Institutionen för systemteknik

Department of Electrical Engineering

Examensarbete

Algorithm for Handoff in VDL mode 4

Examensarbete utfört i Kommunikationssystem

vid Tekniska högskolan i Linköping

av

Rickard Andersson

LiTH-ISY-EX--10/4332—SE

Linköping 2010

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Sammanfattning
Abstract

VDL mode 4 is a digital data link operating in the VHF band, its mainly use is for the aviation industry. VDL4 can as an example provide with positioning data, speed information of aircrafts or vehicles equipped with a VDL4 transponder. A connection between the groundsystem and the airborne system is called a point to point connection, which can be used for various applications. This data link needs to be transferred between groundstations during flights in order maintain the connection, which is called handoff.

The handoff process needs to be quick enough to not drop the link and at the same time a low rate of handoffs is desirable. The data link is regarded as a narrow resource and link management data for handoff is considered as overhead.

This thesis studies how to make the handoff procedure optimal with respect to involved aspects. Previous research of handoff algorithms and models of the VHF-channel are treated. Standardized parameters and procedures in VDL4 and are explored in order to find an optimal solution for the handoff procedure in VDL4.

The studied topics are analyzed and it is concluded to suggest an algorithm based on an adaptive hysteresis including signal quality and positioning data provided in VDL4. Standardized parameters which could be useful in the handoff procedure are commented, since the VDL4 standards are under development.

Nyckelord
Handoff, VDL4, algorithm,

Abstract

VDL mode 4 is a digital data link operating in the VHF band, its mainly use is for the aviation industry. VDL4 can as an example provide with positioning data, speed information of aircrafts or vehicles equipped with a VDL4 transponder. A connection between the ground system and the airborne system is called a point to point connection, which can be used for various applications. This data link needs to be transferred between ground stations during flights in order maintain the connection, which is called handoff.

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Acronyms and abbreviations

ADS-B	*Automatic Dependent Surveillance Broadcast*	23
ATC	*Automatic Traffic Control*	1
ATM	*Air Traffic Management*	1
BER	*Bit Error Rate*	24
DOS	*Directory of Service*	38
ETSI	*The European Telecommunications Standards Institute*	2
Eurocontrol	*The European Organization for the Safety of Air Navigation*	5
FIS-B	*Flight Information Service Broadcast*	23
FDMA	*Frequency Division Multiple Access*	14
FSP	*Free Space Propagation*	12
GNSS	*Global Navigation Satellite System*	24
GPS	*Global Positioning System*	1
GSC	*Global Signaling Channel*	38
GSIF	*Ground information frames*	38
GTD	*Geometrical Theory of Diffraction*	33
KIAS	*Knots Indicated Air Speed*	45
LME	*Link Management entity*	26
NAC	*Navigation Accuracy Categories*	37
NIC	*Navigation Integrity Category*	37
NM	*Nautical Mile*	31
OSI	*Open System Interconnection*	13
PECT	*Peer Entity Contact Table*	37
RSS	*Received Signal Strength*	16
RADAR	*RAdio detection And Range*	23
SCAA	*Swedish Civil Aviation Authority*	1
SNR	*Signal-to-Noise Ratio*	12
SQP	*Signal Quality Parameter*	36
STDMA	*Self organizing Time Division Multiple Access*	24
TCP	*Trajectory Change Point*	39
TDMA	*Time Division Multiple Access*	14
TIS-B	*Traffic Information Service Broadcast*	23
UTC	*Coordinated Universal Time*	24
VDL2	*Very high frequency Digital Link mode 2*	26
VDL4	*Very high frequency Digital Link mode 4*	1
VME	*VDL Management entity*	26
VSS	*VDL Mode 4 Specific Services*	25

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1. Introduction

This chapter gives a background to the thesis. The studied problem as well as the study's purpose and goal is given. Furthermore the chapter presents information regarding limitations and interested parties for the thesis. Finally the disposition of the study is presented.

1.1 Background

There is an expectancy of an increase of air traffic, airspace gets more crowded and ATM, *Air Traffic Management*, plays an important role for the aviation industry. Air traffic planning or correction of flight routes are some of the functions the ATM handles. Predefined flight routes are not enough with an increasing demand. The SCAA, *Swedish Civil Aviation Authority,* is conducting the FRAS, *Free Route Airspace Sweden* project, where predefined flight routes will become a memory. As a first step, a part of Sweden's airspace was recently released, giving pilots the opportunity to plan other paths of flight than the earlier predefined routes.[1]

To achieve an efficient management of the air traffic, a reliable communication is a crucial factor. The SCAA is investigating new technologies to handle a future ATM, with improvements of the needed applications and an increased ability to meet future needs. One candidate for the next generation of ATC, *Automatic Traffic Control,* is a technical platform based on digital communication. The VDL4, *VHF Very high frequency Digital Link Mode 4*, is a standardized data link technology intended to be used in the civil air traffic.[2] The VDL4 standard gives possibilities to transmit different kinds of information, such as weather information or surveillance of traffic based on GPS, *Global Positioning System.* The next generation ATM could give a pilot graphical and textual weather information on a moving map and also information of all other traffic. A continuous update of positions and directions of other traffic or changing weather activities on the path of the flight are some of the possibilities.

In a scenario where a ground operator wishes to communicate with a specific aircraft, a point-to-point connection is used. To maintain an ongoing transmission between a moving aircraft and the ground station, it is, for different reasons, needed to switch the data link to another ground station. The process of moving a data link from one ground station to another is called handoff. This event could for instance occur if an aircraft flies out of reach from a ground station to which the point-to-point is connected or perhaps in the case if the communication channel is too densely populated. Making a good decision of how and when to make a handoff is crucial to maintain a reliable connection between an aircraft and ground.

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[1] http://www.lfv.se/sv/LFV/Flygtrafiktjansten/Vara-Tjanster/Anslaget/Anslaget-nr-2-2009/FRAS-Free-Route-Airspace/
[2] http://www.eurocontrol.it/vdl4/public/standard_page/standards.html

1.2 Problem

The standard documentation, provided from ETSI, *the European Telecommunications Standards Institute*, does not provide any guidelines about algorithms handling the handoff procedure in VDL4. It is therefore a task for different manufacturers to solve the handoff process based on interpretations from the given requirements.

The link management is considered as overhead information on the data link i.e. the radio is considered as a narrow resource and should mainly be used to send other type of information, as example positioning data rather than data concerning link management. Therefore it is important to achieve a low number of handoffs and still maintain the point-to-point link between a mobile and a ground-station.

1.3 Purpose and Goal

The thesis studies how to optimize the handoff process in VDL4. The scenario where an airborne aircraft and a ground-station have established a point-to-point connection is considered.

The purpose of the study is to develop algorithms for an optimal handoff decision between ground-stations.

To fulfill the purpose specific goals are set:

- Develop an algorithm based on VDL4 ETSI standards and use information stated as mandatory as input to a handoff decision.

- The parameters set as optional in the ETSI standard, are to be examined if the optional transmitted information could lead to an improved handoff process.

In case of possible improvements, the handoff algorithm is to be developed with the extension of information.

1.4 Interested Parties

The target group of the thesis is mainly providers of VDL4 equipment. Information to understand relevant parts related to the handoff procedure in VDL4, without extensive knowledge of radio communication, is provided. The thesis is of interest for other students, as well as others, with an interest of radio communication or handoff procedures.

1.5 Limitations

The study does not consider actual choice of equipment, differences in performance between equipment from various manufacturers is beyond the scope of the thesis. A handoff algorithm could perform different in one system compared to another because of implementation aspects. The equipment is considered to perform according to the requirements provided from VDL4 standards.

Much information related to propagation of radio waves concerning the physical channel has been left out. As example polarization or antenna theory etc. although influencing the properties of propagation, it is considered to be outside the scope of the study. The focus of the thesis is the handoff process and the given information is mainly to present some sections involving the complexities of a handoff in VDL4.

The study does not consider the actual placement of ground stations. It is assumed a system where the coverage from ground stations are overlapping i.e. more than one ground station is available for an aircraft to connect to during flight. The design of the ground system is beyond the scope of the study. The developed algorithm is intended for a general structure of a ground network for VDL4.

Models of the VDL4 channel are examined to determine if a model should be used in the handoff algorithm, any modification or development of a VHF model in an air-ground scenario is not handled, mainly due to a need for empirical tests and which is beyond the scope of the study.

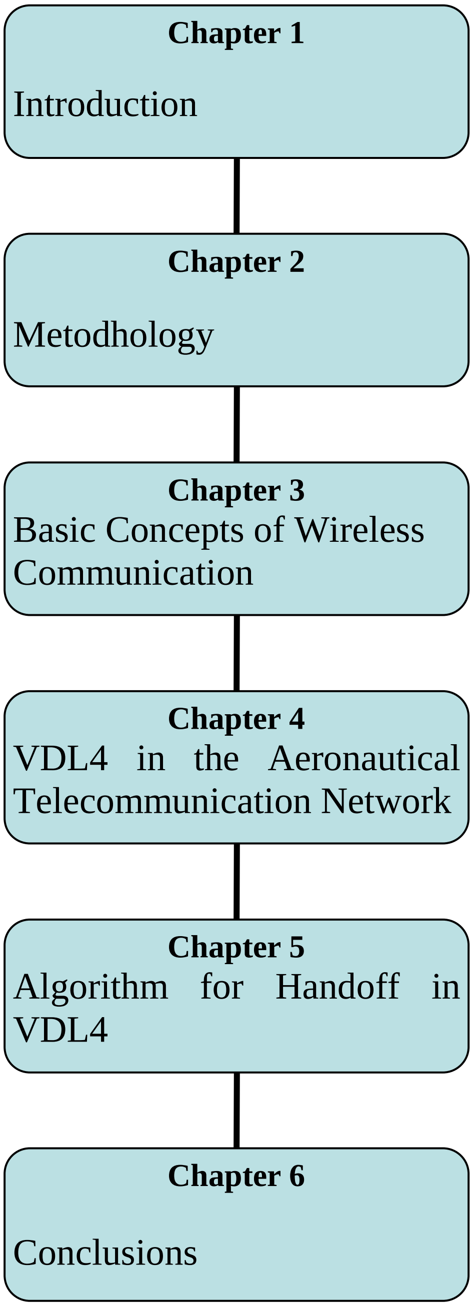
Parameters in VDL4, which influence the performance such as throughput of data or transmission delays, are not considered. Optimization of throughput or transfer delays and similar is not handled when already considered in previous studies.[3]

The target group using point-to-point communication in VDL4 is mainly considered as traffic flights, such as personal transports or goods transports.

[3] Further reading in AMCP WG M2 Appendix M *VHF Datalinks for point to point communications*, 7th meeting ACMP jan 2000

1.6 Disposition

An overview of the thesis's disposition is presented in "Figure 1 Disposition of the thesis". A brief description of each chapter's content is also given.



Chapter 1 gives an introduction to the topic that is studied, the purpose and limitations are presented.

Chapter 2 presents the methodology, presenting how the study has been conducted and the research philosophy.

In chapter 3 a theoretical frame of references is presented.. Topics related to wireless communication are given. This provides with necessary information to understand the studied system and related issues in a handoff process.

Chapter 4 presents the studied system, giving an overview of VDL4. Topics that are important for a further analysis as well as the framework for the handoff procedure in VDL4 is given.

In chapter 5 an analysis based on the earlier information is made, leading to a solution for an algorithm handling handoff for point-to-point VDL4.

Chapter 6 presents the conclusions of the study as well as suggestions for further studies.

Figure 1 Disposition of the thesis

2 Method

This chapter presents an insight of how the study has been made. The approach to the problem as well as the reliability and validity of the study are discussed. How information has been collected and the author's attitude and scientific view are presented. Finally the work method for the study is given.

To facilitate a research study different methods are used depending on the design of the research. By applying a method, a structure in the work process is given

2.1 Scientific Approach

A study's research problem and purpose is the starting point in deciding what method to use.[4] For the study the approach is that based on theory and previous research a solution will be derived.

2.2 Reliability and Validity

Reliability is related to the question whether the results of a study are repeatable or not.[5] Meaning that if the same study is remade the same results would be concluded. It can be argued that used documents and literature possibly have been interpreted incorrect, however assumptions are accounted for in the document providing a high reliability. Other assumptions or interpretations of used sources could perhaps give other results. Validity is to what extent collected data is valid and relevant.[6] The intention has been to gather relevant information and use it properly. Information of the handoff process in VDL4, as well as information about similar systems and related research, has been used to fulfill the relevance criteria. The validity is determined when the result is checked to fulfill the thesis's purpose.

2.3 Collection of Data

Handoff procedures have been extensively researched and in order to fulfill the purpose of the thesis secondary data has been used. Secondary data is defined as data gathered for some purpose other than the objectives of this particular study.[7] The literature and articles within the field of the study have been collected at the University of Linköping, information from databases provided at the library and Internet. Documentation regarding VDL4 standards is achievable from the ETSI webpage and also provided at the Eurocontrol, *The European Organization for the Safety of Air Navigation,* webpage. The used books have for the most part been provided by the library at Linkoping's University and the referred articles have mainly been collected from IEEE, *Institute of electrical and electronic Engineers.* Key words when searching for information have been: handoff, handover, propagation, VDL, handoff algorithm, VHF channel, algorithm optimization.

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[4] Ghauri P. Grønhaug K. *Research Methods in Business Studies*, third edition, Pearson Education Limited, England 2005

[5] Bryman A. Bell E *Business Research Methods* Oxford University Press New York 2007

[6] Esaiasson P. Gilljam a.o *Metodpraktikan* Nordstedts Juridik AB Elanders 2009

[7] Ghauri P. Grønhaug K. *Research Methods in Business Studies*, third edition, Pearson Education Limited, England 2005

2.4 Source Criticism and Scientific View

This study is based on theoretical information and a researcher needs to critically analyze and carefully reflect the used sources.[8] The ETSI document is one of the main components for the providers of VDL4 equipment as well as the SARPS documents. These documents set the requirements of the equipment and on the system and unclear statements or definitions are reflected upon in the report. The used articles are published on IEEE, a globally well known and recognized organization. IEEE provides a wide range of professional and technical information. This leads the author to the assumption that the used articles are trustworthy. Written material appearing to be influenced by commercial or nonobjective interests is handled through a humanistic view.[9]

2.5 Work Method

The work on the thesis has been divided into different steps. Initial theoretical studies are an important part of the progress. To handle a task properly, a good knowledge of the actual problem is required and an outline of this study's work method is presented in "Figure 2 Work Method".

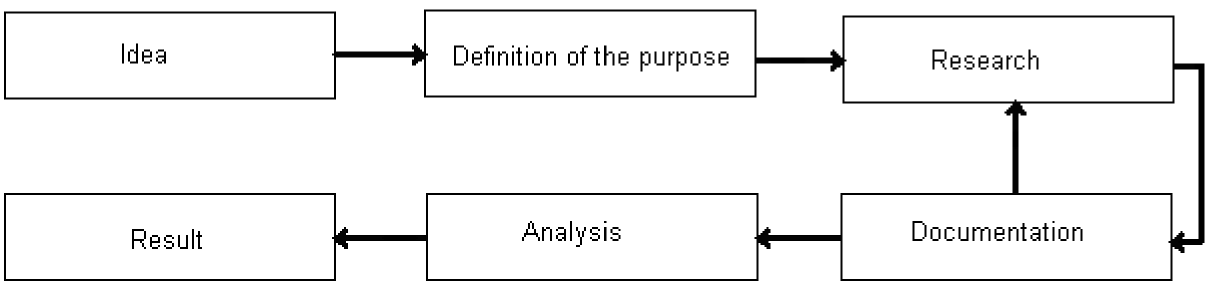

Figure 2 Work Method

The idea is to describe a solution for an optimal handoff procedure during point-to-point communication in VDL4. This idea is then transferred into the purpose of the thesis.

The study investigates methods to handle the handoff procedure in VDL4. A basic understanding of VDL4 was the starting point and general information about the air traffic network and VDL4 was researched. Then a more narrow study of VDL4 was conducted, based on information from ETSI standards. This provided the needed information of available parameters that could be used in a handoff decision. Literature and articles about wireless communication in general, as well as the specifics for the operating conditions for VDL4 were studied. As a topic was treated, other areas of interest came up, and further research needed to be done during the writing process. Throughout the progress of the research, related information has been documented. Based on the purpose of the thesis different areas of interest have been studied and progressively been written. Information from literature and previous research were then analyzed and applied on the handoff process in VDL4 giving the results of the study.

[8] Esaiasson P. Gilljam a.o *Metodpraktikan* Nordstedts Juridik AB Elanders 2009
[9] Holme M. Solvang B. K. *Forskningsmetodik - Om kavalitativa och kvantitativa metoder* Studentlitteratur 1991

3 Basic Concepts of Wireless Communications

This chapter presents general principles in wireless communication. How principles work and how a radio channel could be shared. Problematic issues with wireless communication are presented such as fading or noise. A common tool used in a wireless system design, the link budget and its components, is explained. Furthermore is the OSI reference model presented, where the layers of interest for the thesis, the physical layer and the data link layer are described. The principle of handoff is explained as well as different methods to solve the handoff process and a selection of research concerning handoff algorithms is presented.

3.1 Wireless Communication

To transfer information from one end to another, there exists many different systems, ordinary telephone or mobile etc. are some ways to transfer voice communication, which most people are familiar with. In this study radio communication is of interest and a basic wireless communication system consists of a transmitter and a receiver illustrated in “Figure 3 Basic wireless communication”.

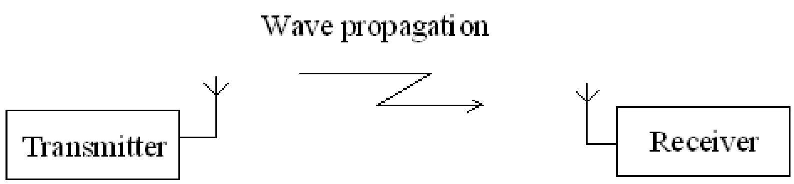

Figure 3 Basic wireless communication

The transmitter converts information into an electric signal which through an antenna propagates through the air. At the receiver the radio wave is collected and a process of the opposite operation occurs. By recovering the signal, the transmitted information is estimated and converted back into the transmitted data.[10]

Problems with Wireless Communication

Since reality is not ideal a selection of problematic issues in wireless communication are described in the following section. Information that is intended to be transported from one location to another is generally under influence of disturbance of different kinds. As a result the transmitted information could be corrupt or the channel for communication could be unavailable. The system architecture could raise problems, other systems could interfere, dynamics of propagation of radio waves etc. As a radio wave propagates a phenomenon called fading could occur. Different classifications of fading exist, small and large scale fading. These categories of fading are related to the impact on received powers. A large scale fading refers to variations of the received mean signal power and small scale refers to fluctuations around the mean value.[11] Two types of fading are further described.

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[10] Haykin S. Moher M., *Modern Wireless Communications*, Pearson Education, Inc. Upper Saddle River,NJ USA 2005 p.13
[11] Ibid. p.44

Shadow Fading
A mobile, which is connected to a ground station, could be moving behind objects such as hills or large buildings. The line of sight gets obstructed between the participants and the communication may be subject to shadowing. Since the objects interfering may be large a mobile could experience shadow fading during a long time.[12]

Multipath Fading
Another type of fading is the multipath fading. This type of fading arises due to the fact that radio waves can reflect and then various paths are possible between a transmitter and a receiver. This event also occurs due to movement of the participants as well as a static scenario. One signal could reflect on objects such as ground, buildings or hills etc. resulting in that received signal components, could cancel each other out or yield a power together far greater than a direct signal.[13] This is also known as constructive and destructive interference. A simple scenario is illustrated in "Figure 4 Multipath in wireless communication."

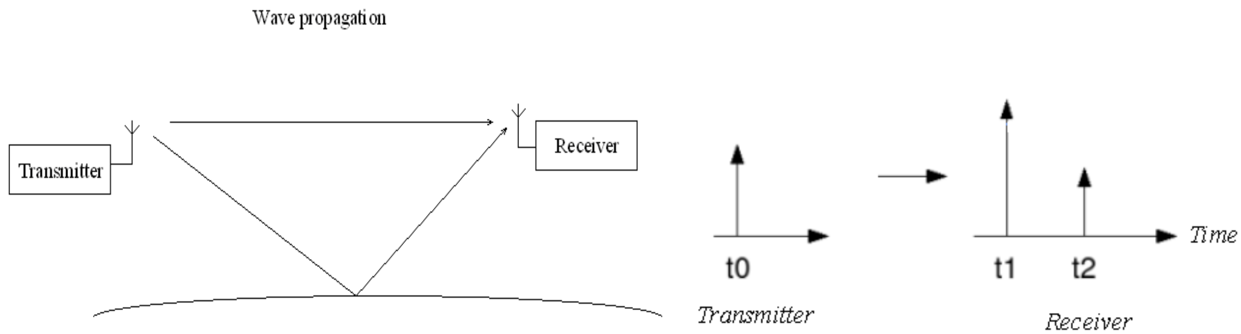

Figure 4 Multipath in wireless communication

The illustration shows the principles of multipath, in this case a 2 ray model. This means that at the receiver two signals are received. Multipath propagation can occur due to reflection on land and water surfaces as well from man made structures. A received signal characterized by multipath fading is known to be more severe over water.[14] The reflected signal has a longer delay, due to a longer path, and also attenuated i.e. a loss of energy occurs on impact with the ground.[15] But the combination of two signals could yield a great difference in comparison if only one signal was received. In the right part of Figure 4, a representation of a digital transmission is pictured. The transmitter receives an impulse which is represented twice, due to multipath. The influence of previous transmissions, gives the impulse at time *t1* a larger amplitude.

[12] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.157
[13] Ibid. p.43
[14] SARPS ANNEX 10 Volume III p.420
[15] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.41

Diffraction
When a radio path is obstructed with a surface that is irregular, it gives rise to secondary waves from the obstructing surface.[16] This phenomenon is called diffraction and allows radio signals to propagate behind objects and around the curved surface of earth.[17] Diffraction can be exemplified with a radio wave hitting a mountain. Due to diffraction there is a possibility to receive the signal behind the object.

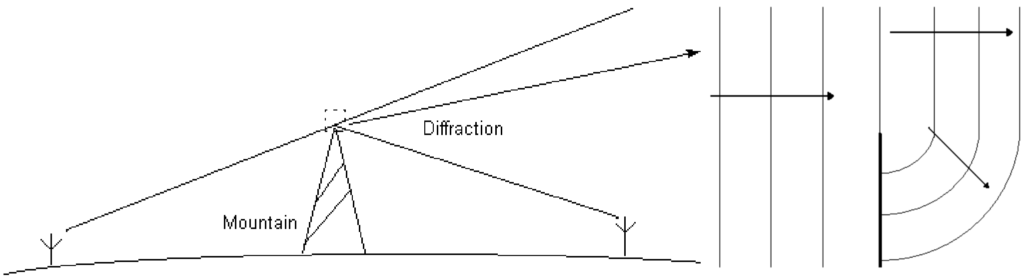

Figure 5 Knife edge diffraction

"Figure 5 Knife edge diffraction" shows a model for diffraction. Even though there is a mountain located between the transmitters, diffraction enables communication. The phenomenon of diffraction is explained through electromagnetic physics. The principle is pictured to the right, a radio wave hitting a sharp edge tends to bend and also propagates in a shadowed region. The power of the transmitted signal gets decreased due to obstruction, however the diffracted power is often enough to produce a useful signal.[18]

Noise
A transmitted signal is in general influenced of disturbance from phenomena's in the environment as well as within the architecture of the equipment. Different kinds of noise are briefly described as well as its sources. Thermal noise is a fundamental property of matter, in all material such as resistors, transistors in a receiver, electrons in the atoms are randomly moving. This occurrence is within material operating in environments where the temperature is higher than $0\ ^{o}$K. This spontaneous movement of electrons generates intermittent currents which are referred to as thermal noise. Another type of noise is the so called man-made noise. Electric equipment, such as sparks in electrical motors, switches or poorly shielded computers in a vicinity of a receiver generates impulsive noise. Another type of man-made noise is signals interfering from other transmitters.[19] There are other sources of noise, such as atmospheric noise where electrical phenomena's in the atmosphere, such as lightning bolts which creates noise with impulsive characteristics and is mainly a problem in frequencies less than 20MHz.

[16] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.36
[17] Ibid. p.52
[18] Ibid.
[19] Haykin S. Moher M., *Modern Wireless Communications,* Pearson Education, Inc. Upper Saddle River,NJ USA 2005 p.70

3.2 Link Budget

When designing a wireless system a so called link budget is normally performed to establish the requirements for a reliable communication. The link budget ensures that the received power is sufficient to meet the requirements for maintaining communication.[20] In the link budget properties of the system as well as characteristics of propagation are included.

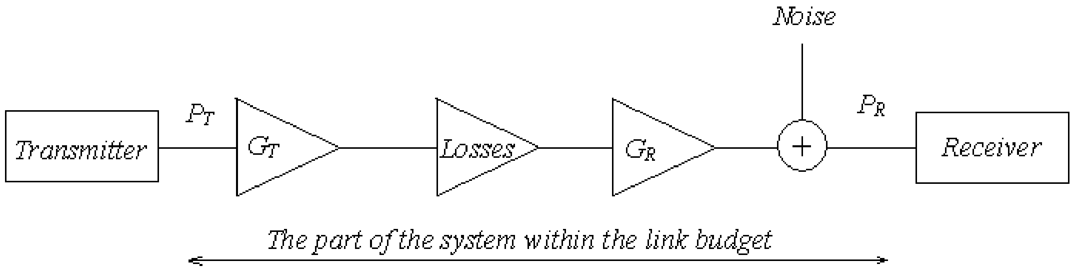

Figure 6 Link budget in a wireless system

The illustration shows the components in a link budget, which are further discussed in the following sections. The Friis equation $P_R = \frac{P_T G_T G_R}{L_P}$ is a base for the link budget.[21] Where:

G_R *– receiver antenna gain*
G_T *– transmitter antenna gain*
P_R *– received power*
P_T *– transmitted Power*
L_p *–pathloss*

The equation expresses the relation between received and transmitted power and the parameters are further explained in the following sections. A system designer can make trade offs in the link budget, transmitter power, gain of receiver etc. to implement an architecture with a performance as good as possible.

Antenna Radiation

An isotropic source transmits power equally in all directions. At the surface of a sphere, with radius R [m] and an isotropic transmitter in the centre radiating power P_T [W]. The power per unit area is then given by:[22] $\Phi_R = \frac{P_T}{4\pi R^2} \left[\frac{W}{m^2}\right]$. In reality most antennas are not isotropic, the antenna would correspond to a point-shaped antenna. Propagation can vary with the shape of the antenna such as a parabolic antenna, where it is possible to direct the distribution.

[20] Haykin S. Moher M., *Modern Wireless Communications*, Pearson Education, Inc. Upper Saddle River,NJ USA 2005 p.75
[21] Ibid. p.19
[22] Ibid. p.13

A common antenna is the dipole antenna, which can be used to create an omni-directional antenna radiation pattern.[23]

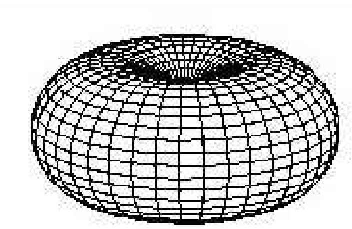

Figure 7 Dipole omni-directional antenna pattern[24]

"Figure 7 Dipole omni-directional antenna pattern" shows a 3D description of the omni-directional radiation pattern.

For non isotropic equipment gain G is used instead for the intensity of radiation. The gain is defined as a relative value to an isotropic antenna according to the following equation:[25]

$$G_T = \frac{Power\ per\ unit\ area\ in\ direction\ (\theta,\phi)}{power\ per\ unit\ area,\ \ isotropic\ antenna}\ [dB]$$

Where θ is normally known as the azimuth angle. The different angels are illustrated in the following figure.

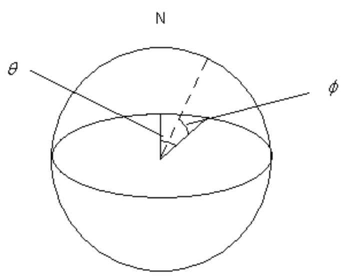

Figure 8 Visualization of angles in direction (θ,ϕ)

The azimuth angle corresponds to the angle in the horizontal plane relative to a reference point, such as north, and ϕ is the angle above the horizontal plane

At the receiver an antenna collects the radiated power from the transmitter. The receiver gain is also defined as a relative measure according to the following equation.[26]

$$G_R = \frac{Effektive\ \ area\ \ in\ \ direction\ (\theta,\phi)}{Effective\ \ area\ ,\ \ isotrophic\ \ antenna}\ [dB].$$

[23] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.114
[24] http://www.statemaster.com/encyclopedia/Antenna-(radio)#Radiation_pattern
[25] Haykin S. Moher M., *Modern Wireless Communications,* Pearson Education, Inc. Upper Saddle River,NJ USA 2005 p.15-p.16
[26] Ibid.

Many antennas are used to both transmit and receive and the locations of receiver or transmitter can be interchanged without transmission characteristics changing according to the principle of reciprocity. i.e. if energy is transmitted on the reverse path the process would have the same environment and properties.[27]

Free Space propagation

The FSP model, Free Space Propagation is a method for making theoretical estimations of the energy at a transmitter. This model assumes there are no obstacles in the transmission and the propagation is based on properties of the electrical field. The characteristic of distortions from the medium is linear i.e. considered as attenuation or superposition.[28] The path loss for a FSP model using an isotropic antenna is:[29] $L_b = \frac{(4\pi R)^2}{\lambda^2}$ where R is the distance between the transmitters and λ is the wavelength of the signal.

A general propagation model for path loss, which includes environmental properties, can be written as: $L_b = \frac{P_R}{P_T} = \frac{k}{d^{\alpha}}$ where α is the path loss exponent, d is the distance between the transmitter and receiver and k is a constant depending on the propagation situation.[30] This constant could be related to frequency or antenna heights etc. This model is generally accepted and is based on empirical performed measurements in various environments. However, this model shows general trends and exceptions exist. The path loss exponents for different environments have been determined. As an example in free-space α =2 or in a dense urban with skyscrapers the path loss exponent is α = 4,5. [31]

Extension of the link budget

To be able to make calculations of the impact of noise in radio communication, noise could be included in the link budget:[32] As an example the noise power, N over a bandwidth B can be expressed as $N = kTB$

k – Boltzmanns constant, converts a system temperature into an equivalent noise density[33]
T – absolute temperature [K]
B – Bandwitdh [Hz]

In the SNR, *Signal to Noise Ratio*, another common used measurement instead of received power then noise is included in the Friis equation. [34]

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[27] Haykin S. Moher M., *Modern Wireless Communications*, Pearson Education, Inc. Upper Saddle River,NJ USA 2005 p.15-p.16

[28] Ibid. p.13

[29] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.40

[30] Ibid. p.84

[31] Haykin S. Moher M., *Modern Wireless Communications,* Pearson Education, Inc. Upper Saddle River,NJ USA 2005 p.31

[32] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.161

[33] Haykin S. Moher M., *Modern Wireless Communications,* Pearson Education, Inc. Upper Saddle River,NJ USA 2005 p.77

[34] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.166

SNR = $\frac{P_R}{N} = \frac{P_T G_T G_R}{L_b N} = \frac{P_T G_T G_R}{L_b FkTB}$, where F is the receivers noise factor. Other types of noise and losses can as well be included in the link budget such as cable losses or antenna losses, atmospheric noise etc. For digital signaling the signal to noise ratio often is used as a quality measure, which could be expressed as:[35] $\frac{E_b}{N_0} = \frac{P_T G_T G_R}{L_b N} = \frac{P_T G_T G_R}{L_b FkTBR}$, where R corresponds to the bit rate.

3.3 OSI Reference Model

A reference for the functions that occur in the communication process is the OSI model, *Open System Interconnection,* which is a description of layout for layered communication.[36]

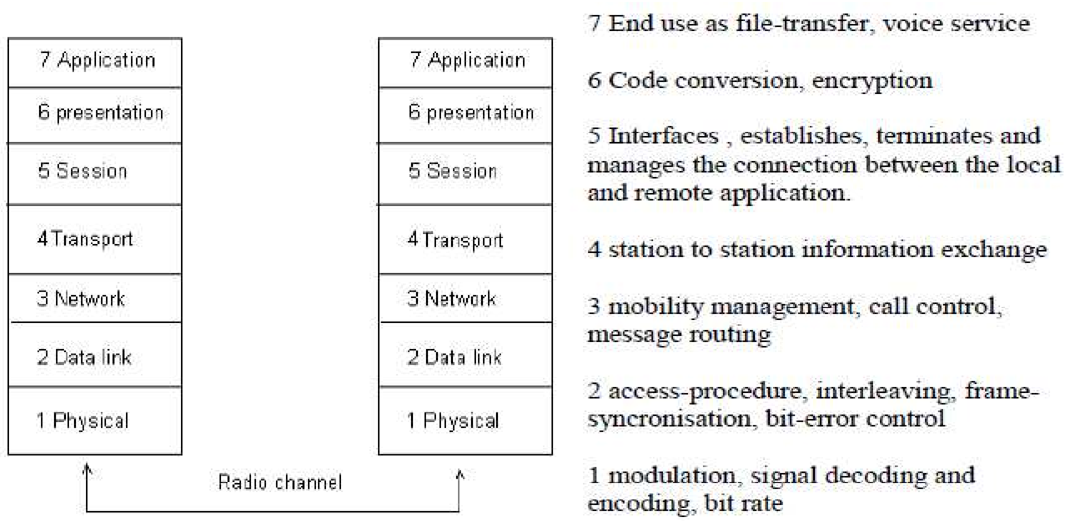

Figure 9 OSI reference model

Each layer has a specific task to manage and in this study mainly the lower layers are of interest. The physical and the data link layers are further discussed in the following sections.

Physical Layer

The key resource in wireless communication is the radio spectrum. At the physical layer functions such as modulation, channel coding and detection techniques to maximize the use of the radio spectrum take place.

Multiple Access

The method of sharing a radio channel between users is called *multiple access.* Different methods are used to share a channel, depending on determined standards or technology of the communication system. Two common methods are described in the following sections.

[35] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.166
[36] Haykin S. Moher M., *Modern Wireless Communications,* Pearson Education, Inc. Upper Saddle River,NJ USA 2005 p.455

Frequency Division Multiple Access

The multiple access technique FDMA, *Frequency Division Multiple Access,* is based on dividing the available bandwidth into smaller sets of channels. Each user's radiofrequency is a part of the larger frequency spectrum.[37] The principle is illustrated in "Figure 10 Illustration of FDMA".

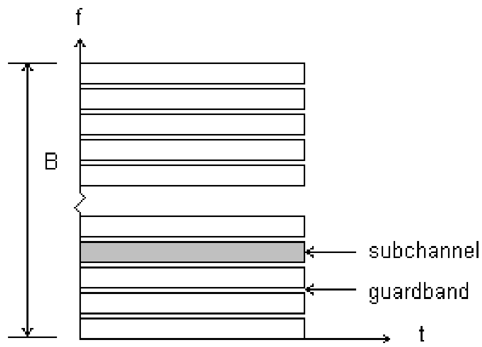

Figure 10 Illustration of FDMA

"Figure 10 Illustration of FDMA" shows the basic idea of FDMA, the bandwidth *B* is divided into smaller sets of channels. Within the frequency spectrum the users are assigned sub channels, all users get separated through guard bands. The guard band prevents different users from using the same channels or interfering with each other. This multiple access method was used in the analogue telephone system such as NMT, *Nordic Mobile Telephone or* AMPS, *Advanced Mobile Phone Systems.*

Time Division Multiple Access

Another way of sharing a channel is called TDMA, *Time Division Multiple access,* where the time is divided into smaller sets of intervals and then letting each user have access to the whole bandwidth in the channel during this time interval.[38] The process is repeated after a while and the idea is illustrated in "Figure 11 Illustration of TDMA".

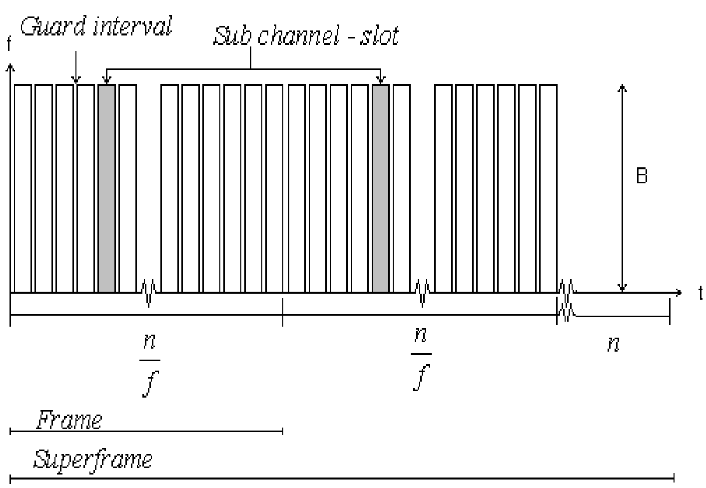

Figure 11 Illustration of TDMA

[37] Black U., *Second Generation Mobile & Wireless Networks,* Prentice Hall PTR Upper Saddle River NJ USA 1999 p.4

[38] Haykin S. Moher M., *Modern Wireless Communications,* Pearson Education, Inc. Upper Saddle River,NJ USA 2005 p.233

"Figure 11 Illustration of TDMA" illustrates the basic concept of TDMA. In this case a superframe corresponds to time n. The superframe is divided into time $\frac{n}{f}$ frames, which is further divided into timeslots that corresponds to the sub channels. A user is assigned a sub channel which uses all available bandwidth *B* during its assigned timeslot. A TDMA system puts high requirements on time synchronization to prevent transmissions in the same timeslot.[39] A TDMA system where the bandwidth *B* is less than 50 kHz is called a narrowband TDMA.[40] This method of multiple access has been used in the GSM mobile cellular system.[41]

Data Link Layer

The objective of the link layer is to ensure a reliable transmission of data across a physical link.[42] Within the data link layer the link management is handled and one of its tasks is to manage the procedure of keeping the receiver connected to a transmitter during an ongoing transmission. At the link layer, emphasis is on how the radio spectrum is shared and other related issues are handover processes or power control of mobile terminals.[43] The emphasis of the thesis is on the handoff process which is a part of the task for the data link layer and is further discussed.

3.4 Handoff

In a scenario where a mobile is in use, such as during a call, a point-to-point connection is established. The area or volume a ground-station covers is referred to as a cell. When a user is moving in a cell and gets out of range from the serving ground-station. A switch of ground-station occurs to maintain a link to the network in order continue the transmissions. The process of changing ground-station is called *handoff*.[44] A scenario for a handoff situation is illustrated:

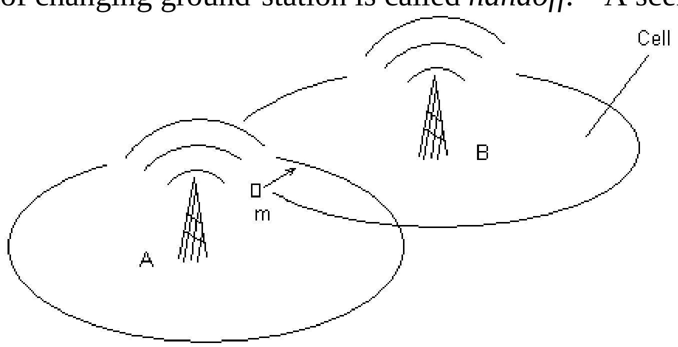

Figure 12 Visualization of a handoff scenario

"Figure 12 Visualization of a handoff scenario" illustrates a situation when a typical handoff occurs. A mobile *m*, connected to station A, is moving into a new cell and a switch occurs to station B. There are two main types of handoff that uses different methods to handle this process which are further described in the following sections.

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[39] Dunlop j. Smith D.G., *Telecomunications Engineering third edition*,CRC Press Florida 1994 p.510
[40] Ibid. p.540
[41] Ibid. p.541
[42] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.13
[43] Haykin S. Moher M., *Modern Wireless Communications,* Pearson Education, Inc. Upper Saddle River,NJ USA 2005 p.455
[44] Ibid. p.465

Soft Handoff and Hard Handoff

The method of *hard handoff* represents the case when the connection to the old cell is dropped in order to connect to a more suitable base-station. The principle is that the old link is dropped and the mobile connects to the new ground station as fast as possible, a "break before make". The communication is shortly interrupted, in the TDMA based GSM system the time for a handoff is about 100ms.[45] When the handoff occurs, during voice communication, the voice channels are muted and this event is normally unnoticed by the user. On the other hand handoff is a problem if data is transmitted or received, data could be needed to be retransmitted which could cause queues in the system.[46]

In systems where the cells use same frequencies, there may be a capability of *soft handoff*. Since cells use the same frequencies there are no need to change channel in order to change ground station i.e. multiple ground statons receive the same signal.[47] In practice this means that a mobile is linked to two cells at the same time. When the mobile has moved into the new cell the old link is dropped and the handoff is then completed.[48] This procedure is also known as "make before break".

Backward and Forward Handoff

Algorithms differ in how the link is transferred between base-stations. A backward handoff initiates the handoff process trough the current serving ground station. An advantage is that the information is transmitted on an already existing link and does not require a new link in the initial stage of the handoff process. A disadvantage is if the current link deteriorates to fast during the process. This method has been used in cellular TDMA systems such as GSM. A forward procedure initiates the handoff via a channel to the target base-station without having to rely on the current base-station. This procedure is faster but reduces the handoff reliability. The forward procedure has been used in digital cordless telephone systems such as DECT.[49]

Reactive and proactive handoff

A handoff is reactive when current information is used. As an example, if the received signal strength is monitored and drops below a certain level, a handoff is triggered. A handoff procedure is proactive when the conditions for handoff are possible to foresee or estimate.[50] This would need a method of prediction. An example of a predictive handoff algorithm is GPHA, *Grey Predictive Handoff Algorithm,* which uses RSS, *Received Signal Strength,* to create a model for prediction of a future RSS. This is made on a stochastic approach and with the assumption that a handoff should occur in the middle of two ground stations and that the serving station provides the best RSS.[51]

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[45] Haykin S. Moher M., *Modern Wireless Communications,* Pearson Education, Inc. Upper Saddle River,NJ USA 2005 p.466

[46] Dunlop j. Smith D.G., *Telecomunications Engineering third edition,*CRC Press Florida 1994 p.516

[47] Haykin S. Moher M., *Modern Wireless Communications,* Pearson Education, Inc. Upper Saddle River,NJ USA 2005 p.466

[48] Nyqvist J, *Din guide till Telekomvärlden*, Studentlitteratur Lund 2004

[49] Bing B., *Broadband wireless access,* Springer Netherlands 2000 p.23

[50] Chao H. Yen Y-S. *Proactive Hand-Off Target Orientation Cache in Fast Handover for Mobile IPV6*, Wireless Networks, Communications and Mobile Computing, Vol2 June 2005

[51] Sheu S-T. Wu C-C., Using Grey Prediction Theory to Reduce Handoff Overhead in Cellular Communication Systems. IEEE Personal Indoor and Mobile Radio Communications Vol. 2 2000

3.5 Methods for Making a Handoff Decision

Different approaches to resolve a handoff procedure have been the solution for different communications systems and the following section gives a description of used methods. There are numerous methods to make a handoff, which have been researched extensively. A selection of studied algorithms is presented in the following section. In the handoff process some kind of algorithm is included to make the decision of when or where to make a handoff. The handoff process consists of different stages, first an evaluation of the link quality followed by an initiation and then an allocation of resources.[52]

The performance of a handoff algorithm is in general measured with respect to the rates of handoffs and the handoff delay. A handoff delay includes time for evaluation of attributes, selection of ground station and the actual switching of grundstation. As stochastic metrics the probabilities for handoff, dropped link and unnecessary handoffs are usually examined. As a summary it is desirable to achieve low rates of handoffs and a short handoff delay. It is wanted that a handoff occurs at the right time or place and only if needed in order to maintain connection and a quality of the link.

Handoff as an Optimization Problem

In a handoff decision, the evaluation of the candidates of ground stations can be modeled as a traditional optimization problem.[53] Meaning a function of interesting parameters, is maximized or minimized. Parameters as input to the optimization model could vary with respect to which quality that is of importance. There are algorithms that handle handoff between different types of wireless systems, such as a handoff between GSM and WLAN. There are many different methods of optimization such as SAW, *Simple Additive Weighting*. Attributes are given a normalized value and multiplied with a weighted value corresponding to its importance, where the network with best overall score is chosen. Another is TOPSIS, *Technique for Order Preference by Similarity to Ideal Solution*, where the candidate network is chosen which is closest to the ideal solution.[54]

Attributes in the optimization could be depending on *Service Type*, which in a point-to-point connection could be of importance. If the case different types of applications or services are offered within a system i.e. all ground stations do not support the same services. For an efficient usage of the network, the *Network Conditions* could be used. Network-related parameters such as traffic load at a ground station or available bandwidth. These parameters may be evaluated to make an efficient balance of throughput. To ensure *System Performance* a variety of parameters can be involved in the decision making process, for instance, channel propagation properties, such as SNR, *Signal to Noise Ratio* or RSS, *Received Signal Strength* etc.

[52] Bing B., *Broadband wireless access,* Springer Netherlands 2000 p.22
[53] Chen W.T Huang H-K Liu J-C. *An Adaptive Scheme for Vertical Handoff in Wireless Overlay networks* IEEE Parallel and Distributed Systems July 2004
[54] Stevens-Navarro E. W.S Wong V., *Comparison between Vertical Handoff Decision Algorithms for Heterogeneous Wireless Networks,* may 2006

Traditional Handoff Procedures

Traditional handoff mechanisms are in general based on RSS.[55] A higher RSS is in general an indication of better quality of a channel. Measurements of the signal strength from the serving station as well as surrounding stations are continuously updated. One method used in GSM is called *Mobile assisted handoff,* where both a groundstation and a mobile makes radio channel measurements and report to the fixed network to make a handoff decision.[56]

Channel fading such as multipath or shadowing, can cause fluctuations in the received signal strength which introduces confusion in making a correct decision if the handoff initiation is based on received signal levels. A general picture of the influence of fading is presented

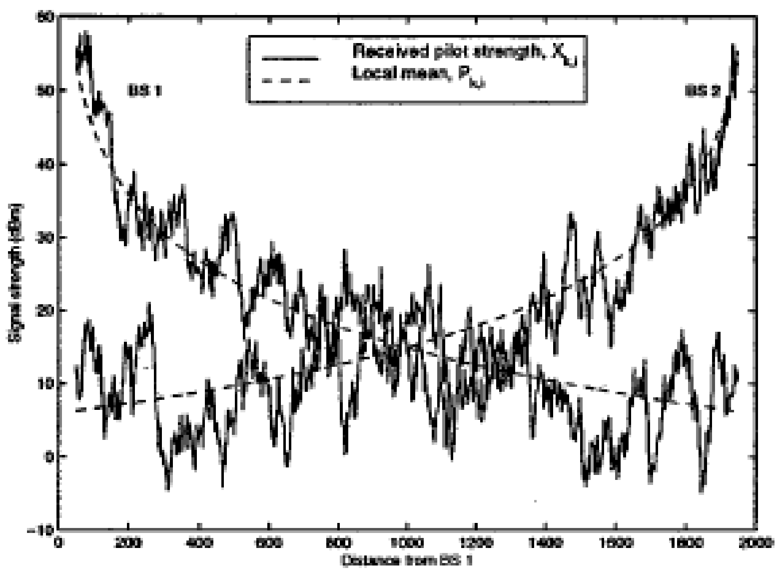

Figure 13 General influence of fading[57]

"Figure 13 General influence of fading" shows how fading influences RSS. Two ground stations are separated 2000 [*m*] and a mobile measures the RSS powers from the serving and an adjacent ground station. The RRS varies because of various reasons, such as distance or fading.[58] There is a decrease of RSS when the mobile moves from the serving station and an increase from the adjacent ground station. The dotted line shows an averaged RSS, which is a way to handle small scale fluctuations, due to fading.[59] There are methods to counteract large scale fading trough the equipment such as diversity techniques. An example is angle diversity, where the different paths in a multipath channel are separated trough the antenna, and could be used to improve performance.[60]

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[55] Wong D. Cox D. , *"A handoff algorithm using pattern recognition"*, IEEE Universal Personal Communications Oct 1998

[56] Dunlop j. Smith D.G., *Telecomunications Engineering third edition*,CRC Press Florida 1994 p.516

[57] Prakash R. *Adaptive Hard Handoff Algorithms* IEEE Journal on Selected Areas in Communications Vol 18 No11 Nov. 2000

[58] Holtzman J. ,*Adaptive Measurement Intervals for Handoff,* Communications ICC '92 Jun 1992

[59] Prakash R. *Adaptive Hard Handoff Algorithms* IEEE Journal on Selected Areas in Communications Vol 18 No11 Nov. 2000

[60] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.354

The averaging of RSS influences the performance of the handoff. A larger averaging window results in a better estimation but also increases the delay in the handoff procedure.[61]

The handoff delay is generally described as a distance from the optimal decision point, which would be exactly in between two ground stations in an ideal case. The ideal case would be an identical propagation pattern, no noise or interference and a symmetric structure of the ground network.

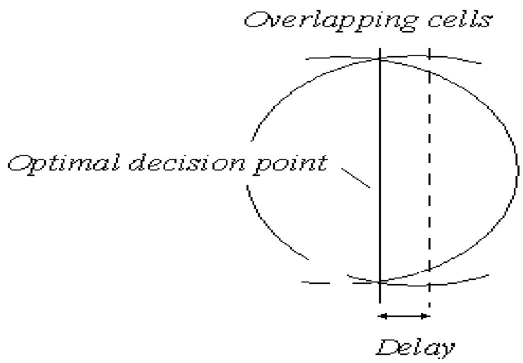

Figure 14 Optimal decision point for Handoff

The handoff delay means that the mobile moves into the adjacent cell and performs a handoff beyond the optimal point described in "Figure 14 Optimal decision point for Handoff". The averaging also lowers the probability for handoff.[62] A larger number of samples reduces the number of handoffs but increases the delay.[63] Studies have shown that in general a longer averaging time is appropriate in macrocells.[64,65] A macrocell, which is of interest in this study, is a cell larger than 1 [*km*].[66]

Another aspect in a handoff algorithm is a way to handle unnecessary handoffs. Depending on the attributes used in a handoff algorithm, an adjacent ground station could appear better than the serving ground station. This could lead to unnecessary handoffs and a switch back and forth between base-stations, this phenomenon is called *ping-pong phenomenon*.[67]

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[61] Liang B. Zahran A. Saleh A. *Networking 2005, Application Signal Threshold Adaptation for vertical Handoff in Heterogeneous Wireless Networks* Springer Berlin/ Heidelberg 2005
[62] Gudmundson M. *Analysis of Handover Algorithms* Vehicular Technology Conference 41st IEEE 1991
[63] Itoh K. Shih J-S. a.o *Performance of Handoff Algorithm Based on Distance and RSSI Measurements* IEEE Transactions on vehicular technology Vol 51 No 6 Nov 2002
[64] Zonoozi M, *Handover delay and hysteresis margin in microcells and macrocells,* Personal, indoor and Mobile Radio Communications sep 1997
[65] Dassanayake P., Faulkner M. Zonoosi M. *Optimum Hysteres Level, Signal Averaging Time and Handover Delay* Vehicular Conference IEEE 47th May 1997
[66] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.82
[67] Zonoozi M, *Handover delay and hysteresis margin in microcells and macrocells,* Personal, indoor and Mobile Radio Communications sep 1997

The scenario is illustrated:

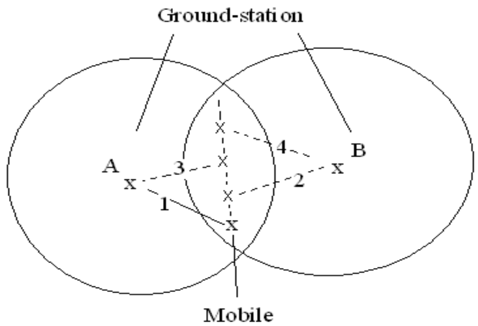

Figure 15 The Ping-Pong phenomenon

The illustration shows the ping-pong phenomenon. A mobile that is moving along overlapping coverage from two ground-stations, A and B. At time-point 1 the mobile is connected to ground station A and in the next time-point ground-station B appears to be better than A triggering a handoff to B occurs. This switching could occur at forthcoming time-point 3 and 4 etc. This behavior is undesirable and as shown the connection to A could have been kept throughout the common coverage from ground-station A and B. The switching increases the overhead data on the radio link i.e. link management, which is undesirable.

Hysteresis and dwell timer

To reduce unnecessary switching, such in the ping-pong phenomenon, a hysteresis, *h*, is introduced. This is a way to add a margin for undesirable events. As an example in the case a handoff is triggered based on RSS. If the received signal strength from the serving station, RSS_S, goes below a fixed threshold, T_F and the candidate ground station provides a higher RSS_C a handoff is triggered.i.e. if $RSS_S < T_F$ *and* $RSS_C > T_F \Rightarrow handoff$. When adding a hysteresis, which could counteract the situation described in “Figure 15 The Ping-Pong phenomenon”. The candidate ground station would need to have a higher RSS for handoff resulting in that the switching is prevented. $RSS_C > T_F + h \Rightarrow handoff$. In the setting of the hysteresis there is a tradeoff, if *h* is to large then the delay increases which could result in a dropped connection. If *h* is to small, it results in increasing handoff rates. [68] However, a macrocell could have a low level of hysteresis.[69] Instead or together with a hysteresis a dwell timer can be used i.e. if a handoff has occurred then a timer prevents from performing a new handoff. The dwell timer is also a method to reduce the number of handoffs.[70]

RSS_C *– Received Signal Strength from a Candidate groundstation*
RSS_S *– Received Signal Strength from the Serving groundstation*
T_F *– Fixed Threshold*
h – Hysteresis

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[68] Itoh K. Shih J-S. a.o *Performance of Handoff Algorithm Based on Distance and RSSI Measurements* IEEE Transactions on vehicular technology Vol 51 No 6 Nov 2002
[69] Zonoozi M, *Handover delay and hysteresis margin in microcells and macrocells*, Personal, indoor and Mobile Radio Communications sep 1997
[70] Leu A. Mark B. *An Efficient Timer-based Hard Handoff Algorithm for Cellular Networks* Wireless Communications and Networking vol 2 March 2003

The use of RSS in handoff algorithms has been researched. Various combinations of absolute $RSS_S < T_F$ and $RSS_C > T_F \Rightarrow handoff$ and relative If $RSS_S < RSS_C \Rightarrow handoff$ exist, as well with a combined hysteresis or dwell timers.[71] As an example DECT uses $RSS_S < RSS_C \Rightarrow handoff$ meaning that a handoff occurs if another cell provides a higher signal level.[72]

Adaptive Hysteresis

Adaptive methods of RSS have indicated that there is an achievement in performance relative to use a fixed threshold. Instead of $RSS_S - RSS_C < h$ a function is introduced $RSS_S - RSS_C < f(r)$ where r is a risk factor for dropped calls, including propagation environment, mobility conditions etc. Simulations have been conducted in different environments, with respect to the degree of shadowing together with different structures of cells, sectorized or circular cells. It showed lower delays and lower handoff rates than a fix threshold.

It was also examined that the use of both absolute and relative RSS was needed to prevent the handoff delay to get to large i.e. increasing dropped connection. An adaptive hysteresis together with timer is a poor solution, since the adaptive hysteresis handles unnecessary handoffs on its own. [73]

Position Aided Algorithms

Position aided algorithms have been examined, with the introduction of GPS or other positioning systems it gives an opportunity to decide the optimal decision point better than estimating distances on basis of signal information.[74]

A classification of position aided algorithms is *Pattern Recognition Algorithms.* The general idea is to find the optimal decision point for handoff with respect to historic data. The received signal strength is considered as consisting of a unique deterministic component and a random component. It is assumed that when a user travels along the same path the received power will be relatively similar as in the previous run.[75] This enables building up a deterministic environment for a ground network with respect to the mobiles path of travel. This path is divided into segments where the measured signal strength is analyzed and a corresponding action taken. The action could be generalized, but is in this case the handoff event and involved base-stations are of interest. This type of method needs training runs and makes a decision based on look up tables. There are similar handoff algorithms which also divide areas into rectangular grids depending on the rate of change of received signal levels. Each grid is connected to an average of measured signal levels and has a different threshold in each grid. The threshold is based on a mobiles location and previous measured signal means provided in a look-up table.[76, 77]

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[71] Ilyas M. *The Handbook of ad hoc wireless networks* Boca Raton USA Dec. 2002
[72] Dunlop j. Smith D.G., *Telecomunications Engineering third edition*,CRC Press Florida 1994 p.569
[73] Abu-Dayya A. Seranath G. Matyas R. *Adaptive Handoff Algorithms Using Relative Thresholds for Cellular Mobile Communication Systems* Vehicular Technology Conference 48th IEEE Vol 2 may 1998
[74] Itoh K. Shih J-S. a.o *Performance of Handoff Algorithm Based on Distance and RSSI Measurements* IEEE Transactions on vehicular technology Vol 51 No 6 Nov 2002
[75] Wong. K. Cox D. *A Pattern Recognition System for Handoff Algorithms* Selected Areas in Communications IEEE Journal on Vol. 18 Issue 7 Jul 2000
[76] Wang S. Wylie-Green M. Rajendran A.Nokia research center *Adaptive Handoff Using Location Information* 12th IEEE International Symposium on Sep 2001
[77] Cox D. Wong D. *A Handoff using Pattern Recognition* IEEE Universal Personal Communications Oct. 1998

With the assumption that the coverage provided from a ground station is known, a position aided algorithm is proposed to be triggered when the distance to the border of a cell is below a threshold distance. This is combined with a lower fixed RSS threshold to reduce handoffs if the channel has a sufficient quality. The new ground station is selected according to the closest one, based on GPS information. In comparison with an absolute RSS algorithm and a fixed hysteresis, simulations showed better performance. It also showed increasing handoff rates, unnecessary handoffs and false handoffs increased if GPS information was inaccurate.[78]

The position information, provided from a GPS, has been used to create a dynamic hysteresis to a relative RSS. The algorithm has been simulated with respect to the usage of coverage provided from ground station and compared to relative RSS with a fix hysteresis. Simulations show better performance than having a fix hysteresis, with respect to unnecessary handoffs and achievement of a high probability of handoff in region of cellboundaries.[79] The same algorithm has been compared with other algorithms. The first comparison is if the RSS from the serving station falls below a fixed threshold i.e. $RSS_S < T_F$ and if an adjacent provides a RSS better by a hysteresis i.e. $RSS_C - RSS_S > h$. Results show a great reduction in handoff rates but with an increase of handoff delay. The second comparison was if a candidate station provides a RSS better than a fixed threshold, $RSS_C > T_F$ and a distance hysteresis i.e. if the distance exceeds a limit from the serving station. Results show poor performance of the distance based algorithm because it is not capable of handling sudden drops in RSS within the distance hysteresis. The study also indicates that the algorithm is robust even if distance errors are present.[80]

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[78] He F., Wang F. *Position aware vertical handoff decision algorithm in heterogenous wireless networks* Wireless communications Networking and Mobile Computing oct. 2008

[79] Lal S. Panwar K. *Coverage analysis of Handoff Algorithm with Adaptive Hysteresis Margin* 10th International Conference on Information Technology 2007

[80] Zhu H. K. Kwak *Improving Handoff Performance by Using Distance Based Hysteresis Value,* LNCS 4238 Springer Verlag Heidelberg 2006

4 VDL4 in the Aeronautical Telecommunication Network

The following chapter is intended to present topics of interest for the handoff process in VDL4. An overview of the communication system in where VDL4 is operating is given, as well as information concerning link management and handoff operations. Properties of the aeronautical VHF channel and related research is provided. Finally available parameters to the handoff decision are presented.

4.1 VDL4 - VHF Digital Link mode 4

The purpose of VDL4 is mainly to give support to ADS-B, *Automatic Dependent Surveillance-Broadcast* which is a surveillance concept using VDL4, a digital data-link and the GPS. The participants equipped with a VDL4 transponder periodically broadcasts an ADS-B report. As an example the ADS-B report contains the identity of an aircraft as well as its position and velocity.[81] Surveillance of traffic is shown in the cockpit in a CDTI, *Cockpit Display of Traffic Information.* To ensure a complete surveillance picture TIS-B, *Traffic Information Services Broadcast,* is integrated in the CDTI together with ADS-B.[82] TIS-B is a complementary surveillance where mobiles can be registered with help of traditional Radar, *RAdio detection And Range.* Another application is the FIS-B, *Flight Information Service Broadcast*, which provides different types of weather information. An aircraft at a runway could be provided with the visual situation or other conditions affecting a departure or a landing. During flight significant changes of weather such as turbulence, thunderstorms etc. could be provided.[83] A basic outline of VDL4 in the ATN is illustrated below.

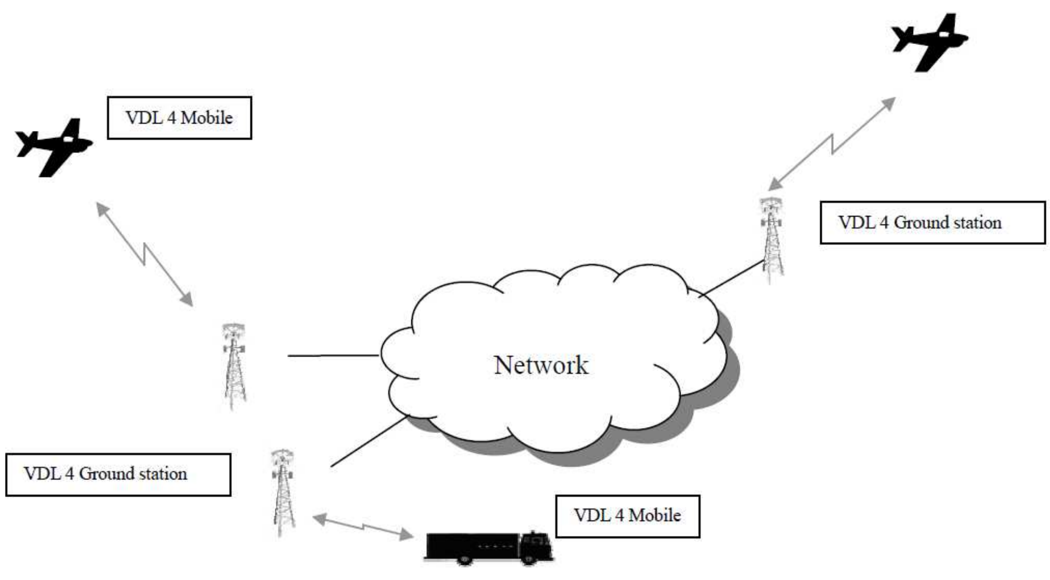

Figure 16 General Overview of theVDL4 Communication system

[81] ETSI EN 302 842-3 v1.2.1 (2006-12) p.16
[82] Ibid. p.13
[83] Ibid. p.14

In “Figure 16 General Overview of theVDL4 Communication” the system architecture is illustrated, several ground-stations are connected forming a ground-network. Mobiles such as aircrafts or vehicles could connect to ground stations providing point-to-point communication. All mobiles and ground-stations are possible to monitor with help of the broadcast transmissions.

To accomplish VDL4 communication between the ground system and a mobile system, they are equipped with a transponder. The VDL4 transponder consists of the three different units illustrated in “Figure 17 A VDL4 transponder”.

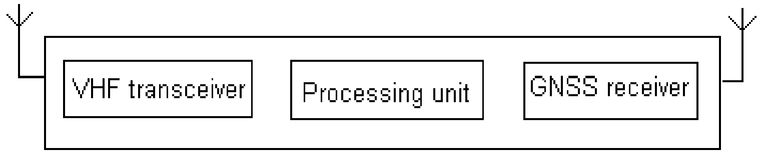

Figure 17 A VDL4 transponder

The VHF transceiver handles the frequency operation in the aeronautical VHF spectrum band, which operates in the frequency range 108-136,975 MHz.[84] The GNSS receiver, *Global Navigation Satellite System*, provides the positioning data and time synchronization to UTC, *Universal Coordinated Time.* VDL4 is intended to operate on multiple VHF channels.[85] Multiple channel operation is accomplished by using FDMA. The VHF frequency range is divided into 25 kHz sub channels, separated with 25 kHz guard bands. The bandwidth of 25 kHz categorizes VDL4 as a narrowband system. As a narrowband TDMA system it offers an opportunity to frame-by-frame monitoring of signal strength and bit error rates enabling both ground stations and mobiles to initiate handoff.[86]

Each sub channel uses STDMA, *Self organizing Time Division Multiple Access.* Self organizing refers to that no centralized co-ordination is needed and the management of reserving timeslots is handled by every station i.e. all stations and mobiles are aware of the reservations in the system. Based on the given information, forthcoming reservations are made.[87] The superframe in VDL4 is one minute and is divided into 4500 slots with a typical guard time of 1,25 [*ms*].[88] Each slot gives an opportunity to transmit or receive and the channel bit rate is 19 200 [*bits / s*].[89] As an example a positioning report requires one slot, but different applications could need other amounts of slots. For the periodic broadcasts, such as ADS-B, reservations are recommended to be made for the forthcoming 4 minutes.[90]

Since VDL4 is a TDMA system there are high requirements on time synchronization, if the stations would not be synchronized the mapping of slots could overlap and transmissions could collide. In VDL4 there is a secondary timing procedure integrated to ensure accurate timing. In the case a mobile looses track of time it is not allowed to transmit.[91] If more than one participant

[84] ETSI EN 302 842-2 v1.2.1 (2006-12) p.10
[85] ETSI EN 302 842-3 V1.2.1 (2006-12) p.20
[86] Dunlop j. Smith D.G., *Telecomunications Engineering third edition*,CRC Press Florida 1994 p.540
[87] http://www.eurocontrol.int/vdl4/public/standard_page/systemdescription.html
[88] ETSI EN 308 842-1 V1.2.1 (2006-12) p.21
[89] Ibid. p.20
[90] ETSI EN 302 842-2 V1.2.1 (2006-12) p.49
[91] ETSI EN 302 842-1 V1.2.1 (2006-12) p.26

transmits simultaneously, one solution in VDL4 is prioritized transmissions. Different types of information can have different priority, giving the transmission with highest priority right to transmit first. As an example a distress communication can be higher prioritized than an administrative message.[92] There is also an opportunity to share slots in VDL4, where reserved slots can be shared under the condition that the transmitting parties are at an enough distance from each other. [93]

End-to-End Communication

To relate VDL4 to the OSI model in chapter "3.3 OSI Reference Model" VDL4 can be considered to be a part in the layered model. An ATN does not support broadcast services[94] and the VDL4 make broadcast transmissions possible as well as VSS, *VDL mode 4 Specific Services* such as point-to-point communication. An overview is presented in "Figure 18 VDL4 in the ATN".

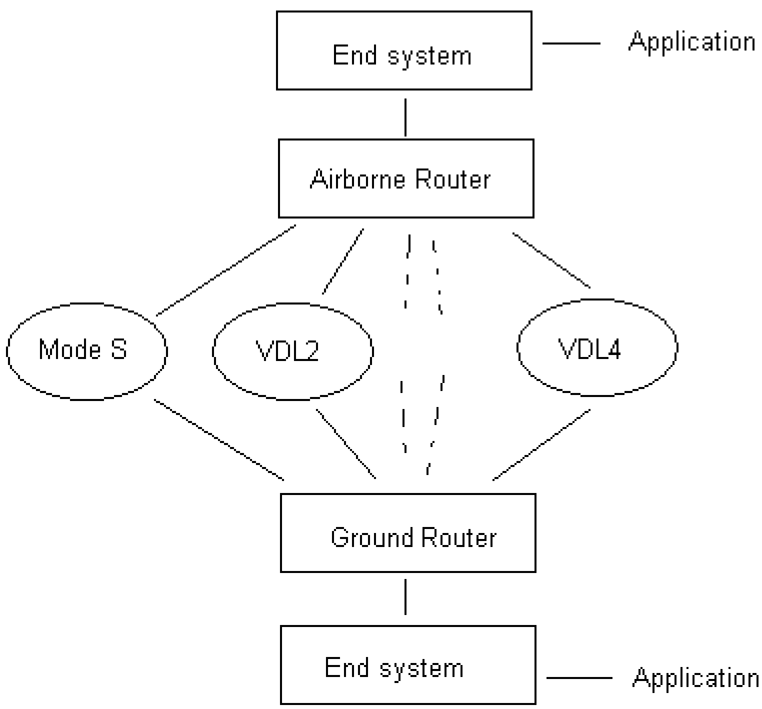

Figure 18 VDL4 in the ATN

"Figure 18 VDL4 in the ATN" describes where VDL4 is intended to function. In an ATN there exist various link technologies such as VDL2 or mode S, providing links for various applications. As an example VDL4 provides the functionality of point-to-point communication between a ground-station and an aircraft.

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[92] ETSI EN 302 842-2 V1.2.1 (2006-12) p.38
[93] ICAO, *"Manual on VHF Digital Link (VDL) Mode 4"*, First Edition 2004 Chapter 1 Part I p.I-2-12
[94] Ibid. p.I-1-3

4.2 Link Management

Referring to the OSI-model in chapter "3.3 OSI Reference Model" VDL4 is to be placed in the lower layers. A comparison between the OSI-model and layered communication in VDL4 is presented in "Figure 19 VDL4 referred to OSI-model".

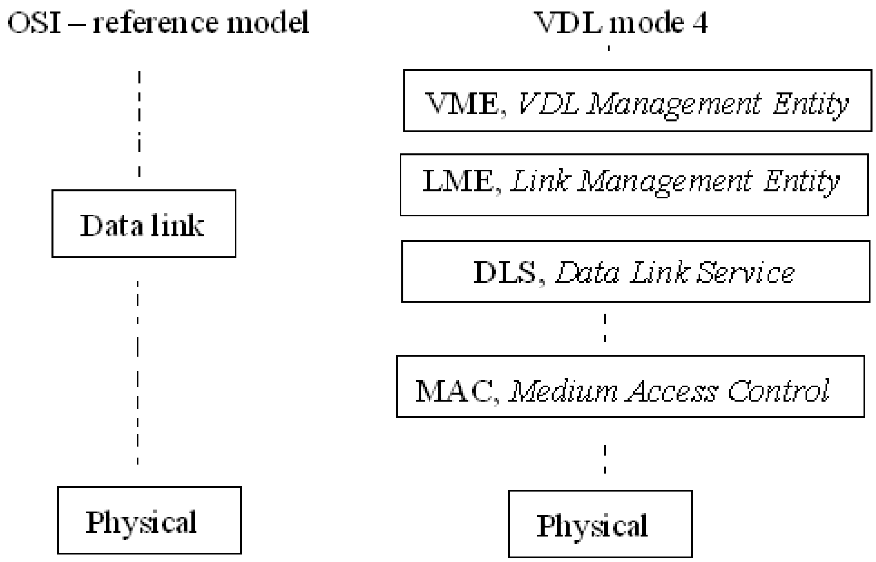

Figure 19 VDL4 referred to OSI-model

The task for the physical layer is to modulate and demodulate transmission and maintain synchronization between transmitters and receivers. The equipments operational parameters should also be monitored in the physical layer, if channels are busy or measurements of the signal quality.[95] When a station receives a message the signal quality is measured and this information is passed on to the upper layer as a notification service.[96] The link management in VDL4 is inspired from the VDL2 *Very High Frequency Digital Link mode 2.* [97] In VDL2 the signal quality is measurements of received power levels.[98]

In each VDL4 transponder, there is a VME, *VDL Management entity*. The VME is responsible for the policy concerning data link management of the system.[99] In the establishment of a link, the VME enables a LME, *Link Management Entity*, which manages the MAC and the physical layer. As an example the LME commands the physical layer to set the transmitting or receiving frequency.[100]

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[95] ICAO, *Aeronautical Telecommunications ANNEX 10 5th edition of volyme 1*, july 1996 p. 282K
[96] ETSI EN 302 842-2 V1.2.1 (2006-12)
[97] Eurocontrol, "*Presentation of Deliverable 3 Capacity Simulations*" ,VDL mode 4 Technical workshop Brussels 11th-12th may 2006
[98] ETSI EN 301 841-1 V1.2.1 (2003-08) p.16
[99] ETSI EN 302 842-4 V1.2.1 (2006-12) p.39
[100] ICAO Standards and Recommended Practices, Annex 10 , volyme III chapter 6 2006

During point-to-point communication, the VME in both systems creates a LME during the time of communication. An illustration is presented in “Figure 20 The active functions in a point-to-point scenario in VDL4”.

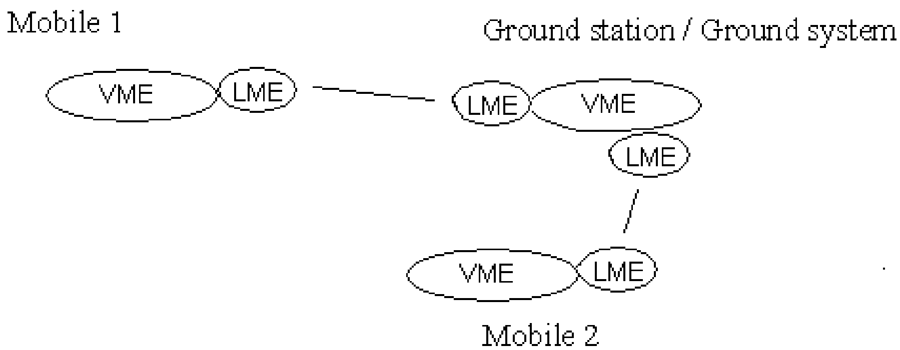

Figure 20 The active functions in a point-to-point scenario in VDL4

In each mobile which is point-to-point connected, the VME establishes an LME to the ground system. In the ground system the VME creates a LME to every mobile system and when the link is disabled the LME is terminated. A VME in a ground system is also responsible for keeping track of all data link communications i.e. which mobile is connected to which ground station.[101]

4.3 Handoff in VDL4

The mobile VME is responsible for setting up an initial point-to-point link.[102] This link is then intended to be available at all time. Even if no data is transferred, a VDL4 link is provided, enabling communication when transmission needed. In the case a mobile, such as an aircraft, moves within the network, the link needs to be transferred between ground-stations in the ground system. There are different ways of accomplishing this transfer. The connection over the VHF link can be maintained through different types of handoffs, according to the ETSI VDL4 standard. The available types of handoffs are presented in the following section.[103]

- *mobile initiated handoff*

  Based on a local link management policy, a mobile shall establish a link to a new ground-station if a station becomes unreachable or the VHF signal quality is significantly better to another ground-station. Another event is if the mobile is at a position, according to the link management policy, which requires a mobile handoff. If a mobile does not receive a response, from a station within a certain time, (5-25s) [104] the mobile should try to connect to another ground-station.

[101] ETSI EN 301 842-4 V1.2.1 (2006-11) p.37
[102] ETSI EN 302 842-4 V1.2.1 (2006-12) p.56
[103] ETSI EN 302 842-4 v1.2.1 (2006-12) p.55
[104] ETSI EN 302 842-4 v1.2.1 (2006-12) p.51

Once a mobile has established a link, the VHF signal quality, according to a local link management policy, shall be monitored on both the current link as well to other stations.[105] There are suggestions of processes that may be evaluated to determine the signal quality such as bit error rate, signal to noise ratio or received signal level.[106]

- *mobile-requested ground initiated handoff*

This type of handoff provides a possibility for a mobile to request the ground system to perform a handoff.

- *ground initiated handoff*

The ground system, suggests the mobile to transfer the link to another ground station. The operation corresponds to the *mobile initiated handoff* but with no similar requirements.

- *ground requested mobile initiated handoff*

This represents the ground system suggesting a mobile to perform a mobile initiated handoff.

- *ground requested broadcast handoff*

This handoff represents the ground system broadcasting that mobiles should drop the connection from a particular station. This might be the case if a station is supposed to be turned off for maintenance and the connected mobiles should switch to another station.

- *Ground-commanded autotune*

This operation represents the ground system commanding a mobile VME to start a *mobile initiated handoff* to another frequency.[107]

[105] ETSI EN 302 842-4 v1.2.1 (2006-12) p.57
[106] Sarps *VDL Mode 4 Standards And Recomended Practices version 6.0.1* Jan 2000
[107] ETSI EN 302 842-4 v1.2.1 (2006-12) p.60

Link Management During a Handoff in VDL4

The handoff procedure in VDL4 can be considered as a soft handoff according to the earlier presented definitions of the two different types in chapter "3.4 Handoff". In a handoff, the old link is active for a predetermined time to allow a complete transmission of old data.[108] In this way there is different link usage during the handoff process. The communication in a handoff scenario is illustrated below.

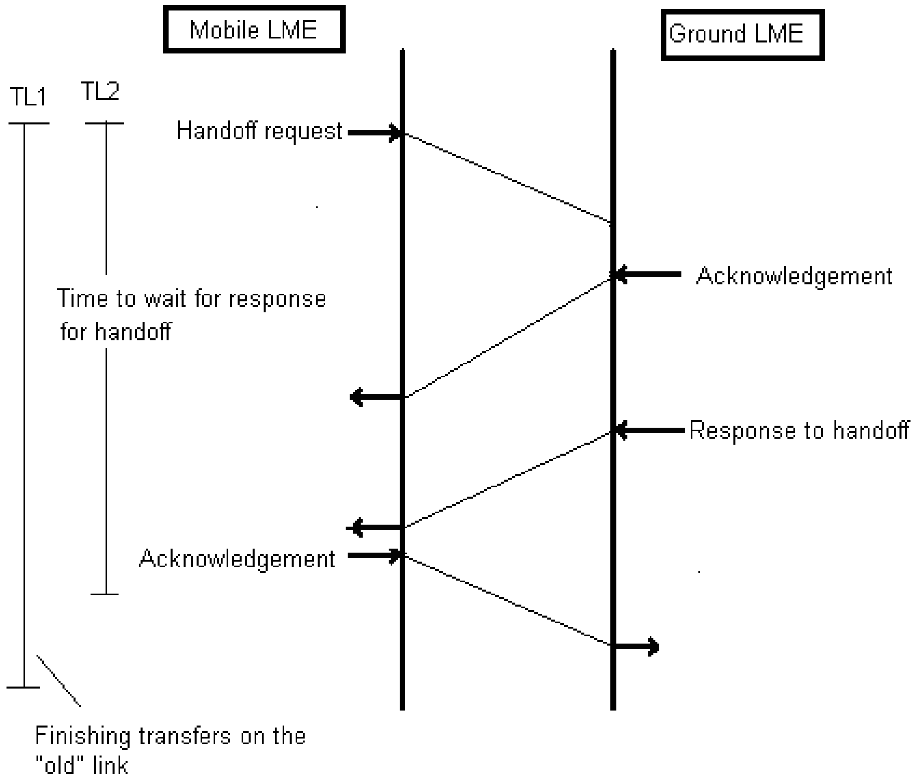

Figure 21 Procedure for communication during mobile initiated handoff

"Figure 21 Procedure for communication during mobile initiated handoff" illustrates the transactions of information during a mobile initiated handoff. A mobile sends a request to handoff and the ground system responses and there is an establishment of a new link to a new ground station.[109] When the response is received the new link is considered as established.[110] Within this transaction there are timers for both the ground-station and the mobile. Timer TL1 sets the boundary for how long time the old link is kept alive, in order to complete transfers.[111] Timer TL2 represents the timeframe within a response is expected, a default set time is 6 seconds.[112] If timer TL2 expires, meaning no response is received, the mobile shall attempt to connect to another station.[113] The change in link-connectivity is registered within the ground VME, which means that all established links are monitored in the ground system. The procedure is the opposite for a ground initiated handoff.

[108] ETSI EN 302 842-4 v1.2.1 (2006-12) p.55
[109] Ibid. p.58
[110] Ibid. p.21
[111] Ibid. p.49
[112] Ibid.
[113] Ibid p.51

A handoff requires resources on the data link, which is considered as overhead i.e. the handoff procedure uses slots that could be utilized better with other information than link management. As an example of used resources, one aircraft performing a mobile initiated handoff requires a total of 5 slots in the communication described in ”Figure 21 Procedure for communication during mobile initiated handoff”. This amount of slots is under the assumption that only mandatory information is provided, with exception for a *ground replacement list* parameter as well as the *autotune* parameter.[114] The mandatory and optional parameters are further discussed in chapter “4.6 Available Parameters for a Handoff Decision in VDL4”.

Simulations have been made regarding the capacity of one channel in VDL4 and point-to-point communication. Based on real radar data from 1998 at the busy Frankfurt airport, the for the capacity requirements corresponds to an 89 % increase of traffic. Three scenarios were considered, enroute, approach and landing. It was shown that the capacity limit was reached at 730 aircrafts and that the probability of a successful transmission in the enroute scenario was low for some types of services.[115]

The performance of a VDL4 channel has been simulated in respect to throughput, transfer delay and lost packages. Throughput corresponds to the amount of user data that is transferred within a decided timeframe. Transfer delay is the time a transfer takes, such as the time between a request and acknowledgement showed in “Figure 21 Procedure for communication during mobile initiated handoff”. A lost package is data that is transmitted but not received. It was shown that an increase of users in one VDL4 channel entails the likelihood that the transmissions start to fail and transfer delays increases.[116]

4.4 VDL4 Link Budget

The basis for the link budget in VDL4 is the specified receiver sensitivity, stated as -98$[dBm]$.[117] The receiver sensitivity is a parameter, which indicates the required power-level needed at the antenna terminal to provide a reliable communication and is defined as the lowest signal lewel to obtain a certain SNR.[118] The sensitivity depends on several factors such as transmission rate or design etc.[119] In the ETSI standards the sensitivity is specified according to the illustration.[120]

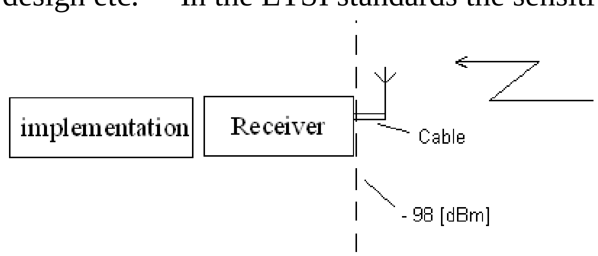

Figure 22 location of specified receiver sensitivity

[114] Micallef J. Fistas N. *v.07a VDL Mode 4 Channel Load Estimation* 2004-09-20 p. 11
[115] N Fistas Eurocontrol *VHF Datalinks for ATS point-to-point Communications* May 2001 p. 16
[116] Parkinson A. RavenHill P. Helios Technology, *VDL Mode 4 Performance Simulator:DLS Simulations*,april 2005
[117] ETSI EN 302 842-1 V1.2.1 (2006-12) p.18
[118] Haykin S. Moher M., *Modern Wireless Communications*, Pearson Education, Inc. Upper Saddle River,NJ USA 2005 p.465
[119] Ibid. p.15
[120] ETSI EN 302 842-1 V1.2.1 (2006-12) p.18

"Figure 22 location of specified receiver sensitivity" shows where the specified receiver sensitivity is located in the VDL4 system architecture in VDL4. In the link budget, provided in Appendix A2, includes a cable loss at the receiver. At the transmitter a corresponding situation is considered and then includes feeder loss. The influence of noise from the system architecture is integrated in the specified receiver sensitivity, as well as losses such as implementation losses etc. This gives manufacturers a freedom to choose different hardware as well as different architectures, as long as the requirement at this point is fulfilled.

There are two classes of mobile transponders in VDL4, class A and B, which are differing in levels of output power.[121] A class A transponder has a nominal output power of 15 W and a class B transponder 4 W. All transport aircraft shall use a class A transponder and other aircraft or vehicles if practicable. The class B transmitter may be used for small aircraft, such as gliders, or ground vehicles when size, weight, cost or power consumption prevents a class A installation.[122]

Given the allowed variation in mean output power, the possible theoretical transmitting distance for a class A transponder is presented in "Figure 23 theoretical transmitting distance, class A transponder".

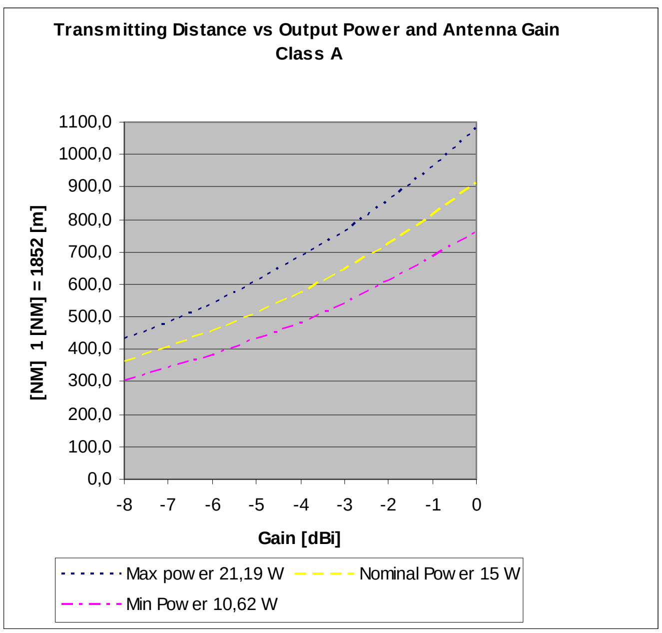

Figure 23 theoretical transmitting distance, class A transponder

The "Figure 23 theoretical transmitting distance, class A transponder" shows how the possible distance of transmission varies with the variations in output power for different antenna gains. As an example a mobile with a total transmitting gain of -5 $[dB_i]$ would have the transmitting distance $600[NM] \geq d \geq 430[NM]$.[123]

[121] ETSI EN 302 842-1 V1.2.1 (2006-12) p.21-22
[122] ETSI EN 302 842-2 V1.2.1 (2006-12) p.24
[123] Appendix A.2

Line of Sight

Concerning ground-stations, they are not specified in terms of output power. The transmit power is manufacturer specific but is required to have a maximum variation of $\pm 1[dB_W] \approx \pm 1{,}26[W]$.[124] A recommendation is that a ground-station should have a transmit power of less than 25 [*W*]. The typical radiation pattern is in general omni-directional i.e. donut shaped.[125] Another recommendation is to provide a field strength of at least -109 [dB_W / m^2] within the area where aircrafts operate, on basis of free space propagation.[126] At the installed equipment at ground, the antennas are most likely to be located at a position, maximizing line of sight for departing and approaching aircrafts.[127]

Since the point-to-point communication is an air-ground scenario the environment sets a boundary for the range communication. A geometrical interpretation is given in the following figure.

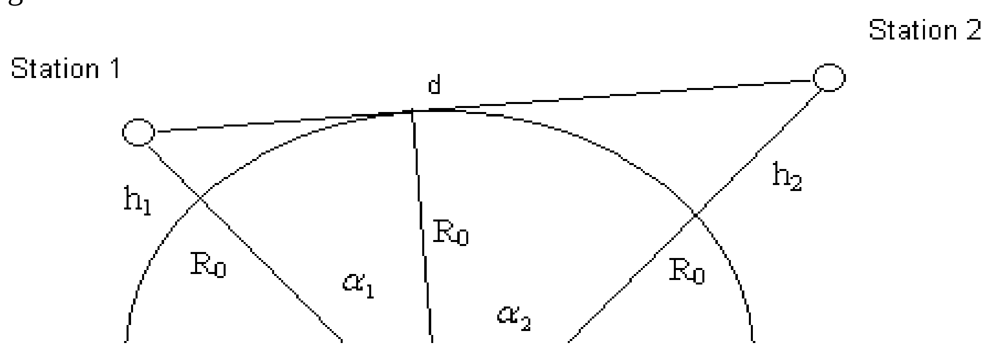

Figure 24 Line of sight scenario

The "Figure 24 Line of sight scenario" shows the situation for the calculation of the maximum distance, *d* for line of sight. Two stations are communicating and at a certain point the earth blocks the direct path. If assuming a relatively flat surface, the distance can be determined through geometrical calculations as $d = (R_0 + h_1)\sin\alpha_1 + (R_0 + h_2)\sin\alpha_2$ and further simplified into:[128] $d = \sqrt{2R_0}\left(\sqrt{h_1} + \sqrt{h_2}\right)$

d = transmitting distance [*km*]
h=height from earth surface to station [*m*]
R_0 =earth radius [*km*]
α = angle between point of blocking and station relative to the center of earth [*Rad.*]

When using the line of sight equation the distance for communication between a ground station and an aircraft is determined to be less than 232 [*Nm*]. [129] When considering an enroute scenario on heights from 10 000 [*m*] and lower. This calculation assumes a ground station with an antenna

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[124] ETSI EN 301 842-1 V1.3.1 (2006-11) p.20
[125] Aeronautical Frequency Committee, *61094 Rev. A Ground Station Installation Guidelines,* May 2009
[126] Annex 10 volyme III ch. 6.2 § 6.3.2
[127] Aeronautical Frequency Committee, *61094 Rev. A Ground Station Installation Guidelines,* May 2009
[128] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.66
[129] Appendix A.6

at 20[*m*] height. However propagation is possible beyond the horizon due to diffraction or reflection.[130]

Guard range

As described in chapter **"**4.1 VDL4 - VHF Digital Link mode 4**",** VDL4 is based on TDMA with a guard time of 1,25 [*ms*]. The transmissions suffer a delay, due to propagation, and a maximum range of communication is 201 [*NM*].[131] If transmissions occur at a longer range, there is an increasing possibility transmissions will overlap due to the delay. This event is referred to as collisions which is undesirable.

4.5 Channel Properties in the VHF band

The following section describes some properties of a channel, operating in the VHF band. A selection of information from earlier studies is presented. Studies of the VHF channel treat different environmental issues as well as a variety of approaches for modeling and predicting propagation in an air-ground scenario.

Radio waves operating in the VHF frequency range 30-300 MHz are influenced by buildings and terrain, or mountains could shield the path of propagation.[132] In VDL4 the wavelength is approximately 2m.[133] When the wavelength is larger than objects blocking the path the radio waves propagates rather unaffected.[134] In the other case when the object is larger, diffraction, discussed in chapter "3.1 Wireless Communication", could enable communication. The main source of disturbance in VDL systems is proposed to be multipath distortions, due to non-directional antennas at ground or on aircrafts.[135] However as mentioned in "3.1 Wireless Communication", there are more possible sources of disturbance such as that VHF signals are affected by cosmic noise.[136]

Studies and Models of VHF Propagation

A study using a terrain sensitive model, based on GTD, *Geometrical Theory of Diffraction*, where the propagation path loss is studied in the case where a ground station is placed in a forested area. Two different locations were used for empirical tests, with the use of an aircraft flying in orbit 20 NM at 1000m altitude. Measurements were made during both winter and summer and results showed that if a ray propagates through a forested area it is attenuated by approximately 1,5 [dB] every 30 m. Variations of approximately 10-15 [dB] of the signal level occurred due to the forest and multipath reflections from the top of the trees, which seemed to interfere with the direct signal.

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[130] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.29
[131] Appendix A.5
[132] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.29
[133] Appendix A.1
[134] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.52
[135] Roturier B. Chateau B, *A general model for vhf aeronautical multipath propagation channel,* AMCP Hawaii 19-28 jan 1999 p.13-14
[136] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.29

Also the importance of a detailed map as input was concluded. The model seemed to work where there terrain was irregular but did not explain observed variations in the size of 10-15 [dB] where the landscape was relatively flat.[137]Another study showed that rain has a significant influence on multipath components if propagation occurs through a forest. An additional observation was that the VHF propagation over the treetops is not affected by the presence of rain and is similar to the free space propagation.[138]

A model to predict path loss, based on knife-edge diffraction, was empirically examined in a hilly forested terrain at low altitudes, up to 600m at ranges from 7 to 15km. A terrain profile was created based on data from maps and on the path of propagation. In the profile the height of the terrain was included and also adjusted for the height of the forest. Measurements were made at a helicopter at six different locations with different terrain profiles. The study concluded that two knife edges were sufficient to characterize diffraction caused by the terrain.[139]

Another approach to predict VHF-propagation was based on an iterative matrix calculation for a three dimensional space. A large database of measurements for three sites in Canada were compared with different models, knife-edge model and others, using terrain profiles as input. The terrain profiles were both hand-read maps as well as digital files with a resolution of 30[m] and 100[m]. It was found that the accuracy of models was very much depending on the resolution of the terrain profile. Apart from that result there were still contradictive results, where the cause was unclear.[140] Predicting the path of every radio wave, based on data describing terrain and parameters of reflections etc. could lead to excessive computations.[141]

Another attempt to characterize the VHF channel in an air-ground scenario was made at two different airports. Measurements in range of 20NM took place at Duluth and Aspen airports, having different environments, one mountainous and one hilly suburban. The study included small and large scale fading, path loss and time delays between the direct signal and a second reflected in a multipath model. The path loss exponents, presented in chapter “3.2 Link Budget” , were determined in relation to distance. The study concluded the exponent to 2.27 at Duluth, at Aspen two exponents were needed 1.33 and 3.9 for distances greater than 5km.[142]

A deterministic VHF air-ground propagation model has been developed and measured. This model was based on a two ray multipath as pictured in “Figure 25 Empirical studies of received power levels at 6000m”, and includes the properties of small and large scale fading.
An aircraft flied at different flight levels, in the range of 0 to 20[NM] from one ground station, and measurements of received power levels were made.

[137] Chamberlin, *The Effect of Tree Cover on Air-Ground, VHF propagation Path Loss,* ieee transactions on communication Vol. Com-34 No 9 september 1986
[138] Meng Y. Hui Lee Y. Chong B. *Investigation of Rainfall Effect on Forested Radio Wave Propagation,* ieee antennas and wireless propagation letters Vol 7 2008
[139] Meeeks M. L. *VHF Propagation over Hilly, Forested Terrain,* ieee transactions on Antennas and propagation May 1983
[140] Edison J. Johnsson J.T, Shin R.T a.o ,*A Method of Moments Model for VHF Propagation,* Antennas and Propagation Society International Symposium,. AP-S Digest. July 1996 ieee
[141] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications*, Studentlitteratur Naryana Press Denmark 2006 p.83
[142] Dyer G. ,Gilbert T.G AMCP /WG-D/8-WP/19 ,*Channel sounding measurements in the VHF A/G radio communication channel,*dec 1997

When the model was adjusted, determining an assumed constant small scale variation of average power for this particular test site, the model seems successful, at least when compared with measurements at altitudes above 2000 [*m*].[143]

The study showed that there is a highly probable combination of a direct and a reflected path yields a fast variation of large scale mean values.[144]

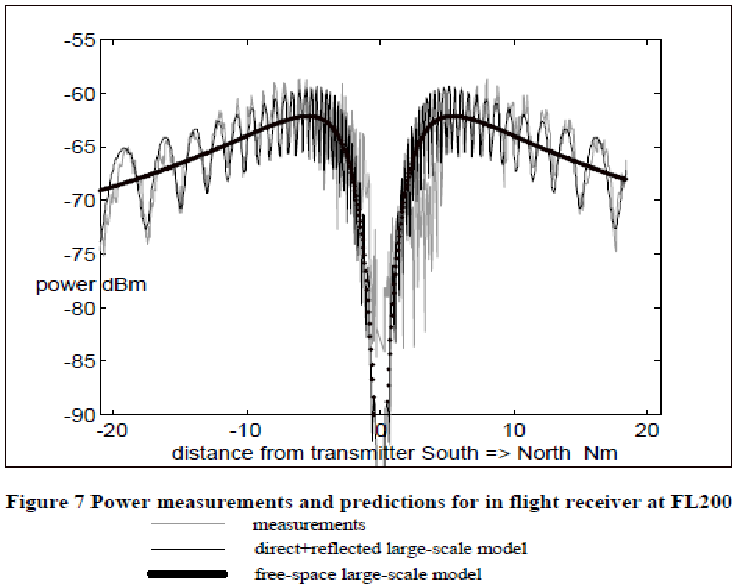

Figure 25 Empirical studies of received power levels at 6000m

"Figure 25 Empirical studies of received power levels at 6000m" shows measured data compared with the adjusted model, as well is the free-space model included. According to the study it can be seen in figure that the suggested model is corresponding quite well to measured data. The study showed that there is a highly probable combination of a direct and a reflected path yields a fast variation of large scale mean values and that the Rice factor varies with the position of mobiles and is inappropriate to set to a single value.[145]

The statistical nature of multipath fading for aeronautical multipath fading is known to have a Rice distribution.[146] A Rice distribution includes properties of a dominant direct signal as well as a diffuse *component* based on multipath. The ratio of powers between a deterministic direct signal and the variance of the diffuse component is called Rice factor which is mathematically described as:[147] $K = \frac{{a_0}^2}{2\sigma^2}$ where a_0 is a constant amplitude and $2\sigma^2$ the variance of the diffused component. The Rice factor corresponds to the amount of line of sight i.e. *K=0* no line of sight and $K \rightarrow +\infty$ an ideal channel, a perfect line of sight.

[143] Roturier B. Chateau B, *A general model for vhf aeronautical multipath propagation channel,* AMCP Hawaii 19-28 jan 1999
[144] Ibid.
[145] Ibid.
[146] SARPS ANNEX 10 Volume III p.420
[147] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.151

Measurements of the aeronautical VHF band have shown Rice factors between 2 to 20 [*dB*] and a typical Rice factor for the VHF band is suggested to be about K=15 [*dB*].[148] Another suggestion is that the carrier to multipath ratio is expected to be less than 10 [*dB*].[149] However, the Rice factor is very dependant of the antenna pattern.[150] The factor is also variable with aircraft altitude and ground reflection coefficient.[151] There are models that suggest other than Rice distributions in the enroute scenario.[152]

Measurements of received power levels, both at ground and in the air, have been conducted using VDL2. The handoff trigger is based on RSS in VDL2,[153] which were examined with a relative RSS and a hysteresis of 4dB. An aircraft flied at an altitude of 3300m along a predefined route with two adjacent airports. The results showed that the RSS were fluctuating more at the airborne mobile than at a ground station, which showed a linear behavior. At most the RSS were switching back and forth about 8dB from in the airborne mobile.[154]

The environment for wireless communication is not ideal, disturbances from terrain as well as influence from other phenomena's earlier discussed. An example of a calculated estimation of the transmitting ranges from two ground-stations is presented in following figure:

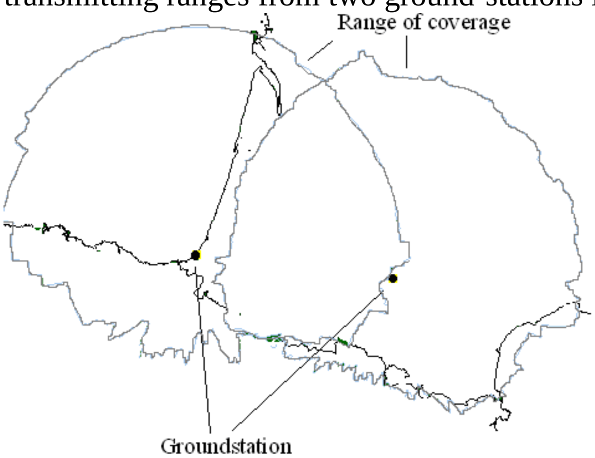

Figure 26 Estimated coverage of two ground stations [155]

"Figure 26 Estimated coverage of two ground stations " shows an estimated coverage from two ground-stations. This estimation is made with respect to the surrounding terrain. A noticeably shorter range of transmission is visible in the direction "south" of the stations, which depends on a hilly environment. This type of irregularities has been confirmed, during a VDL2 flight test.

[148] Hoeher P. Haas E. *Aeronautical Channel Modeling at VHF-Band*, Vehicular Technology Conference, 1999, VTC-Fall IEEE VTS 50th
[149] SARPS ANNEX 10 Volume III p.420
[150] Neul A. Hagenauer J. a.o *Propagation Measurements fort he aeronautical Satellite Channel* Vehicular Technology Conference 1987 37th IEEE
[151] Elmoubi S. Mitre Corp. *A Simplified Stochastic Model for the Aeronautical Mobile Radio Channel* Vehicular Technology Conference 1992 IEEE 42nd
[152] Hoeher P. Haas E. *Aeronautical Channel Modeling at VHF-Band,* Vehicular Technology Conference, 1999, VTC-Fall IEEE VTS 50th
[153] ETSI EN 301 841-1 V1.2.1 (2003-08) p. 16
[154] Martinez F. sofréavia, *AVCL Test Report ATM-TLSE/C1038/TR01_10* , Eurocontrol 2001-07-19
[155] Ibid.

The reception from a ground-station was lost much earlier than expected, which had the result of a dropped communication. It was found that the coverage provided from a ground-station is not uniform and could result in areas without coverage from any station.[156]

4.6 Available Parameters for a Handoff Decision in VDL4

This section presents a selection of parameters provided in the VDL4 communication, which could be used in a handoff decision. Additional information which is considered as relevant for a further discussion is also given.

Default ADS-B Reporting

The following sections accounts for potential parameters for a handoff algorithm provided from the ADS-B transmission according to ETSI standards. All VDL4 stations should transmit an ADS-B report twelve times per minute.[157] When a VDL4 station receives a report, information is maintained in a PECT, *Peer Entity Contact Table*. The PECT contains information of other stations, from which a report has been received in the last 15 minutes. As a minimum: station ID, last known position and altitude, time of transmission, reserved slots and type of station i.e. mobile or ground station should be stored and updated.[158]

As mentioned, the ADS-B transmission includes a stations *position*, the position is a self determined value. To ensure a quality of the positioning data there is a control, calculations concerning the reliance transmitted positioning data occurs. Two performance parameters for a surveillance system are integrity and accuracy. Integrity is the probability that estimation, such as horizontal position, provides misleading information to an application without alerting and accuracy refers to the nominal bounds on velocity or position.[159] For evaluation of positioning data level of NAC, *Navigation Accuracy Categories* and a NIC, *Navigation Integrity Category*, is calculated and submitted together with the positioning data. These levels are included in the ADS-B reported to surveillance applications to decide whether the reported position has an acceptable accuracy and integrity.[160]

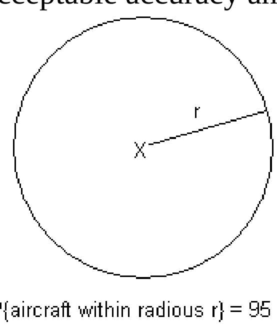

Figure 27 Accuracy of received positioning data

"Figure 27 Accuracy of received positioning data" shows the principle of NAC_p. An aircraft positioned in the center of the circle reports its position which, based on the calculated NAC

[156] Eurocontrol *Preliminary Test of Air/Ground Data Link Phase II vol. 2 v 0.5*, 12 April 2002 p. 1-5
[157] ETSI EN 302 842-3 V1.2.1 (2006-12) p28
[158] ETSI EN 302 842-2 v1.2.1 (2006-12) p.97
[159] 242A-WP-6-12A, *Proposed Revisions to ADS-B MASPS:Integrity and Accuracy Monitoring*, July 2001
[160] RTCA/DO-242A, *Minimum Aviation System Performance Standards For Automatic Dependent Surveillance Broadcast (ADS-B* 2002*)* p.39

value, is within a certain radius with 95% probability.[161] A NAC_p level is generated for the positioning data, including the vertical and the horizontal position. The NIC level decides a 95 % probability of position error exceeding a stated containment bound without warning.[162] i.e. the probability that an undetected error is received by an application given that the transmitter is supplied with correct data.

The direction of a moving mobile is also provided in the ADS-B report and the *direction* is a value referenced to north, corresponding to 0 degrees.[163] According to ETSI standards no indication of the quality of the parameter is provided, similar to positioning. The direction is manufacturer specific to determine, but could be provided by the GPS in the transponder. Due to the resolution of transmitted parameter, an error of maximum $\pm\left(\frac{1}{2}\right)^{12} \approx 2{,}44\times10^{-4}$ degrees could be generated.[164]

Broadcasted Information from Ground-stations

Ground-stations, supporting VDL4 services, broadcasts GSIF, *Ground information frames,* at least once a minute.[165] The GSIF is transmitted on a GSC, *Global Signaling channel,* where mobiles can acquire the broadcasted information.

The mandatory parameters, which could be of interest for the thesis, provided in a GSIF are *nearest airport*, which airport that is most closely to the ground-station. *Airport coverage,* indicates if the ground station provides communication with a mobile on ground. A ground-station is allowed to transmit only one of these parameters in the GSIF, not both at the same time.[166]

Optional Information in the GSIF

There is optional information, which could be provided in the GSIF. This possible information is given in the following sections.

In the broadcast of the GSIF a DOS, *Directory of Service,* parameter could be included. The DOS is a notification of supported applications at the broadcasting ground-station. Today 5 applications are defined such as ADS-B or FIS-B.[167] Reservations have been made, in the coding of the parameter, to enable additional applications. Up to 255 different applications are possible. As an example a service provider have the possibility to enable up to 30 private applications.[168]

The *ground replacement list* parameter corresponds to a list of other ground-stations, from which the mobile VME can make a selection. This list should be in order of preference decided in the

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[161] RTCA/DO-242A, *Minimum Aviation System Performance Standards For Automatic Dependent Surveillance Broadcast (ADS-B* 2002*)* p.39
[162] RTCA/DO-242A, *Minimum Aviation System Performance Standards For Automatic Dependent Surveillance Broadcast (ADS-B* 2002*)* p.39
[163] ETSI EN 302 842-3 V.1.2.1 (2006-12) p.16
[164] Ibid. p.21
[165] ETSI EN 301 842-4 v1.2.1 (2006-11) p.53
[166] Ibid. p.50
[167] ETSI EN 302 842-3 V1.2.1 (2006-12) p.30
[168] ETSI EN 301 842-2 V.1.5.1 (2006-11) p.31

ground LME.[169] If this list is transmitted, all the parameters must be valid both at the transmitting station as well as for the stations in the list, except for *airport coverage* or *nearest station* parameters.[170] As an example if a DOS is included, all stations in the list need to support the same services. The *ground replacement list* is also possible to provide in the ground initiated handoff procedures.

Additional Parameters

In the mobile initiated handoff procedures described in "Figure 21 Procedure for communication during mobile initiated handoff p.29" there are optional parameters that could be of interest as input to a handoff decision. These parameters could also be transmitted during the establishment of the point-to-point link. The previous described GSIF parameters are also possible to include in this communication.

A mobile can include an *acceptable alternate ground station* parameter. This parameter is a list of preferred ground-stations generated in the mobile station, where the ground system is provided with the mobile VME preferred alternatives.[171]

A *destination airport* parameter is also available to transmit from the mobile, providing information of which airport the aircraft is intending to travel to.[172]

Additional Broadcasted Information

An additional concept, under development in VDL4, is the broadcasting of *TCP, Trajectory change point*. A TCP is information about the aircrafts intent. This means that an aircraft reports future information, when and where changes of its trajectory will occur.[173] The TCP is consists of four points, one current and three future points.[174] The future points are related to the aircrafts time going there, a *time to go* parameter is included in every point. A TCP shall be broadcasted when an aircraft has either 4 minutes or 8 minutes left to its change point.[175] The time is depending on type of transmitting equipment and to ensure safety. As shown in chapter "4.4 VDL4 Link Budget" different classes of transponders gave different ranges of communication.

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[169] ETSI EN 301 842-2 v1.2.1 (2006-11) p.44
[170] ETSI EN 302 842-4 v1.2.1 (2006-12) p.58
[171] Ibid. p.42
[172] ETSI EN 301 842-4 V1.2.1 (2006-11) p.50
[173] ETSI EN 302 842-3 V1.2.1 (2006-12) p.18
[174] Ibid. p. 18
[175] RTCA DO-242A, *Minimum Aviation System Performance Standards For Automatic Dependent Surveillance Broadcast (ADS-B* 2002*)* p.137

5 Algorithm for Handoff in VDL4

The analysis is based on the purpose of the thesis, to develop an optimal handoff algorithm in VDL4. Presented information in chapter 3 and 4 gives the framework for this chapter. The assumptions and the analytical approach and requiremenets on the handoff algorithm are presented. The development of the handoff algorithm in VDL4 is divided into two parts. The first part considers an algorithm based on only mandatory information provided in VDL4. The second part is extended to analyze if optional transmitted information could improve the handoff algorithm.

5.1 Assumptions and Requirements on the Handoff Algorithm

This section presents the assumptions and conditions that are set in the analysis to constitute the frame for the algorithm in for the handoff process in VDL4.

Architecture of a VDL4 Ground System

When considering placement of ground-stations an assumption is that several ground-stations will intentionally not be located such that numerous cells are available a single position. A more likely structure of the VDL4 ground-system is pictured in "Figure 28 Assumed structure of cells in a ground system". The radiation pattern from a ground-station is assumed to be omni-directional which approximately would be circular in a 2D view. The scenario is illustrated:

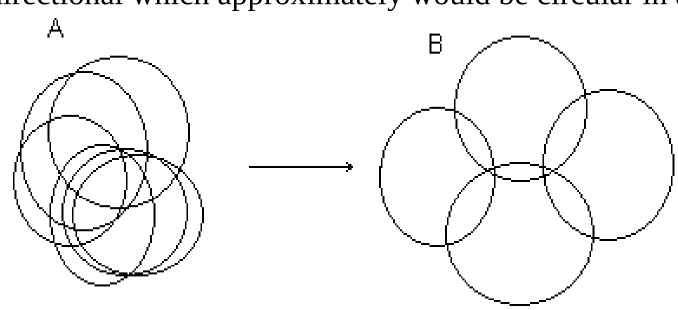

Figure 28 Assumed structure of cells in a ground system

"Figure 28 Assumed structure of cells in a ground system" shows the considered structure of the cells at ground with respect to coverage. The scenario A is not considered as a very likely scenario, partly of economic reasons. A system designer would probably optimize the ground system with respect to maximize estimated coverage and at the same time minimize the number of needed stations. An assumed structure is made on basis of the recommendations of ICAO. As the intended algorithm is handling an en-route scenario it is stated as desirable to use smallest number of ground stations in order to minimize the probability for simultaneous uplink transmissions to avoid collisions of the transmitted data.[176] This was discussed in chapter "4.4 VDL4 Link Budget". Another assumption is that the ground system enables point-to-point communication with a Class B transponder i.e. with respect to a transponder with a shorter range of transmission.

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[176] ICAO *Intenational Standards and recommended Practices, Aeronautical Telecommunications* Annex 10 Vol III p. 425

Asymmetry in the Down-link and Up-link

As mentioned in chapter "3.1 Wireless Communication" a system is reciprocal when the same antennas are used to transmit and receive. This is not the case in the studied VDL4 system. A VDL4 transponder has different antennas to transmit and receive which could have different properties, gains or influence of disturbance might vary between at the receiving and transmitting antenna. Furthermore a ground-station is not specified with reference to transmit power or more antennas could be used. The communication between the ground-system and the mobile system is then non-reciprocal. This is indicated in the flight tests in VDL2 presented in chapter "4.5 Channel Properties in the VHF band", which has a similar setup with separate transmitting and receiving antennas. The ground station had another view of the transmissions than the aircraft with respect to RSS.

In a point-to-point communication both the down and up-link is required to function. As a consequence of non-reciprocal communication, a ground-station and a mobile might not experience the channel equivalent. An example in case of a handoff procedure implemented in the mobile system is presented. A mobile could make a handoff decision based on up-link information, such as received ADS-B, GSIF reports or point-to-point communication. When attempting to make a mobile initiated handoff to a new ground-station it could fail because the mobile does not have an equivalent range in the down-link. This event would result in an unsuccessful attempt, which is considered as a waste of radio resources, since slots are reserved for link management. This event would introduce an unnecessary delay until a new attempt can be made. The procedure is described in "Figure 21 Procedure for communication during mobile initiated handoff, the handoff request requires reservations and then entails a waiting time for a response in TL2 seconds. When TL2 expires a new attempt to another ground-station is made.

During the point-to-point communication between a ground-station and an aircraft, the participant with the poorer conditions sets the boundaries to maintain the VDL4 link. The transmitted data is acknowledged, meaning that a transmission requires a receipt that the transaction was successful. A failure could occur on other levels than at the link layer, such as in an application, which could require a retransmission. This means that both parties, in the point-to-point communication, are restricted to the participant with the worst conditions in the uplink or in the downlink.

5.1 Analytical Approach

To be able to develop an optimal handoff decision, it is concluded that certain information is desirable. The algorithm will be derived based on the achieved level of desired information, which is regarded as consisting of the following information.

- *Quality of the channel* - A certain quality of the radio link is required to provide communication

- *Capability of a ground station* - to evaluate its support for a point-to-point link.

- *Possible duration of the link*

If this information is known, it is assumed that an optimal handoff algorithm could be achieved.

5.2 Evaluation of Available Mandatory Information

Based on the analytical approach, this section evaluates if the mandatory information in VDL4 should be a part of a handoff algorithm.

Quality of the Channel

According to ETSI, the signal quality is determined in accordance with the decided "local link management" which gives freedom to the manufacturers to define "signal quality".[177] In general the quality of a communication link is defined as the SNR, Signal-to-Noise Ratio.[178] In VDL2 the signal quality is defined as a measurement of received levels of power. The VHF signal quality is monitored in a VDL4 station as mentioned in chapter 4 "link management". A measurement of signal quality in VDL4 should be provided from the physical layer, regardless of definition.[179]

In the rest of the paper signal quality is regarded as being RSS, *Received Signal Strength.* This parameter is one suggestion provided from SARPS as well as being used in VDL2. The receiver sensitivity gives an indication of required power to withhold a reliable communication according to the definition. Therefore the received signal strength is a useful parameter to determine if the channel has a sufficient quality for communication. There are claims that the handoff decision based on solely signal strength has a high rate of success in the aeronautical VHF band.[180] How this handoff algorithm is implemented is not stated.

Capability of a Ground Station

When mandatory information is available, a ground-station provides either the *nearest airport* or *airport coverage* parameter in the GSIF. ETSI recommends if mobile initiated handoff is supported that if a mobile has commenced approach to its destination airport and the cell of the current ground-station does not cover this airport. Then the mobile should hand off to a ground-station where the airport lies within coverage.[181] However a provider could choose to transmit either *nearest airport* or *airport coverage*, this would lead to that needed information would not be available at all times. The location of the airports provided in these parameters is not included in VDL4. This could result in that more than one ground station has the same airport in the *nearest airport* parameter. It is determined that these parameters would not enhance a handoff procedure.

Load Balancing

A scenario where the mobiles are evenly distributed between ground-stations would be favorable in a capacity point of view, according to simulations results presented in chapter "4.3 Handoff in VDL4 p.27" However, the load at a ground-station is difficult to determine. The slots which continuously are reserved are for the periodic broadcast transmissions, such as the ADS-B or the GSIF. Therefore a mobile or a ground-station has knowledge of all periodic reservations in the coming 4 minutes. For a point-to-point transmission slots are reserved as it occurs.

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[177] ETSI EN 302 842-4 V1.2.1 (2006-12) p.57
[178] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.160
[179] Chapter 4.2 Link Management
[180] Arinc, *ATN/VDL mode 2 Capabilities,* ICNS Conference 2007 p.14
[181] ETSI EN 302 842-4 V1.2.1 (2006-12) p.57

The ground VME establishes a LME to each aircraft as well as an aircraft creates a LME to each ground system as showed in “Figure 20 The active functions in a point-to-point scenario in VDL4 p.27”. A ground-station connected with a great number of point-to-point users in one channel does not necessarily mean that the radio resource is heavy loaded. Another ground-station with fewer users could be more loaded depending on used applications. Under the assumption that there is a similar use of applications i.e. two aircrafts require a comparable bandwidth. It implies that a distribution of the number of point-to-point links between ground-stations would be favorable for the performance.

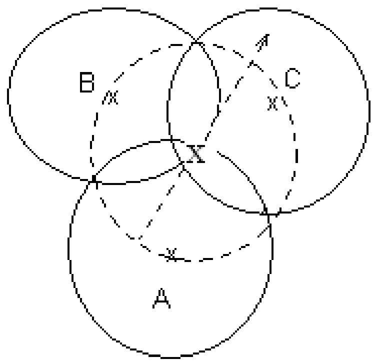

Figure 29 A Handoff Scenario for Load Balancing

The illustration shows a scenario where capacity is used in a handoff procedure. An aircraft, travels along the dashed line at position “X” point-to-point connected to ground-station A, is at a point for handoff. If station B is having a less amount of users then a handoff to B occurs. This would later be followed with a handoff to C as the aircraft gets out of range from station B. With respect to maximize the duration of the point-to-point link, a proper choice should have been station C from the beginning. Since the capacity could lead to an increase of number of handoffs it is concluded that capacity should be counteracted with more channels instead of distributing the users between ground-stations.

Possible Duration of the Link

In order to maximize the duration of a link, there is certain information needed. An aircrafts intended path of flight and at the same time a method to determine the range of acceptable coverage of the involved cells. The situation is illustrated in the following figure, a mobile travels along a straight line at position “x”, with its belonging cell is at a point for handoff.

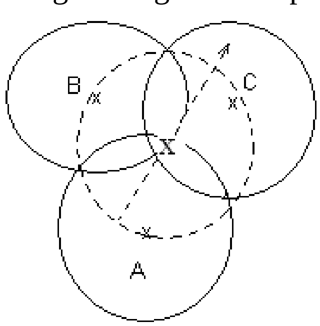

Figure 30 Handoff decision based on duration of the point-to-point link and path of flight

"Figure 30 Handoff decision based on duration of the point-to-point link and path of flight" shows an aircraft point-to-point connected to ground-station A. The situation is where a handoff has been triggered. In the case ground-station B and C is equivalent, the path of flight could be used to decide whether ground-station B or C could provide a longer duration of the link, given that the size of cell B and C were known.

In determining the path of flight based on only the mandatory information there is *direction* as well as *position* provided in the ADS-B report from a VDL4 transponder. Direction is manufacturer specific to determine, but could be provided by the GPS receiver, interpolation of the direction based on previous ADS-B reports or triangulation etc.

If assuming an aircrafts path of flight to be relatively straight, the positioning data could be used to filter the candidate ground stations along the path of flight. The idea is illustrated in "Figure 31 Relative Change of Distance to Ground Stations". If ground-station B or C should be chosen is to calculate the change in distance. A mobile receives ADS-B reports from station B and C, which leads to a known distance to all the stations.

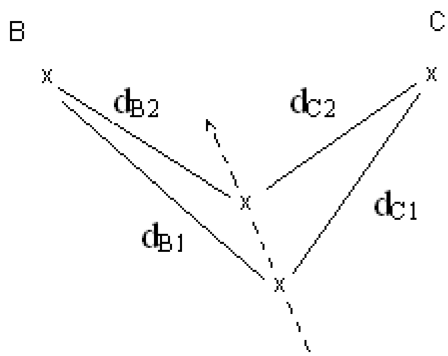

Figure 31 Relative Change of Distance to Ground Stations

A mobile flying in the path of the dashed line, decides which station is favorable with respect to the distance. If $d_{B1} - d_{B2} > d_{C1} - d_{C2}$ it is decided that an aircraft is moving more towards ground-station B than towards C. To determine if the aircraft is traveling towards or away from a ground-station, $d_{i,j} - d_{i,j+1} > 0$ means a path towards a ground-station i and $d_{i,j} - d_{i,j+1} < 0$ away from ground-station i. The $d_{i,j}$ means a mobiles distance to ground-station i when receiving report j. This reasoning holds for the mobile system while the opposite is true for the ground system.

The flight routes that have been predefined and their usage are at change. The FRAS project, mentioned in the introduction, has resulted in airplanes taking a straighter path of flight.[182] However as mentioned, VDL4 is intended to support more than the ordinary airlines, such as gliders which might have a more irrational behavior. If considering that only mandatory information is available, then no information reveals an aircrafts intentions whether to fly straight forward or turn around etc. As an example in the case a queue sets in, of aircrafts wanting to land at an airport. The aircraft could get holding instructions. This instruction refers to a specific area where the aircraft is supposed to uphold, until clearance for landing.

[182] http://www.lfv.se/sv/LFV/Flygtrafiktjansten/Vara-Tjanster/Anslaget/Anslaget-nr-2-2009/FRAS-Free-Route-Airspace/

Holding can occur on any altitude and there could be several holding spaces belonging to a specific airport. A standard holding pattern is that the aircraft turns 180° at $3^{\circ}/s$ and then flies in a straight line for 1 minute and then another 180° right turn and so on. In a holding scenario the velocity is restricted to various speeds. As an example the velocity is 265 KIAS, *Knots Indicated Air Speed* at altitudes greater than 14 001 feet. There are other cases when aircrafts makes a greater turn such as a "circling", where an aircraft circles an airport before going into landing.[183]

This scenario is considered as increasing handoffs if the space for holding is located where there are overlapping cells. This implies that a holding location would be positioned relatively far from the intended airport. It is determined not to be an unrealistic assumption, based on studied holding locations for Newark airport in New York.[184]

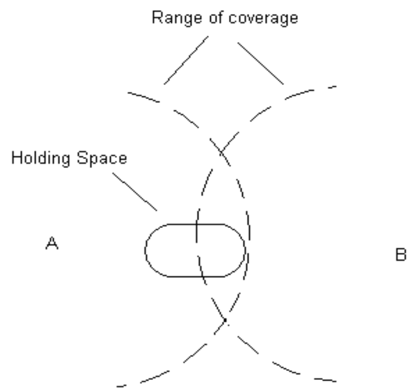

Figure 32 Example of holding

"Figure 32 Example of holding" shows one scenario where an increase in number of handoffs could occur when adding the property that an aircraft is traveling in a certain direction. If a point-to-point link is established to station A then a switch to station B would occur as the aircraft turns around and travels in favorable assumed path of flight. The procedure would again be followed with the opposite operation. This would introduce an increase of the ping-pong phenomena, described in "Figure 15 The Ping-Pong phenomenon p. 20".

Cell sizes - Prediction of Range

The other part in maximizing the duration of a link consists of determining the size of the cells involved in a communication scenario. The signal quality of a received transmission is determined in VDL4, which provides a measurement of the current situation. If knowing the path of flight, it is considered as favorable to also know or estimate the forthcoming signal quality i.e. possible size of a cell. A predictive function could then be used in the handoff algorithm.

What to include in a predictive function is an issue, several different models have been examined. If a function should be based on knife-edge, multipath, or include variations of terrain or perhaps some other combination is difficult to determine. The processing and calculation of a predicted range requires capable equipment. The limitation of the equipment is not considered.

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[183] Federal Aviation Administration, *Instrument Flying Handbook chapter 10,* sep 2009

[184] Smith A. Bateman H. *Management of holding patterns: a potential ADS-B application,* oct 2008 Digital Avionics conference 2008, DASC 2008, IEEE/AIAA 27th

The study handling influence of rain in the VHF-band concluded that the propagation is not affected over tree tops but more similar to free space propagation. Therefore weather information is considered as not providing useful information a predictive function. A handoff procedure working well in one scenario with a mobile communicating with a ground-station in one type of terrain such as a flat landscape, might maybe not work as well in another type with mountains or hills. If data of the terrain is added to a predictive function, an issue is whether input data is correct or at an enough resolution. One examined study, which compared measurements with models using terrain profiles, concluded that results are very sensitive due to the terrain data.

As presented in "4.5 Channel Properties in the VHF band p.33" there has been a number of models and studies of the VHF-channel. Several models are empirical justified but at a very limited amount of trials and only handling a limited amount of phenomena. One example is at the trials, where the pathloss exponent was determined, at the two airports. Even at a single ground-station the exponent varied. Considering the exponents influence when calculating pathloss as described in chapter "3.2 Link Budget" a prediction based on basic pathloss is regarded as a blunt tool. However, the difference between the stations still indicates that one ground-station will be unique from another. The studies have shown that propagation is very much depending on local variations and dynamics of surrounding environment. A conclusion to draw is that a general model for aeronautical VHF propagation is almost impossible to make. There are propagation models which have shown very good predictions in the VHF band, but they are intended for mobile cellular communication at ground.[185]

The theoretical calculation of transmitting ranges, based on the free space propagation model in chapter "4.4 VDL4 Link Budget" showed that VDL4 stations can have great variations, depending on the gains of antennas and differing output power. This calculation did not consider influence from the environment such as shadowing, multipath or noise etc. These phenomena could make the variations of signal quality even larger. Calculations show that the range in an air-ground scenario is more depending of the line of sight.[186] The study where the Rice factors were determined for the VHF band, shows a varying factor. Although a typical value is suggested, there are contradicting conclusions whether to set a single value or not. One conclusion to draw based from presented Rice factors is that the air-ground communication in general operates in line of sight. Although with exceptions since K=0 is equivalent to no line of sight and K=2 has been reported, indicating that a degree of shadowing was present.

There is a lack of information of the used equipment in many of the examined studies. Actual hardware could have had an influence of measurements. None of the models that have been found, have been verified independent of the particular trial or enough empirical justified. An important aspect in the development of a handoff algorithm intended for VDL4 is the lack of official documentation regarding flight tests for VDL4. The available official information of flight tests of ground-air communication, which has been found, has been carried out using VDL2. There are differences between the two systems such as modulation or coding techniques. However an assumption is that the found information still could indicate the behavior of the channel in a point-to-point scenario in VDL4. Based on the findings from the research of the

[185] Cichon D. Kürner T. *Evaluation and verification of the VHF/UHF Propagation Channel Based on a 3-D-Wave Propagation Model* IEEE Transactions on antennas and propagation vol. 44 No. 3 March 1996
[186] Appendix A.5

VHF channel it is established to not include estimations of propagation of the channel in a handoff algorithm in VDL4.

5.3 Requirements on the Handoff Algorithm in VDL4

In the ETSI standards states when a mobile sets up the initial link it shall "choose a ground-station based on its capability to support a link and maximize the likely duration of the connection to the ground station"[187] This reasoning is only stated for the initial link but is assumed to also be the case in a handoff situation. For the handoff algorithm this would mean that unnecessary handoffs need to be avoided, if not performing a handoff the duration would be longer. As a result the overhead information for channel management would be reduced at the same time. To maximize the connection time it is considered not solely maximizing the likely duration to the serving ground station but as well as to the forthcoming.

If a mobile initiated handoff is supported, there are events that trigger a handoff described in chapter "4.3 Handoff in VDL4". If there is no response from a ground-station during handoff or if a serving ground-station becomes unreachable. A handoff should occur if the VHF signal quality to the serving ground-station is determined to be insufficient another ground-station provides a significantly better quality. This requirement implies a solution, with respect to defined signal quality RSS. Meaning that if the $RSS_S < T_F$ and $RSS_C - RSS_S > h$ a handoff should occur if interpreted literally. Where:

RSS_C *– Received Signal Strengths from candidate ground-stations*
RSS_S*- Received Signal Strength from the serving ground-station*
h – Hysteresis
T_F *– Preset Threshold value*

The previous described usage of RSS has been showed to have a poor performance, according to studies, as example higher handoff rates if the hysteresis is set too low or introducing longer delays with an increased hysteresis than other solutions.

Another event is if "the mobile is at a position, according to the link management policy, which requires a mobile handoff". This event suggests a handoff algorithm based on position, this has also been shown to be outperformed by other methods, described in chapter "3.5 Methods for Making a Handoff Decision". Eurocontrol gives a suggestion to base the handoff specifications on GPS information.[188] The data concerning position, based on the examination of the ETSI standards, is regarded as reliable information. However an algorithm solely based on positioning data is considered as a blunt approach. With this approach it has to be assumed that all stations provide a similar range of coverage, which might not be the case. However, *the local link management policy*, is considered as giving freedom for manufacturers to implement other solutions. It is determined that measurements of the quality of the channel need to be integrated in the handoff algorithm.

[187] ETSI EN 302 842-4 v1.2.1 (2006-12) p.56
[188] Eurocontrol, *Presentation of Deliverable 3 "Capacity Simulations"* ,VDL mode 4 Technical workshop Brussels 11th-12th may 2006 p.23

To summarize the requirements on the point-to-point handoff algorithm in VDL4 the objective is to:

- *Maintain connected to the serving ground station within service area*
- *Achieve a low handoff rate*
- *Prevent Ping-Pong phenomenon*
- *Achieve a short handoff delay*

As a remark, the question of handoff between different ground systems is not of interest. A mobile system entering a new ground system performs a new link establishment.[189]

5.4 Handoff Algorithm Based on Mandatory Information

This section presents an algorithm for the point-to-point handoff in VDL4.

To fulfill the purpose the first task is to:

- Develop an algorithm based on VDL4 ETSI standards and use information stated as mandatory as input to a handoff decision.

The discussed algorithms are described in chapter "3.5 Methods for Making a Handoff Decision". A predictive function as the Grey predictive RSS, algorithm could have difficulties handling the task if the channel deteriorates to fast. A pattern recognition algorithm could function as a deterministic procedure. This type of method is proposed for a cellular environment, which could be considered as a 2 dimensional space. With respect to avionics operating in a 3D environment, the task of dividing the operating space into 3D grids is considered as a very difficult task. The paths of flight are not restricted to certain routes, which results in that the "training" stage would be very time consuming. Another consideration is also that each mobile system would need its own look up table. There would be differences between individuals as a result of different types of equipment such as antennas. If a change of equipment would occur a new training stage could be required. There would also be needed a transfer of information between the ground system and the mobile system depending on which system that handles the handoff. The mobile system would measure the up-link properties and the ground system the down-link which would be needed to be compared. This implies that the handoff algorithm in VDL4 is to be designed with a reactive approach.

According to found information VDL4 does not have any power control i.e. uses static transmission powers, which makes these types of algorithm approaches improper. Researchers conclude that it is impractical to design a handoff algorithm compensating for multipath fading and is considered as being handled in the system by different preventive techniques.[190] Studies imply that the VHF channel is showing a fast fading characteristic in the enroute scenario. In a

[189] ETSI EN 302 842-4 V1.2.1 (2006-12) p.57

[190] Akar M. *Integrated power and handoff control for the next generation wireless Networks* Springer Science+Business Media Sep. 2007

handoff algorithm the fast fading characteristics is normally counteracted with the help of averaging the received signal strength.

The studies of algorithms imply that adaptive methods provide lower handoff rates and lower delays than using a fixed threshold. There are also results that indicate that some adaptive approaches increase the handoff delay. The parameters for a handoff algorithm based on mandatory information have been narrowed down to include positioning information and quality measurements of the channel and is proposed to be based on relative RSS with an adaptive hysteresis as followed: [191]

$RSS_C - RSS_S > h.$

RSS_C – Received Signal Strengths from candidate ground-stations
RSS_S -Received Signal Strength from the serving ground-station
h – Hysteresis

The hysteresis is set to be adaptive according to: $h = max\left[\alpha\left(1-\left(\frac{d_s}{R}\right)^{\beta}\right), \eta\right]$

α - Coefficient to prevent handoff within service area.
d_s – Distance between serving ground-station and aircraft
R – Cell Radius
β - Determines the shape of the function
η - Minimum hysteresis threshold

An example of the hysteresis is illustrated:

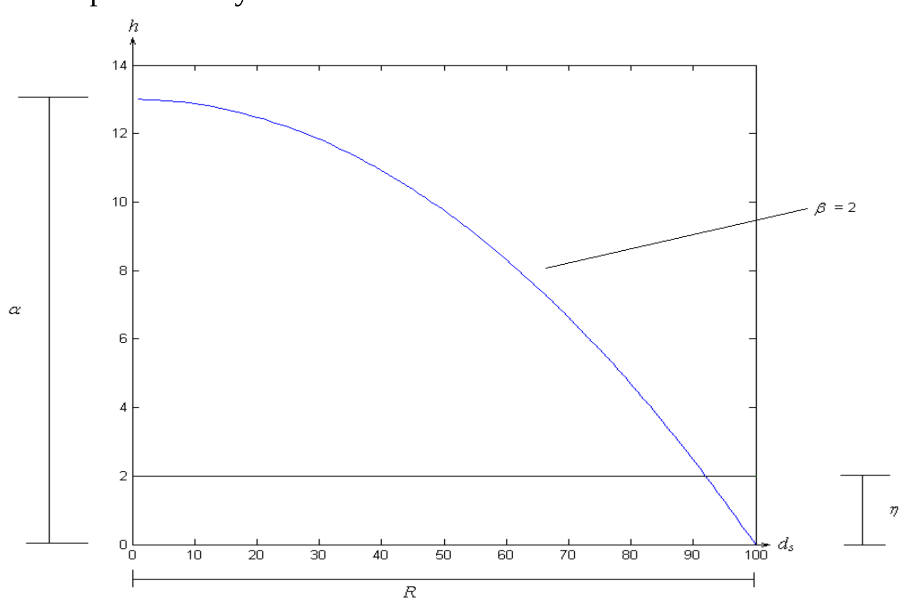

Figure 33 Example of the adaptive hysteresis[192]

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[191] Huamin Z. Kwak K. *Adaptive Handoff Using Distance Information* Vehicular Technology Conference IEEE 63rd VTC 2006

[192] α = 13[dB] , R = 100[NM], β = 2, η = 2 [dB], d_s = varying

The parameter α sets the upper bound for the hysteresis and enables the algorithm to prevent handoff within the service area to the serving ground station. The parameter η sets the minimum threshold, which should be > 0 since the environment is not noise free. The exponent β determines the shape of the function for the adaptive hysteresis. The distance d_s is provided from the GPS receiver and *R* is the cell radius of the serving ground station. The handoff algorithm strives to achieve the best quality of the link and will make a switch if better quality is available to another ground station according to the adaptive hysteresis. To address the issue of errors in a reported position from an ADB-B report, there is a study of the proposed algorithm, which indicates that it is robust even if distance errors are present.[193]

The cell radius *R* is of concern in the design of the algorithm, since it has been shown that coverage provided from a ground station is not uniform, according to flight tests pictured in "Figure 26 Estimated coverage of two ground stations p.36". One approach is to use the distance between ground stations. This would make the algorithm to adapt to the current structure of the ground network. Ideal would be to set the boundary for the cell between the serving ground station with respect to the candidates.

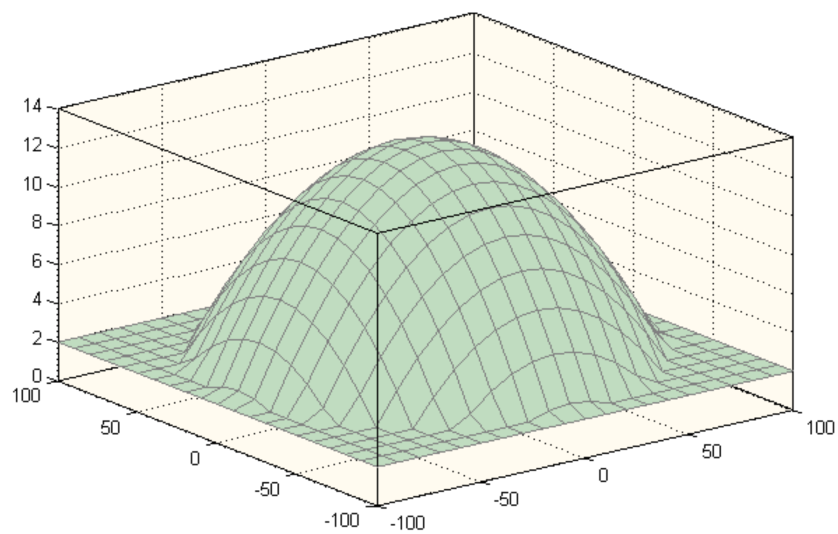

Figure 34 3D view of the adaptive hysteresis [194]

The figure shows how the hysteresis would look for one candidate ground station 200[*NM*] away, with respect to the serving ground station. If more candidates are present the hysteresis would adapt to the distance between the ground stations.

[193] Zhu H. Kwak K. *Improving Handoff Performance by Using Distance-Based Hysteresis Value* LNCS 4238 Springer-Verlag Heidelberg 2006

[194] α = 12[dB] , *R* = 100[*NM*], β = 2, η = 2 [*dB*], d_s = varying

If several candidates fulfill to be better than h it does not necessarily mean that the highest relative RSS would maximize the duration of the link. To order the preference of ground stations the change of distance Δd_i could be used. A scenario is illustrated in "Figure 35 Scenario for order of preference".

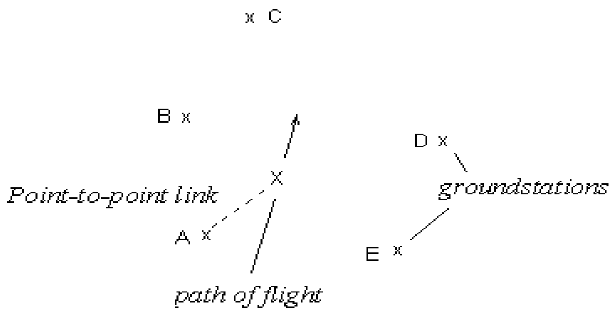

Figure 35 Scenario for order of preference

The figure shows how the direction could set the order of preference in case of handoff. An aircraft is point-to-point connected to ground station A. As candidates ground stations B-E are possible i.e. RSS_C -RSS_S > h for ground station B-E holds. As a result ground station C would be chosen since the aircraft is approaching C more than B, D, E. There is a benefit if a ground station ahead of the aircraft is chosen, it is considered as very likely that a longer duration of the link could be provided.

Target Environment for the Handoff Algorithm
Since the basis for developing a handoff algorithm is originating from the ETSI documentation the intended target environment needs to be clarified. As mentioned in chapter "4.3 Handoff in VDL4" the handoff procedure is possible to be handled in either the ground-system or the mobile system as well as in both.

Due to the asymmetric situation, the handoff algorithm should be active in both the mobile and the ground system. This would result in that the mobile system respectively ground system has an opportunity to trigger a handoff, depending on the properties of the up-link or down-link. The *mobile requested ground initiated handoff* and *ground requested mobile initiated handoff* could be usable if either system has advantage of information as input to the decision. However this is not the case in the suggested algorithm. Therefore the *mobile initiated handoff* and *ground initiated handoff* is considered.

Regarding the choice of forward or backward handoff, presented in chapter "3.4 Handoff p.15", it is determined that a forward procedure is the most suitable choice of operation. This means that a mobile or a ground-station makes the handoff request to or from a candidate ground-station. The forward procedure is recommended since the proposed algorithm uses averaged measurements. Averaging introduces a delay in the handoff procedure. During the delay the aircraft is expected to have moved closer to the candidate ground station resulting in an assumed better quality of the link and reducing the probability for failure.

5.5 Evaluation of Optional Information

This section provides an evaluation according to the analytical approach. It will be determined if the optional information could be useful for a handoff decision.

Quality of the channel

The optional information does not provide any additional information about the quality of the channel. It is determined as previous described in “5.4 Handoff Algorithm Based on Mandatory Information”.

Capability of ground-station

A ground station could provide information of what kind of services and applications it supports in the DOS parameter. In a future services could be point-to-point specific, since reservations have been made in the ETSI standards.

As mentioned, up to 255 different applications are possible in VDL4, and it is considered as important that a required service is provided at a candidate ground-station. The DOS-parameter is single sided information. The mobile system can not provide the ground system with information which specifies needed applications. However the DOS parameter is a complex matter to involve in a handoff process. As an example, the mobile system performs a comparison between two ground-stations. Different amount and varying applications are supported at the two ground-stations. This gives raise to a number of issues that needs to be resolved. Should the amount services be interest or perhaps the active applications in the mobile should correspond as much as possible to supported services at a ground station. Maybe one application is of a higher importance than another. In the case an application is not supported at any candidate station, it could result in that the mobile would not have any candidates. If the relative importance of an application is unknown there will be a tradeoff, a probable loss of the point-to-point link or a failure in unsupported applications.

The integration of DOS in the handoff process is considered as favorable. However, the relative importance of different applications would need to be resolved first. From another standpoint, a ground-system is very likely to be installed from a single provider, which probably would result in that the supported applications would be equivalent within the whole ground network. In the case of that an application is specific for a certain ground-station, it is assumed to have a low overall importance. In the case a mobile switches ground-system, the mobile system is obliged to perform a new link establishment. The available services within the ground system could be provided in the establishment procedure. It is concluded that the integration of a DOS-parameter in the handoff procedure is better handled in progress of new applications and when an evaluation is easier accomplished.

Possible Duration of the link

As mentioned the range of communication is desirable to maximize the duration of the point-to-point link. It consist of two parts, an aircrafts intended path of flight and size of cells.

Path of flight
As optional information the *destination airport* parameter could be transmitted, that provides information of which airport the aircraft is intending to travel to. However, the parameter does not reveal its location and therefore determined not to be useful in the handoff procedure.

The concept of TCP could provide a more accurate assumption about an aircrafts intended path of flight, since the trajectory change points are most likely to occur. The TCP is still under development and it is unclear from where data originates i.e. manually entered or perhaps provided within the VDL4 system. If the data is considered to be reliable it could be used to deactivate the selectivity based on distance information. A scenario such as holding could increase the handoff rates and if more than two *time to go* parameters are within 3 minutes an aircraft is likely to be in a holding route.

Cell sizes
Regarding the size of cells the optional information does not provide any additional information and is considered as in chapter "5.2 Evaluation of Available Mandatory Information".

5.5 Handoff Algorithm with Additional Optional Information

It is determined that optional information could enhance the handoff procedure in VDL4. As stated in chapter "1.3 Purpose and Goal p.2" the handoff algorithm is to be developed with the extension of information.

- The parameters set as optional in the ETSI standard, are to be examined if the optional transmitted information could lead to an improved handoff process.

Reduction of asymmetry
The procedure for handoff is the same as presented in chapter "5.4 Handoff Algorithm Based on Mandatory Information". A forward handoff using *mobile initiated handoff* and *ground initiated handoff.* There is optional information, which could reduce previous discussed asymmetry. There is a possibility to enable a cooperative decision between the mobile and ground system. Both *mobile initiated handoff* and *ground initiated handoff* supports to provide a *ground replacement list* respectively an *acceptable alternate ground station* parameter. If candidates are set in order of preference, the ground system or the mobile system has an opportunity to control if the quality of the channel is sufficient i.e. if $RSS_S - RSS_C > h$ holds for the alternatives.

If lists are transmitted there will be an increase of overhead information, there is a tradeoff between increasing relevant information and the utilization of the VDL4 point-to-point link. Calculations show that up to 6 candidates can be transmitted in one slot.[195] However, if lists are provided there would be more certain that both downlink and uplink provide a required quality of the channel.

[195] Appendix A.4

6 Conclusions

This chapter presents the results of the analysis in chapter 5. The fulfillment of the purpose of the study is given. Some benefits and weaknesses of the suggested handoff algorithm are discussed. Then considerations regarding the ETSI VDL4 standards are made. Finally proposals for further studies are presented.

6.1 Fulfillment of the Purpose

The purpose of the study was to develop optimal algorithms for VDL4. To fulfill the purpose subtasks were developed. The first subtask was:

- Develop an algorithm based on VDL4 ETSI standards and use information stated as mandatory as input to a handoff decision.

The suggested algorithm is based on received signal quality according to:

$RSS_C - RSS_S > h$.

RSS_C – *Received Signal Strength from candidate ground-stations*
RSS_S- *Received Signal Strength from the serving ground-station*
h – Hysteresis

With an adaptive hysteresis, $h = \max\left[\alpha\left(1-\left(\frac{d_s}{R}\right)^{\beta}\right),\eta\right]$

α - *Coefficient to handle drops in received power and prevent handoff within service area.*
d_s – *Distance between serving ground-station and aircraft*
R – Cell Radius
β - *Determines the shape of the function*
η - *Minimum hysteresis threshold*

The algorithm is determined to use a forward handoff procedure, since it is considered that the channel quality is likely to improve.

If more than one candidate ground station fulfills the criteria, to be better than the adaptive hysteresis, the change of distance could be used to order the preference. This is done by comparing the change of distance between the aircraft and the available ground stations. It is likely that a ground station ahead is chosen.

The second subtask was:

- The parameters set as optional in the ETSI standard, are to be examined if the optional transmitted information could lead to an improved handoff process.

In order to reduce asymmetry in the down-link and uplink it is proposed that the *acceptable alternate ground station* and *ground replacement list* parameter should be provided in the handoff transmission. This enables to control that both up-link and down-link and down-link fulfills requirements of channel quality. The TCP could be used to deactivate the distance selectivity, in the case of a circular movement of an aircraft.

Benefits of the Algorithm

Previous simulations and research indicates that the algorithm maintain connection within service area. It reduces the amount of handoffs and has a short delay, in comparison to other algorithms. An adaptive algorithm has a benefit in handling ping-pong phenomena's, due to its characteristics. It integrates an opportunity to adapt the hysteresis with respect to placement of ground stations.

Weakness of the Handoff Algorithm

The algorithm could increase the handoff rates due to aircraft behavior if distance selectivity is included. How likely that is to occur is unclear, the holding position need to be located at a region where two cells overlap and the hysteresis needs to be fulfilled. The distance traveled during holding is approximately 7 [*NM*] [196], varying depending on an aircrafts velocity. How likely this scenario should be considered and examined with actual tests.

The proposed algorithm could, according to studies, possibly introduce a larger handoff delay. A slightly larger delay in a macrocell is, according to research, not a significant problem if not too large. However, the exact definition of "too large" needs to be examined with help of simulations.

A weakness to implement a general handoff algorithm could be that it does not perform well in every scenario. Studies indicate that the coverage provided from ground stations varies individually, it might be needed to adjust parameters for each ground station for an optimal performance. However, this needs to be examined with simulations.

Concluding Remarks

It has been shown that the point-to-point communications are very dynamic. Propagation from ground stations seems to vary individual, according to previous research. The studied predictive models for propagation, has been determined to not be able to perform sufficiently to be a part of a handoff algorithm in a VDL4 point-to-point communication.

The involvement of balancing an assumed load in the handoff algorithm in VDL4 is determined to be excluded. To perform a handoff to another ground station due to load balansing is determined to be better handled with an increase of channels. This is concluded on basis of the assumed ground structure where ground stations do not cover large parts of the same space.

[196] Appendix A.3

Suggestions Concerning ETSI VDL4 Standards

The foundation of this thesis is based on the VDL4 standards provided from ETSI and some remarks are made concerning the VDL4 standards.

A handoff algorithm in VDL4 is very much depending on where the handoff process is implemented, in the mobile system or the ground system. The VDL4 standards give manufacturers freedom to implement the handover process in either system. To ensure interoperability, between different providers of VDL4 equipment, at least support of one type of handoff should be required. A VDL4 mobile system designed for ground controlled handoff procedures would most likely perform poor together with an opposite design.

The required action for a ground-station receiving the *alternate ground-stations* parameter is unspecified in the ETSI VDL4 standards.

No information reveals the location of airports in VDL4. Parameters such as *nearest airport, airport coverage* or *destination airport* would be more useful if positioning data of the included airports were available.

6.2 Further Studies

A study of modeling air-ground propagation seems to be needed and could be of further use in a handoff procedure. There is an expressed need for a more realistic propagation model to improve simulations and refine handoff algorithms in the VHF-band.[197] If measurements are conducted there would be an opportunity to create a justified and verified model for VHF air-ground propagation. This could be of interest for simulation purposes as well as enable a proactive handoff algorithm operating in the aeronautical VHF-band.

The suggested algorithm includes averaging of received power levels as well averaging of distance. The method of averaging could further improve performance of the handoff algorithm. If using a fix averaging window or a varying number of samples is undetermined. The subject of averaging is left as a future study. The influence of rectangular, exponential or adaptive averaging could be of interest. [198,199] In general macrocells are more insensitive to a longer averaging time, which implies a longer averaging period.[200] But methods need to be examined.

Previous simulations with the proposed handoff algorithm have been made with other models of propagation. It is needed resolve the performance with the stochastic properties of the VHF channel together with a reasonable propagation model. Research concerning air-ground stochastic models has been developed and could be used for simulation purposes.[201]

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Appendix

A.1 Wavelength in the aeronautical VHF-band

$$\lambda = \frac{c}{f} = \frac{2{,}98 * 10^8}{137 * 10^6} \approx 2{,}2m \;,\; f = 137\,[MHz]\,^{202}\;,\; c = 2{,}98 * 10^8\,[m/s]^{203}$$

A.2 Linkbudget VDL4 – theoretical range of communication

Assumptions:
Calculations are based on the scenario where an aircraft, of class A and B, is transmitting to a groundstation i.e. downlink. Free Space Propagation is assumed. All parameters used, are based from "a worst case" scenario i.e highest operating frequency, lowest power from transmitters etc. Positive gain could improve the range of communication transmission, while a negative gain decreases the range. Only negative gain is considered.

Received and transmitted power

Minimum required power at the receiver:[204] $P_R = -98\,[dBm] = 10^{\left(-98/10\right)-3}[W] = 10^{-12{,}8}\,[W]$

Transmit power:[205]

Class A $P_{TA} = 15\,[W] \pm 1{,}5\,[dB_W]$

Transmit $p_{MaxA} = 15[W] + 1{,}5[dB_W] = 10LOG(15)[dB_W] + 1{,}5[dB_W] = 13{,}26..[dB_W] = 10^{\left(13{,}26../10\right)}[W]$

Transmit $p_{MinA} = 15[W] - 1{,}5[dB_W] = 10LOG(15)[dB_W] - 1{,}5[dB_W] = 10{,}26..[dB_W] = 10^{\left(10{,}26../10\right)}[W]$

Class B $P_{TB} = 4\,[\mathrm{W}] \pm 1{,}5\;[dB_W] = 6{,}23 \pm 1{,}5\,[dB_W]$

Transmit $p_{MaxB} = 4[W] + 1{,}5[dB_W] = 10LOG(4)[dB_W] + 1{,}5[dB_W] = 7{,}52..[dB_W] = 10^{\left(7{,}52../10\right)}[W]$

Transmit $p_{MinB} = 4[W] - 1{,}5[dB_W] = 10LOG(4)[dB_W] - 1{,}5[dB_W] = 4.52..[dB_W] = 10^{\left(4{,}52/10\right)}[W]$

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[202] The highest operating frequency in the VHF-band gives the shortest wavelength
[203] Halliday D. Resninck R. Walker J., *Fundamentals of Physics 7th edition part 2,* John Wiley & Sons Inc. 2005
[204] ETSI EN 302 842-1 V.1.2.1 (2006-12) p.21-22
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Gains and losses: (referenced to "Figure 22 location of specified receiver sensitivity"), assuming same properties for Class A and B.

Antenna Gain[206] G_{TA} = -3 $[dB_i]$, Feeder loss[207] F_L= 2 $[dB]$
Resulting total transmitter Gain $G_T = G_A - F_L$ = - 2 $[dB_i] = 10^{-0,2}$ $[W]$

Receiver Antenna Gain:[208] G_{RA} = 2,15 $[dB_i]$, the cable loss[209] C_L= 2$[dB]$.
Resulting total Receiver Gain $G_R = G_{RA} - C_L$ = 0,15 $[dB_i]$ = $10^{0,015}$ $[W] \approx 1[W]$

Power law link budget:

Friis equation: $P_R = \frac{P_T G_T G_R}{L_b} \Rightarrow L_b = \frac{P_T G_T G_R}{P_R}$ (1)

Path loss, Free Space propagation, $L_b = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi d)^2}{\left(\frac{c}{f}\right)^2} \Rightarrow d = \sqrt{\frac{L_b\left(\frac{c}{f}\right)^2}{(4\pi)^2}} = \frac{c}{4\pi f}\sqrt{L_b}$ (2)

Combining (1) and (2) gives:

$$d = \frac{c}{4\pi f}\sqrt{L_b} = \frac{c}{4\pi f}\sqrt{\frac{P_T G_T G_R}{P_R}}$$

As an example

Class A: $d_{\min} = \frac{c}{4\pi f}\sqrt{\frac{P_T G_T G_R}{P_R}} = \frac{2{,}98*10^8}{4\pi*137*10^6}\sqrt{\frac{10^{\left(10{,}26/10\right)}*10^{-0,2}*10^{0,015}}{10^{-12,8}}} \approx 710119{,}5\ [\text{m}] \approx 380\ \text{NM}$

ClassA: $d_{\max} = \frac{c}{4\pi f}\sqrt{\frac{P_T G_T G_R}{P_R}} = \frac{2{,}98*10^8}{4\pi*137*10^6}\sqrt{\frac{10^{\left(13{,}26/10\right)}*10^{-0,2}*10^{0,015}}{10^{-12,8}}} \approx 1003071\ [\text{m}] \approx 540\ \text{NM}$

Class B: $d_{\min} = \frac{c}{4\pi f}\sqrt{\frac{P_T G_T G_R}{P_R}} = \frac{2{,}98*10^8}{4\pi*137*10^6}\sqrt{\frac{10^{\left(4{,}52/10\right)}*10^{-0,2}*10^{0,015}}{10^{-12,8}}} \approx 366704\ [\text{m}] \approx 200\ \text{NM}$

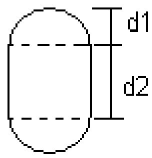
Class B: $d_{\max} = \frac{c}{4\pi f}\sqrt{\frac{P_T G_T G_R}{P_R}} = \frac{2{,}98*10^8}{4\pi*137*10^6}\sqrt{\frac{10^{\left(7{,}52/10\right)}10^{-0,2}*10^{0,015}}{10^{-12,8}}} \approx 517983[\text{m}] \approx 280\ [\text{NM}]$

[206] An assumed reasonable figure
[207] Thorblad B C.N.S Systems, *Installation and Operation Manual VDL 4000/GA*, 2001-12-21 p.23
[208] Aeronautical Frequency Committee, *61094 Rev. A Ground Station Installation Guidelines,* May 2009 p. 1-2
[209] Thorblad B C.N.S Systems, *Installation and Operation Manual VDL 4000/GA*, 2001-12-21 p.23

A.3 Holding distance

Velocity v = 265 KIAS
Turning rate 3° /s for 1 minute
Distance d2 is flown in 1 minute
$2\pi d1 = P$ *(Perimeter)*

Total distance = 2*d1 + d2 = $\frac{265}{60}\left(\frac{2}{\pi}+1\right) \approx 7{,}2$ [NM]



A.4 Overhead when ground replacement list / acceptable alternate list is provided

The following calculation provides with the amount of ground-stations that could be provided in 1 slot in the *ground replacement list* parameter.

Superframe, S = 4 500 [*slots / minute*][210] corresponds to slot time $S_t = \frac{60}{4500} = \frac{1}{75}$ [*seconds / slot*]

Data rate, r = 19 200 bits/s[211]
Guard time, T_G = $1{,}25\,[ms]$ [212]

Efficient slot time $S_{te} = S_t - T_G = \frac{1}{75} - 1{,}25 * 10^{-3}$

Maximum number of bits per slot $b_M = S_{te} * r \approx 231$

Ground replacement list parameter encoding[213]
Parameter ID, P_{ID} = 8 bits
Parameter length, P_l = 8 bits,
Parameter value i.e. specific ground-station, P_v = 32 bits

Givess a total of $\frac{b_M - (P_{ID} + P_l)}{P_v} = 6{,}71 \approx 6$ ground-stations / slot

[210] ETSI EN 301 842-1 V1.3.1 (2006-11) p.13
[211] Ibid. p.20
[212] ETSI EN 308 842-1 V1.2.1 (2006-12) p.21
[213] Ibid. p.47

Appendix A.5 Guard range calculation

A radiowave propagates approximately at the speed of light trough air. The guard time would give a guard range up to 201 [*Nm*].

R_G = Guard range

c = speed of light = 2,98 * 10^8 [*m/s*] [214]

T_G = Guard time = 1,25 [*ms*] [215]

$R_G = c^* T_G$ = 2,98 * 10^8*1,25*10^{-3} = 372 500[*m*] $\approx$201 [*Nm*]

Appendix A.6 Line of sight calculation

A smooth surface of earth is assumed.

h_1=*height from earth surface to aircraft* = 3000, 10 000 [*m*]

h_2=*height from earth surface to ground-station* = 20 [*m*]

R_0 =*earth radius* = 6, 37 [*km*][216]

Line of sight equation $d = \sqrt{2R_0}\left(\sqrt{h_1} + \sqrt{h_2}\right)$ yields

$211 \leq d \leq 373[km] \Leftrightarrow 114 \leq d \leq 201[Nm]$

If refraction is considered: R_0 =*earth radius* = 8,5 [*km*][217] $\Rightarrow 131 \leq d \leq 232\ [Nm]$

[214] Halliday D. Resninck R. Walker J., *Fundamentals of Physics 7th edition part 2,* John Wiley & Sons Inc. 2005

[215] ETSI EN 308 842-1 V1.2.1 (2006-12) p.21

[216] Ahlin L. Zander J Slimane B, *Principles of Wireless Communications,* Studentlitteratur Naryana Press Denmark 2006 p.64

[217] Ibid.