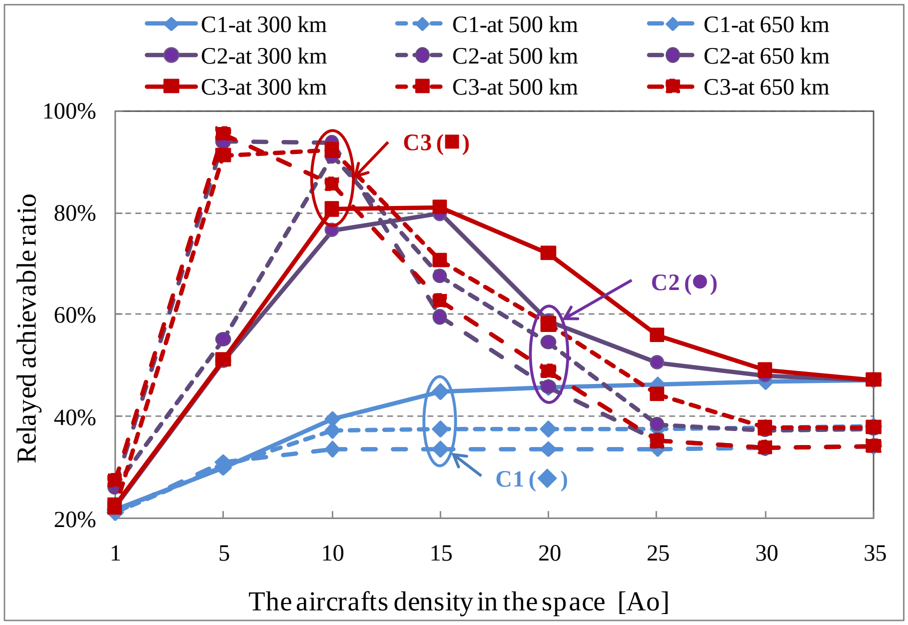


Figure 5.5: System performance in terms of achievable relayed packet rate

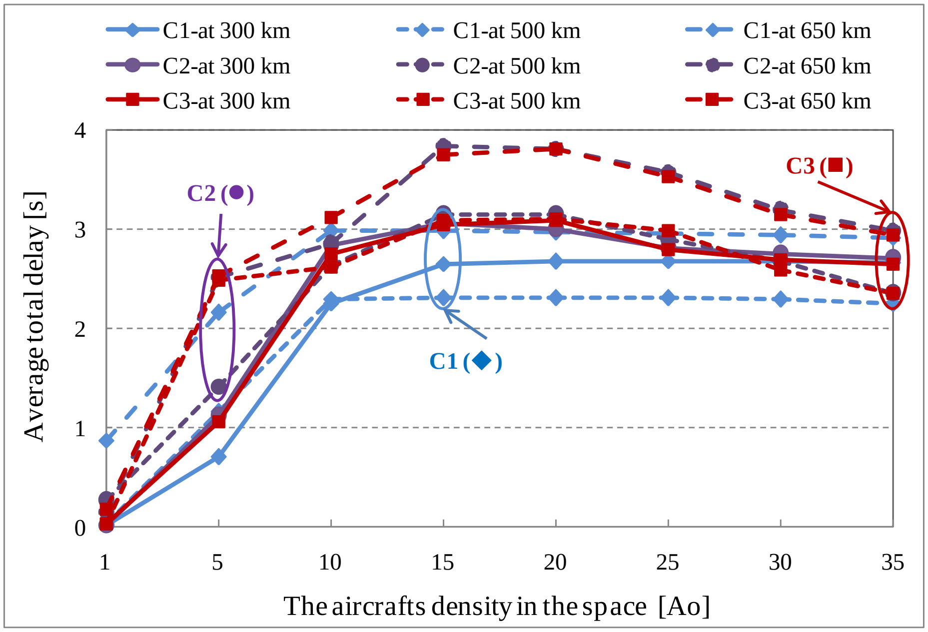


Figure 5.6: System performance in terms of the average accumulated delay.

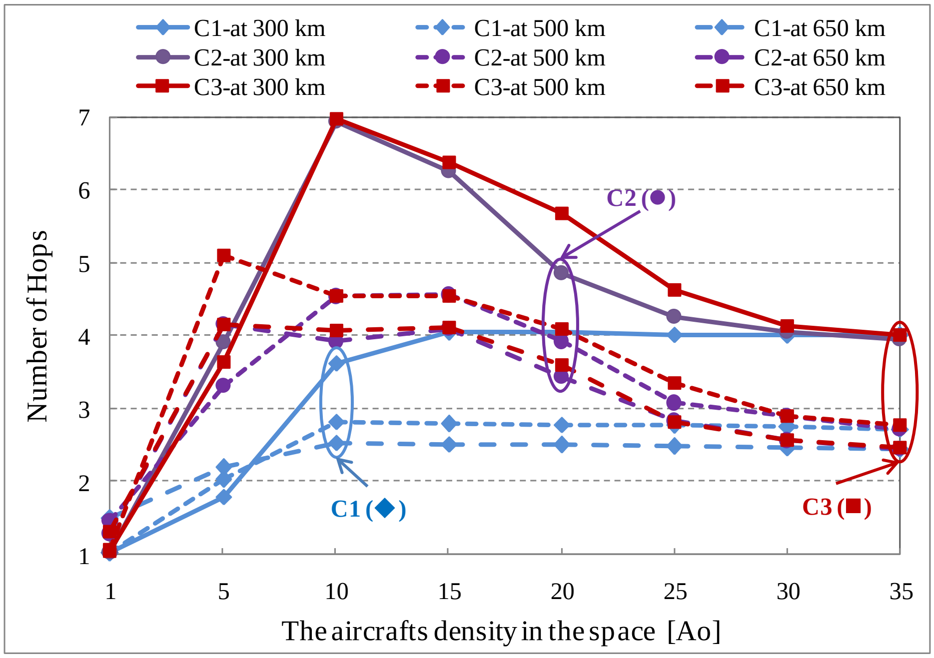


Figure 5.7: System performance in terms of the number of relay hops.

It should be noted that, the achievable relayed packet rates were lower than 80% regardless of aircraft density. This could be explained by the limited connectivity of the multi hop ad hoc network at low aircraft density. At high aircraft density, we expected this because a high number of packets reach allowable delay value due to a lack of timeslots or radio spectrum. Therefore, the system performance in the case of two or more radio frequencies becomes an interest to us in the next part.

5.7.3 Simulation Results with Two Radio Frequencies

Based on the results of the one RF simulations described above, the achievable relayed packet rate has become better with shorter frame length. Therefore, we selected a channel assignment for 2-RFs (Fig. 5.8), which was developed from the one RF case (Fig. 5.1). This channel assignment enables the frame length to be half that of the single RF's frame length. For example, the sub space frames SSF-3, SSF-4 are assigned with sub time frames STF-3, SFT-4, respectively. These sub time frames start at the same time with STF-1, STF-2, which are assigned for the sub space frames SSF-1, SSF-2. To do so, each aircraft needs two transceivers so that it can transmit/receive data at the same time on both RFs. The behavior of the aircraft in each RF is identical to the behavior in the single RF used for the previous simulation.

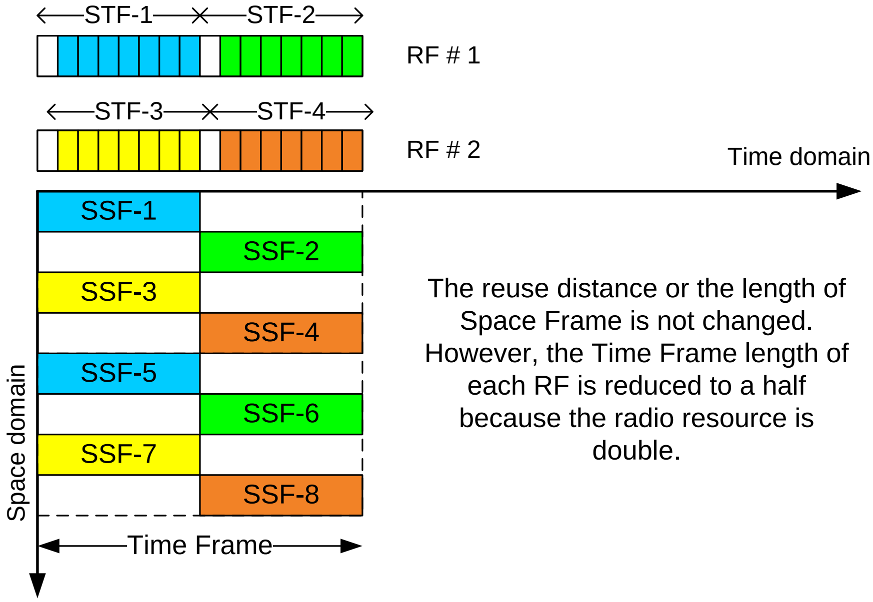


Figure 5.8: Channel assignment for the case of 2-RFs.

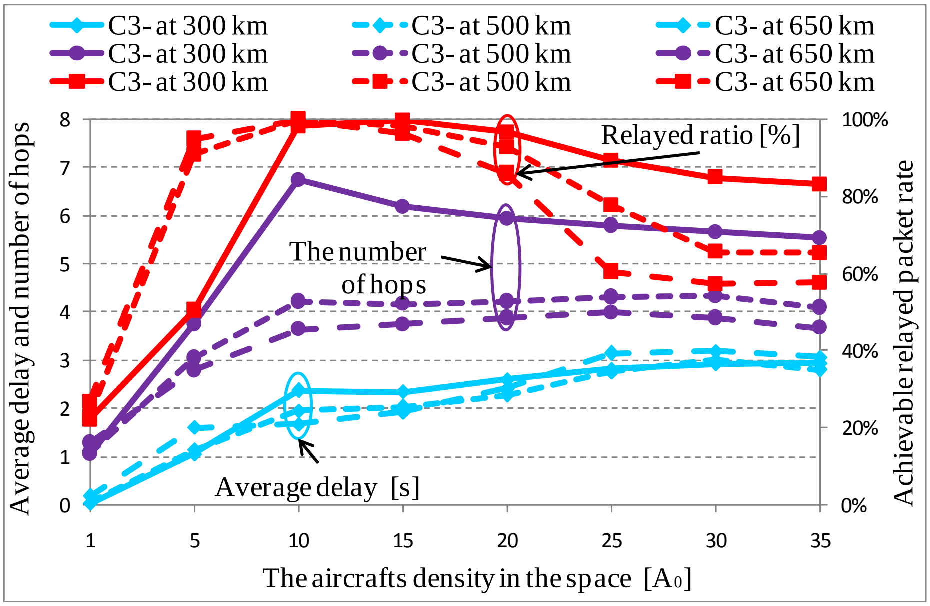


Figure 5.9: System performance applied with 2-RFs and advanced aircraft data

For comparing with the best results from the single RF simulations, the configuration of C3 is used for the 2-RFs simulations. Figure 5.9 and 5.10 show that system performance with 2-RFs is much better than that with a single RF, especially in terms of achievable relayed packet rate. This rate reaches 100%, if only basic requirement on aircraft data is applied. However, the rate is not as high if advanced aircraft data is required, and at high aircraft density values.

It is obvious that the achievable relayed packet rate in both the case of single RF and 2-RFs are affected most by the aircraft density. As analyzed earlier, at low aircraft density, it is necessary to improve network connectivity. This could be done by increasing the transmission range up to the maximum and most effective, at 650 km. At high aircraft densities, however, the solution is to add more RFs into the system. As mentioned earlier, a multiple RFs (more than two RFs) system could be extended from the case of 2-RFs that was explained and displayed in Fig. 5.8.

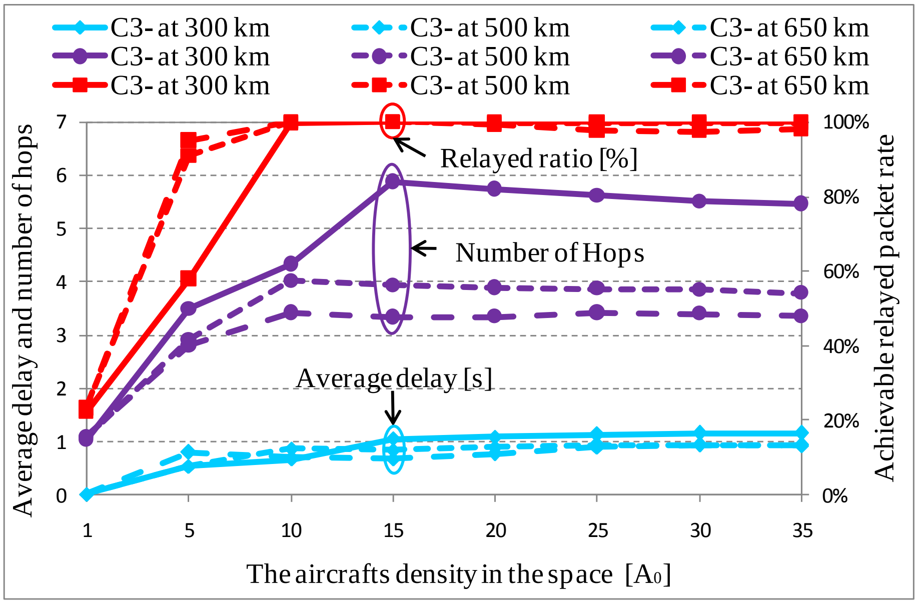


Figure 5.10: System performance applied with 2-RFs and basic aircraft data

Regarding to adding more radio frequencies, the number of RFs in the system is usually predefined in advance. Therefore, to improve the achievable relayed packet rate, only transmission range could be adjusted in the case of low aircraft density. However, this could make the SNIR (Signal Noise Interference Ratio) larger than the threshold SNIR ($SNIR_0$), since the space frame length does not change. The SNR (Signal Noise Ratio) was not a major issue because the transmitted power was increased enough for a longer communication range, which ensures ($\mathrm{SNR} \geq \mathrm{SNR}_0$) at reception. Therefore, only the noise interference ratio (NIR) is needed to be resolved.

5.7.4 The Simulation Results with 2-RFs and IB-NS Scheme

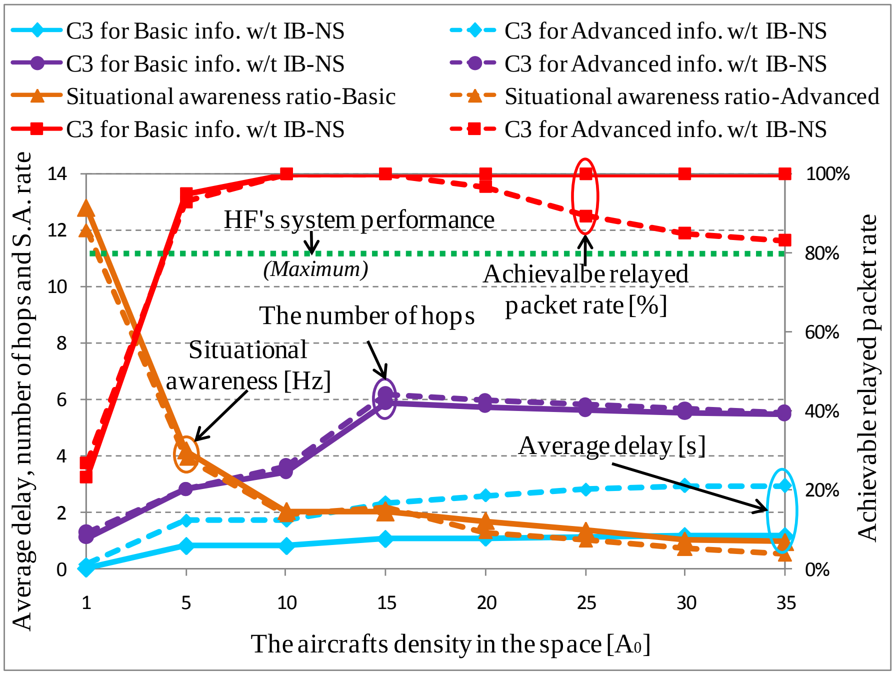


Figure 5.11: System performance applied with 2-RFs and IB-NS scheme

The results of simulations in the cases of applying 2-RFs, IB-NS scheme, and both the cases of basic and advanced requirements on aircraft data are shown in Fig. 5.11. This figure shows that when aircraft density was no larger than $10A_0$, the system performance in achievable relayed packet rate was significantly improved compared to that of the case of without IB-NS scheme (Figs. 5.9-5.10).

In the condition of basic aircraft data, Fig. 5.12 shows the achievable relayed packet rate that is further analyzed in each SSF. In addition, Fig. 5.12 demonstrates that the performance of the proposed system is better than that of the HF radio based system at high aircraft densities ($4A_0$ - $35A_0$). Moreover, at the values larger than $10A_0$, all the position reports originated from all aircraft in the airspace are successfully relayed to their relevant ground station, and no data was relayed through the current ATC system. At low aircraft density values ($1A_0$ - $4A_0$), the performance of our system is not as good as that of the HF system due to the shortage of network connectivity. However, still part of the data has been relayed via the proposed system. For instance, the data originated from the aircraft located in the SSF close to the ground station such as SSF-1, SSF-12 was relayed via the proposed system (Fig. 5.12). The other part of the data is relayed via SATCOM system. Actually, in these conditions, the separation distance between the two aircraft is large; hence, the conventional HF radio based system could still be used for oceanic air traffic control communication in the case of VHF and proposed systems are not available.

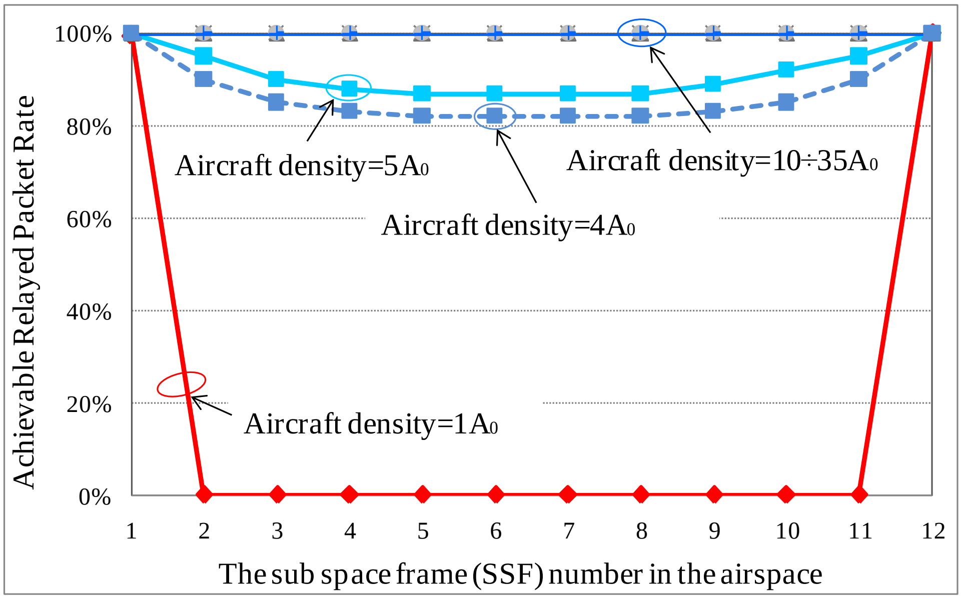


Figure 5.12: The achievable relayed packet rate at each sub space frame

Regarding to the averaging total delay as shown in Fig. 10, it could be counted in seconds. However, the aircraft transmit their own position information periodically at intervals, as shown in Table 3. Therefore, the air traffic controller at the ground station can receive one aircraft's data at an interval equal to the aircraft data transmission interval requested on this aircraft.

Furthermore, situational awareness rate is another important indicator describing the frequency that the aircraft can advertise its position information. Therefore, the higher the situational awareness rate, the better aircraft can acknowledge other nearby aircraft. The high values of situational awareness rate also enable the ATC controller to quickly and accurately guide the aircraft. In the simulation of this system, the situational awareness rate is counted when the aircraft transmits or broadcasts its own position information. Figure 12 shows that the lower the aircraft density, the higher the situational awareness rate. This is because under low aircraft density conditions, there are more idle timeslots that can be reused by the aircraft (with the schemes PATR and DBTA) to broadcast their own position information. In the worst-case, the highest aircraft density case, each aircraft still has its own timeslot and can advertise its position information at least one time per second, if basic aircraft data is required. The situational awareness rate will increase if more RFs are added to the system for any given aircraft density. This factor has become one of the most important parameters in realizing the concept of free flight in the future of air traffic control, is recently reported in [10].

5.8 Conclusion

The communication system based on multi hop ad-hoc network and S-TDMA is proposed for oceanic air traffic control. The system parameters in S-TDMA were optimally calculated based on experiments in the field.

With all three schemes, PATR, DBTA, and IB-NS, the aircraft data were fully relayed if we apply the constraints of basic requirement of aircraft data, and the use of only two radio frequencies (VHF). In addition, the situational awareness rate is high which improves the safety of oceanic flights. These constraints can be used for the starting phase of implementing this system in future oceanic air traffic control communication. If the advanced requirement is applied for the aircraft data, then additional radio frequencies are necessary and similar evaluations can easily be conducted. This system promisingly supplements to the current HF and satellite based communication systems. Therefore, this system can enhance ATC communication on the oceanic flight routes, especially under high aircraft density cases. In addition, there is currently another study being performed to utilize other aircraft from more diverging flight routes. Moreover, our proposed system can be developed into a system that is used for continental flight routes in areas such as the crowded airspaces of America and Europe. This future system can improve the current situation, which consists of large airports where radio communication is saturated by data sent from many aircraft to the airport. This future system can send data from aircraft to under-saturated airports using a relay data system.

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6

COMMUNICATION SYSTEM EMPLOYING UNMANNED AERIAL VEHICLE

UAV has emerged as a new dimension in aeronautical communication. The consideration in terms of how this aerial vehicle affect to the safety of the current air transportation service is highly concerned. However, this issue can be covered by the prior air to ground communication systems. In this chapter, further concern is the promising communication between the UAV and a system on the ground such as the Wireless Sensor Network (WSN). This kind of communication system is expecting to be meaningful and useful in several kinds of applications in modern society. Especially, such systems are necessary in providing communication relates to natural disasters and in extending the communication range for the isolated networks. The content in details will be fully described in this chapter.

6.1 Introduction

In this study, we only concern a communication protocol that can be utilized between an unmanned aerial vehicle (UAV) and a large area wireless sensors network (WSN), which is named as a WSN-UAV system [1]. WSN-UAV systems are utilized for a variety of applications in both academic and civil fields, as presented in [2] and [3]. However, for large WSN-UAV systems, the mobility of the UAV and the large number of sensors in a wide area creates challenges for using the medium access control (MAC) protocol present in this system. The MAC protocol needs to satisfy the system's requirements such as limits on the Packet-Error-Rate (PER), energy consumption of the sensors, multi-sensor interference, and the time interval for sending data [4]. However, the MAC protocol does not need to satisfy any requirements regarding the latency of data transmission between the sensors and the

UAV. This is because direct communication is used, instead of the multi hop communication employed in other conventional wireless sensor networks.

The PFSC-MAC protocol utilizes a novel Prioritized Frame Selection (PFS) scheme to divide the active sensors into several groups (priority groups), where each group is given a different transmission priority. These priorities are assigned based on the beacon signal's receiving power, and the variation trend of this power. The sensors then access the channel using FRA. In FRA, the UAV divides the channel access time into several frames. In each frame, the sensors will select a timeslot order for channel access until a channel is established. After a channel is established with all the active sensors, the UAV will initialize CDMA-based data transmission. The aim of this protocol is to maximize the number of transmitting sensors during the availability of the UAV.

As explained earlier, this system uses a MAC-based protocol; however, the existing MAC protocols are not feasible for WSN-UAV systems. There has been a lot of research for the MAC protocols used in wireless sensor networks and multi hop ad hoc systems, which are summarized in [5], [6], and [7]. However, an appropriate MAC protocol for a WSN-UAV system should be different from these protocols due to the mobility of the UAV. The IEEE 802.11 CSMA/CA is a widely used protocol in WLAN and WSN network systems [8], [9], but it might not be suitable for a WSN-UAV system. This is due to two major reasons: a high PER due to the well known hidden terminal effect; and the large overheads exchanged among the sensors as well as transmitted between the sensor and the UAV. To reduce energy consumption, in particular of the static sensors in a large network in a WSN system, the Time Division Multiple Access (TDMA) scheme has been proposed as a substitute for CSMA as presented in [10], [11], and [12]. In a WSN-UAV system, the active period of each sensor is short; therefore the energy reduction from using TDMA is not significant. Another widely utilized scheme for WSN systems is Frequency Division Multiple Access (FDMA), but it is difficult to synchronize the frequencies distributed at the sensors [13]. CDMA is a promising MAC protocol for WSNs, and several advantages have been shown in [14], [15]. In general, these MAC protocols are tailored and matched for WSNs. They entirely use multi hop ad hoc networking without a specific central node. However, they might not be suitable for a WSN-UAV system because the UAV acts as a centralized movable node, and the single hop communication between the UAV and the sensors. In addition to these schemes, a multi-carrier transmission study was performed for WSNs employing a high altitude platform (HAP) [16]. These HAP systems have a similar architecture to a WSN-UAV system. However, these systems are not efficient for WSN-UAVs because they are designed for a high data-rate, and hence have sensor network complexity not necessary for a WSN-UAV system.

A CDMA-MAC protocol specifically designed for WSN-UAV systems was proposed in [17], [18], [19], [20], and [21]. However, this protocol is always evaluated with the assumption that only a few active sensors have the right to transmit their data at a given time. In general, the sensors with the highest channel gain between the UAV and the sensor are selected for transmission. As a result, the period for completing a data-collection mission is large; and it is not guaranteed that all the sensors have sent their data to the UAV. Therefore, this system cannot be applied in situations where obtaining as much information as possible is necessary, such as natural disasters, etc. In addition, in order to increase the number of transmitting sensors in this system, the time frame length assigned for data transmission must be significantly enlarged [22]. Furthermore, how to assign unique Pseudorandom Codes (PN) to each sensor was not explained; and hence, the possible problem of different sensors getting the same PN has not been solved. Finally, the issue of channel fading was not taken into account.

To address these issues, in our previous MAC protocol we tried to maximize the number of transmittable sensors [23], [24], [25]. These sensors are able to simultaneously transmit their data by spreading each data transmission on a distinguishable PN code. This is useful in the case where obtaining as much data as possible is necessary, such as emergent data collection over a wide area. However, the issues of channel fading and multi-sensor interference to system degradation were not addressed.

This study, however, provides an optimal system design with the consideration of both channel fading and multiuser interference on the system performance. In particular, this chapter will explain the following contributions:

(1) Propose the FRA scheme mentioned earlier for sensors to quickly access a channel in the WSN-UAV system. This scheme is validated to be more efficient than CSMA/CA.

(2) Derive a theoretical formula to evaluate the PER of a WSN-UAV system with QPSK modulation, Rice fading channel, and incident angle based K factor. The PER in the three cases of using CDMA, TDMA, and CSMA/CA were calculated and compared.

(3) Propose the PFSC-MAC and the CPFSC-MAC protocols. The protocols are evaluated using the formula derived in “(2)”. The results have shown the ability of this system to obtain a minimal PER.

6.2 The WSN-UAV System Description

6.2.1 Introduction of a WSN-UAV System

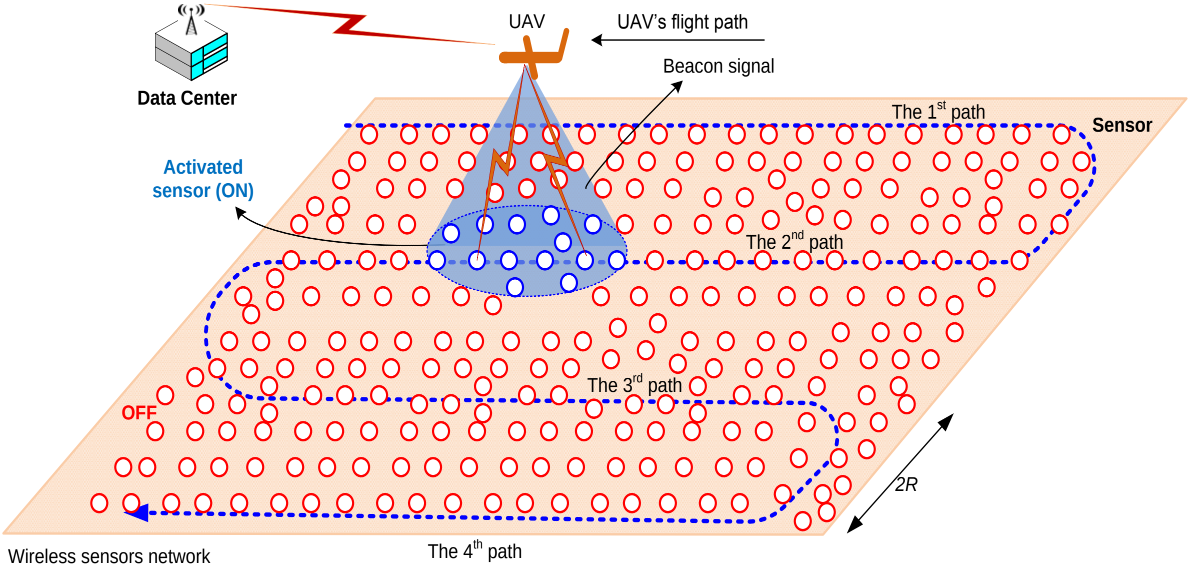

Figure 6.1: General architecture of a WSN-UAV system

This system model is a WSN-UAV which is described in Fig. 6.1. The UAV will receive and collect the active information sensed by the sensors on the ground. In order to save the energy, the sensors are in the sleep state. The sensors are only activated (turned on) if the beacon signal or an on-going communication is available. The possible method of waking up the sensors is the usage of the RF signal, specially the beacon signal in this case. However, in this communication system, the sensors are not intentionally activated by the signal of other nearby sensors’ transmission. Therefore, the beacon signal frequency must be different from the frequency for the sensors’ transmissions. In order to enable the RF signal wakeup method, each sensor needs to be equipped with an energy detector. Assuming the receiving power level starting to activate the sensor is predefined in the energy detector of each sensor.

Therefore, the sensors that have obtained the receiving beacon signal power larger than the power level will be activated. This level is unchanged as the assumption; hence, the UAV needs to control the beacon signal transmitting power in order to enables only the sensors within the beacon coverage activated. After being waken up, during the active period, each sensor needs to send its sensed data to the UAV in each data transmission interval. The flight path of the UAV in this system is assumed to be static as in Fig. 6.1. However, it can be random in other scenarios.

The most attractive features of WSN-UAV systems are the simplicity in system deployment and data collection. In addition, the low energy usage is another attraction. Another advantage comes from the physical features of the channel between the UAV and the sensor, such as low propagation path loss. In fact, WSN-UAV system has a similar architecture with the communication between the aircraft and the air traffic control tower. From our prior studies [26], [27], [28], in the worst case, the signal still decays only by a power of 2.25 of the distance between sensor and UAV. However, there is significant path loss for communication between sensors, as the signal decays to the fourth power of distance [29]. Therefore, with the direct communication between the sensor and UAV instead of a multi hop relay network of sensors, WSN-UAVs have relieved the sensors from energy-consuming tasks.

6.2.2 Comparison of CSMA/CA and Frame Based Random Access (FRA) Scheme for Channel Access

In many WSNs, CSMA/CA is the normally used method for channel access and data communication. For this scheme, the period of channel access is proportional to the size of the network. For a small network, this effect can usually be ignored; but this is a major issue for a large WSN. Also, in a WSN-UAV system, due to the limitation of the connection time between the sensor and the UAV, minimal channel access time is desired. Therefore, CSMA/CA is not suitable anymore. However, this issue has not discussed or it was ignored in the previous studies and publications.

In the WSN-UAV system, in order to access the channel, each sensor needs to successfully transmit a header to the UAV. The header usually contains the sensor identity. It may also contain other supplemental information that relates to the applied transmission method or system management. If the UAV receives this header successfully, the UAV will immediately send an acknowledgement to the sensor. Assuming that CSMA/CA is used for accessing the WSN-UAV channel, the time period needed for the channel access must be extremely large if all the sensors successful transmit their headers. For example, if we assume the time needed to send a header and then receive an ACK/NACK is T_0; and the channel access period is $T = MT_0$; where the probability that no contention in the channel is greater than $e^{\frac{-3P(P-1)}{2M}}$ (P is the number of sensors that contend the channel) [30]. Therefore, in order to obtain a high probability of no channel collision, M has to be large; and T is also large.

In our proposal, the channel access period is intentionally divided into consecutive sub periods, called frames. In each frame, the sensors randomly try to access the channel. We name the scheme as Frame-based Random Access (FRA). These frames contain a specific number (N_{TS}) of timeslots. The timeslot duration is T_{TS}, which might be larger than T_0 because it contains additional information in the feedback. In FRA scheme, there are two stages in each frame. In the first stage, each sensor randomly selects a timeslot among the N_{TS} timeslots orders assigned by the UAV. In the second stage, each sensor transmits its header on the exact timeslot order it selected. At the UAV side, it will immediately send a feedback to the transmitted sensor if no collision is detected. The feedback's content is dependent on the transmission method that will be discussed in the later part. For example, in the TDMA-based data transmission, the feedback will contain a timeslot order. However, in the case of CDMA-based transmission, it contains a specific PN code used for data spreading. If this sensor correctly receives the feedback from the UAV, it waits for its' data transmission in the next period (Sect. 6.3.3).

There are two parameters to be determined in an FRA scheme. They are the number of timeslots in each frame ($N_{TS/Frame}$), and the total required number of timeslots for channel access period (N_{TS}). These parameters are also dependent on the actual number of sensor in the network or the density of sensors. In addition, the timeslot duration T_{TS} is also concerned. This value varies at the different transmission method (i.e., TDMA or CDMA). For comparison, we assume the header and the feedback has the same length in bytes, hence, the feedback will be half of T_{TS}. It is noticeable that the ACK/NACK in CSMA/CA scheme is just a few bits. Hence, the T_{TS} in FRA scheme becomes nearly double of T_0 in case of CSMA/CA.

Fig. 6.2 shows the simulated results of the total number of timeslots needed by FRA scheme; and the ratio between the channel access periods required by CSMA/CA and FRA schemes. These results were calculated based on an assumption that successful ratios of channel access are 98% for CSMA/CA, and 100% for FRA. The results show that the period for FRA scheme is substantially shorter than in a CSMA/CA scheme, despite the FRA having a 2% higher channel access success ratio. Therefore, the proposed scheme enables sensor in a WSN-UAV system to quickly and successfully access the channel. Fig. 6.2 also provides the size of each frame, in terms of number of timeslots, which leads to a minimum number of total timeslots required by FRA scheme. The results show that the optimal value of the frame size increases as the number of sensors contend the channel increases.

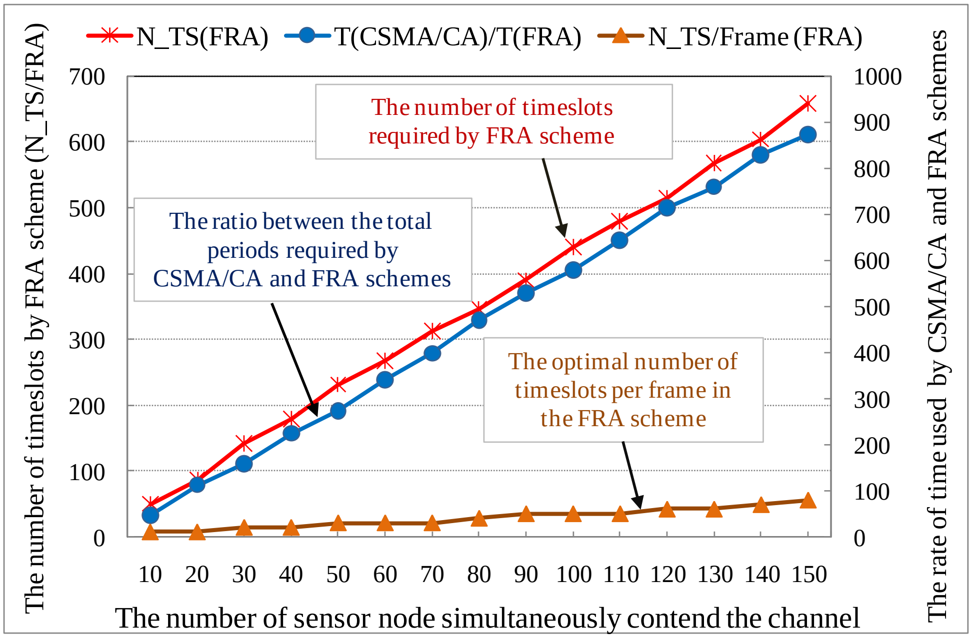

Figure 6.2: Comparison of the CSMA/CA and FRA schemes

6.2.3 Data Transmission Method for WSN-UAVs

After the channel access phase, the data transmission period is initialized by the UAV and the sensors will start to transmit their data. This part analyzes the dependence of this period on the applied transmission method. If CSMA/CA is utilized, each of the sensors senses the channel and transmits its data if idle channel is detected. In the case of using TDMA, at the end of the channel access period, there will be a list of consecutive timeslot orders as we have explained above. By following these orders, the sensors will complete their data transmission within the transmission period. For the case of CDMA, in order for all the sensors to transmit at the same time, the UAV must clarify the PN code for each sensor in the channel access period. In order to have less interference caused by the multi-sensor transmission, the UAV must keep these codes synchronous and orthogonal.

Because the timeslot durations for data transmission in the two cases of TDMA and CDMA are the same, the transmission period in a CDMA based system can be shorter than that in a TDMA based system. The large transmission period of a TDMA system may lead to a high PER due to the limited connection time between the UAV and the sensor. In the case of CDMA, the transmission period is small but the multi-sensor interference may affect the system performance. In Sect. 6.4, the dependence of system performance on the effect of those factors will be shown in the three cases of using CSMA/CA, TDMA, and CDMA.

6.3 Performance Comparison of Three Schemes: CSMA/CA, TDMA, and CDMA for WSN-UAV System

6.3.1 Incident Angle Based K Factor

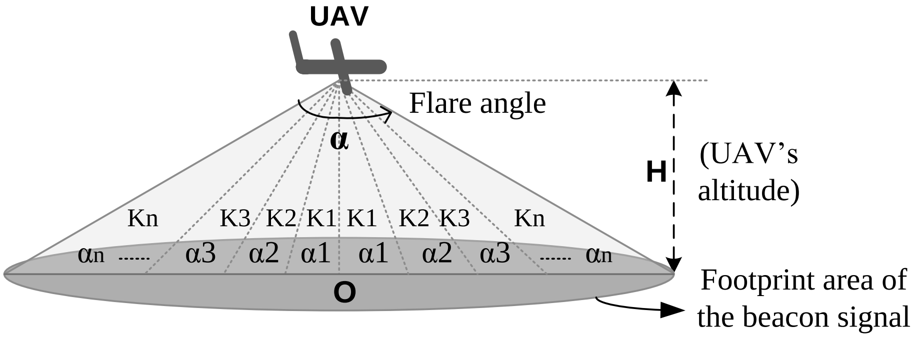

Figure 6.3: Incident angle based K factor

TABLE 6.1: K-FACTOR (MEASURED AT FREQUENCY OF 1.2 GHz)

Angle($\alpha/2$)	***K*-factor** [dB]	**Angle**($\alpha/2$)	***K*-factor** [dB]
10^o	18.6	50^o	8.9
20^o	15.2	60^o	4.1
30^o	13.5	70^o	2.2
40^0	11.4	80^o	1.5

6.3.2 PER Formula under QPSK and Rice Fading

First we derive the PER of the WSN-UAV system with QPSK modulation, and incorporating the incident angle based *K* factors (K_i). Following [32], the average error probability in Rice fading channel is:

$$\overline{P_s} = \frac{\alpha}{\pi}\int_0^{\pi/2} \mathrm{M}_{\gamma_s}\left(\frac{-g}{\sin^2\phi}\right)d\phi \tag{1}$$

In the case of Rice fading channel, we also have:

$$\mathrm{M}\left(\frac{-g}{\sin^2\phi}\right) = \frac{(1+K_i)\sin^2\phi}{(1+K_i)\sin^2\phi + g\gamma_s}\exp\left[-\frac{K_i g\gamma_s}{(1+K_i)\sin^2\phi + g\gamma_s}\right] \tag{2}$$

The parameter of γ_S = E_s/N_0; α and g are determined by the moment generating function (MGF):

$$\overline{P_s}(\gamma_s) = \alpha Q\left(\sqrt{2g\gamma_s}\right) \tag{3}$$

With QPSK modulation scheme, we also have:

$$\overline{P_s}(\gamma_s) \approx 2Q\left(\sqrt{2\gamma_s}\right) \tag{4}$$

As a result from (3) and (4), we have $\alpha = 2$ and $g = 1$.

Then, we discuss the multi-sensor interference in a CDMA based transmission system. Increasing the number of transmission sensors degrades the system performance because the signal interference ratio (SIR) is decreased. The approximation of the SIR based on the number of sensors is described as follows [33]:

$$SIR(N_{user}) \approx \frac{3G}{\xi(N_{user}-1)} \tag{5}$$

where N_{user} and ξ are the number of simultaneous sensors, and the constant characterizing the code cross-correlation respectively. The value of ξ depends on the spreading code properties and other system assumptions (i.e., ξ =1, 2, 3 etc.).

6.3.3 Performance in PERs of CSMA/CA, TDMA and CDMA based Transmission Techniques for WSN-UAV System

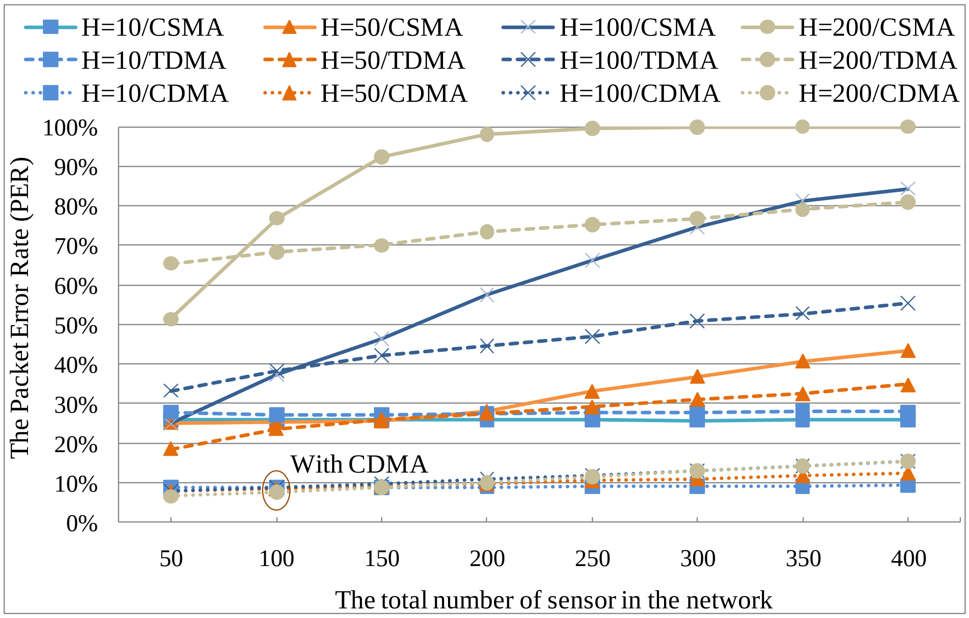

Figure 6.4: Comparison of PER in CSMA, TDMA, and CDMA

Assume the number of sensors in the area of 300×300 (m^2) is varied from 50 to 400 [33]. The minimum and maximum of the UAV’s altitude are typically selected at 10 and 200 meters. The UAV's speed is assumed at 10 mps; the flare angle of the antenna at the UAV is 90°. The interval of data transmission is assumed at 1 second. The data packet size is typically fixed at 25 bytes and data bit rate is selected at 25 kbps. The SIR is theoretically assumed at 10 dB. There are some additional assumptions for the CSMA/CA system, the CIFS and DIFS are selected at 0.5 and 2.5 times of the timeslot duration; contention windows are varied from 1 to 4. For the case of a CDMA based system, the spreading gain is assumed at 255 and ξ is 3.

For the simplicity of the graphs, only the values at 10, 50, 100, and 200 meters are selected for the UAV's altitudes. The dependence of PER on the variation of the total number of sensors in the network, and the altitudes of the UAV are described as in Fig. 6.4. In this figure, at each value of the UAV's altitude, there are three lines which represent the PERs simulated for the WSN-UAV system in the cases of using CSMA/CA (*solid line*), TDMA (*dashed line*), and CDMA (*dotted line*). The results show that, irrespective of the number of sensors in the network and the altitude of the UAV, the PER with the CDMA based transmission always has the lowest value. However, even for CDMA, the PER is still high at approximately 10%, even at a low number of sensors (i.e. 50), and increases to nearly 20% at a higher number of sensors (i.e. 400). The expected reason is the multi-sensor interference in the case of CDMA based transmission. Therefore, our idea is to divide the active sensors into a number of groups, and the detailed information is presented in Sect. 6.5.

6.4 PFS Based CDMA MAC (PFSC) Protocol and Its Evaluation for WSN-UAV System

6.4.1 Protocol Description

The PFSC-MAC protocol is the one adopts the Priority Frame Selection (PFS) scheme and leverages the CDMA based transmission method. This scheme is proposed to facilitate the sensors to transmit their data to the UAV at the same time with a low PER. There are three scenarios of the PFS scheme whose names are High Power High Priority (HH), High Power Low Priority (HL), and the Directional HH-HL (D-HHHL). These three schemes are all based on the strength of the beacon receiving signal. For dividing the activated sensors group into a number of priority groups, the UAV needs to send some additional information to these sensors during the channel access which is described in FRA scheme. This information may include: the number of priority groups, the two extremes of the receiving beacon signal for each priority group. Base on that information from the UAV, the sensors in the respective areas are activated and prepare for their communication with the UAV. The optimal number of priority groups that is used by UAV to inform the sensors will be derived later, which is dependent on the different conditions of sensor network density, the UAV's speed and the packet rate. The activated sensors in each priority group will follow its own priority to access to the channel (with the UAV) and to do communication with the UAV. The next section will explain in detail the concept and behaviors of each of the PFS schemes.

6.4.1.1 High Power High Priority (HH) Scheme

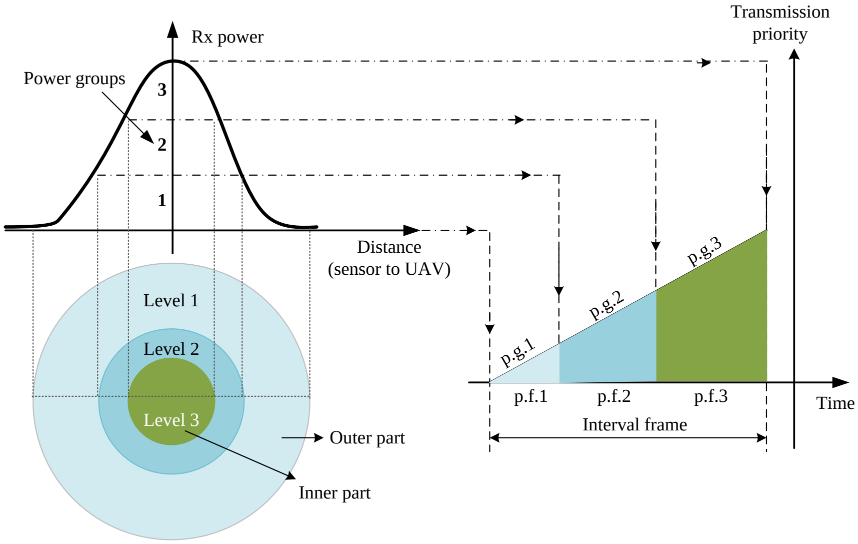

Figure 6.5: General description of the HH scheme

In this scheme, the relation between the power and the priority for transmitting data of each sensors group follows this rule: the higher the receiving beacon signal power, the higher priority of data transmission. As can be seen from Fig. 6.5, the central sensors (low incident angle) will transmit earlier than the sensors located near the edge (high incident angle), because of the difference in receiving power. By this way, the sensors with the best channel condition will transmit their data immediately. Meanwhile the sensors located on or near the border of the beacon receiving signal area will transmit after other central sensor's transmissions. During the waiting for their transmission, the data link connection with the UAV these bordering sensors may be lost. This factor may degrade the system performance. However, the transmission of the central sensors is highly successful because their channel condition at transmitting period is good. The simulation in the next part will evaluate the tradeoff of these two constraints. Beside the PER, the transmission interval is also another criterion we evaluate in the simulations. Transmission interval is minimum period of time that all of the sensors can refresh their data transmission. It is also understood as the interval frame of the time frame described in each scenario. This value could be calculated by summing all priority frames that are presented as in Fig. 6.5.

6.4.1.2 *High Power Low Priority (HL) Scheme*

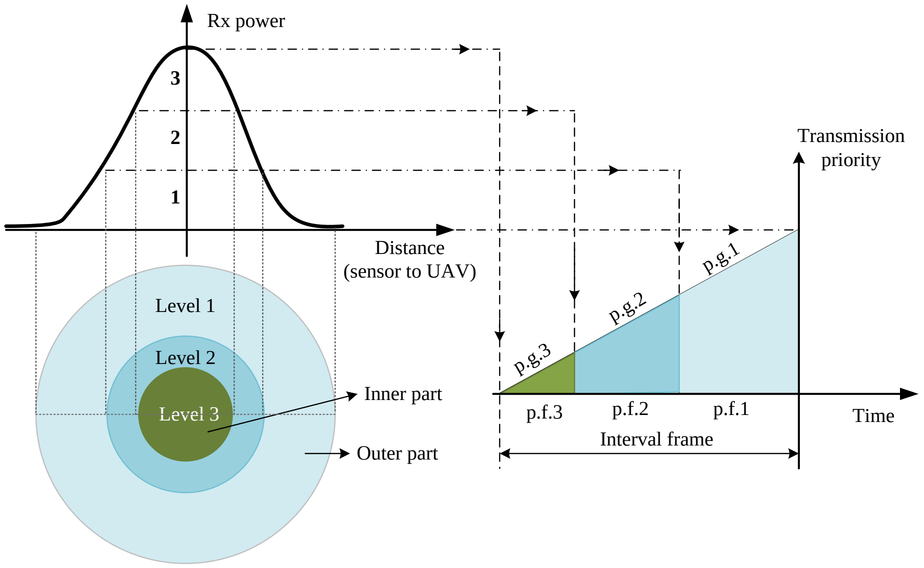

Figure 6.6: General description of the HL scheme

This scheme is opposite of the HH scheme, HL scheme intentionally prioritizes the sensors that are located near the edge of the footprint of the beacon signal. Therefore, the sensors with low receiving power of beacon signal will transmit data in advance. By following the HL scheme, the probability of losing connection between a sensor and the UAV is reduced. As a result, the number of packet loss due to losing the connection is reduced. However, the on time transmission of the sensor that are at good channel conditions are not guaranteed because they must wait for other sensors. This scheme also has a tradeoff between the transmission for the low receiving signal power sensor group and high receiving signal power sensor group. Similar to the HH scheme, the computer simulation will also evaluate the system performance for HL scheme and explain the results.

6.4.1.3 Directional HH-HL Scheme

In this scheme, we add another factor to the way of dividing the active sensor group, which express the moving direction of the UAV. The division of the sensors group therefore includes two steps. The first step is to divide the active sensors into two groups, called directional groups. The first group contains the sensors locating in front of the UAV, and the second group is for the sensors located behind the UAV.

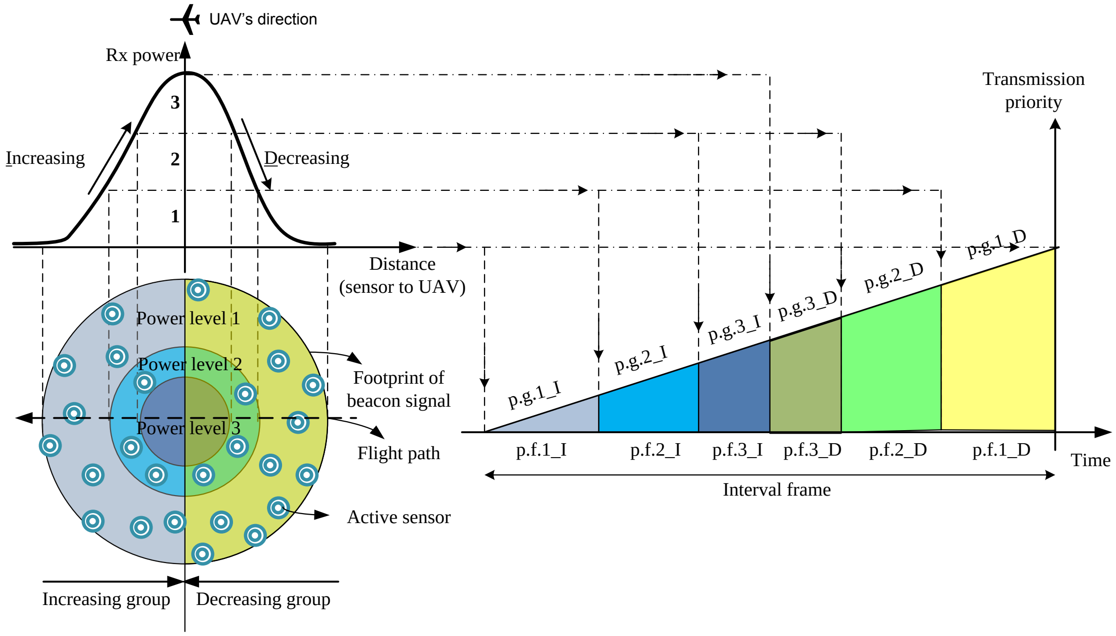

Figure 6.7: General description of the D-HHHL scheme

We name these groups as the increasing and decreasing groups. The sensors of the increasing group will have an increasing received beacon signal because the UAV-sensor distance is decreasing. The sensors located in the decreasing group will suffer a decreasing received beacon signal power due to an increasing UAV-sensor distance. In the second step, the behaviors of these two groups are different. In the increasing group, the sensors are divided into small groups by using the HH scheme in the Sect. 6.5.1.2. For the decreasing group, the HL scheme in the Sect. 6.5.1.3 is applied. As following both the schemes of HH and HL applied for the increasing and decreasing group, almost of the sensors that are at their best channel conditions have been taken into account by providing them with high priority to transmit their data. For instance, with the increasing group the HH scheme is applied; hence, the central sensors with the best channel condition are selected for transmitting their data. Meanwhile, other bordering sensors that located in front of UAV but low receiving power does not loss the connection with UAV even they must wait for a while. In addition, the receiving signal power at these bordering sensors is increasing; hence, the channel condition is getting better after a while. A similar explanation could be applied for the decreasing group. For this group, the bordering sensors is losing the connection with the UAV soon, therefore they have high priority to transmit their data. This is possible because the scheme of HL is active to this group.

If we label the increasing groups with ‘_I’ and the decreasing group with ‘_D’, the priority groups and priority frames are listed as in Fig. 6.7.

6.5 System Performance Evaluation

6.5.1 Simulation Parameters

Table 6.2 shows all the parameters used for the system performance evaluation. The maximum number of priority groups is set at 15 because of the system complexity limitation. In addition, all the previous schemes including the proposed PFS schemes, the incident angle based K factor scheme, and the proposed FRA scheme will be applied to the WSN-UAV system for its evaluations.

6.5.2 Performance Evaluation under Rice Fading Channel

As introduced, in our simulations, the number of priority groups varies between 1 and 15. However, for the simplicity of the figure’s description, only two results at values of 2 and 5 are represented. There are several concerned parameters in a WSN system such as PER, sensor power consumption, system throughput etc. Nevertheless, in the case of the WSN-UAV system, we only activate the sensors when it connects with the UAV; therefore, power consumption is not an issue. In addition, the sensor does not require frequently transmitting data, so the throughput is also not a high concern. As a result, PER is the major concern.

TABLE 6.2: SIMULATION PARAMETERS

Parameters	Values
The area of WSN [m^2]	300 x 300
# sensors, N	50 - 400
The altitude, H [m]	10- 200
Flare angle [°]	90
UAV’s speed [m/s]	10
Data bit rate [kbps]	25
Packet length [bytes]	25
Data transmission interval [s]	1
Carrier frequency [GHz]	1.2
# Gold codes gain (G)	255
E_bN_0 [dB]	10
Modulation scheme	QPSK
UAV’s flight route	Fig. 6.1
Priority Frame Selection schemes	PFS (HH, HL, D-HHHL)
The number of priority groups	1-15
Data transmission method	CDMA-based method
ξ	3
Rice factor	Incident angle-based K factor
Fading channel	Rice fading channel

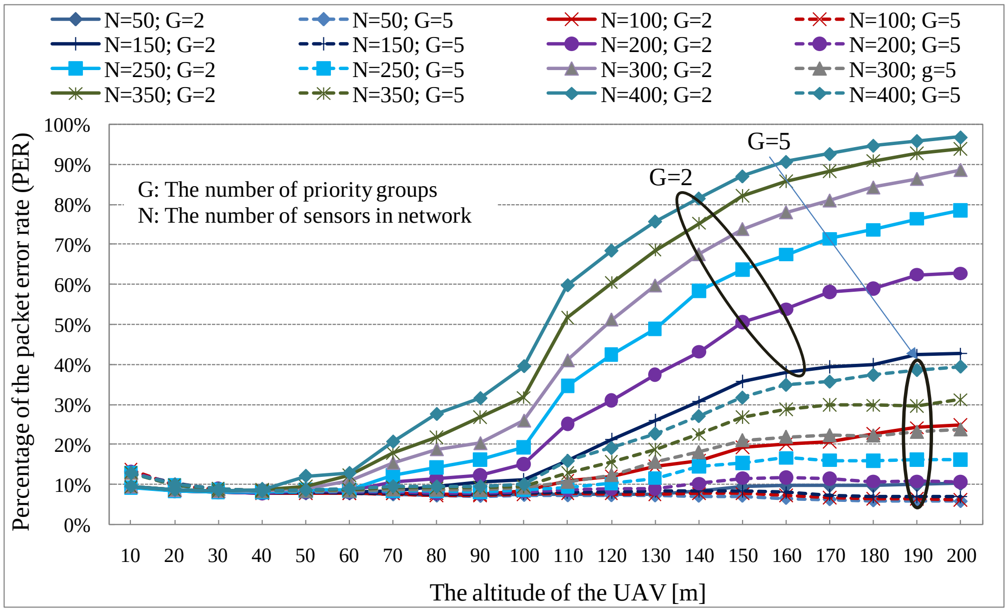

Figure 6.8: HH scheme based PER evaluation under the Rice fading channel

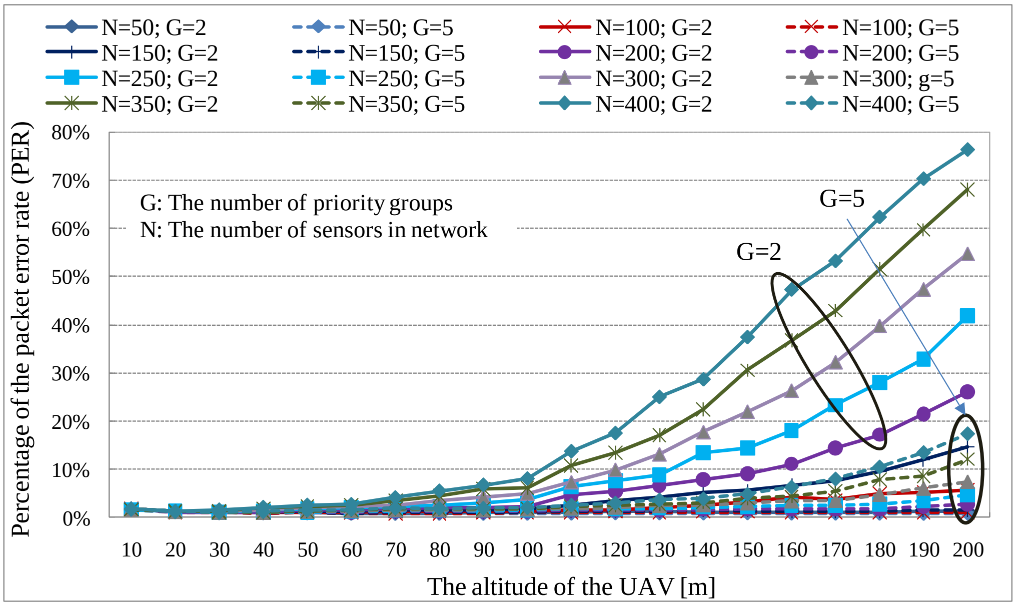

Figure 6.9: HL scheme based PER evaluation under the Rice fading channel

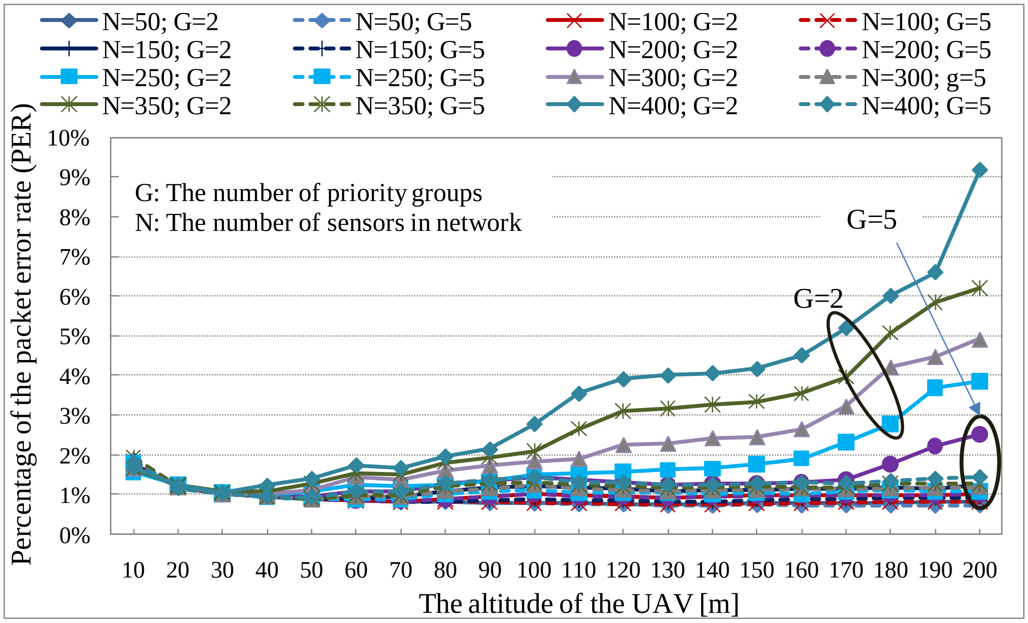

Figure 6.10: D-HHHL scheme based PER evaluation under the Rice fading channel

Figures 6.8-6.10 show the results of PER in the three cases of HH, HL, and D-HHHL, respectively. For clear graphs reasons, we only describe the results at which the number of priority groups is selected at 2 and 5. These figures state that, at low altitudes (i.e. 10 meters), the PER is high because the footprint area of the beacon signal is small and therefore the connection lost is easily occurred. This figure also shows that, the system obtains the best performance at the D-HHHL scheme, especially at high altitude and large number of sensors in the network. In addition, at this scheme, the system performance will get better when the altitude increases up to 40 meters; but it gets slightly worse again when the altitude increases above 40 meters.

Figure 6.11 shows the optimal number of priority groups at which the system obtains the minimum PER. The two groups of curves stand for the optimal number of priority groups, and the respective minimal PER for each group. It shows that by properly selecting the number of priority groups, PER can be minimized. The optimal value depends on the altitude of the UAV and the number of sensors in the network. Figure 6.11 also shows that, at the high altitudes or large number of sensors in the network, the number of priority groups tends to quickly reach the maximum number of the priority groups, at 15 (Table 6.2).

In Figs. 6.8-6.10, at any UAV altitude, PER is always above 1%, if the number of priority groups is 2 or 5. However, in Fig. 6.11, at any UAV altitude above 30 meters, the PER is always below 1%.

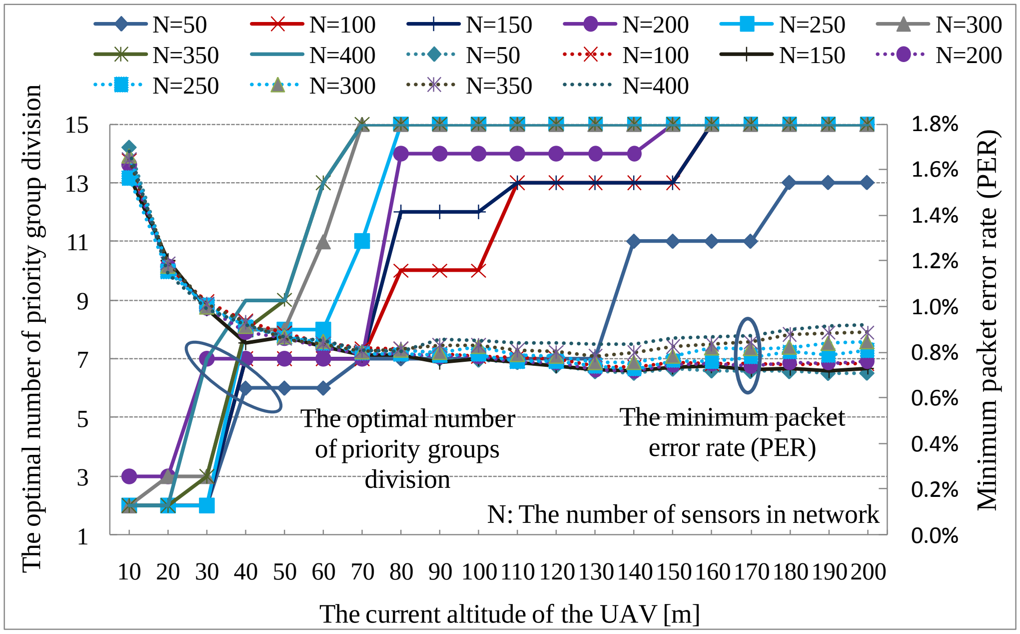

Figure 6.11: Optimal number of priority groups in the PFSC

6.6 CPFS Based CDMA MAC Protocol and Its Evaluation for WSN-UAV System

6.6.1 Protocol Description

CPFSC-MAC (Constrained Priority Frame Selection-Based CDMA MAC Protocol) is devised from PFSC-MAC. However, CPFSC-MAC protocol selects a limited number of priority groups to transmit their data, as opposed to PFSC-MAC, which enables all the priority groups to transmit their data. The selected groups contain the sensors with the best channel condition, specifically the best values of K factor. Following the incident angle based K factor scheme in Sect. 6.3.1, these sensors should belong to the inner part of the beacon's footprint. From the evaluations in the Sect. 6.5, the scheme of D-HHHL has always obtained the best results compared to the other two schemes of HH and HL. Therefore, this CPFSC-

MAC protocol only applies the D-HHHL scheme. The target for this scheme is to find the optimal number of selected groups at which the system obtains the best performance. This issue will be discussed in details in the next Sect. 6.6.2.

6.6.2 System Performance Evaluation

From the simulation results in Fig. 6.11, PFSC-MAC will obtain the lowest PER if the UAV selects an appropriate number of priority groups. We assume that the number of priority groups to the system is equal to the optimal number presented in the case of PFSC-MAC. This part discusses the new optimal value, which stands for the selected number of priority groups. The parameters applied for CPFSC-MAC are the same as the ones in Table 6.2, except the number of priority groups. This value is varied between one and the optimal values founded in Sect. 6.6.

From Fig. 6.12, at any value of the number of sensors in the network and the altitude of UAV, if UAV selects a number of priority groups that is one group less than the optimal value derived from Fig. 6.11, the CPFSC-MAC protocol will obtain the lowest PER. In addition, the results of PER shown in Fig. 6.11 was fluctuated at low altitudes of the UAV, but the results in Fig. 6.12 are quite stable and lower than 0.68% regardless the variations of the UAV's altitude, and the number of sensors in the network.

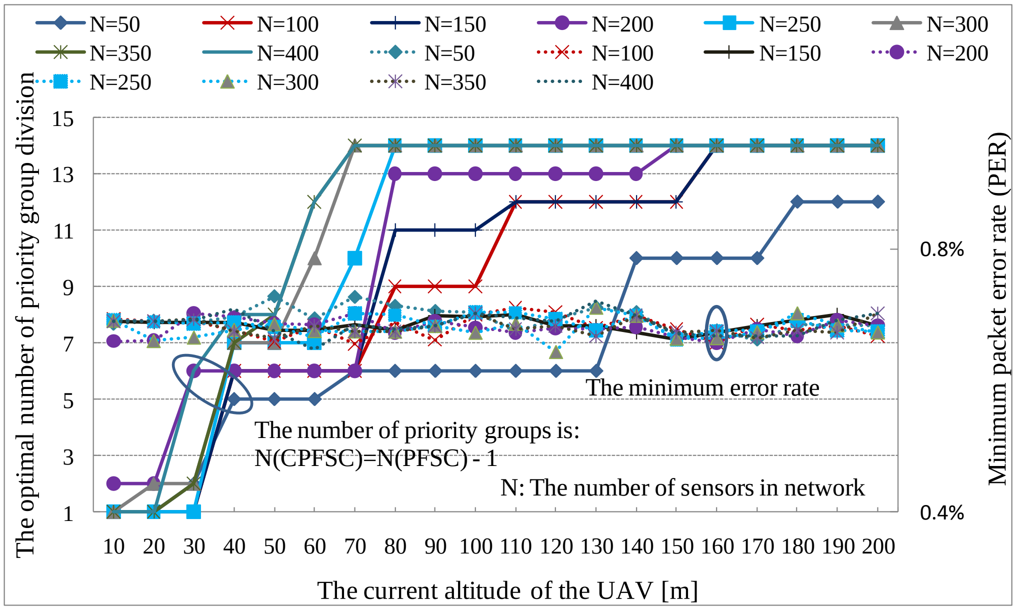

Figure 6.12: Optimal number of priority groups in the CPFSC

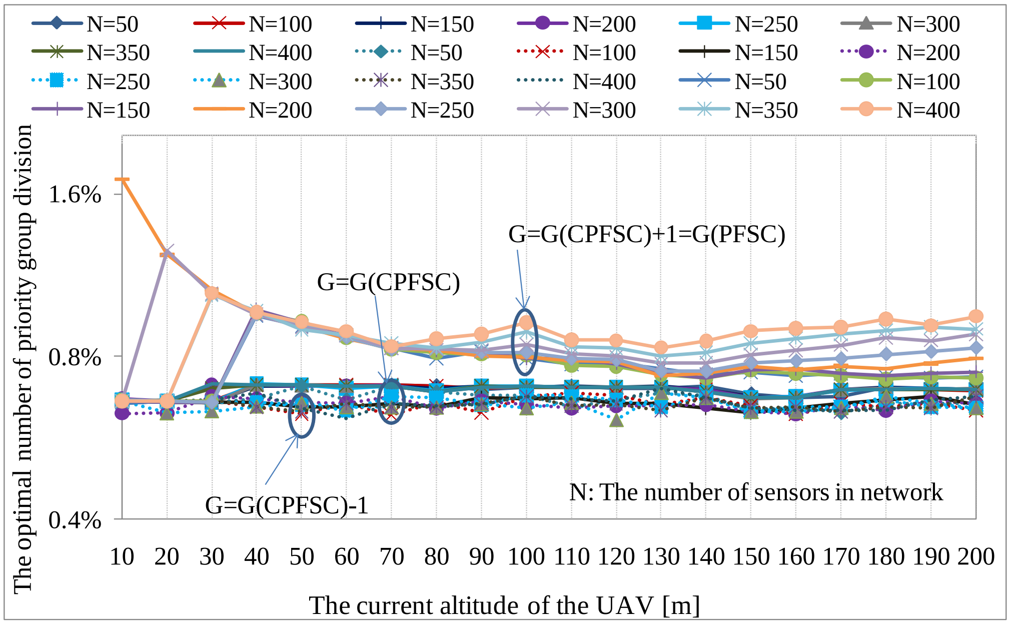

Figure 6.13: Validation of the optimal number of priority groups in the CPFSC

For further information to validate the PER at the optimal number of priority groups in CPFSC-MAC protocol, Fig. 6.13 represents the three groups of curves. The first group shows the PER at which the number of priority groups is one group larger than the optimal CPFSC-MAC protocol. The second group of lines are for the PER in case the number of priority group is one group larger than the founded value in the case of using CPFSC-MAC. And the final group show the PER of the system at a lower value of priority group compared to the optimal value of CPFSC-MAC. The results show that, even the system decrease the number of priority group to become lower than the found optimal value, the time for data collection mission will be increased, but the system performance in PER still does not change. This result show that, the optimal value of CPFSC-MAC protocol is the best value that the system can get the best PER and spends the shortest time period for completing the mission.

6.7 Conclusion

This is the first time the popular multiple access schemes of CSMA/CA, TDMA, and CDMA were numerically compared and evaluated for a WSN-UAV system. The results have shown the advantages of a CDMA based protocol compared to others. In addition, in order to guarantee all the active sensors join the data transmission, a novel MAC protocol has been proposed, called PFSC-MAC. This protocol has demonstrated the ability to accommodate all the transmissions of the sensors at the same time at low altitudes, low UAV speed, and a small number of sensors in the network. At unfavorable conditions, CPFSC-MAC has shown an even lower PER. For CPFSC-MAC, the smaller number of selected priority groups causes a larger time-span needed for the UAV to totally serve the network. Our results show that among both protocols, best system performance can be achieved with CPFSC-MAC with the number of priority groups equal to one less than the optimal number for PFSC-MAC. These two protocols provide flexible configurations for the WSN-UAV systems to obtain acceptable PER at certain values of: UAV altitude, number of sensors, UAV speed, etc. Based on these protocols, further research has been conducted for a WSN-UAV system with multiple UAVs that could be autonomously collaborated. In addition, it is meaningful to develop this protocol of PFSC and CPFSC for the WSN-UAV system in cases of sensors are movable.

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7

CONCLUSION AND DISCUSSION

In this dissertation, we focus on the two communication groups of aircraft and the lower altitude air vehicle, UAV. The studies in the former group are described in chapter 3, 4, and 5. For the latter group, the related content is presented in chapter 6. The brief conclusion on the achievements and discussion on the opening issues are as following:

Regarding to the contents in aeronautical communication, our studies and achievements are briefly concluded as following:

(1) An empirical study has been conducted in chapter 3 in order to find the feasibility of a new and wide spectrum frequency (5090-5150 MHz) for aeronautical communication, the following items are found:
    a) Channel characteristic of this band is done for air to ground communication when the aircraft is within 100 km distance from airport. The most typical factors have been analyzed are the Rice (K) factor and the signal propagation models. These results have shown that these parameters are dependent on the positions of aircraft; or more generally they depend on the phases of the flight.
    b) The evaluations of this band in case of using the same parameters that are applied for aeronautical VDL-2 system has been done. The results have shown the applicability of this wide band for air to ground communication in the case of aircraft is near the airport.

   c) In addition, the system performance has been evaluated in case of employing multi carrier transmission, MC-CDMA, for this new band. The results have indicated the feasibility to apply a wideband communication services for air traffic control at advanced airports.

(2) A new concept of multi hop data relay network is proposed for aeronautical communication in chapter 4. The accomplishment of this study has enabled the system to:
   a) Describe the relation between the signal receiving power and the distance of the two oceanic aircrafts. This formula also shows the difference between the actual receiving power and theoretical one. In fact, the free space transmission is always assumed for this kind of communication. Moreover, this result is also essential in estimating the actual receiving power which is fundamental for a safe communication that is the highest concern in the avionics system.
   b) Extract the optimal transmission distance for the air to air communication between any pair of oceanic aircrafts, which is about 650 km.
   c) Enhance the air traffic control communication for the oceanic flight routes with only one VHF channel system that bases on TDMA multiple access scheme.
   d) Increase the situational awareness for oceanic flights. It is a fundamental condition to strengthen the safety of any flights, and use the airspace more efficiently.
   e) Improve the Packet Error Rate with IB-NS (interference based node selection) and NADA (node additional delay allowance) schemes.

(3) Another multi channel based on VHF band is also introduced to the communication of oceanic flight routes, presented in chapter 5. There are these following major achievements:
   a) An autonomous access scheme for oceanic aircraft which is based on S-TDMA. This proposal is more advanced than the one in chapter 4 because the scheme does not depend on ground system.
   b) Two supporting schemes of PATR (position aid timeslot reuse) and DBTA (distance based timeslot assignment) have significantly improved the usage of timeslots by self swapping the timeslots of the aircraft in each sub space.

c) In case of applying the basic aircraft position message and a two-channel system, each aircraft can broadcast its own position at a frequency up to 1 Hz . This value is as high as the frequency that is being expected in the trial ADS-B system. As following to ADS-B system, this reporting frequency is enough for a future aircraft surveillance requirement. If the advanced aircraft position message is used, another addition of frequency channel is needed and similar evaluations are easily conducted.

For the communication between UAV and the wireless sensor network on the ground, chapter 6 has demonstrated a novel communication protocol which is simple but promising for their future applications employing UAV for collecting information from sensor network:

(1) A PFS (priority frame selection) scheme and a FRA (frame based random access) are the major components that construct the PFSC-MAC protocol. The benefits of each scheme are shown in details in this chapter.

(2) This PFSC-MAC protocol shows its favorable features in applying to the communication system including a UAV and a ground system network (i.e. wireless sensor network). The most advantage is to feasibly adjust the number of priority group in order to obtain a required level of PER. This result is dependent on the actual information such as UAV’s altitude, UAV’s speed, the packet size, and the sensor density in the network.

(3) Constrained PFSC-MAC protocol is another founded value which shows the ability of getting minimal PER with a minor compromise. If applying only one group minus from the optimal number of group in CPFSC-MAC protocol, CPFSC-MAC protocol could provide the best PER as compared to all other cases.

Based on the studies we have concluded above, there are some discussions which can be applied for the researches in the related fields:

For aeronautical communication:

(1) Based on the empirical studies in 5-GHz band, a wide spectrum is available for the air to ground communication system. A preliminary evaluation has been done for this band in multi carrier transmission. It is expected that, further experiments and

evaluations are worth to contribute to the development of communication for advanced airports.

(2) Regarding to the communication for oceanic aircrafts, the current limitation of transmission bit rate in VHF based communication (i.e. 31.5 kbps) can be affected to the data communication between the aircraft such as delay issues. It could be developed by modifying the communication protocol applied for the air to ground communication that has been developed for advanced airports at 5 GHz band. With this band, the high bit rate communication may be possible if the two aircrafts are near each other. This assumption is practical when the aircraft in the airspace increasing.

For communication system employing UAV:

The above study has opened a new communication trend in which UAV is employed to complete a mission. This promising system and communication protocol can be adjusted to the case of multi-UAV and momvable sensor network. These systems are useful but need to be further studied and evaluated. In cases of multiple UAV jointly serve the communication with the ground network, two following things is needed to be studied more 1) the UAVs must keep their moving in order to keep the UAVs network connected. This is important for collaborating and completing the mission; 2) the communication protocol and the UAV’s movement need to obtain a maximal sum rate for communication between the UAVs and the ground network.

Research Achievements

Category (Subheadings)	
Articles in refereed journals	① Dac-Tu Ho, Jingyu Park, Shigeru Shimamoto, and Jun Kitarori, Performance Evaluation of Multi hop Relay Network for Oceanic Air Traffic Control Communication, IEICE Transaction on Communications, Volume E94-B, No. 1, pp. 86-96, January 2011. ② Dac-Tu Ho and Shigeru Shimamoto, Mobile Ad-Hoc Network Based Relaying Data Sysem for Oceanic Flight Routes in Aeronautical Communications, International Journal of Computer Network and Communication (IJCNC), ISSN: 0975- 2293, pp. 33-44, April 2009.
Presentations at international conferences	③ Dac-Tu Ho, Jingyu Park, and Shigeru Shimamoto, Performance Evaluation of the PFSC Based MAC Protocol for WSN Employing UAV in Rician Fading, in Proceeding of IEEE WCNC, Cancun Mexico, March 2011. ④ Dac-Tu Ho, Jingyu Park, and Shigeru Shimamoto, QoS Constraint with Prioritized Frame Selection CDMA MAC Protocol for WSN Employing UAV, in Proceeding of IEEE GLOBECOM Workshop of Wireless Networking for Unmanned Aerial Vehicles: Architectures, Protocols and Applications, Miami, December 2010. ⑤ Dac-Tu Ho, Jingyu Park, and Shigeru Shimamoto, Novel Multiple Access Scheme for Wireless Sensor Network Employing Unmanned Aerial Vehicle, in Proceeding of IEEE/AIAA 29th Digital Avionics System Conference (DASC), pp. 5.C.5.1-5.C.5.8, Salt Lake City, Utah, October 2010. ⑥ Dac-Tu Ho, Jingyu Park, Shigeru Shimamoto, and Jun Kitarori, Performance Evaluation of Communication System Proposed for Oceanic Air Traffic Control, in Proceeding of IEEE WCNC, pp.

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