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# Increased Capacity for VDL Mode 2 Aeronautical Data Communication

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**INCREASED CAPACITY FOR VDL MODE 2**

**AERONAUTICAL DATA COMMUNICATION**

**SANJIN ĐERIĆ**

# ABSTRACT

VDL Mode 2 is the principal data communication technology for aeronautical communications implemented in the NextGen project for the National Airspace System (NAS), with potentially worldwide service. Aeronautical communications have strict transmission delay standards for safety considerations. Meeting the strict standards significantly drops the capacity of the number of aircraft that can communicate using the Very High Frequency (VHF) Data Radio (VDR). In this thesis, three methods of increasing the capacity while maintaining the strict standards are evaluated: transmit power control, load regulation and ground station placement. A simulation model using OPNET software is used for testing. Load regulation shows some improvement, while transmit power control is not beneficial. The best results are obtained from optimal ground station placement, with over 300 percent capacity improvement in certain scenarios.

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# NOMENCLATURE

| Acronym | Definition |
|---|---|
| ACARS | Aircraft Communications Addressing and Reporting System |
| ADS-B | Automatic Dependent Surveillance-Broadcast |
| AMCP | Aeronautical Mobile Communications Panel |
| AOA | ACARS over AVLC |
| AOC | Aeronautical Operational Control |
| ATC | Air Traffic Control |
| ATN | Aeronautical Telecommunications Network |
| AVLC | Aviation VHF Link Control |
| BER | Bit Error Rate |
| CMU | Communication Management Unit |
| COCR | Communications Operating Concepts and Requirements |
| CSMA | Carrier Sense Multiple Access |
| D8PSK | Differential 8 Phase Shift Keying |
| EFIS | Electronic Flight Instrument System |
| FAA | Federal Aviation Administration |
| FANS | Future Air Navigation System |
| FMS | Flight Management System |
| FRS | Future Radio Systems |
| HDLC | High-Level Data Link Control |

| Acronym | Definition |
|---|---|
| IATA | International Air Transport Association |
| ICAO | International Civil Aviation Organization |
| IEEE | Institute of Electrical and Electronics Engineers |
| IPS | Internet Protocol Suite |
| ISO | International Organization for Standardization |
| ITU-T | International Telecommunication Union - Telecommunication Standardization Sector |
| LME | Link Management Entity |
| LOS | Line of Sight |
| MAC | Multiple Access Control |
| MASPS | Minimum Aviation System Performance Standards |
| MOPS | Minimum Operational Performance Standards |
| NAS | National Airspace System |
| NASA | National Aeronautics and Space Administration |
| OPNET | Optimized Network Engineering Tools |
| OSI | Open Systems Interconnection |
| PCSMA | Prioritized CSMA |
| PLOC | Prolonged Loss of Communications |
| PRNG | Pseudo-Random Number Generator |
| RTCA | Radio Technical Commission for Aeronautics |
| SARPs | Standards and Recommended Practices |
| SIR | Signal-to-Interference Ratio |

| Acronym | Definition |
|---|---|
| SNAcP | Subnetwork Access Protocol |
| SNR | Signal-to-Noise Ratio |
| TPC | Transmit Power Control |
| VDL | VHF Data Link |
| VDR | VDF Data Radio |
| VHF | Very High Frequency |
| VME | VDL Management Entity |

# CHAPTER I

# INTRODUCTION

The traditional means of communication between aircraft and Air Traffic Control (ATC) is voice radio. Although voice communication is still in use today for ATC, in 1978 a data communication system was implemented for sending text messages between aircraft and ground stations, called Aircraft Communications Addressing and Reporting System (ACARS). ACARS already found widespread use in the 1980's for various aeronautical services. Wireless data communications provide many benefits for relaying information between aircraft and ground systems. The ACARS data link is being used regularly as part of civil aviation operations for many Aeronautical Operational Control (AOC) messaging services. But as the airspace is getting more congested and more services are being added, the ACARS system is unable to accommodate the increased amount of data traffic. In addition, ATC services are being transitioned to data communications, whereby ACARS cannot meet the strict delay requirements. Therefore the technology is being upgraded.

The Federal Aviation Administration (FAA) together with many partner organizations and companies are currently upgrading the infrastructure of the National Airspace System (NAS). This project is called NextGen. The outlook is that air traffic congestion will continue to increase, which the traditional voice communication and ACARS will not handle well. One of the aims of the NextGen project is to solve this by implementing newer communication technologies to increase the capacity and data throughput.

The element of NextGen responsible for the upgrade of the communication system is Next Generation Data Communications (NextGen Data Comm). The main technology for aeronautical communications services is VHF Data Link Mode 2 (VDL Mode 2).

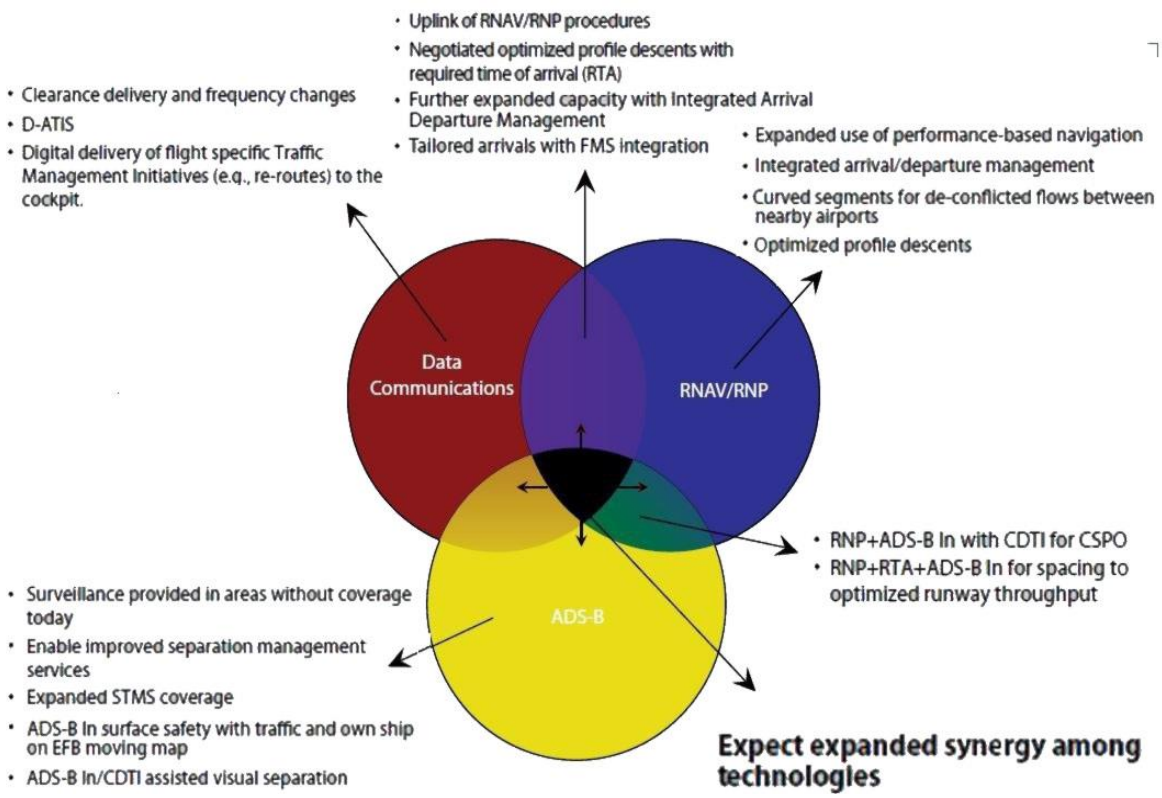


Figure 1 - Synergy of NextGen [1]

Compared to ACARS, the main benefit of VDL Mode 2 is its ability to provide more than ten times the data rate (31.5 kbps vs. 2.4 kbps). The purpose of the upgrade is to make the communication system capable of handling a larger load of data and aircraft. The three key NextGen technologies for communication, navigation and surveillance are planned to work in synergy, where each compliments the others. This synergy, along with the delivered capabilities, is shown in figure 1. According to the FAA, "Investment in FAA's NextGen Data Communications technologies is the critically important next step for improving air safety, reducing delays, increasing fuel savings, improving the environment and leading U.S. aviation into the 21st century".

VDL Mode 2 is currently utilized in the United States for AOC, while in Europe it was already implemented for AOC as well as ATC. VDL Mode 2 services are also available in Japan and Brazil. The plan is to make data communication the primary way of communication between aircraft and ground stations. The International Air Transport Association (IATA), which represents 84% of the world's total air traffic, envisions that data communications between flight crews and controllers is the key step to One Sky... global Air Traffic Management. VDL Mode 2 has a key role because "over 270 IATA member airlines agree VDL Mode 2 is the only practical solution to support ATC datalink services for the years to come" [1] . By utilizing data instead of the traditional voice communication, more information can be sent in less time, while also potentially preventing the miscommunications that can occur during voice communication. Data communication also reduces pilot and controller workload [2].

In order to verify the operation of the VDL Mode 2 protocol in the National Airspace System, a simulation model of the protocol was developed in collaboration between Cleveland State University, NASA Glenn Research Center and the FAA. The modeling effort is ongoing and testing all the necessary scenarios to determine the optimum setup for the most efficient implementation, and also to determine any possible problems in a simulation setting before they can occur in the airspace.

Since aeronautical communications have strict standards on transmission delay times, the capacity that meets the current or future standards may not be adequate. Therefore, it may be necessary to implement techniques to increase the capacity while meeting the strict standards.

The main objective of this thesis is to determine and evaluate potential ways of increasing the capacity of VDL Mode 2 for aeronautical communications. Previous research is summarized and three methods of increasing capacity are explained and tested using simulations: transmit power control, load regulation and ground station placement. All three methods focus on optimizing the implementation of frequency reuse in the en-route domain of flight. Based on the simulation results, the three methods will be evaluated to determine if and how effectively they can increase the capacity. An economical implementation of VDL Mode 2 is critical for the aeronautical industry, thus, the method must also be cost-effective. The most promising results of the thesis aim to potentially open new doors for research and implementation in the NAS for aeronautical data communication with VDL Mode 2.

# CHAPTER II

# VDL MODE 2 OVERVIEW

VDL Mode 2 is an aeronautical wireless data communication technology, standardized by the International Civil Aviation Organization (ICAO) in 1996/97 and was defined by the Aeronautical Mobile Communications Panel (AMCP) of the ICAO. The technology is commonly also referred to as VDL M2 or VDL2. The primary purpose of VDL Mode 2 is to exchange data between aircraft and ground stations at a higher data rate and more reliably then ACARS. VDL Mode 2 operates in the Very High Frequency (VHF) spectrum, where the assignable aircraft band for VHF radio is 118–136.975 MHz. This frequency band is divided up into 760 communication channels in the NAS, whereby each has a bandwidth of 25 kHz.

As the VDL Mode 2 name suggests, there are several other VDL modes. The legacy ACARS technology is sometimes referred to as VDL Mode 0 or VDL Mode A. VDL Mode 1 was standardized at the same time as VDL Mode 2, but it fell out of favor due to its inferior modulation technique and was never implemented [3]. VDL Mode 3 and Mode 4 also exist and were planned to be implemented. VDL Mode 3 allows for both data and digitized voice communication over one radio. It was originally planned as part of a project called NEXCOM, but the FAA decided not to implement it because the requirements for voice and data communication were changed, according to the U.S. Government Accountability Office [4]. The most recent in the set is VDL Mode 4. It was originally intended as the communication standard for the Automatic Dependent Surveillance-Broadcast (ADS-B) surveillance system. However, it was superseded by the Mode S communication technology, even before it was implemented. There are no plans for implementation of either VDL Mode 3 or Mode 4 in the USA. Therefore, VDL Mode 2 is the only VDL Mode with a bright future for certain implementation and utilization in the NAS, with practically worldwide service. Considering the long economic life of aeronautical technologies, VDL Mode 2 could be the main civil aviation data communication technology for the next several decades to come.

## 1. Standards

Three main documents exist for the development and operation of VDL Mode 2 avionics. The first one is the *Signal-In-Space Minimum Aviation System Performance Standards for Advanced VHF Digital Data Communications* [5], which is referred to as MASPS. The other is called *Minimum Operational Performance Standards for Aircraft VDL Mode 2 Physical, Link, and Network Layer* [6], or simply MOPS. Both of these documents are based on the original document where VDL Mode 2 was standardized by the ICAO: *International Standards and Recommended Practices* (SARPs) – Annex 10 – Aeronautical Telecommunications – Volume III – Communication Systems [7].

## 2. Protocol Stack

VDL Mode 2 is defined on the bottom three layers of the OSI standard protocol stack: physical layer, link layer, and the lower part of the network layer, the subnetwork layer. A diagram of the protocol stack is shown below.

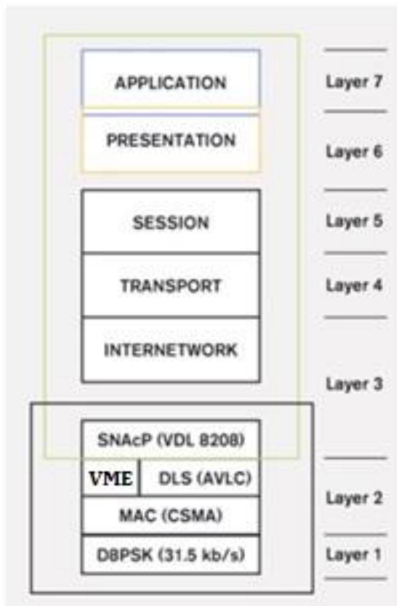


Figure 2 - VDL Mode 2 Protocol Stack [8]

At the physical layer, the binary data to be transmitted is scrambled for clock recovery and grouped into 3-bit symbols. The data is modulated as Differential-8 Phase Shift Keying (D8PSK) for transmission. The eight phases allow for three bits to be transmitted per symbol ($\log_2 8$), resulting in a bit rate three-times the symbol rate. The symbols are transmitted at a rate of 10,500 symbols/second. The resulting total bitrate of VDL Mode 2 is 31,500 bits/seconds. Raised-cosine filter pulse-shaping reduces inter-symbol interference. Reed-Solomon coding and parity check are utilized for forward error detection and correction.

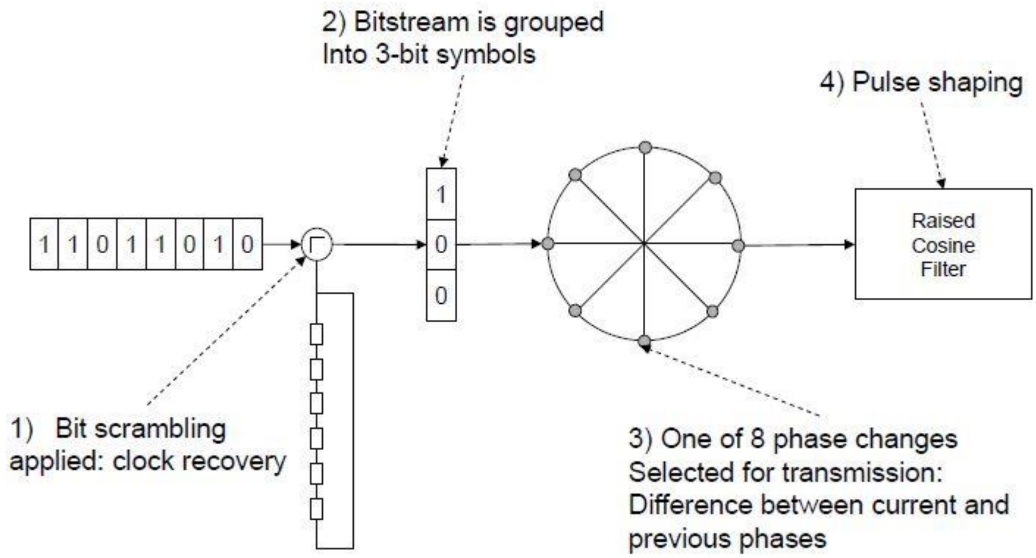


Figure 3 - VDL Mode 2 Physical Layer Operations [9]

The link layer is defined by the Aviation VHF Link Control (AVLC) protocol and the VDL Management Entity (VME). The AVLC protocol is derived from the ISO High-Level Data Link Control (HDLC) protocol. The main purposes of AVLC are to sequence the frames in proper order, handle addressing of the frames, detect errors in received frames, and schedule retransmissions and acknowledgements based on timers. The VME creates a Link Management Entity (LME) for each connection, where the LME then establishes and maintains the connection to peers. VDL Mode 2 is therefore mainly connection-based, unless the messages are broadcasted.

The link layer also includes a Multiple Access Control (MAC) sub-layer for random access to the channel by multiple transmitters, based on p-persistent Carrier Sense Multiple Access (CSMA). The CSMA protocol is responsible for determining when a message can be sent over the link. It listens in on the wireless channel and sends messages, with probability p, when it determines that the channel is available.

VDL Mode 2 only defines the Subnetwork Access Protocol (SNAcP) sublayer of the OSI network layer, which is the third layer. The employed protocol is the ISO 8208, which is the X.25 International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) protocol. “It provides packet exchanges over a virtual circuit, error recovery, connection flow control, packet fragmentation and reassembly, and Subnetwork connection management functions” [6].

Another important protocol is the ACARS over AVLC (AOA), defined in the ARINC 618 document. Inherently, it is not part of the VDL Mode 2 protocols, and it takes the place of the ISO 8208 protocol if AOA is operational. The purpose of AOA is to permit VDL Mode 2 radios to transmit legacy ACARS data. Backward compatibility allows for more cost effective transitioning to the newer technology, by providing a higher data rate of VDL Mode 2 to ACARS applications. As a result, less equipment has to be replaced, which makes it more cost effective to upgrade.

## 3. Systems

The major data communication systems between an aircraft pilot and the controller on the ground are denoted as FANS, which stands for Future Air Navigation System. The legacy systems that utilize ACARS are FANS 1/A, where FANS-1 is the standard of Boeing and FANS-A is the Airbus standard.

The FANS equipment onboard an aircraft include several avionics such as the VHF Data Radio (VDR), Communication Management Unit (CMU), Flight Management System (FMS), Electronic Flight Instrument System (EFIS), etc. The typical architecture is pictured in figure 4. The main concern in this thesis are the VHF Data Radio and the CMU where VDL Mode 2 is implemented, as well as their antenna.


Figure 4 - Typical FANS Architecture [10]

A recent upgrade to the FANS architectures, called FANS 1/A+, allows the utilization of VDL Mode 2 data radios. FANS 1/A+ provides an interim step to use existing ACARS applications over new VDL Mode 2 radios by operating on the AOA protocol, and thereby increase the transmission rate in a cost effective way.

However, the future of aeronautical datalink networking is in Aeronautical Telecommunication Network (ATN).

> The Aeronautical Telecommunications Network (ATN) was developed through the International Civil Aviation Organization (ICAO) to provide a more universally capable and reliable ATC data communications system. The version called ATN Baseline 2 will be needed for full participation in NextGen in continental U.S. airspace. The standards for this version are under development and are being harmonized internationally [11].

Both Boeing and Airbus have FANS systems that are compatible with ATN Baseline 1, which are collectively called FANS 2/B. These are already implemented in Europe with the Link 2000+ Programme. The implementation in the NAS has a different approach.

> The FAA published installation guidance on dual stack data communication capabilities in 2012. Dual stack aircraft have both Future Air Navigation System (FANS) 1/A+ and Aeronautical Telecommunication Network (ATN) Baseline 1 data link systems installed with the goal of seamless operations. The FAA is working with industry to revise installation and operational guidance for ATN Baseline 2, currently planned in 2014 [12].

The equipment that will support the ATN Baseline 2 networking is expected to be called FANS-3 and FANS-C, depending on the aerospace company [13].

## 4. Services and Implementation

A joint study was conducted by the FAA and EUROCONTROL in 2006 to plan the aeronautical data services and their required performance. Their findings were published in the Communications Operating Concepts and Requirements for the Future Radio System (COCR) document [14]. However, the timeline from the COCR was just an estimate and the actual implementations in Europe and USA took on different schedules, whereby Europe is ahead in implementing their data communication services by several years. The most recent roadmap for the implementation of data services in the NAS is shown in figure 5.

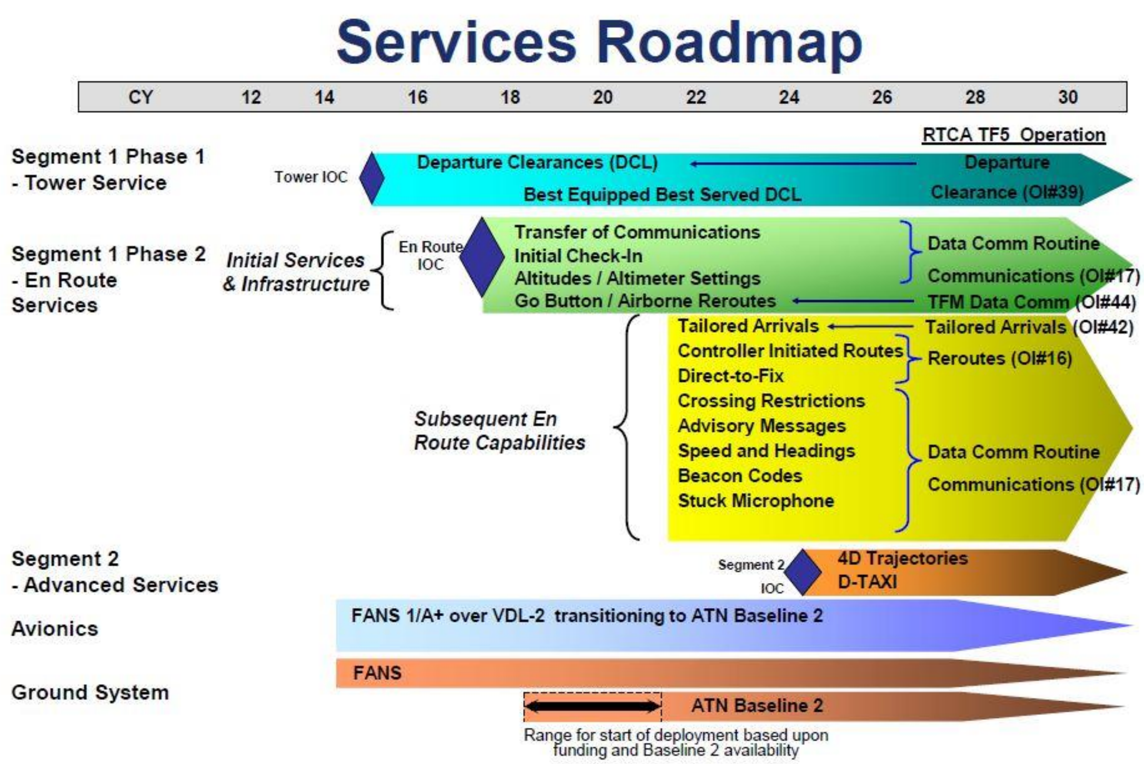


Figure 5 - Data Services Roadmap in the NAS [15]

The implementation of Data Comm data services is divided up into two segments. “Segment 1 will address tower services and upgrades to support data communications in the high-altitude environment, and Segment 2 will address terminal environment enhancements and Data Comm’s advanced capabilities” [11]. The Segment 1 services are further divided up into two phases and their details can be seen in figure 5. Since the implementation has been changed and delayed several times already, it can be expected that the roadmap is subject to change in the future. A selection of data services for FANS 1/A+ and the future ATN capable equipment is shown below.


Figure 6 - Data Comm services for FANS 1/A+ [16]

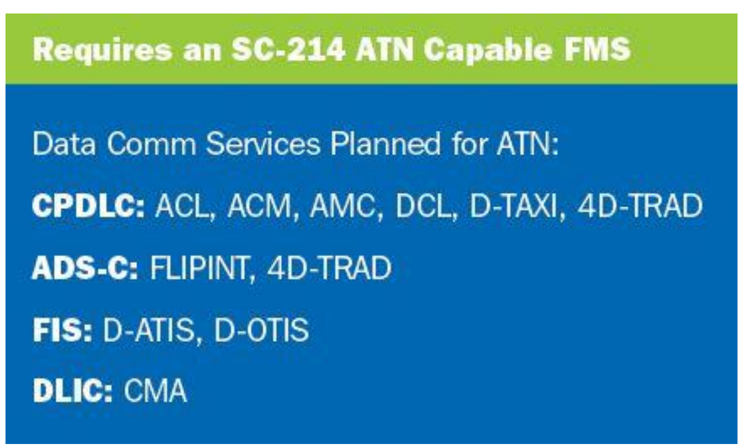


Figure 7 - Data Comm services for ATN [16]

# CHAPTER III

# VDL MODE 2 OPNET SIMULATION MODEL

The simulation model for evaluating the performance of VDL Mode 2 was developed at the NASA Glenn Research Center by Steven Bretmersky. The model is implemented in the OPNET® Modeler software package. The essential features of the VDL Mode 2 protocol stack are modeled by finite state machines in the C programming language, as well as the internal Kernel Procedures of the software.

## 1. Description of Protocol Model

The model is designed to simulate the most important features necessary for evaluating the capacity of VDL Mode 2. It is defined on three modeling domains: network, node, and process. The process domain is where the internal functions of each protocol are defined. The node domain connects these processes together at a higher level of abstraction. The node model can be considered as a top-level overview of the protocol layers, which is shown in figure 8 for VDL Mode 2.

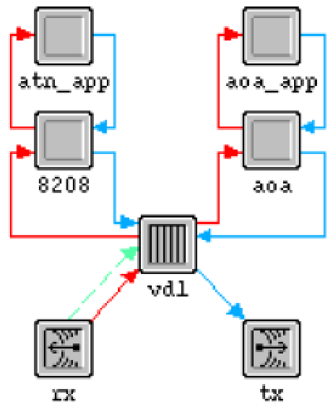


Figure 8 - VDL Mode 2 OPNET Node Model

The physical layer is defined in the *rx* and *tx* node blocks. Mainly the modulation and the transmit power are defined here, next to several other physical layer properties. The communication channel is simulated by pipeline stages. These are defined in special purpose files, which are assigned in the *tx* and *rx* blocks. The pipeline stages may multiply to provide specific properties for each receiver, which is shown in figure 9 for one transmitter with three receivers.

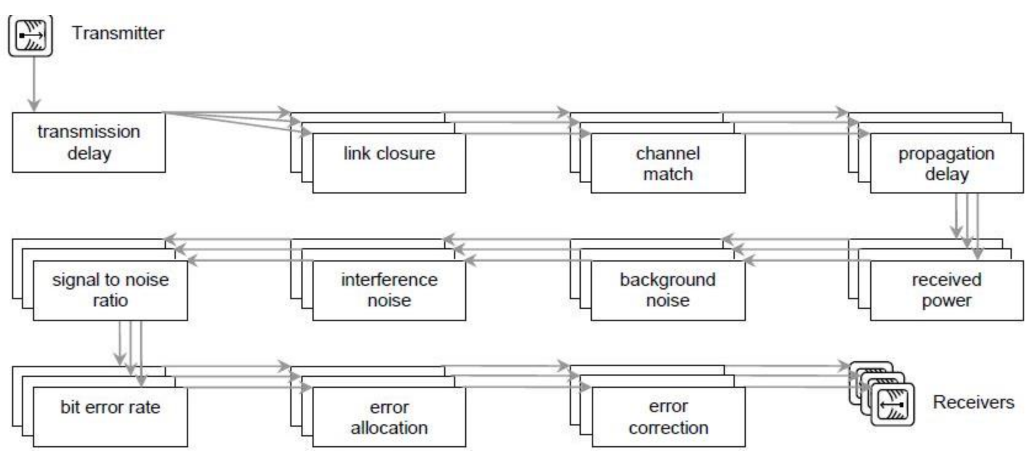


Figure 9 - VDL Mode 2 Pipeline Stages within Opnet [17]

The data link layer is entirely defined within the *VDL* node block. All the functions and procedures of the protocols are developed in the process domain, whereby each process model may have one or several child processes. The child processes can, in turn, have child processes as well. The interoperability of many processes allows the functionality of several protocols within a layer to be defined in only one node block. Figure 10 shows the main processes within the VDL node connected with data and control paths.

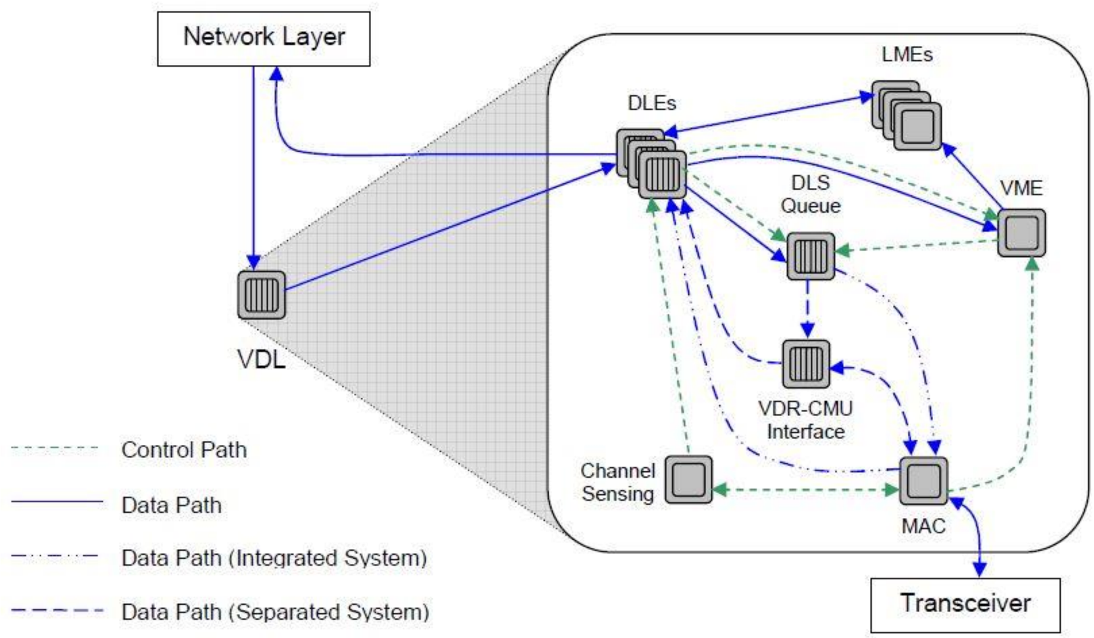


Figure 10 - Data link layer functions combined in one VDL node block [17]

The subnetwork layer is defined in the *8208* and *aoa* blocks, shown in figure 8. Only one of these blocks can be operational per radio, which is set before a simulation occurs. The layers above the subnetwork layer are not defined in detail, as they are not necessary for evaluating the capacity. Instead, the two *atn_app* and *aoa_app* application blocks simply create the services which produce stochastic data to be transmitted. The data services are based on assumptions, since accurate data is not available.

The parameters of the protocols and the hardware options were kept the same for every simulation to ensure that the results can be compared. Options that were changed were the ones tested for. The most important parameters are shown here:

| | |
|---|---|
| VDL | |
| Frequency | CSC |
| Mode 2 Parameters | (...) |
| MAC Parameters | (...) |
| TM1 (seconds) | 0.0045 |
| TM2 (seconds) | 60 |
| M1 | 135 |
| p | 13/256 |
| Frame Grouping | enabled |
| DLS Parameters | (...) |
| T1min (seconds) | 1.0 |
| T1max (seconds) | 15 |
| T1mult | 1.45 |
| T1exp | 1.7 |
| T2 (seconds) | 0.5 |
| T3min (seconds) | 6.0 |
| T3max (seconds) | 15 |
| T3mult | 1.45 |
| T3exp | 1.7 |
| T4 (minutes) | 20 |
| N1 (bits) | 8312 |
| N2 | 6 |
| k (frames) | 4 |
| Skip N2 Handoff | disabled |
| VME Parameters | (...) |
| TG1 (seconds) | 240 |
| TG2 (seconds) | 240 |
| TG3 (seconds) | Not Used |
| TG4 (seconds) | Not Used |
| TG5 (initiator) (seconds) | 20 |
| TG5 (responder) (seconds) | 60 |

| | |
|---|---|
| ISO 8208 | |
| 8208.DTE Address | Auto Assigned |
| 8208.DTE Facilities | (...) |
| Sequence Numbering | Normal |
| Packet Size (bytes) | 1024 |
| Window Size (packets) | 7 |
| Restart Request Timer | (...) |
| T20 (seconds) | 180 |
| R20 | 1 |
| Call Request Timer | (...) |
| T21 (seconds) | 200 |
| Reset Request Timer | (...) |
| T22 (seconds) | 180 |
| R22 | 1 |
| Clear Request Timer | (...) |
| T23 (seconds) | 180 |
| R23 | 1 |
| Window Indication Timer | (...) |
| T24 (seconds) | Disabled (Use A) |
| Window Rotation Timer | (...) |
| T25 (seconds) | Disabled |
| R25 | 0 |
| Interrupt Timer | (...) |
| T26 (seconds) | 180 |
| Reject Timer | (...) |
| T27 | 60 |
| R27 | 0 |
| Fast Select | Enabled |
| 8208.Logical Channels | (...) |
| Two-way LTC | 1 |
| Two-way HTC | 4095 |
| tx.channel [0].power | 20 |

Figure 11 - VDL Mode 2 simulation parameters

At the highest level of abstraction is the network domain. Entire systems are usually defined there, such as a data radio or a router. The network domain allows for practical development of simulation scenarios with different settings by reusing the lower level blocks in different configurations. The main model at the network layer is the service volume. The service volume is the enclosed 3D sector, within which the aircraft are communicating with the ground station. A typical service volume is shown in figure 12. The circle defines the boundary of the sector within which the aircraft are flying. All the other objects are stationary. The antenna of the VDL ground station is located at the center, with the ground station communication infrastructure connected to it. An important feature is that the ground antenna is at 15.24 meter (50 feet) altitude, while the aircraft are at a much higher altitude. In this thesis the altitude of the aircraft is set at 10,000 meters (33k feet) altitude.

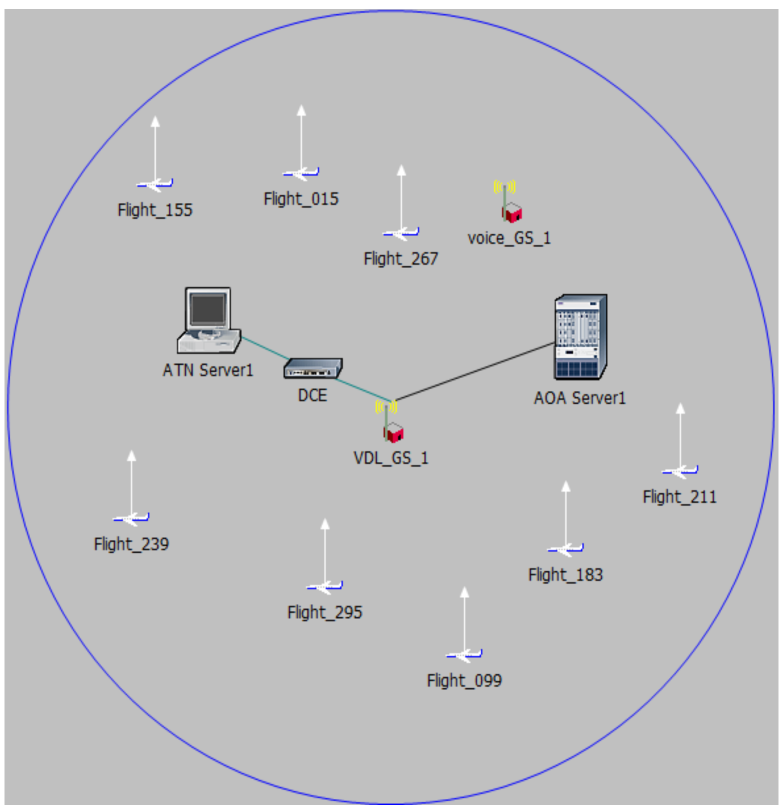


Figure 12 - Service Volume

## 2. Propagation Model

Next to the protocol stack, the other main property which determines the performance of a wireless communication system, and thereby also the capacity of VDL Mode 2, is the radio signal propagation through the wireless channel.  The propagation of a wireless signal is calculated using the link budget formula:

$$P_r = P_t G_t G_r * Path\ Loss$$

$P_r$ = received power

$P_t$ = transmit power

$G_t$ = transmitter antenna gain

$G_r$ = receiver antenna gain

| **TRANSMITTER** | **Unit** | **Ground** | **Air** |
|---|---|---|---|
| Transmit Power | dBm | 43.01 | 43.01 |
| Transmit Antenna Gain | dBi | 2.1 | -4 |
| Transmit Line Losses | dB | 3 | 3 |
| Transmit EIRP | dBm | 40.86 | 40.86 |
| **CHANNEL** | | | |
| Frequency | MHz | 137 | 137 |
| Excess Path Loss | dB | 4.5 | 4.5 |
| **RECEIVER** | | | |
| Receive Antenna Gain | dBi | 2.1 | -4 |
| Receive Line Loss | dB | 3 | 3 |
| Receiver Noise Figure | dB | 10 | 14 |
| Receiver Noise Power Density | dBm/Hz | -164 | -160 |
| External Noise Figure | dB | 20 | 20 |
| External Noise Power Density | dBm/Hz | -154 | -154 |
| Total System Noise Power Density | dBm/Hz | -156.2 | -155.2 |
| Total System Noise Power in 10.5 kHz | dBm | -116 | -115 |
| **LINK REQUIREMENTS** | | | |
| Raised Cosine Filter Loss | dB | 1.8 | 1.8 |
| Transmitter Implementation Loss | dB | 1 | 1 |
| Receiver Implementation Loss | dB | 1.2 | 1.2 |

Table I - Link Budget Data

The link budget formula estimates the received power based on the transmit power, the gain of the antennas and the path loss. The detailed link budget parameters are shown in table I. The path loss of the radio signals can be approximated in certain settings with a free space model using the following equation:

$$\left(\frac{\lambda}{4\pi d}\right)^2$$

$\lambda$ = wavelength

$d$ = separation between transmitter and receiver in same unit as wavelength

The AMCP, which also defined VDL2, has proposed a more accurate propagation model for the VDL technology in the VHF band [18]. The model is based on a multipath propagation principle. It features two paths, also called rays. The first ray is direct, while a second bounces off the ground before reaching the same point, to add on to the total signal received. The basic budget equation for calculating the received power is the same as with a free space model, except that the calculation of the path loss is different. The equation for the path loss is the squared magnitude of the transfer function:

$$|H_{LS}(f,t)|^2$$

Whereby the transfer function $H_{LS}(f,t)$ is the following [18]:

$$H_{LS}(f,t) = \frac{\lambda}{4\pi} g_{T\max} g_{R\max} \left\{ f_T^{Dir} f_R^{Dir} \frac{e^{-jkr_D}}{r_D} + \rho R_{Vert.Smooth} f_T^{Ref} f_R^{Ref} \frac{e^{-jkr_R}}{r_R} \right\}$$

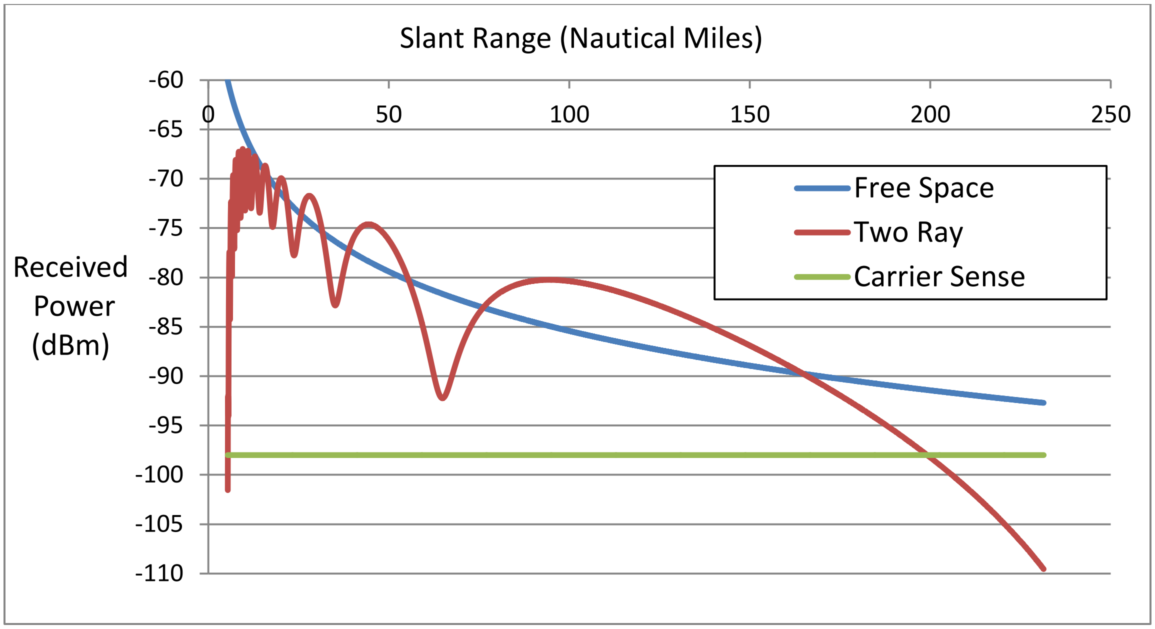


Figure 13 - Received power with transmitter at 50ft and receiver at 33k ft (cuts off at radio horizon)

A comparison between the received power of the free space model and the two-ray model is shown above in figure 13. What both of these models show is that the received power essentially decreases with more distance. However, the received power in the multipath model fluctuates due to constructive and destructive interference. The main source of distortion for VHF Digital Link (VDL) systems is the multipath propagation [18].

The two-ray model from AMCP is the main model used for evaluating results in this thesis. Real world measurements have shown that the two-ray model is much more accurate at predicting the received power than the free space model. The free space model is still used in some cases for comparison purposes, and to potentially draw more insights to the results. The straight carrier sense line represents the minimum -98 dBm at which the CSMA protocol senses a busy signal in the channel.

Another critical feature of the propagation model is the line of sight (LOS). The VHF radio signal travels with the LOS to the horizon of the Earth. However, the maximum propagation distance generally turns out to be greater, due to the refraction of the radio signal. The signal is bent depending on the properties of the atmosphere.

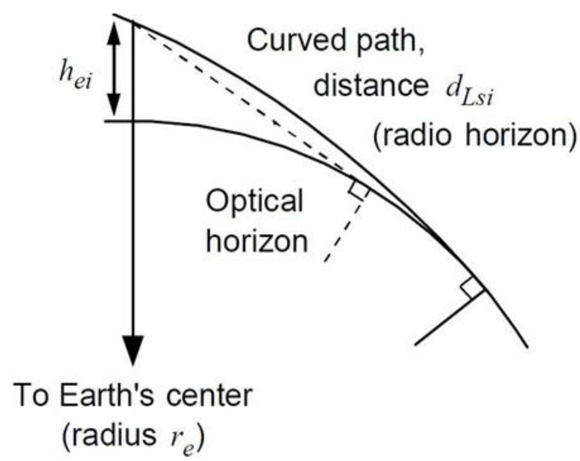


Figure 14 - Radio horizon and optical horizon [23]

A typical way to take the refraction into account is to scale the radius of the earth by 4/3, which is called the k factor. The factor does change with weather, and different locations exhibit different refractive properties, hence the maximum distance is variable. The maximum distance of the radio signal is called the radio horizon. The maximum LOS between two objects comes from calculating the radio horizon of each object and adding them together. The LOS in this thesis refers to the radio line of sight, which includes the refractive k factor. All simulations are executed with the k factor of 4/3.

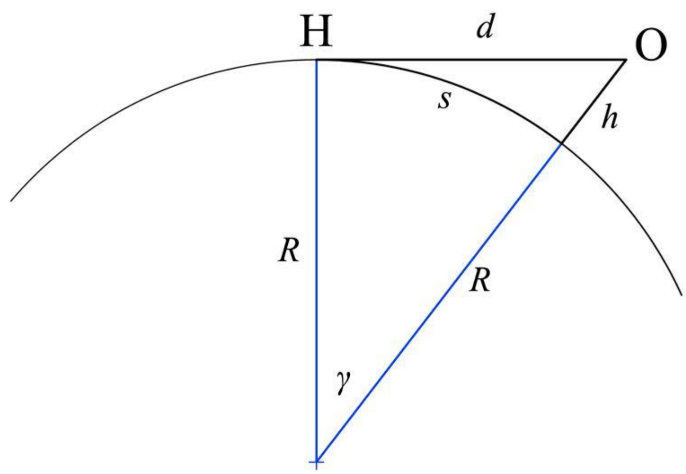


Figure 15 - Geometric Distance to Horizon [19]

$$\boldsymbol{d = \sqrt{(2 * R * k + h) * h}}$$

d = Distance to horizon

R = Radius of Earth (6378 km)

h = Height of transmitter

k = Earth radius factor (4/3) (varies based on weather conditions and location)

Figure 16 - Maximum LOS between two transceivers includes radio horizon of both

The simulation setting is on a spherical model of the Earth with a radius of 6378 kilometers. The ground is set to be smooth and dry everywhere for ease of evaluation and shorter computation time. The costly terrain module for detailed modeling of ground characteristics was not available for the studies in this thesis.

## 3. Frequency Reuse Simulation Scenario

The main means of increasing the capacity of VDL Mode 2 is the cellular frequency reuse principle. Frequency reuse is an arrangement of clusters of cells, which allows sets of frequencies to be reused. This particular arrangement of cells is regularly used by cellular phone networks, and is the actual reason why cell-phones are named as such. A cluster of cells is arranged in a way to avoid interference between cells that are on the same frequency. One or several cells on a different frequency are placed in between the cells of the same frequency to prevent the signals from reaching each other. Figure 17 shows one type of cellular frequency reuse configuration, where the red cells are on the same channel, i.e., frequency. Interference which does occur is termed co-channel interference.

One major difference between frequency reuse for the cellular phone and aeronautical communication is that the users, in this case the aircraft and aircrew, are usually at a very high altitude. For this thesis, which focuses on the en-route domain of flight, the aircraft are always at high altitude. This makes the analysis in many cases different from cell-phone frequency reuse.

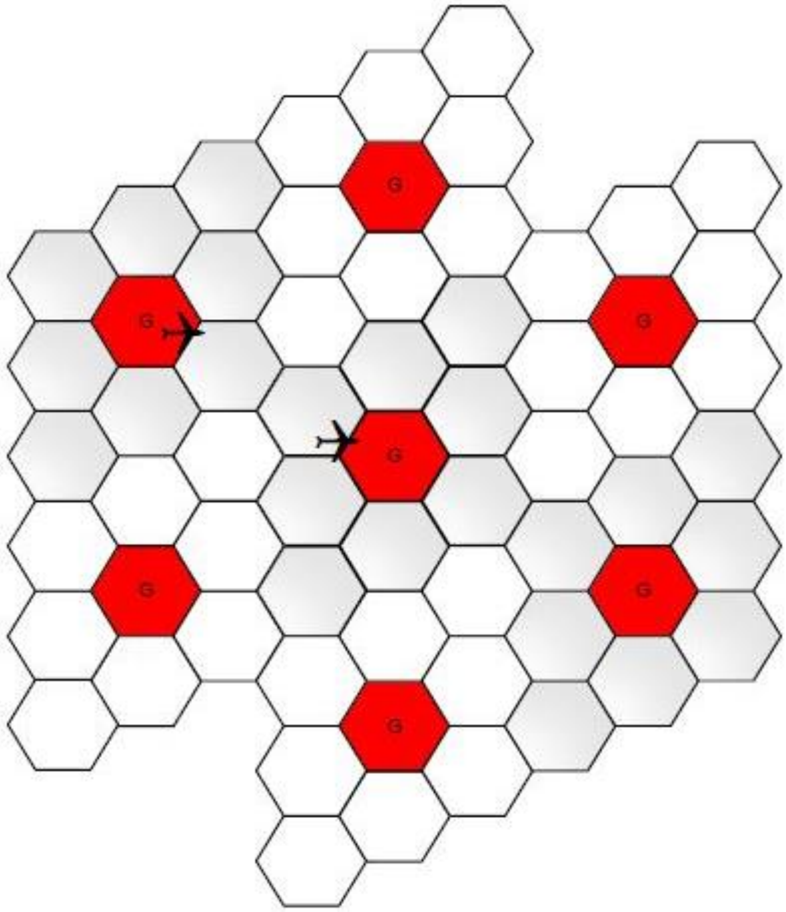

Figure 17 - Frequency reuse principle: red cells are on the same frequency [21]

To simplify the model of the frequency reuse configuration, all the cells were modeled by circles instead of hexagons as shown in figure 18. The frequency reuse configurations in the simulation does not include cells on a different channel, since the assumption is that proper frequency planning was conducted, and therefore inter-channel interference from nearby cells is not significant. Only the Tier 1 co-channel cells were simulated, that is, only the closest cells operating on the same channel.

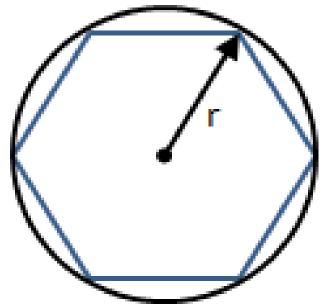


Figure 18 - Circumscribed hexagon with radius r as service volume in simulations

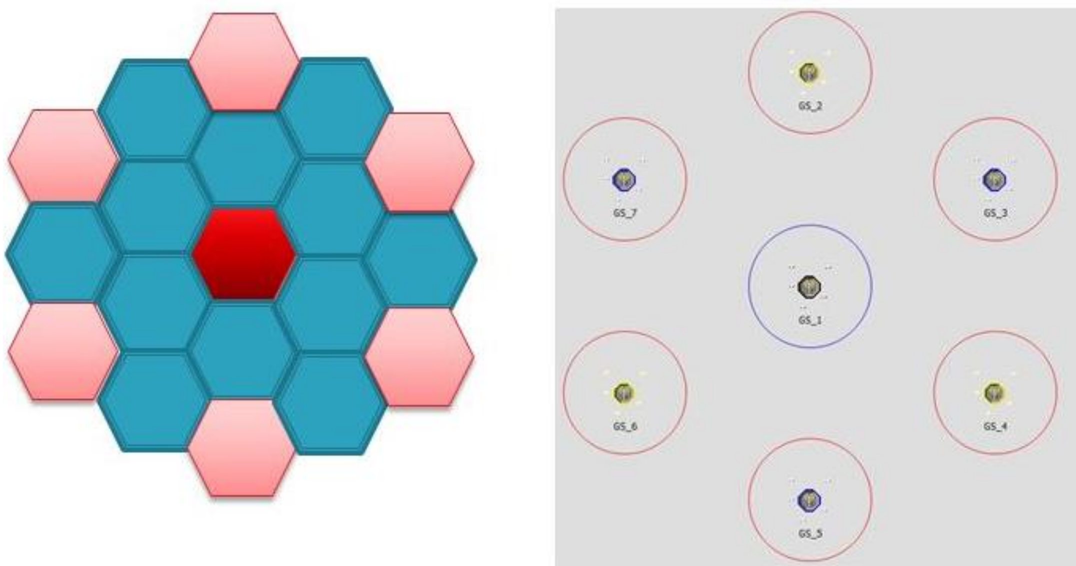


Figure 19 - Frequency reuse in theory (left) and simulation (right)

## 4. Scientific Integrity of Simulations

To ensure the validity and scientific accuracy of the simulation results, important simulation procedures and guidelines are followed. The most important guidelines are from *On Credibility of Simulation Studies of Telecommunication Networks* [20].

The main way of establishing credibility of the simulation results is to use a valid simulation model and also ensure that the model is used in valid experiments. The validity of the model is established by utilizing a mathematical propagation model that is credible and aligns with real-world results. Moreover, the hardware and protocol models that simulate the actual devices are as accurate as necessary. Valid experiments are ensured by understanding how the model operates and by developing scenarios which produce results with the least amount of ambiguity. Some assumptions have to be made when no real-world data is available. The assumptions are stated and evaluated as to how they affect, or would affect the results.

The simulations are all steady-state based. Each simulation is executed for 15 hours of simulation time, and results from the first 10 minutes are removed to get rid of the transients. The data is evaluated based on all the results obtained, starting at the 10 minutes and ending at 15 hours, to have sufficient samples for statistically valid results.

Due to the large amount of simulations required to execute, an optimized approach was developed for finding statistically accurate results with less computation time. To get shorter computation times, the approach is to initially execute simulations with only one seed value, in order to pinpoint the settings where results can be found. Once a good range for results was established, the settings are executed with 5 different seed values and with a Pseudo-Random Number Generator (PRNG) called Mersenne-Twister. Mersenne-Twister has excellent statistical properties with an astronomical cycle of $2^{19937}$-1, ensuring that the random numbers do not repeat within the simulation time.

# CHAPTER IV
# PROBLEM IDENTIFICATION AND ANALYSIS

Currently there is only one channel available for VDL Mode 2 in the USA NAS, but more will be allocated in the future as VDL Mode 2 becomes more prominent. Although 760 channels appears to be a sufficient amount, the spectrum is still congested with ATC and AOC voice channels, AOC data channels, emergency and guards channels, etc. Every additional channel needed for VDL Mode 2 means that another channel must be removed. Therefore, measures are being undertaken to minimize the amount of needed channels.

Several simulations of the VDL Mode 2 protocol involving the entire NAS have shown that under the currently planned number of assigned channels, the capacity which meets the required transmission delays would be low and further measures should be implemented to improve it. The main measure consists of dividing large areas of the NAS based on the frequency reuse principle. This allows the same frequency to be reused, which cuts down on the amount of needed channels for nationwide coverage.

However, a low amount of channels requires the co-channel service volumes to be close together, causing a lot of interference. Besides interference, the other main issue that takes a toll on the delay times is the hidden node problem.

## 1. Hidden Node Problem

One of the major causes of high delay times is the result of a phenomenon called hidden node problem in the networking literature. This is a major drawback of the CSMA protocol used in VDL Mode 2. The main feature of CSMA protocol listens to the channel to determine if the channel is available. If the channel is available, it sends a message (with probability p). If the channel is busy it waits a designated time and checks again. The problem arises when there are more than two nodes and not all nodes "see" each other. An example is shown in the following figure, where both of the airplanes see the ground station. However, the airplanes do not see each other and cannot detect when the other airplane is sending. This often results in both airplanes transmitting at the same time, since they sense that the channel is available. But the signal arriving at the ground station is two messages that are overlapped and garbled.

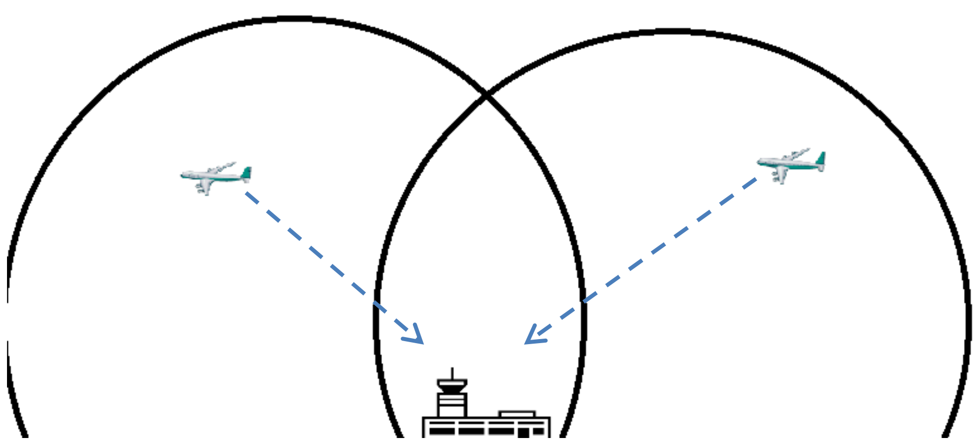

Figure 20 - Hidden node problem

## 2. Co-channel Interference

The other main cause of high delay times comes from co-channel interference which results in retransmissions. Only non-foreign sources of interference will be looked at here, meaning only interference coming from VDL Mode 2 radios. There are several different scenarios where this interference occurs and the fundamental ones are described here.

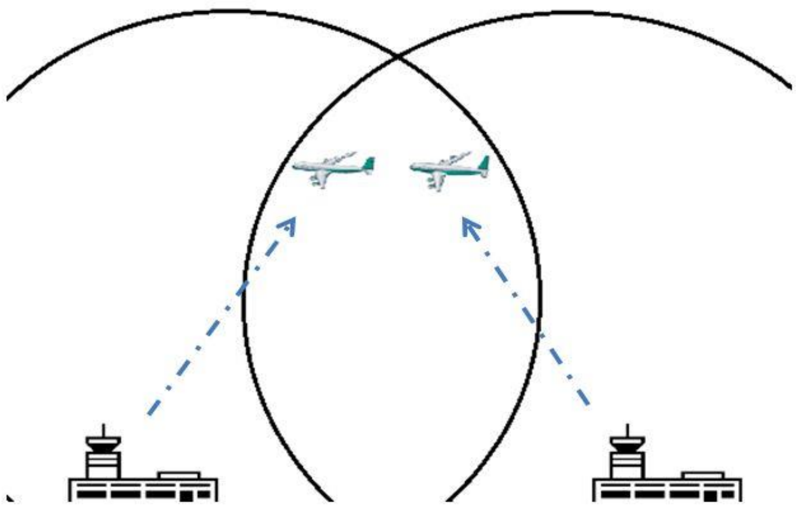

Figure 21 - Two ground stations are trying to transmit to two different airplanes, but since their coverage overlaps and are on the same frequency, they will interfere with each other.

In most cases, the range of coverage of a ground station does not reach the other ground stations. However, there can be areas where their coverage overlaps in the air. Figure 21 shows one such scenario. The circles represent the range of coverage of the transmitting entity, in this case the two ground stations. This is again a case of the hidden node problem. It is designated as co-channel interference because the airplane to which a ground station wants to communicate is within its own service volume, while the second airplane is within a different service volume. The ground stations are trying to transmit to two different airplanes, using the same frequency at the same time. If the SIR (Signal-to-Interference Ratio) at the designated receiving airplane is too low and hence the BER (Bit Error Rate) too high to properly decode and correct the data, the faulty messages will be dropped and will have to be retransmitted. This inevitably results in higher delay times. A possibly exists that the interference is above -98 dBm, where the CSMA would detect a busy channel and wait for another try. This is more favorable than simply interference, since the delay is less compared to retransmissions.

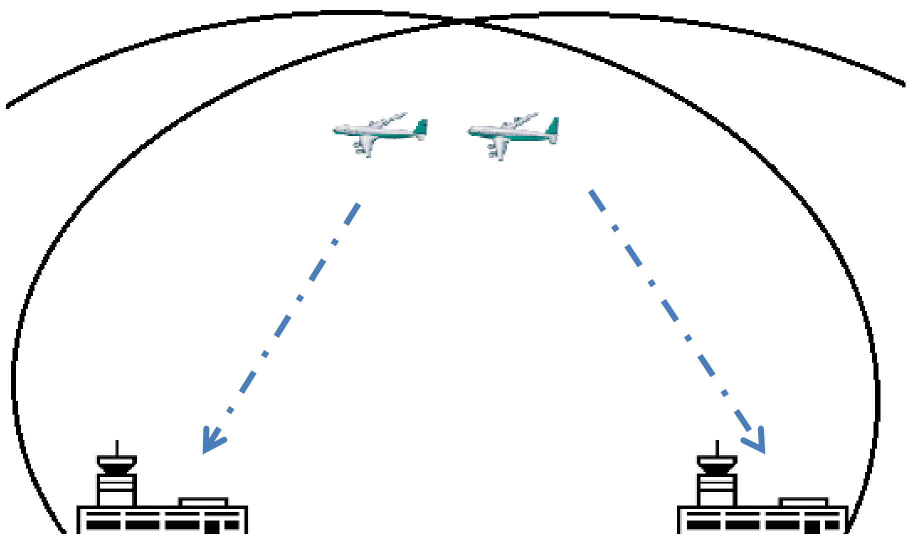

Figure 22 -Downlinks from both airplanes are interfering with each other

In figure 22, there are two airplanes that are trying to transmit data packets at the same time and on the same frequency to two different ground stations. The circles represent each of their ranges of coverage. It shows that the airplanes can “see” each other and they also both see the two ground stations. There are two possible events here which will result in increased delay times. In the first case, the two airplanes try to transmit at the exact same time. Due to the propagation delay, the signal may not arrive fast enough for CSMA to detect a busy channel. Both airplanes would then have to retransmit. In the second possibility, where there is a slight time difference between the transmissions, one of the airplanes will not transmit immediately. CSMA will sense a busy channel and wait a certain time before trying to transmit. This is minimal delay compared to a retransmission. But there is still a chance that interference will occur on subsequent attempts.

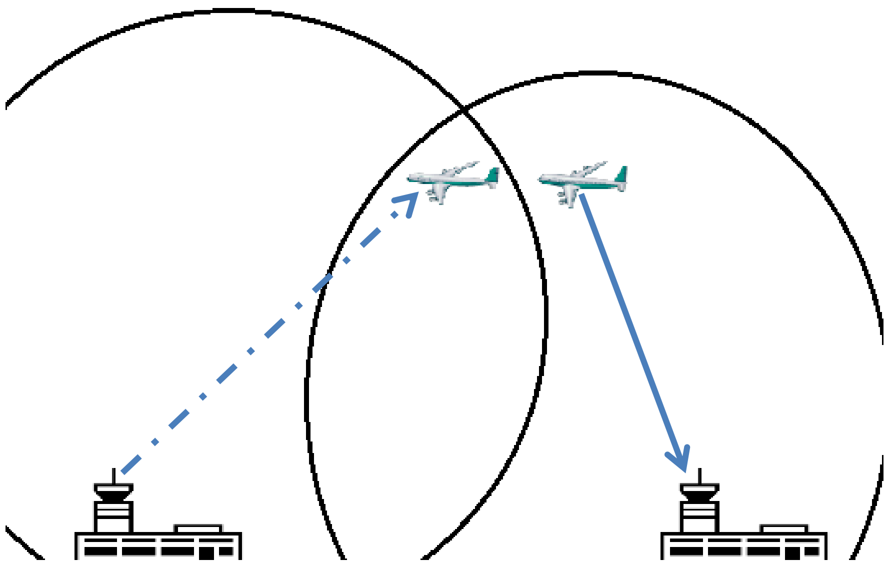

Figure 23 - Uplink to the left airplane is interfered due to the downlink transmission of the right airplane

In figure 23, one of the airplanes is receiving a signal from a ground station, while the other is transmitting down to a different ground station. The left circle represents the coverage of the left ground station, while the right circle is the coverage of the right airplane. In this scenario, there will not be interference on the downlink from the right airplane, since the coverage of the left ground station does not reach the other ground station.  But there will be interference on the uplink to the left airplane because it will receive the signal from both, its ground station and from the second airplane. The CSMA protocol will not be able to detect a foreign transmitting signal on either of the transmissions, because it cannot sense that the other object is transmitting. This is again also a case of the hidden node problem.

## 3. Thesis Statement

The main purpose of the thesis is to test three different methods of improving capacity for VDL Mode 2 in the frequency reuse configuration: transmit power control, load regulation and ground station placement. All three will attempt to mitigate the hidden node problem and the co-channel interference. Preventing the main issues would increase the capacity. The goal is to determine if the methods can improve the capacity in a significant manner for implementation in the National Airspace System.

A secondary purpose of the thesis is to find methods of making the simulation model more accurate for evaluating the capacity. This will make future studies more accurate.

# CHAPTER V

# CAPACITY OF VDL MODE 2: EVALUATION AND RESEARCH

The capacity of VDL Mode 2 is here defined as the maximum amount of aircraft within a service volume that can successfully meet the required communication standards. The capacity varies depending on the amount of data traffic. The data traffic for this thesis is defined by the data services offered in the Segment 1 implementation of NextGen Data Comm services.

## 1. Capacity Evaluation

The main criterion for evaluating the capacity of VDL Mode 2 is the 95$^{th}$ percentile of transmission delays. The COCR V2.0 document defines the required transmission delays for Future Radio Systems (FRS). The delay times for FRS are defined for the bottom two layers of the protocol stack and the subnetwork layer. Therefore, from the beginning of either the ISO 8208 or AOA subnetwork at the transmitter to their counterpart at the receiver. The next figure shows this specification for the ATN protocol stack and compares it to the OSI reference model, as well as the IPS (Internet Protocol Suite) stack.

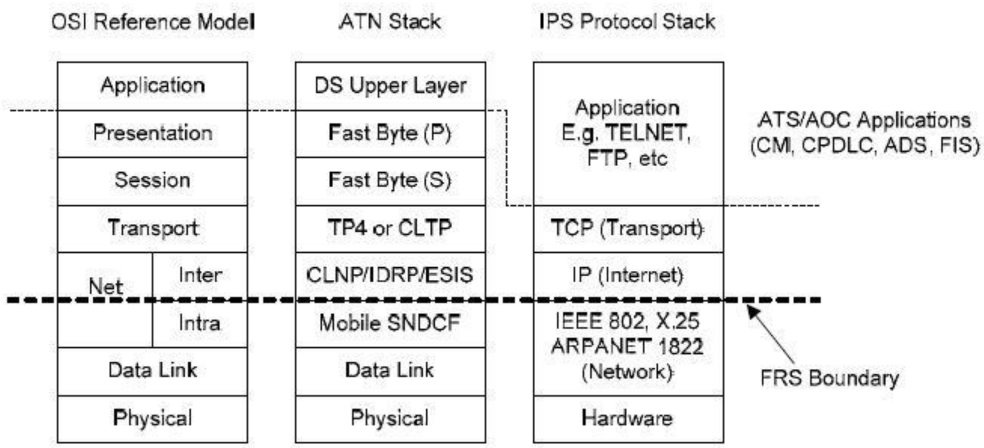


Figure 24 - FRS Boundary [14]

The COCR document defines the communication standards for many services, whereby only a subset of them will be implemented for VDL Mode 2. The capacity of Segment 2 implementation of Data Comm will be lower than Segment 1, because more services are added and hence more data is required to be transmitted. The focus here is on those services which will be offered in the Segment 1 of NextGen Data Comm.

The delay times for the data services are generally set depending on the service priority. The delay times for the high priority ATC services have to stay within a 3.8 second limit for the 95$^{th}$ percentile of total data traffic delays, as defined by the COCR. Medium priority data has a higher limit at 4.7 seconds. The lower priority data traffic tolerates up to 13.6 seconds at the 95$^{th}$ percentile.

As far as the VDL Mode 2 protocols are concerned, the physical layer, together with the CSMA protocol at the link layer are the most critical components that determine the capacity. These determine how much data can be sent reliably over the channel and how multiple transceivers share the channel. However, improving the capacity of the

VDL Mode 2 protocols would generally involve changing the international standard, which is not likely to occur. That is why it is important to also look at possibilities of implementing the existing protocols and hardware more efficiently.

## 2. Literature Review

There were several studies conducted and research papers published for improving the capacity of VDL Mode 2. The study titled *Evaluating VDL Mode 2 Performance Through Simulation* evaluated the capacity based on different subnetwork parameters of VDL Mode 2 protocols [22]. The research concluded that it would be optimal to adjust the parameters based on the amount of aircraft served using the Link Parameter Modification command from the ground.

EUROCONTROL conducted a study of VDL Mode 2 capacity with one channel [23]. Some of its findings for increasing the capacity include airborne Hand-Off algorithm improvement and allocating separate channels for the en-route and airport area domains. Another suggestion is to simply make the specifications more tolerant to delays, by increasing the $95^{th}$ percentiles.

One more simulation study at NASA looked at implementing Prioritized CSMA (PCSMA) to improve the capacity of VDL Mode 2 [24]. The drawback here is that a fundamental VDL Mode 2 protocol would have to be changed. The issue is even greater when one considers the amount of VDL Mode 2 already in service, which would have to be either replaced or upgraded.

# 3. Evaluation of Possible Capacity Improvements

Three different methods will be evaluated in this thesis for improving the capacity of VDL Mode 2. The goal is to reduce the $95^{th}$ percentile delay times as much as possible for the existing data traffic, which can then potentially allow for a higher amount of data traffic to meet the required standards and hence increase the maximum capacity.

However, the quality of the method depends on more than just the improvement of capacity. The main concern is the cost effectiveness of actually implementing the improvements. Although no actual cost calculations will be undertaken, some statements will be made as to what would it take for implementation, such as buying new hardware, or upgrading existing equipage.

Another major difficulty would be in changing the existing VDL Mode 2 standards. It would have to be internationally recognized and accepted, which is not a simple task. Therefore, the proposed approaches for improving the capacity will emphasize on the possibility of implementation with the existing VDL Mode 2 standards.

# CHAPTER VI

# GROUND STATION PLACEMENT

The proper placement of ground stations operating on the same channel is crucial for capacity. If co-channel ground stations are spaced sufficiently far apart, where the signals within a service volume do not interfere with the transmissions in co-channel service volumes, the capacity can be fully optimized. But when the ground stations are too close together, the interference is significant and severely lowers the capacity. The big issue is that placing ground stations sufficiently far apart, where there is no co-channel interference, requires a very large amount of channels. Therefore it is important to look at cases in the mid-range, with fewer channels, and therefore with less than perfect ground station placement.

## 1. Theory and Hypothesis

The interference between two co-channel service volumes can be categorized in five different cases. The first is the worst case scenario, where the ground station can reach the co-channel ground stations as well as most of the aircraft within co-channel sectors. This results in the least capacity. The second case, which results in better capacity, is when the ground station signal is out of LOS of the co-channel ground stations, while still reaching some co-channel airplanes.  This is a typical case with few channels available for frequency reuse. The third case is when ground stations cannot reach the co-channel ground stations and also cannot reach any of the co-channel airplanes. This will often be the best practical implementation, because it does not require a very large amount of channels and good capacity results can be obtained. The most optimal configuration is when the transmissions of the ground stations and of all the aircraft operating within the service volume cannot reach any receiver in co-channel service volumes.

| **Transmitters within service volume** | **Reach co-channel ground station** | **Reach co-channel airplanes** | **Degree of co-channel interference** |
|---|---|---|---|
| Ground station and airplanes | Yes | Yes | Worst case |
| Ground station and airplanes | No | Yes | Bad to good case |
| Only Airplanes | No | Yes | Best practical case |
| None can reach | No | No | Best case scenario: No Interference |

Table II - Interference between co-channel transmitters

These listed cases are the fundamental cases, but each of them also has varying degrees of possible co-channel interference. For example, it may be that a ground station has LOS to only a few co-channel airplanes or many, depending on how far apart they are spaced and the probability of where the airplanes are flying. It also depends on the intensity of the interference, and if the interference triggers the carrier sense of CSMA, or not.

In the theoretical frequency reuse configuration, the distance between ground stations is determined by the following equation:

$$d = r\sqrt{3 * R}$$

*d* = distance between ground stations

*r* = service volume radius

*R* = reuse factor

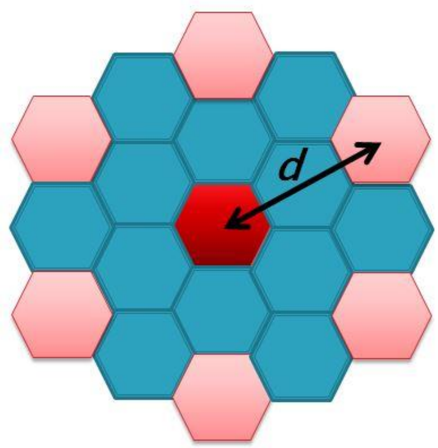


Figure 25 - Distance between ground stations (center-to-center of service volume)

The equation shows that the service volume radius and the reuse factor determine how far apart the ground stations can be placed. What also becomes apparent is the significant impact of the service volume radius on the distance between co-channel ground stations. The hypothesis of this experiment is the following: by simply changing the size of the service volume the capacity can be significantly altered, even with the same amount of channels.

## 2. Simulation Experiment

Several different reuse factors were selected for testing the ground station placement, which were 4, 7, 13, and 25. These provide good representations of the ground stations being close together and also further apart. At each of these reuse factors, four different service volume sizes were tested: 60 NM, 80 NM, 100 NM, and 120 NM. The purpose of the different service volume sizes is to determine how much of an impact they make on the capacity. Based on these selections, the total simulation scenarios resulted in 16 different test cases, for which the capacity had to be determined.

## 3. Results and Analysis

| Reuse Factor | Service Volume Size | Capacity |
|---|---|---|
| 4 | 60 | 12 |
| | 80 | 15 |
| | 100 | 20 |
| | 120 | 28 |
| 7 | 60 | 18 |
| | 80 | 23 |
| | 100 | 50 |
| | 120 | 79 |
| 13 | 60 | 29 |
| | 80 | 94 |
| | 100 | 100 |
| | 120 | 92 |
| 25 | 60 | 120 |
| | 80 | 110 |
| | 100 | 100 |
| | 120 | 90 |

Table III - Capacity results with two-ray model

The resulting capacities of the simulations are shown in table III. As can be seen, the capacity can vary significantly by simply changing the service volume size. The simulation results with the lower amount of channels of 4, 7, and especially 13, show that increasing the service volume radius can have a major impact on capacity. The capacity of frequency reuse 13 and service volume radius 100 NM, can handle a capacity of 71 more aircraft, than with a service volume radius of 60 NM. This is a significant improvement with over 300 percent higher capacity.

| Reuse Factor | Service Volume Size | Capacity |
|---|---|---|
| 7 | 60 | 22 |
| | 80 | 24 |
| | 100 | 46 |
| | 120 | 70 |
| 13 | 60 | 24 |
| | 80 | 72 |
| | 100 | 76 |
| | 120 | 76 |

Table IV - Capacity results with free space model

The same scenarios were also evaluated with the free space model. Although the overall capacities were lower, the improvement was still over 300 percent. The results for reuse factors 7 and 13 with the free space model are shown in table IV.

Another just as important observation is with the larger frequency reuse factor of 25. The capacity results are actually better with a smaller service volume radius. The large amount of channels allows ground stations to be placed sufficiently far apart to where, even a radius of 60 NM, a lot less co-channel interference occurs. Smaller service volume sizes at the greater reuse factors increase the capacity because the hidden node problem is less likely to happen. With larger service volume size there is a greater possibility that airplanes do not see other airplanes transmitting, as the received power is more likely to drop below -98 dBm. The hidden terminal problem also occurs due to the longer propagation delay between aircraft flying at the outer edges, where the signal is not fast enough to detect a busy channel.

Another major reason for lower capacity is that larger service volume sizes make the airplanes cross a section where the destructive interference of the signal is significant. This section is located between 60 and 80 nautical miles. Results have shown a significant amount of retransmissions in this area, indicating a Prolonged Loss of Communication (PLOC). This is a phenomenon which has been often reported for voice communication and ACARS, but it has not been researched or documented for VDL Mode 2. It should, however, be an important subject of research.

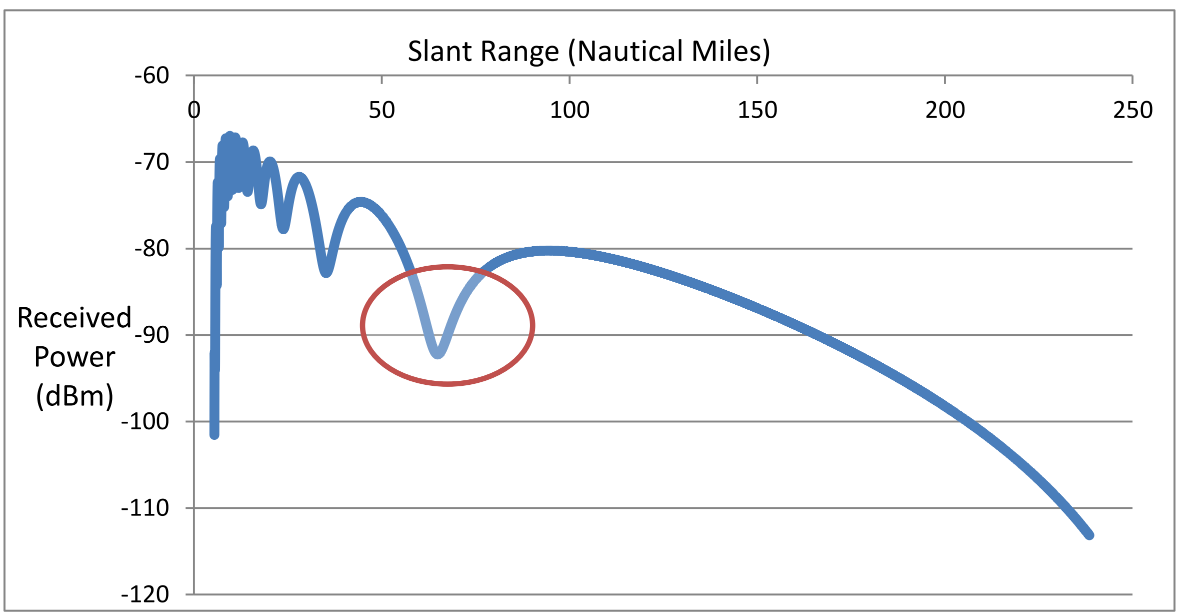


Figure 26 - Heavy destructive interference area

# CHAPTER VII
# LOAD REGULATION

The significant property of aeronautical communication with VDL Mode 2 is that one main transceiver with an antenna is stationary at a low altitude, while there are multiple mobile transceivers usually at a much higher altitude trying to communicate with it. The stationary transceiver is the ground station, which is generally located at the center of the service volume. The mobile transceivers are aircraft with VDL Mode 2 capabilities that vary their geographical locations as well as the altitude. The location of the aircraft with reference to the ground station has a significant impact on the received power as well as the SNR. This part of the research for capacity will focus on evaluating how the data is transmitted with respect to the location of the aircraft with reference to the ground station.

## 1. Hypothesis

Based on the two-ray propagation model, it is apparent that transmissions that occur in closer proximity between ground and aircraft will have a higher received power. Also, there will generally be less interference in the vicinity of the ground stations then on the outer borders of the service volume. When the aircraft are at the outer borders of the service volume and at high altitude, they are the most likely to cause co-channel interference. As a matter of fact, these are the main causes of co-channel interference and the MASPS calls these the "Critical Points" as shown in figure 25. From this, it can be deduced that the capacity will be more optimal when messages are more likely to be transmitted at times when the aircraft are within the vicinity of their designated ground station.

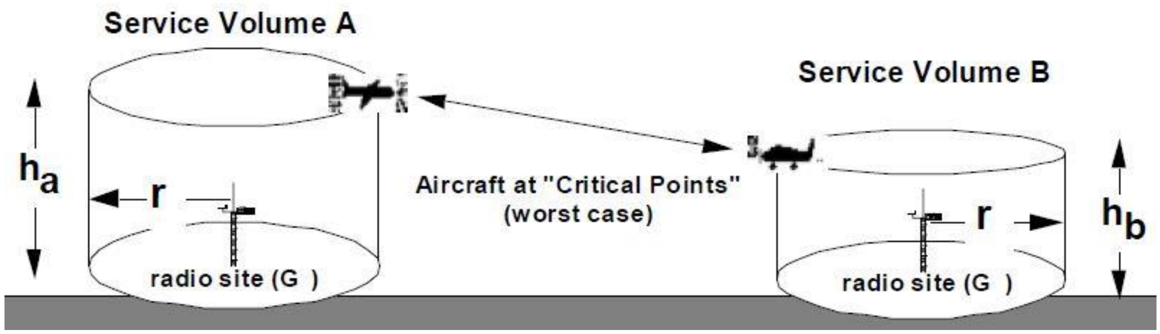


Figure 27 - Aircraft at Critical Points [5]

## 2. Simulation Experiment

The overall data traffic generated per aircraft is a combination of all the offered data services. The transmission times for each service are determined by Poisson distributions with various mean values in the simulation. However, the generated data is not directly correlated to the distance between the aircraft and ground stations. Instead, the movement of airplanes within their service volume determines if more data will be sent when the airplanes are closer or further to the ground station.

Based on a random movement of aircraft with a normal distribution within a service volume, the aircraft is more likely to be located on the outer areas, since there is more area. This causes many more messages to be sent when the aircraft is far from the ground station. A histogram of the sent messages was compiled and can be seen in figure 28.

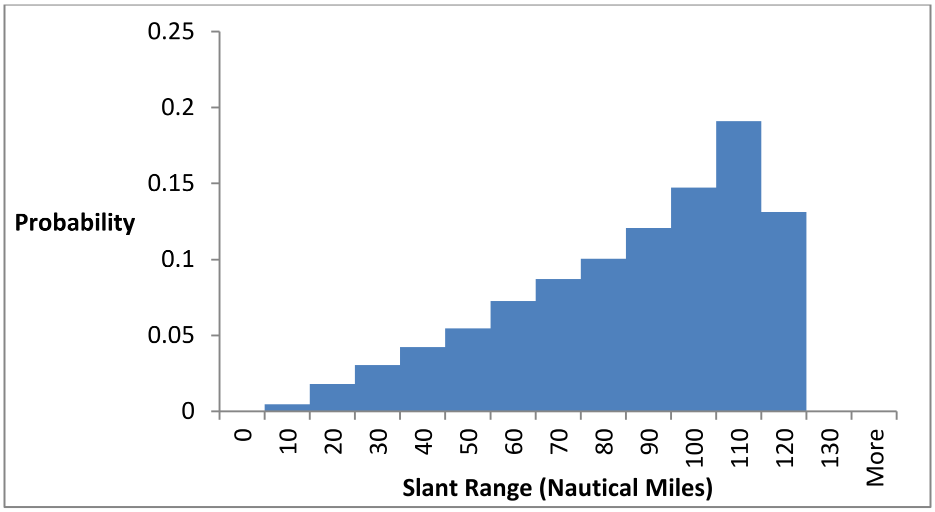


Figure 28 - First distribution of messages sent

To make the aircraft send more messages when it is closer to the ground station, a different movement configuration was developed. Its distribution is shown below.

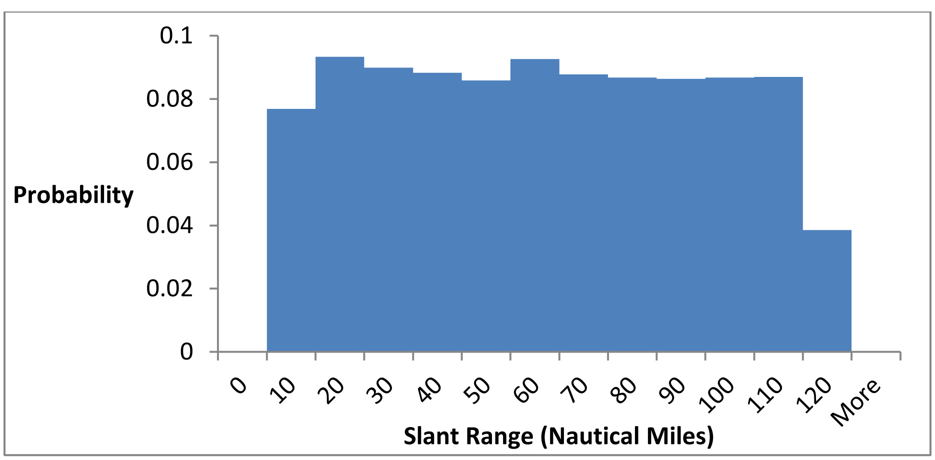


Figure 29 - Second distribution of messages sent

The same configurations of frequency reuse and service volume size were chosen as for the ground station placement experiment. All the simulations were newly executed with the exact same parameters, except with having the new distribution.

## 3. Results and Analysis

| Reuse Factor | Service Volume Size | First Distribution Capacity | Second Distribution Capacity |
|---|---|---|---|
| 4 | **60** | 12 | 10 |
| | **80** | 15 | 14 |
| | **100** | 20 | 18 |
| | **120** | 28 | 28 |
| 7 | **60** | 18 | 18 |
| | **80** | 23 | 26 |
| | **100** | 50 | 56 |
| | **120** | 79 | 89 |
| 13 | **60** | 29 | 30 |
| | **80** | 94 | 103 |
| | **100** | 100 | 107 |
| | **120** | 92 | 98 |
| 25 | **60** | 120 | 121 |
| | **80** | 110 | 114 |
| | **100** | 100 | 104 |
| | **120** | 90 | 97 |

Table V - Load Regulation Capacity Comparison

The capacity was usually increased with the second distribution for frequency reuse of 7, 13, and 25. The greatest increase was with larger service volume sizes. In the case of 120 NM service volume size and reuse factor of 7, the increase in capacity is by 10 aircraft.

It is important to note that the capacity actually dropped slightly with a frequency reuse of 4. The most likely reason why this happens is that the very close distance of co-channel transmitters causes the CSMA protocol to detect a busy channel. This makes it more favorable for delay times, since the transmitters wait for their turn before transmitting. However, the improvement in capacity is not significant.

Since there is no real world data available to show the actual distribution of messages sent, the experiment done here is simply for comparison purposes to determine which would be better. The results show that better capacities can be obtained when the sent messages are more uniformly distributed compared to messages that are more likely to be sent from larger distances. For this to occur, it is required to have more than the minimal amount of channels. From this research a logical follow-up would be to develop a distribution that is skewed to the close proximity of the ground station. This is a possible area for future research.

# CHAPTER VIII
# TRANSMIT POWER CONTROL

Transmit power control (TPC) has been in use for cellular phone systems for many years already and has therefore been heavily researched. TPC also finds applications in wireless LAN and sensor networks, as it can significantly increase the data capacity in many applications.

Data capacity of VDL Mode 2 depends on the co-channel interference, which becomes critical when service volume sectors on the same communication frequency are in close proximity. It is also highly affected by the hidden node problem, which takes a toll on the transmission delay times. The experiment was to determine if TPC can mitigate these problems and thereby increase the capacity in a frequency reuse setting. The focus was on the Segment 1 implementation of NextGen data services and the main constraint was the low amount of channels.

## 1. Transmit Power Control Hypothesis

High delay times in VDL Mode 2 usually result from retransmissions. A retransmission is required when the received signal contains errors that cannot be corrected. Significant interference occurs when a foreign signal is strong enough at the receiving end to corrupt the desired signal beyond repair. This causes the received message to be garbled and must be retransmitted.

The purpose of transmit power control is to adjust the $P_t$ (transmit power), so that the $P_r$ (received power) at the designated receiver is sufficient to deliver data at a satisfactory SIR and BER. The signal should also reach all the other nodes within the service volume with at least -98 dBm. Ideally, the transmit power will be the minimum power required to reach all the nodes within the service volume but it should not reach any nodes in the co-channel service volumes. These will typically be aircraft and ground stations in a different sector on the same frequency (co-channel).

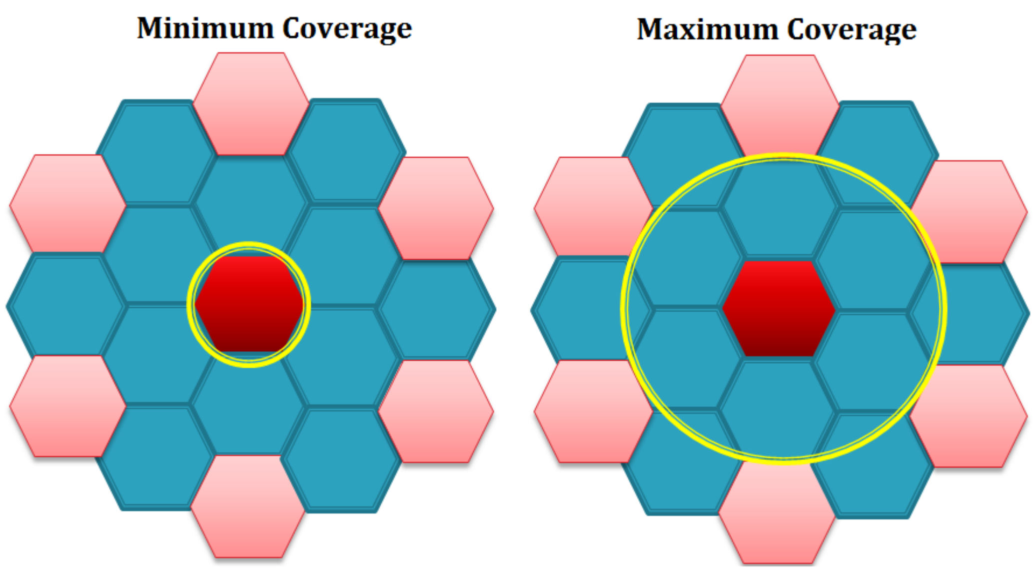


Figure 30 - TPC should at the minimum cover the personal service volume, but not reach co-channel cells

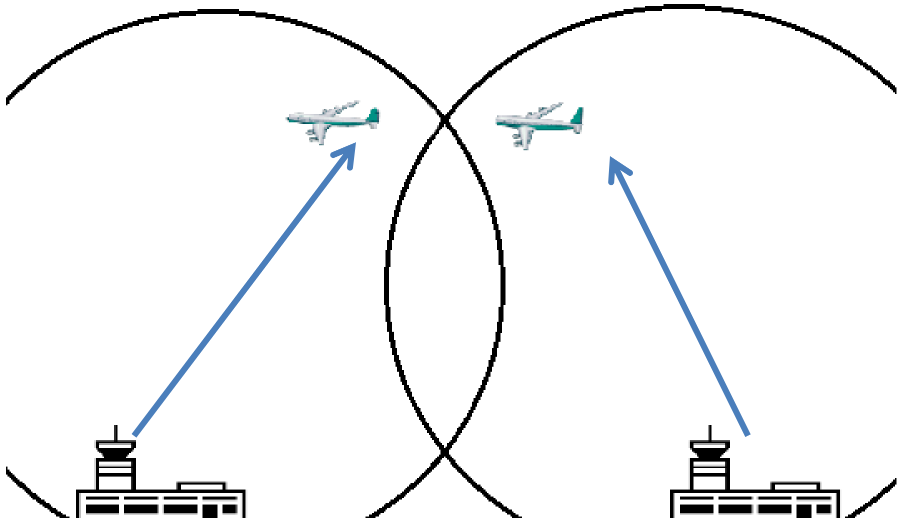

Figure 31 - Both ground stations are successfully transmitting messages to the airplanes since power control has decreased the range of coverage (Representation of concept, not drawn to scale or realistically)

The above diagram shows the same scenario as figure 19, except that the power levels are decreased and hence the range of coverage has decreased. As is shown, the coverage is not overlapping anymore where the airplanes are located. This has hypothetically caused the interference levels to decrease and therefore both ground stations are able to transmit messages to the airplanes successfully.

The power control methods can be categorized as open loop or closed loop, which tell if they are utilizing feedback of the performance to dynamically adjust the power levels for best performance. They can also be implemented centrally, where a single source sets the power levels for many users. In this case, the ground station would set its own power levels and also the power levels on the airplanes. Conversely, TPC can be implemented in a distributed configuration, where each transmitter has its own power control. The power control algorithms can also be categorized into different approaches to changing the power level.

The transmit power control must reduce the co-channel interference as much as possible while ensuring that communication standards are not compromised. The main benefit would be obtained if the transmission power control can improve the capacity to the point where less frequency channels are needed for VDL Mode 2, while keeping the cost economical for implementation in the NAS. Therefore a simpler implementation is sought after.

## 2. Simulation Model

A simpler implementation was used here with open loop control and distributed configuration to first determine if TPC has a positive effect, before attempting more complicated implementations. The model for transmit power control was developed to work with the CSMA protocol in conjunction with the physical layer. The CSMA model was adjusted from the original model, but different implementations may be possible without adjusting the main protocol. Once the CSMA protocol is ready to transmit a message, it calculates the slant range to the receiver.  Based on the location of the designated receiver, the TPC process model sets the transmit power before the signal is sent over the channel. The overview of the procedure is pictured in figure 32. The process simulation model for TPC is shown in figure 33.

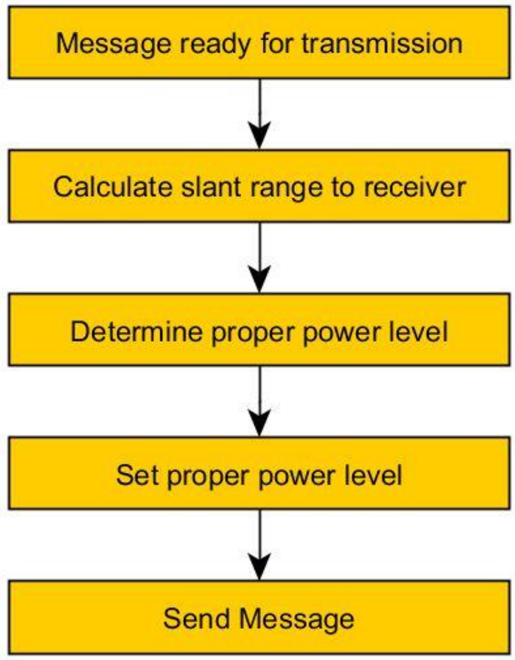


Figure 32 - TPC procedure overview

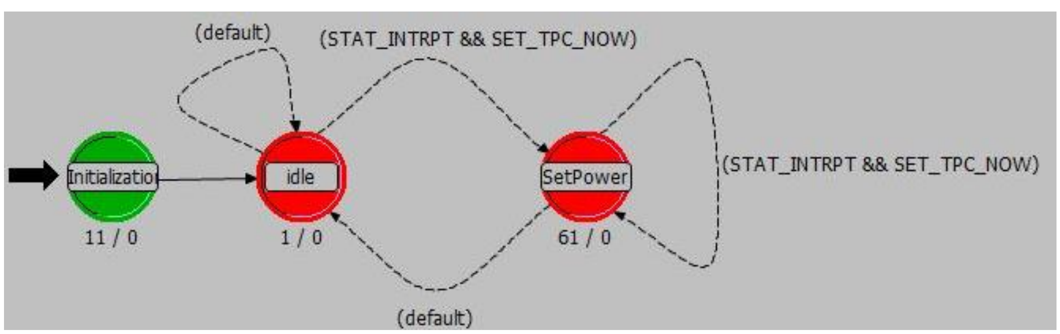


Figure 33 - Transmit power control process model

## 3. Simulation Tests Conducted

The main tests conducted were to implement TPC only on the ground stations, then only on the airplanes, and also for both ground stations and airplanes. The experimental transmit power range and levels were determined based on observing the received power at different distances. A selection of a few power levels is shown below. As is shown, 5 Watt would be too low, since it would drop below -98 dBm within the service volume and cause the hidden node problem.

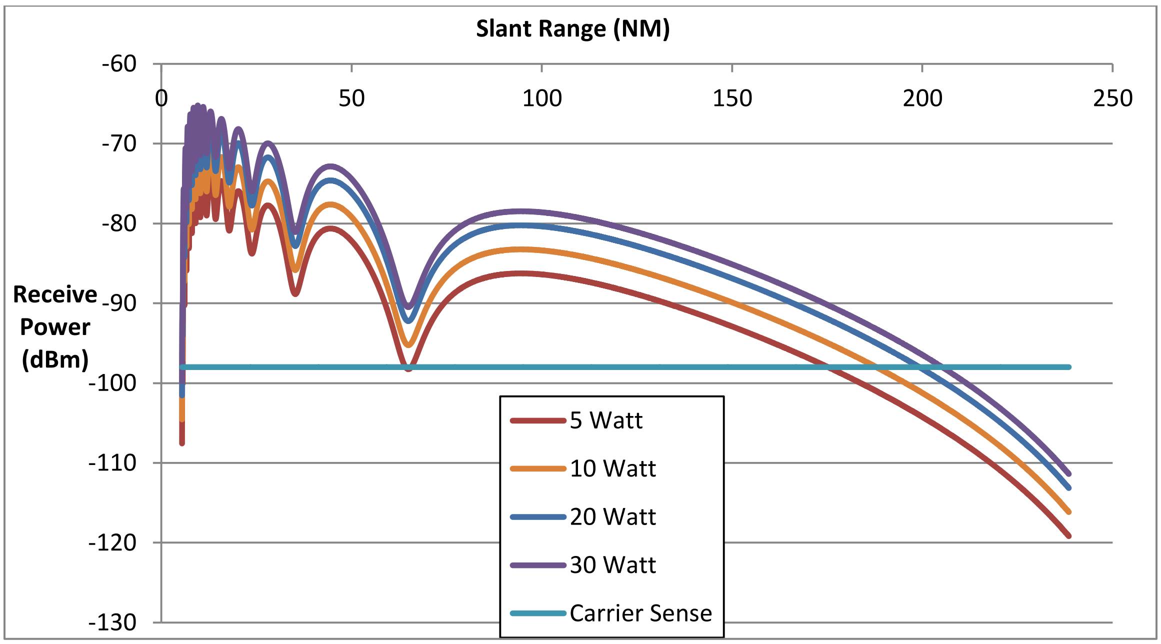


Figure 34 - Ground-to-Aircraft variable transmit power

It is also important to prevent the hidden transmitter problem in the airplane-to-airplane propagation. Although there is no actual communication occurring between aircraft, the signal should still reach all the aircraft within the service volume with at least -98 dBm.

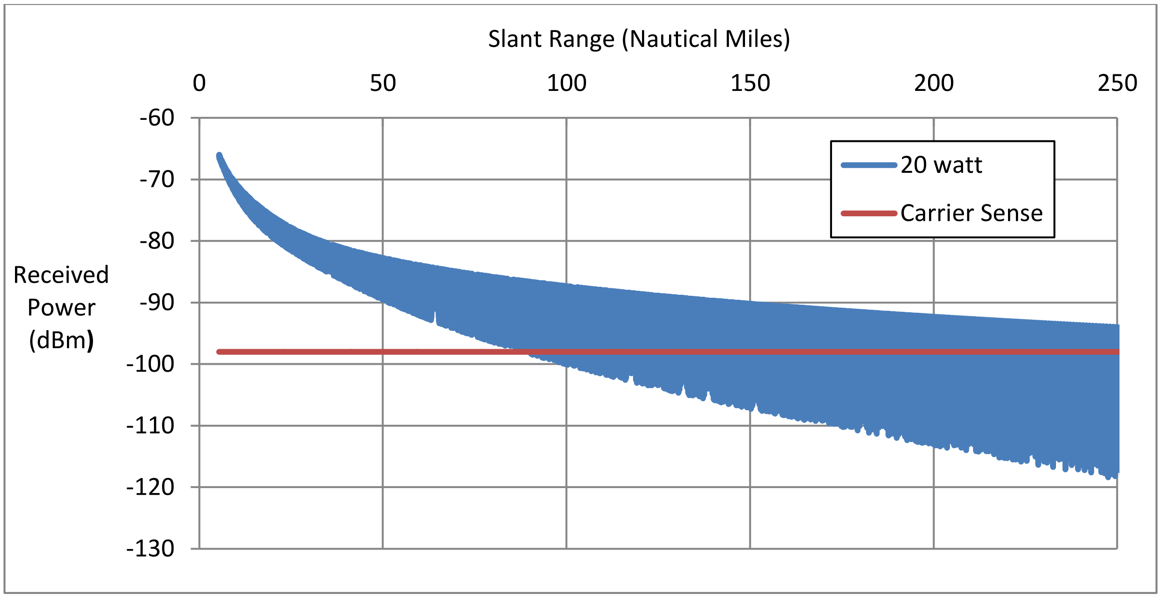


Figure 35 - Aircraft-to-aircraft received power with 20 Watt transmit power

It becomes apparent that with the nominal transmit power of 20 Watt the received power starts dropping below the carrier sense busy threshold at 90 nautical miles slant range. The issue here is that for an airplane at the edge of a service volume, to cover the entire area, the signal must reach a distance of two times the service volume radius. The diagram shows that this cannot happen entirely, even with a smaller service volume radius of 60 NM (120 NM edge-to-edge), since the received power starts dropping intermittently already at 90 NM.

When zoomed in to a range of 90-100 nautical miles, it shows how the signal varies a lot at a small range. These are the signal properties derived from the AMCP two-ray model for airplane-to-airplane signal propagation. It must be noted that no real-world measurements exist to validate this model.

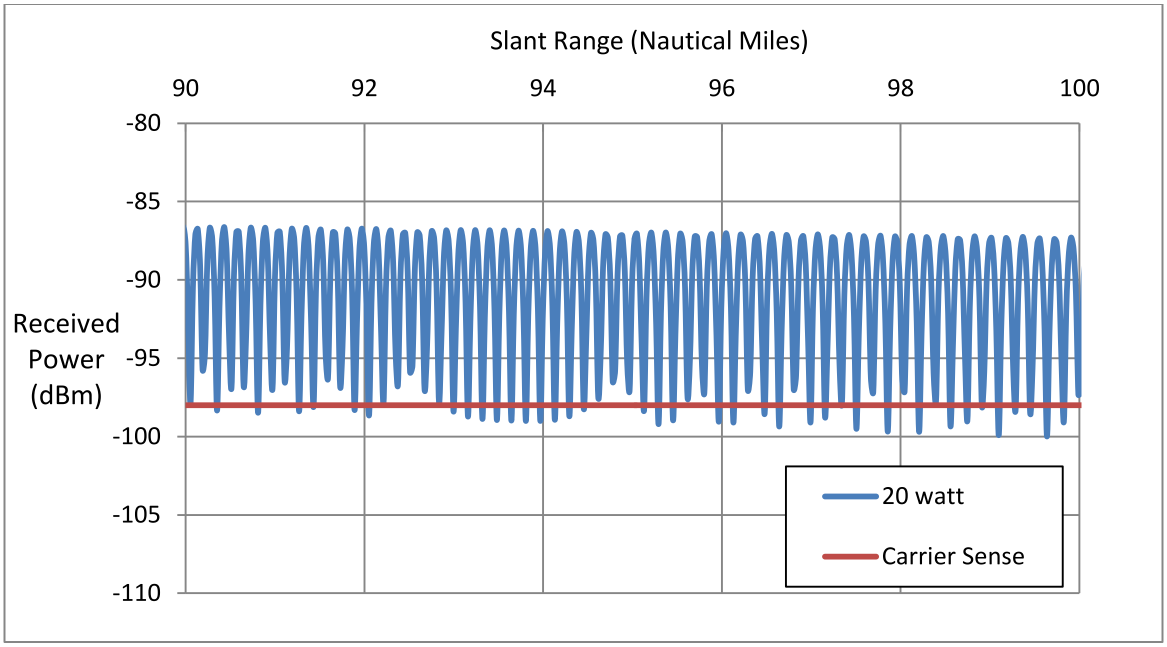


Figure 36 - Close-up of aircraft-to-aircraft received power

## 4. Results and Analysis

In none of the cases did the results significantly reduce the transmission delays to improve the capacity. In most cases the capacity would actually drop and sometimes be significantly lower. The main explanation is that reducing the transmit power increases the hidden transmitter problem, while increasing the transmit power increases the co-channel interference. It is reasonably sure that the simulation model executes satisfactorily. The possibility exists that the propagation model, especially aircraft-to-aircraft, does not accurately model the real world propagation, since no real-world measurement exist to confirm it.

There are still possibilities that TPC can benefit VDL Mode 2, but it is relatively certain that it would not be of much benefit in the tested cases. Since the test cases in this thesis focused on a limited amount of channels, there is a possibility that TPC would be beneficial with more than 25 available channels. The thesis also did not test intervals of transmit power smaller than 5. The likelihood exists is that smaller intervals in the range of 15-25 watt could improve the capacity. This was not tested, because it was not expected to gain significant improvements.

# CHAPTER IX

# CONCLUSION AND FUTURE RESEARCH

The simulation results have shown that the most critical means for improving the capacity of VDL Mode 2 is by proper ground station placement. It was determined that under certain settings, the capacity can be significantly improved by more than 300 percent, while keeping the amount of channels the same. With a smaller amount of channels it is beneficial to keep the service volume size large, while a large amount of channels benefit from smaller service volume size. The great benefit of this approach is that it can be implemented without adjusting the VDL Mode 2 standards.

Ground station placement could immediately improve the capacity of the aeronautical VDL Mode 2 implementation, without making any changes in the technology. Only the proper placement of the ground station antennas is required. The issue here is that many of the ground station antennas have already been placed and many are simply located at the location of airports. A solution would be to relocate the antenna to a place where better capacity would be achieved, when possible. What this research did not look into is the capacity based on the total area that is covered, but focused on the capacity per ground station. Increasing the capacity per ground station allows less ground stations to be utilized, which makes it more cost effective. However, to increase the capacity to the maximum in the limited area of the NAS, a focus should be on the capacity per unit area. This could be a subject of future research. A future research project could also analyze the currently placed antennas and determine the optimal placement of ground stations in the NAS. Due to the great gain of capacity with moderate implementation cost, ground station placement is the most favorable area research for improving the capacity of VDL Mode 2.

From the load regulation experiment an observation was made which could also improve the capacity. To reduce the impact of the hidden transmitter problem and co-channel interference, it is recommended to reduce the amount of messages that are sent from aircraft to ground stations while they are very far apart. This could be implemented at the application layer by simply not sending or delaying the transmission of unnecessary data, maybe low priority data, when the aircraft are far from the ground station. Again, no changes are needed to the VDL Mode 2 standards. Load regulation is not necessary for messages on the uplink from ground to aircraft, when the ground stations are sufficiently far apart to not cause co-channel interference to aircraft.

The load regulation experiment showed that the capacity can widely vary, depending on the distribution of messages sent correlated to the distance to the ground station. Since no data exists which shows the actual distributions in the NAS, it may be favorable to specify the capacity in future research experiments in a range such as 50 ±5. A better approach would be to obtain real-world measurements and incorporate them into the simulation model.

Transmit power control is not beneficial for VDL Mode 2 based on the simulation results. However, there are still possibilities for further testing. A major issue with TPC is that it would most likely require changing the VDL2 standards. The other major issue is that currently operational radios would need to be updated or replaced, which would be costly. If a good solution were to be found that only requires the upgrade of ground station radios, it would not be as costly to implement. Otherwise, transmit power control is not a good solution for improving the capacity of VDL Mode 2.

The most important effort to determine how accurate this simulation results are, would be to verify the AMCP two-ray propagation model. Although the model was already verified up to a distance of 20 NM and matches real world measurements closely, service volumes are likely to have a radius between 40 and 120 NM. Therefore it would be of great benefit to check if received power at the greater distances matches the model. It would be equally important to determine how well the received power between two aircraft behaves, since this is a determining factor for the hidden node problem.

A significant observation was made during the thesis for safety hazards. The simulation model predicts large areas with the potential for Prolonged Loss of Communications (PLOC). To ensure safe and reliable communications, it would be imperative to determine the risk of PLOC in the NAS.

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