Satellite Communications

Strategy selection for optimal LEO satellite communication

by

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Declaration

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26th November 2012

Abstract

A low earth orbit satellite system can be useful in numerous communication applications where physical connections are not possible. Communication time available from any point on earth to the satellite is less than one hour per day. This one hour is fragmented into smaller time slots due to the satellite orbiting. This is not much time to transfer data and there is even less time available to transfer data when there are other external factors affecting the system. It is thus crucial to optimise the satellite communications link so that more data can be transferred per orbit.

The goal of this thesis is to improve the performance of a low earth orbit satellite communication channel by varying certain parameters of the system, such as the protocol used, modulation scheme, packet size, transmission power etc. and then to observe how these parameters influence the system. The protocols that were chosen to be implemented are CSMA-CA, CSMA-CA with DSSS technology and Round-Robin Polling.

A simulator for each protocol was designed with the Opnet platform, so that specific parameters could be changed and the results observed, in order to optimise the communications link between the satellite and ground stations.

The results showed that there is no particular configuration of modulation scheme, packet size, transmission power etc. presenting the best overall solution for LEO satellite communications. It must be considered what the specific LEO satellite application would be used for and the characteristics required by that specific application. A suitable configuration must subsequently be chosen from the set of configurations available to satisfy most of the application requirements.

Opsomming

’n Satelliet met ’n lae wentelbaan kan gebruik word in verskeie kommunikasie toepassings waar fisiese verbindinge nie noodwendig moontlik is nie. Die kommunikasietyd van enige punt van aarde af na die satelliet, is minder as een uur per dag. Hierdie tyd word nog verder verklein omdat die satelliet besig is om, om die aarde te wentel. ’n Uur is glad nie baie tyd om data oor te dra nie en in realiteit is daar nog minder tyd beskikbaar as daar eksterne faktore op die sisteem inwerk. Dus is dit baie belangrik om die satelliet kommunikasiekanaal te optimiseer sodat soveel moontlik data as moontlik oorgedra kan word per omwenteling.

Die doel van hierdie tesis is om die deurset van die kommunikasiekanaal van n lae wentelbaan satelliet te optimiseer, deur verskeie parameters te verander soos, protokol wat gebruik word, modulasie skema, pakkie grootte, transmissiekrag ens. en dan waar te neem hoe dit die sisteem beïnvloed. Die protokolle wat geïmplementeer is, is CSMA-CA, CSMA-CA met DSSS tegnologie en Round-Robin Polling.

’n Simulator vir elke protokol was ontwerp in die Opnet simulasie platform, sodat die spesifieke parameters verander kon word om die resultate te bestudeer met die doel om die kommunikasiekanaal tussen die satelliet en grond stasies optimaal te benut.

Die resultate het bewys dat daar geen spesifieke konfigurasie van modulasie skema, pakkie grootte, transmissiekrag ens. is wat die algehele beste oplossing is nie. Die spesifieke applikasie waarvoor die lae wentelbaan satelliet gaan gebruik word moet geanaliseer word sowel as die spesifieke karakteristieke van daai applikasie. Daarvolgens moet n unieke konfigurasie opgestel word wat meeste van die applikasie se behoeftes bevredig.

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List of Abbreviations

8PSK	8-Phase Shift Keying
ACK	Acknowledgment
ACM	Adaptive Coding Modulation
AM	Amplitude Modulation
BCH	Bose, Chaudhuri, Hocquenghem
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
CPU	Central Processing Unit
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear To Send
DSSS	Direct Sequence Spread Spectrum
DSSS(CSMA-CA)	Direct Sequence Spread Spectrum added to CSMA-CA
ETE	End-To-End
FCC	Federal Communications Commission
FEC	Forward Error Correction
FHSS	Frequency Hopping Spread Spectrum
FM	Frequency Modulation
GEO	Geostationary Earth Orbit
ISM	Industrial, Scientific and Medical
ITU-R	International Telecommunication Union - Radio communication

LDPC	Low Density Parity Check
LEO	Low Earth Orbit
LOS	Line Of Sight
MAC	Medium Access Control
MEO	Medium Earth Orbit
PM	Phase Modulation
QPSK	Quadrature Phase Shift Keying
RTS	Request To Send
RTT	Round-Trip Time
SNR	Signal-to-Noise Ratio
STK	Satellite Tool-Kit
TTC	Telemetry, Tracking and Control
UHF	Ultra High Frequency
VCS	Virtual Carrier Sense
VHF	Very High Frequency
WLAN	Wireless Local Area Network

Chapter 1

Introduction

1.1 Background

The Stellenbosch UNiversity SATellite (SUNSAT) was the first Low Earth Orbit (LEO) micro-satellite designed and developed in South Africa. It was built by post-graduate engineering students in the Electronics Systems Laboratory, in the Department of Electrical and Electronic Engineering at the University of Stellenbosch. It was launched on a Delta II rocket on 23 February 1999 from the Vandenberg Air Force base in California, USA. It orbited the earth for two years before communication was lost on the 19th of January 2001, [6].

On 17 September 2009 the SumbandilaSat, a South African micro earth observation satellite, was launched on a Soyuz-2 launch vehicle from the Baikonur Cosmodrome. SumbandilaSat was designed collaboratively between SunSpace & Information Systems (Pty) Ltd (SSIS), the Department of Science and Technology at the University of Stellenbosch and the CSIR (Council for Scientific and Industrial Research) Satellite Application Centre (SAC). SumbandilaSat was designed to have a circular sun-synchronous polar orbit. With this type of orbit, the entire surface area of the earth is covered by the satellite in the orbital cycle, [1].

Both SUNSAT and SumbandilaSat are LEO satellite systems. Due to the low altitude that LEO satellite systems operate at, communication time is intermittent. With limited time available, the overall throughput of LEO satellite systems is low. The designers of SumbandilaSat are in the process of designing their third LEO micro-satellite. With the new design, they are trying to use the intermittent time slots more efficiently to increase the data throughput.

The CSIR is also in need of information regarding the optimisation of LEO satellite communications, as they have a couple of projects running based on LEO satellites. These projects do not make use of large data transfers and are typically used in agricultural projects.

Figure 1.1 – SumbandilaSat, [1]

1.2 Objectives

The work carried out under this project, had the following objectives:

- First, to overall define the limiting aspects of LEO satellite communications.
- Thereafter do the systems design of a LEO satellite communication system to transfer very small data files or emails from rural settlements. The design included aspects such as antenna types, transmission power, packet structures and sizes, modulation schemes, physical limitations, protocols, error correcting coding etc.
- To implement the design in a discrete event simulator. The simulator would be run and different variables of the system altered to observe the effect of each on the system.
- The results had to be interpreted to determine the effect of all these variables on each other and the effect on the system in terms of optimising. It would also determine the optimal configuration for optimal LEO satellite communications.

1.3 Summary of results

- Three simulators were successfully built to simulate the three chosen protocols. Different variables of the simulators could be changed to determine the effect of each change on the system results.

- From the simulation results it was found that the Quadrifilar Helix antenna proposed in the design specifications should work very well. A fixed, high gain, Yagi antenna is recommended for systems with low transmission power. A tracking antenna would be the ideal solution for LEO satellite communications, but due to the cost of implementation such a design it was discarded.

- Increasing the transmission power, increases the overall performance of the system; as expected. It is suggested that the system be run with the highest possible transmission power of 10 W to obtain maximum performance.

- Round-Robin Polling displayed the best overall efficiency in performance. Thus, if a system has to be selected in terms of efficiency only, Round-Robin Polling is the protocol to use. The performance of the Round-Robin protocol also stays constant with the increase in number of ground stations.

- The Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) system performs very poorly and would not be recommended if more than 10 ground stations are to be used. The protocol's poor performance is due to the collisions of Request-to-Send (RTS) packets for channel contention.

- The Direct Sequence Spread Spectrum Carrier Sense Multiple Access with Collision Avoidance DSSS(CSMA-CA) system has the best overall throughput performance and the overall second best efficiency performance. This protocol would be recommended if the system has a lot of data to be transferred.

- The larger the packet size of a system, the better the overall performance of that protocol. It is thus recommended to use as large a packet size as possible for every configuration, though preferably not bigger than 1 Mb. The larger the packet size, the more data is transferred per data packet transfer and thus less time is spent on overhead, increasing throughput and efficiency.

- The 8-Phase Shift Keying (8PSK) modulation scheme performs very poorly overall because of the small time frame available in which communications can take place, where the Signal to Noise Ratio (SNR) is better than the required minimum BER of 10^{-6}. It would not be recommended that this modulation scheme be used at low transmit power. For this scheme the transmit power needs to be well above 10 W. This increase in transmission power will increase the time frame available for communications to take place, thus improving the overall performance.

- The Quadrature Phase Shift Keying (QPSK) modulation scheme performs best out of all the modulation schemes simulated. Binary Phase Shift Keying (BPSK) and QPSK have the same minimum SNR, but QPSK has double the data rate and outperforms BPSK for that reason. The 8PSK has double the data rate of QPSK, but also has a much higher minimum SNR, which results in the QPSK modulation scheme outperforming 8PSK. It is recommended that QPSK be used for a reliable and effective modulation scheme.

- The BCH (Bose, Chaudhuri, Hocquenghem) Forward Error Correction (FEC) scheme works well enough but a more efficient scheme such as LDPC would increase the performance of the system. The actual code implementation was not part of the project objectives and the judgement was made on known performance comparison with BCH.
- There is no particular configuration of modulation scheme, packet size, transmission power etc. presenting the best overall solution for LEO satellite communications. It must be considered what the specific LEO satellite application would be used for and the characteristics required by that specific application. A suitable configuration must subsequently be chosen from the set of configurations available to satisfy most of the application requirements.
- However, the work carried out mids this project, provides a set of tools to assist with the design and configuration of an optimal LEO satellite system.

1.4 Contributions

This thesis makes the following contributions to the communication design process for LEO satellites:

- An in-depth analysis of the influence of key parameters on LEO satellite communications.
- A simulator built in Opnet to simulate the CSMA-CA protocol as applied to a LEO satellite network. Parameters such as packet sizes, modulation schemes, transmission powers, antenna types and FEC can be varied to evaluate the effect on system performance.
- A similar simulator for DSSS(CSMA-CA).
- A third Round-Robin Polling Opnet simulator with similar characteristics as the other two.
- Provision of guidelines in terms of parameter selection to satisfy particular applications.
- In summary, the set of tools developed as part of this work provides a valuable aid to enable pre-emptive systems design and decrease system performance uncertainties.

1.5 Overview of thesis

- Chapter 2 provides the motivation for the work done, as well as an overview of previous work.

- Chapter 3 focuses on the various physical constraints on the system resulting from the communication medium and the orbital characteristics of the satellite.

- In Chapter 4, various design aspects are investigated. The design aspects include antenna types, transmission power, packet structures and sizes, modulation schemes, minimum BER required for satellite communications, receiver sensitivity, protocols and error correction coding.

- In Chapter 5 the Opnet platform in which the simulators are coded is discussed, plus functioning of the simulators. The simulators are tested and the results of these tests discussed.

- Chapter 6 presents the results of the simulations. A detailed discussion on each configuration set is provided based on results obtained from the simulations.

- Chapter 7 concludes and summarises this thesis and presents suggestions for future work.

Chapter 2

Background and Related Work

2.1 Background

LEO satellites are defined as satellites that orbit above an altitude of 160 km and below 2000 km, [7]. These altitudes are considered as low and thus high velocities are required to balance the earth's gravitational field so that the satellite can stay in orbit. An advantage of using a LEO satellite is that the time it takes a signal to reach the earth is very short compared with that from other orbits like Medium Earth Orbits (MEO) and Geostationary Earth Orbits (GEO).

There are three types of circular LEO orbits,

- Inclined Non-Polar: A satellite that has an inclination of less than 70 degrees. Satellites in Inclined Non-Polar orbits are not sun-synchronous.
- Polar Sun-Synchronous: A satellite that passes all latitudes at the same local solar time each day. Orbits lie within 20 degrees of a 90 degree inclination from the equator. To maintain this synchronicity, the orbital plane must rotate about 1 degree per day.
- Polar Non-Sun-Synchronous - Satellite maintains a polar orbit that does not synchronize latitude passes with solar time.

Out of the three, the Polar Sun-Synchronous orbit has the best footprint and covers most of the earth's surface. As mentioned in Section 1.1, the orbit used by the Sumbandila satellite is a Polar Sun-Synchronous orbit and thus it is used in the simulations.

One of the biggest problems when it comes to LEO satellite systems is the discontinuity in communication time. As a satellite is orbiting the earth it will pass over a ground station. Communication can take place only while the ground station and satellite are in Line Of Sight (LOS) of one another. In the case of a LEO satellite with a 500 km altitude, this time frame is very small. If the satellite or ground station does not send the data it has in its buffer in the limited time frame, it has to wait for the satellite to orbit around the earth before trying again. It is thus crucial to transmit as much data as possible in every pass of the satellite.

Not only should as much data as possible be transferred, but it needs to be transferred reliably. To increase the reliability of data transfer a Forward Error Correction (FEC) scheme is implemented. Other factors such as antenna design, transmission power, packet size, receiver sensitivity and protocol used can influence the data transfer reliability of the system. Some of these parameters are interdependent and thus it is very difficult to do a mathematical analysis on such a system.

A simulator is the best way of determining how each of these parameters influence each other and the system's performance. Three protocol simulators are built and run with different parameter sets to obtain a better insight into the workings of such a system. The aim is not so see which protocol has the highest throughput, but finding out how each protocol performs under a specific set of conditions. These findings will then be used to determine the optimum LEO satellite system.

2.2 Related Work

During the research no other work previously done on this specific topic could be found. A lot of research on Adaptive Coding Modulation (ACM) and other parameters that can influence the performance of a LEO satellite system is available, but very little work has been done to determine which protocol with which specific static parameter setup is the optimum solution for LEO satellite systems.

2.3 Summary

Therefore, key aspects in a LEO satellite system were identified to determine their influence on LEO satellite system performance. Aspects such as frequency band, antenna design, transmission power, packet sizes and structure, modulation scheme, data transfer protocol and FEC schemes were identified as important aspects. All of these were implemented in the simulators in such a way that each one could be altered independently to evaluate the influence each has on the system and each other.

2.4 Next chapter

In the next chapter, the physical limitations and constraints of a LEO satellite system is investigated.

Chapter 3

System Constraints

As with any communication system, there are constraints and limitations. In this chapter we will be looking at the physical limitations and constraints between the ground station and satellite, in a LEO satellite communication system. This constraints will later be used in Chapter 4 as design specifications and limitations.

3.1 Satellite orbit

The satellite to be used in the system is a LEO satellite that points constantly to the nadir. The orbit is circular, polar, sun-synchronous and the satellite orbits approximately 500 km above the earth's surface.

3.2 Distance to satellite

The distance from the satellite to any ground station it wants to communicate with is very important.

The communications system frequency will be in the Ultra-High Frequency (UHF) band, for reasons mentioned in Section 3.5. The frequencies in this band travel in a straight line and are easily absorbed by the atmosphere, mountains and ground. Thus the satellite can only communicate with a ground station if they are in LOS of each other. It is important to know what the maximum LOS distance is, because it will affect certain implementation and design choices.

The satellite orbits at a height of 500km $(h = 500km)$ above the earth's surface. To calculate the LOS distance from the satellite to the ground station, co-ordinate geometry will be used to derive a formula for distance D, as shown in Figure 3.1 The circle represents the earth and the point $(0, h)$ is the satellite's position. We take the earth's radius to be 6378 km $(Re = 6378km)$.

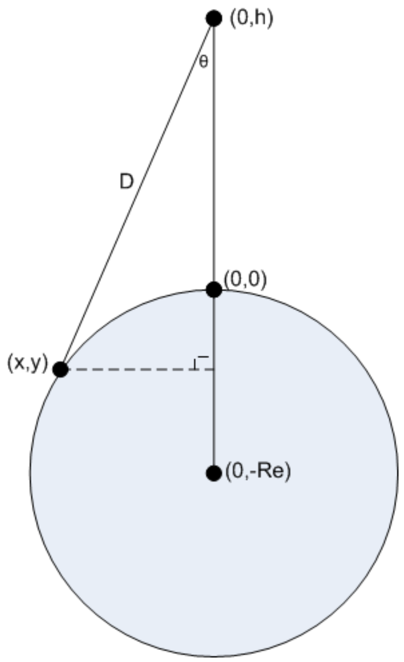


Figure 3.1 – Co-ordinate geometry solution

The circle can be described by the equation [7],

$$r^2 = (x - a)^2 + (y - b)^2 \tag{3.2.1}$$

where (a, b) is the centre of the circle and r is the radius of the circle. In this case we take the the centre of the circle as $(0, -Re)$. Equation 3.2.1 then becomes

$$x^2 + (y + Re)^2 = Re^2 \tag{3.2.2}$$

A ground station is located at the point (x, y). The line from the satellite to the ground station can be described as a straight line,

$$y = mx + h \tag{3.2.3}$$

going through points (x, y) to $(0, h)$. Substituting Equation 3.2.3 into 3.2.2, we get

$$x^2 + (mx + c + Re)^2 = Re^2 \tag{3.2.4}$$

Equation 3.2.4 can be simplified into the form,

$$ax^2 + bx + c = 0 \tag{3.2.5}$$

where

$$a = (m + 1)$$

$$b = (2mh + 2mRe)$$

$$c = (h^2 + 2hRe)$$

Using the standard formula to factorise quadratic polynomials,

$$x_1, x_2 = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{3.2.6}$$

we are able to solve x in terms of m. From Figure 3.1 and Equation 3.2.3, it can be seen that m is the gradient of the straight line and can be calculated as,

$$m = \frac{1}{\tan\theta} \tag{3.2.7}$$

Substituting the x value, obtained from factorising Equation 3.2.4, into Equation 3.2.3 it is possible to solve for y in terms of m. Using Pythagoras, the distance D can be calculated with

$$D = \sqrt{x^2 + (h - y)^2} \tag{3.2.8}$$

where both x and y are dependent on m and m is dependent on θ. A Matlab script, distance.m, was used to sweep through all the possible values of θ and calculate the distance D. Figure 3.2 shows the results of the Matlab script. From Figure 3.2 it can be seen that the maximum LOS distance is 2231 km. In other words the maximum distance between the satellite and a ground station is 2231 km. If this distance becomes any bigger communication would be impossible. The propagation time is dependent on the distance between the satellite and ground station.

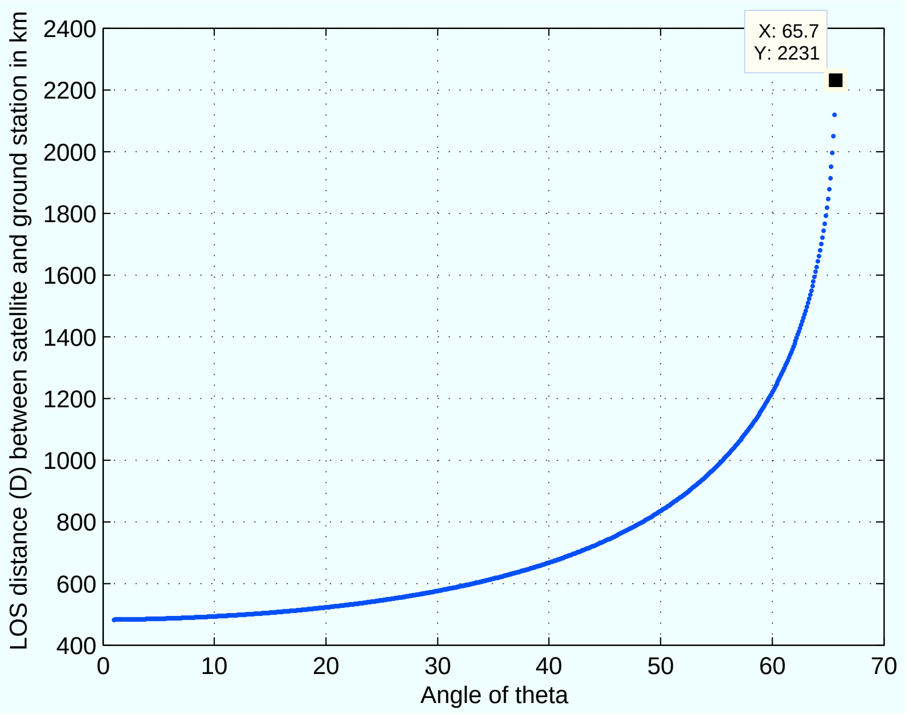


Figure 3.2 – Line of sight distance

3.3 Propagation time

Propagation time, also known as the propagation delay, is the time it takes a signal to travel from the transmitter to the receiver. In satellite systems the propagation time is usually very large and slows down the data rate considerably. Radio waves travel at the speed of light in a vacuum $(c = 3 \times 10^8\ m/s)$. To calculate the propagation time we use,

$$t_p = \frac{D}{c} = \frac{2231 \times 10^3}{3 \times 10^8} = 7.436\ ms \tag{3.3.1}$$

where D is the propagation distance and c is the speed of light. To calculate the maximum propagation time, we use the maximum LOS distance D calculated in Section 3.2. Thus it will take a packet a maximum of 7.436 ms to travel from the transmitter to the receiver and vica versa.

The Round Trip Time (RTT) is the time it takes a packet to travel from the transmitter to the receiver and back. The RTT is simply the propagation time, times two, if there is a very small, or no delay in processing the packet at the receiver.

$$RTT = t_p \times 2 \tag{3.3.2}$$

$$RTT = 14.872\ ms$$

3.4 Orbital calculations

It is important to know how many times a satellite will pass over a ground station and how long the ground station will be in view of a passing satellite. We can use a combination of Newton's and Kepler's laws to solve this problem. A full explanation of orbiting principles can be found in [8], but for now we will use the equations they provide.

The number of times a satellite will orbit around the earth, per day, will depend on it's orbital period which can be related to the satellite's altitude. We use, from [8],

$$Rev/Day = 16.997 \left(\frac{Re}{Re + h}\right)^{\frac{3}{2}} \tag{3.4.1}$$

to calculate the number of orbits per day where $Re = 6378\ km$ is the earth's radius and $h = 500\ km$ the satellite's altitude. The length of time the satellite will be visible in each revolution depends on the satellite's altitude and orbital inclination, as well as on the latitude and distance from nadir of the ground station. If the satellite passes directly over the ground station, the maximum time the satellite will be visible is,

$$t_{view} = \frac{2\cos^{-1}\left(\frac{Re}{Re+h}\right)}{\frac{360}{84.49}\left(\frac{Re}{Re+h}\right)^{\frac{3}{2}} - \frac{260}{1436}} \tag{3.4.2}$$

where the arc cosine is in degrees. Any pass that is not directly over the ground station will result in the satellite being visible for less time.

Now, using Equation 3.4.1, we calculate the number of orbits per day,

$$Rev/Day = 16.997\left(\frac{6378}{6378+500}\right)^{\frac{3}{2}} = 15.17 \tag{3.4.3}$$

Since a day is 24 hours long and the satellite will orbit 15.17 times around the earth per day, one revolution will take 94.9 minutes. Out of this 94.9 minutes the satellite will only be visible for a maximum time (if the pass is directly over the ground station) of,

$$t_{view} = \frac{2\cos^{-1}\left(\frac{6378}{6378+500}\right)}{\frac{360}{84.49}\left(\frac{6378}{6378+500}\right)^{\frac{3}{2}} - \frac{260}{1436}} = 12.73min \tag{3.4.4}$$

Thus for a specific ground station the satellite is only available $(12.73/94.9)\times 100 = 13.41\%$ of the time per revolution. If the satellite does not pass directly over the ground station, the time the satellite is visible will decrease. Due to the small amount of time available, it is of utmost importance to optimise the communications link between the satellite and the ground station in order to transfer as much data as possible in the given time frame. Many other factors come into play when looking at the communications part of the satellite system. One of these is the frequancy band in which communications takes place.

3.5 Frequency band selection

As mentioned earlier, the frequency band in which the system operates in is a very important aspect when it comes to satellite communications. The International Telecommunications Union Radio Communication (ITU-R) sector manages the international radio frequency spectrum, satellite orbit resources and develop standards for radio communication systems with the objective of ensuring the effective use of the spectrum, [9]. To determine the best frequency band to operate in for a specific application, a few things should be kept in mind.

- The type of data or information that will be sent over the channel.
- The data rate at which communications must take place.
- The interference in the selected band.
- Frequency band licensing.
- Maximum transmit power.
- Distance between transmitter and receiver.

These are just a few key factors to keep in mind when choosing the frequency band.

The Very-High Frequency (VHF) band is the radio frequency range from 70 MHz to 300 MHz. Its propagation characteristics are good for short distance terrestrial communication. Due to the low frequencies, the ionosphere doesn't reflect the radio waves transmitted, [10]. And, depending on the transmit power and transmitter antenna gain, this band is more likely to be used for short distance line of sight communications. It will also have a low data rate capacity, due to its rather long wavelengths.

The UHF band is the radio frequency range from 300 MHz to 3 GHz. The ISM-band is a set of frequencies within the UHF band ranging from 2.4 GHz to 2.4835 GHz. An advantage of UHF transmission over VHF is the physically shorter wavelength that is produced at these high frequencies. The reception antenna is related to the size of the radio wave and thus an UHF antenna is stubby and short. A smaller and lighter antenna can be used with these higher frequencies. Another good reason for using the ISM-band is cheap commercially available radios and antennas.

Most new, and a small number of older, satellites make use of the ISM-band for data transmission. The high frequencies used in the ISM-band makes it very popular in satellite communications due to the $\frac{\Delta f}{f_c}$ factor, where Δf is the bandwidth and f_c the carrier frequency. From practical experience, a good ratio for $\frac{\Delta f}{f_c}$ is about 0.005%. From this, it can be seen that the higher the frequency band, the bigger the bandwidth can be. And the bigger the bandwidth the higher the data transfer rate. A disadvantage is that higher frequencies mean higher transmit power. It is thus crucial to get the ratio between the bandwidth and frequency band just right.

Many of devices emit electromagnetic waves in the 2.4 GHz band. Some of these are: microwave ovens, Bluetooth, Wireless Local Area Networks (WLAN), weather radar, satellites, surface ship radar, cordless phones, car alarm remotes and video devices, to name just a few. Electromagnetic interference in the 2.4 GHz band can become a problem if it is not taken care of.

The data to be sent to and from the satellite is going to be quite varied. It could be from Telemetry, Tracking and Control (TTC) commands, configuration file downloads and uploads to simple communication to remote areas. No large data files, such as high quality pictures or videos, will be sent over the link.

Taking all the above mentioned factors into account, the 2.4 GHz band is chosen as the perfect frequency band in which to operate. Two channels were chosen in the 2.4 GHz band for the uplink and downlink, to make the system a full-duplex system. The bands are shown in Table 3.1.

Band	Bandwidth (kHz)	Frequency (MHz)
Uplink	100	2400 - 2400.1
Downlink	100	2400.2 - 2400.3

Table 3.1 – Uplink and downlink frequency bands

3.6 Link budget

As mentioned in Section 3.5 the frequency band that is going to be used is the ISM-band. Link budget calculations were done in Matlab before the simulator was developed.

3.6.1 Minimum bandwidth

Before the link budget analysis could be done the bandwidth, maximum data rate and minimum SNR had to be calculated for a system that needs to transmit at a maximum baud rate of 76 kBd. 76 kBd is pre-chosen as this is a generally fast baud rate for LEO satellite systems. Using the Shannon limit [11] equation,

$$C \leq 2B\log_2\left(1+\frac{S}{N}\right) \tag{3.6.1}$$

where C is the maximum data rate in bps, B is the bandwidth in Hz, $\frac{S}{N}$ is the power ratio (signal power divided by the noise power in raw form not in dB). Also using Hartley's equation, also from [11],

$$C = R\log_2(M) \tag{3.6.2}$$

where C is the maximum data rate in bps, R is the baud rate and M is the number of symbols used. Substituting Equation 3.6.2 into 3.6.1 and solving for B we end up with

$$B \geq \frac{R\log_2(M)}{\log_2\left(1+\frac{S}{N}\right)} \tag{3.6.3}$$

With Equation 3.6.3 the minimum bandwidth needed to transmit at a specified baud rate with a specified modulation scheme can be calculated.

3.6.1.1 Calculating minimum bandwidth

To calculate the minimum bandwidth needed we use Equation 3.6.3.

$$B \geq \frac{R\log_2(M)}{\log_2\left(1+\frac{S}{N}\right)}$$

We take the baud rate R as 76 kBd, M and $\frac{S}{N}$ will be dependent on the modulation scheme used. The modulation schemes chosen are BPSK, QPSK and 8PSK. For further details on the modulation schemes please refer to Section 4.5. Table 3.2 is the result of using Equation 3.6.3 with BPSK, QPSK and 8PSK respectively. From Table 3.2, it can be seen that a theoretical minimum bandwidth of 38 kHz is needed for all three modulation schemes. The 38 kHz is

Modulation Scheme	Minimum B (kHz)
BPSK	38
QPSK	38
8PSK	38

Table 3.2 – Minimum bandwidth for a specified modulation scheme

theoretical, but from past experience and for practical reasons a bandwidth of 100 kHz is chosen for a maximum baud rate of 76 kBd. Choosing a bandwidth of 100 kHz and using the ISM-band, gives the ratio of $\frac{\Delta f}{f_c} = \frac{100\ kHz}{2.4\ GHz} = 0.0041\%$ which is close to the 0.005% mentioned in Section 3.5.

3.6.2 Minimum SNR for modulation scheme

The minimum $\frac{S}{N}$ power ratio can be calculated using the Shannon limit Equation 3.6.1 and Nyquist's maximum bit rate formula,

$$C \leq 2B\log_2(M) \tag{3.6.4}$$

where C is the maximum bit rate in bps, B is the bandwidth of the system and M is the number of symbols used. Substituting Equation 3.6.1 into 3.6.4 we end up with,

$$\frac{S}{N} = M^2 - 1 \tag{3.6.5}$$

Using Equation 3.6.5, the minimum $\frac{S}{N}$ power ratio can be calculated for a given modulation scheme.

As mentioned earlier the modulation schemes chosen are BPSK, QPSK and 8PSK. BPSK has two symbols, QPSK four and 8PSK has eight. Substituting M = 2 into Equation 3.6.5 we get,

$$\frac{S}{N} = 2^2 - 1 = 3$$

$$SNR_{dB} = 10\log\left(\frac{S}{N}\right) = 4.77\ dB$$

Thus we need a minimum SNR_{dB} of 4.77 dB in order to use the BPSK modulation scheme. Table 3.3 provides the minimum SNR values for the given modulation schemes. The result in

Modulation Scheme	M	Minimum $\frac{S}{N}$	SNR_{dB}
BPSK	2	3	4.77
QPSK	4	15	10.76
8PSK	8	63	18

Table 3.3 – Minimum $\frac{S}{N}$ for specified modulation scheme

Table 3.3 is the minimum SNR required for that specific modulation scheme to work. It is, however, not the minimum SNR that will ensure that communications can take place reliably. The minimum SNR for reliable communication is calculated in Section 4.6 that will ensure that the system operates at a BER of 10^{-6}.

3.6.3 Link budget calculation

A link budget is used to determine how much stronger the received signal is than the noise in the system. The result is expressed as a SNR and usually in decibels. The SNR is an indication of how reliable communications will be between the transmitter and receiver. A value of 11dB is chosen as our minimum SNR for BPSK and QPSK and 14dB for 8PSK; this is explained later in Section 4.6.

The received power and the noise power in the system are calculated separately and then divided to get the SNR.

Received power calculation

The received power is calculated as,

$$P_R = P_T + G_T - L_T - L_P - L_M + G_R - L_R \ \ dB \tag{3.6.6}$$

where P_R is the received power, P_T is the transmit power, G_T is the transmitter antenna gain, L_T is the transmitter losses, L_P is the free space path loss, L_M miscellaneous losses, G_R is the receiver antenna gain and L_R is the receiver losses, all in decibels.

For example purposes, a transmission power of 5 W is chosen and P_T is set to 7 dB. Both the transmitter antenna gain, G_T, and the receiver antenna gain, G_R, are set to 10 dB. The transmitter losses, L_T, receiver losses, L_R, and miscellaneous losses, L_M, are set to 1 dB each.

The free space path loss can be calculated by,

$$L_P = \left(\frac{\lambda}{4\pi D}\right)^2 \tag{3.6.7}$$

$$L_P = \left(\frac{0.124}{4\pi 500000}\right)^2 = -154 \ dB$$

where λ is the wavelength of the selected frequency and D is the propagation distance in meters. The ISM-band was chosen as the frequency band in Section 3.5 and the bandwidth was chosen as 100 kHz in Section 3.6.1.1. The communications channel will start at 2400 MHz and will end at 2400.1 MHz. Taking the centre of the channel as the frequency to calculate the wavelength,

$$\lambda = \frac{c}{f} \tag{3.6.8}$$

$$\lambda = \frac{3 \times 10^8}{2400.05 \times 10^6} = 0.124 \ m$$

where c is the speed of light ($c = 3{\times}10^8 \ m/s$) and f is our centre frequency ($f = 2400.05 \ MHz$).

The received power can then be calculated as,

$$P_R = (7) + (10) - (1) - (154) - (1) + (10) - (1) = -130 \ dB \tag{3.6.9}$$

$$P_R = -100\ dBm$$

Noise power calculation

There are three types of noise present in the system, interference noise, background noise and ambient noise. For simplicity, the interference noise is set to zero. For the background noise and ambient noise, the noise figure F is set to 6 dB. The noise figure can be converted to a noise temperature T using,

$$T = (F - 1) \times T_0 \tag{3.6.10}$$

$$T = \left(10^{0.6} - 1\right) \times 290 = 864.5\ K$$

where T_0 is 290 K and F is not in decibels.

If the background temperature T_{bkg} is set to 290 K, the total temperature is

$$T_{tot} = T + T_{bkg} = 864.5 + 290 = 1154.5\ K$$

The background noise is calculated using

$$N_{bkg} = KT_{tot}B \tag{3.6.11}$$

$$N_{bkg} = 1.379 \times 10^{-23} \times 1154.5 \times 100000 = 1.592 \times 10^{-15}\ W$$

where T_{tot} is the total temperature, B is the bandwidth in Hz and k is Boltzmann's constant ($1.379 \times 10^{-23}\ JK^{-1}$).

The in-band ambient noise is calculated using

$$N_{amb} = B \times A$$

$$N_{amb} = 100000 \times 10^{-26} = 1 \times 10^{-21}\ W$$

where N is the ambient noise, A is the ambient noise level of 1×10^{-26}. The total background noise in the system is then calculated as

$$N_{tot} = N_{bkg} + N_{amb} = 1.592001 \times 10^{-15}\ W \tag{3.6.12}$$

$$N_{tot} = -118\ dBm$$

SNR calculation

The SNR can now be calculated as

$$SNR = 10\log(P_R/N_{tot})\ dB \tag{3.6.13}$$

$$SNR = 17.9\ dB$$

A Matlab script, matlab_snr.m, was used to compute the SNR at different distances D between the transmitter and receiver. Table 3.4 shows the resulting SNR values when the distance was

D in km	SNR in dB	Received Signal Power in dBm	Received Noise Power in dBm
500	17.85	-100.10	-117.96
673.1	15.27	-102.68	-117.96
846.2	13.28	-104.67	-117.96
1019.3	11.67	-106.28	-117.96
1192.4	10.31	-107.64	-117.96
1365.5	9.13	-108.82	-117.96
1538.6	8.09	-109.86	-117.96
1711.7	7.17	-110.78	-117.96
1884.8	6.33	-111.62	-117.96
2057.9	5.57	-112.38	-117.96
2231	4.86	-113.09	-117.96

Table 3.4 – SNR values at different distances D.

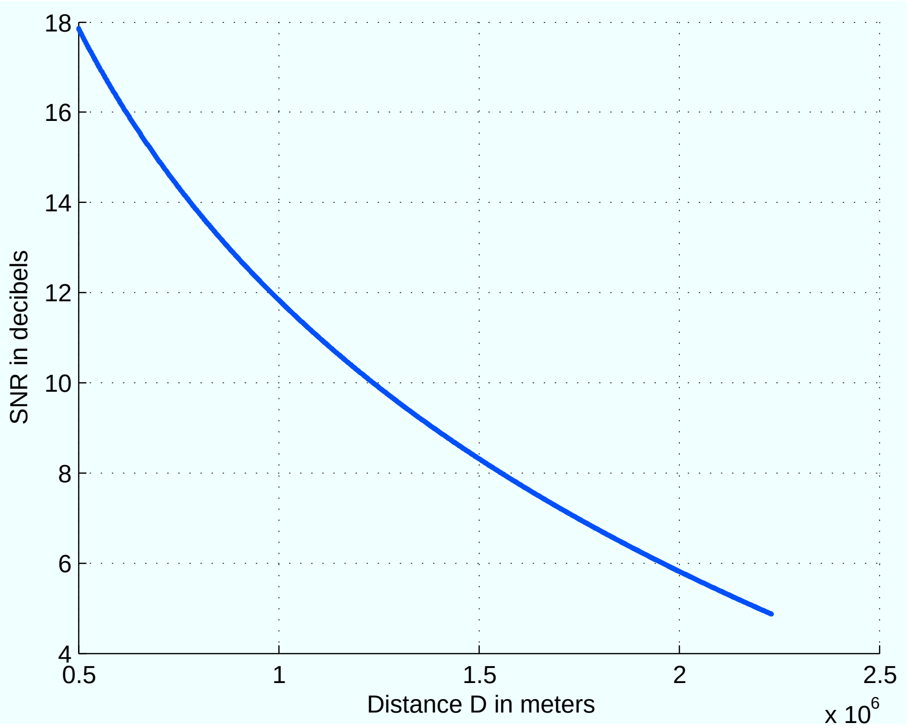


Figure 3.3 – SNR at different distances D

varied from the minimum LOS distance (D=500 km) to the maximum LOS distance (D = 2231 km) calculated in Section 3.2. Keeping in mind that we have set a lower limit of 11 dB for the SNR, it can be seen from Table 3.4 that communication will only be possible for distances smaller than 1019.3 km. In Figure 3.3 it's easy to see that the SNR decreases exponentially as the distance increases linearly. As mentioned earlier the SNR is an indication of how reliably communications will take place. The maximum distance D is now further decreased by doing the link budget. The new maximum distance D is now 1019.3 km to get a SNR of 11dB. Thus the time during which communications can take place during one orbit is now shorter than the calculated 12.73 min in Section 3.4.

3.7 Summary

- The maximum LOS distance between the satellite and the ground station is 2231 km, if the orbit is circular, polar and sun-synchronous and the satellite orbits approximately 500 km above the earth's surface.
- The propagation time is 7.436 ms and the RTT is twice as long.
- The satellite will orbit around the earth approximately 15 times per day. If the satellite passes directly over the ground station, it will be in sight for a maximum of 12.73 min per orbit.
- The frequency band to be used is the ISM-band which stretches form 2.4 GHz to 2.4835 GHz.

3.8 Next chapter

Now that the physical limitations and constraints of the LEO satellite system is set, the system design aspects are discussed in the next chapter.

Chapter 4

System Design Aspects

For a wireless communication system to work effectively, it has to be designed in such a way that is can withstand almost any failure or error without collapsing the entire network. The design of such a network is a very complex process and there are numerous factors to consider. For example the modulation scheme to be used, the type of access protocol, the error correction and detection scheme. Some of these aspects are directly and indirectly dependent on one another. In this chapter, some of the important design aspects will be looked at and explained.

4.1 Basic types of communication

Communication methods can be compared with the following criteria.

- **Simplex:** Communication can only take place in one direction, e.g. a car radio.
- **Half-duplex:** Communication can take place in both directions but not at the same time. A good example is a Walkie-Talkie.
- **Full-duplex:** Communication can take place in both directions at any time, e.g cell phone.

It was decided to implement a full-duplex system. Thus the satellite and ground stations can send and receive packets at the same time. To view the uplink and downlink frequency bands, please see Section 3.5.

4.2 Antenna design

The choice of the antenna on both the satellite and ground stations have a very large influence on system performance. The convention is to use an antenna with a high gain when the system transmits at low power. In this case the transmission powers are not very high and thus antennas with high gains are chosen. The antenna choices for the satellite were a high gain Yagi or Patch Array antenna. The width of South Africa, from the west coast to the east coast, is approximately 1500 km and the satellite will orbit at an altitude of 500 km above sea level. With these specifications in mind the antenna pattern chosen can be seen in Figure 4.1. The maximum antenna gain was set at 11dB with $\theta = 72$ degrees. With $\theta = 72$ degrees and the satellite orbiting at an altitude of 500 km, almost half of South Africa's surface will be in the satellite's view.

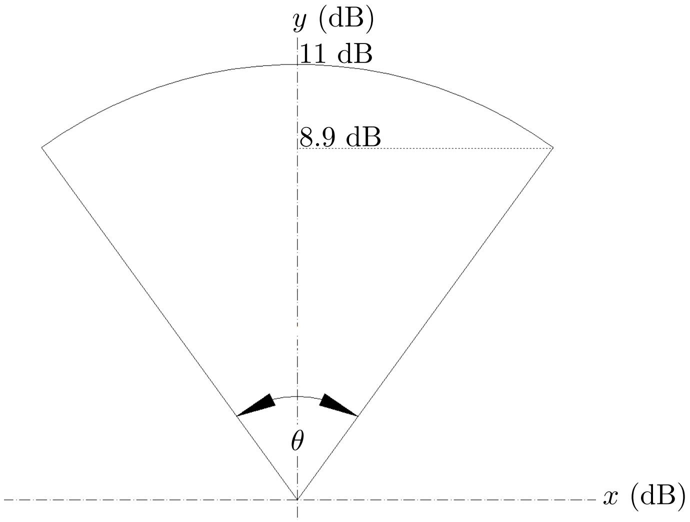


Figure 4.1 – Simplified satellite antenna pattern

Three types of antenna design were considered for the ground stations. The first was a fixed, high gain, Yagi antenna. With a fixed Yagi antenna, the satellite will only be in view for a very short time but data will be transfered more reliably, due to the higher gains that can be achieved with this type of antenna. The disadvantage is that the satellite is only in view for a very short time and this has a negative effect on the total amount of data transfered.

The second antenna design was the tracking Yagi antenna. The tracking antenna was not chosen, because of the extra cost of implementing the tracking system.

The third design was a high gain Quadrifilar Helix antenna. With this design the satellite will be in view even if it passes just above the horizon. The Quadrifilar Helix antenna is relatively easy to design and manufacture. For these reasons it was chosen as the antenna to be implemented in the simulations. The desired antenna pattern of the Quadrifilar Helix for the ground stations can be seen in Figure 4.2. The value of θ is chosen as 45 degrees.

All the antenna gains are set as high as possible. By setting the antenna gains as high as possible the transmission power can be decreased to achieve the same performance as it would have with a low gain and higher transmission power. In Section 3.6, a link budget

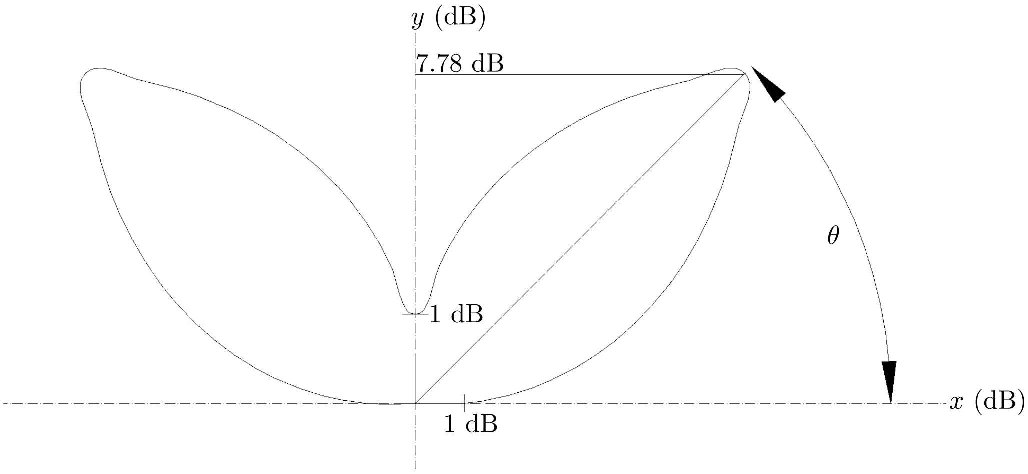


Figure 4.2 – Simplified ground station antenna pattern

analysis was done in Matlab with 5 W transmission power and a Quadrifilar Helix antenna for the ground stations and a Yagi antenna for the satellite. Both antennas had a maximum gain of 11 dB. The results can be seen in Chapter3, Table 3.4. With the satellite at the maximum distance from the ground station the SNR is 4.86 dB. The minimum SNR required for the BPSK modulation scheme is 4.7 dB and thus a system with a Quadrifilar Helix antenna would still be able to operate in even the worst case scenario. The Quadrifilar Helix and Yagi antennas work sufficiently well enough to be implemented in the simulations.

4.3 Transmission power

The maximum transmission power chosen to simulate was 10 W. It was found during the research that most LEO satellite equipment could handle 10 W transmission power, which is thus not unrealistic. The initial idea was to simulate transmission powers of 1, 2, 3, ... , 10 W, but it quickly became apparent that this would not be possible because of the amount of time it would take to simulate all these transmission powers. To run a single simulation takes about 14 hours. Thus it was decided to simulate only two levels of transmit power, 5 W and 10 W. Since 10 W is the highest transmit power chosen, 5 W is chosen as the halfway mark to see what influence the decrease in transmission power has on the system.

4.4 Packet structure and sizes

Six types of packet are used in the simulations. This is because of the different protocols and how they function. This section will give only a short description of each packet. To understand where each packet is used and in which protocol, please refer to Section 4.9.

Data packet

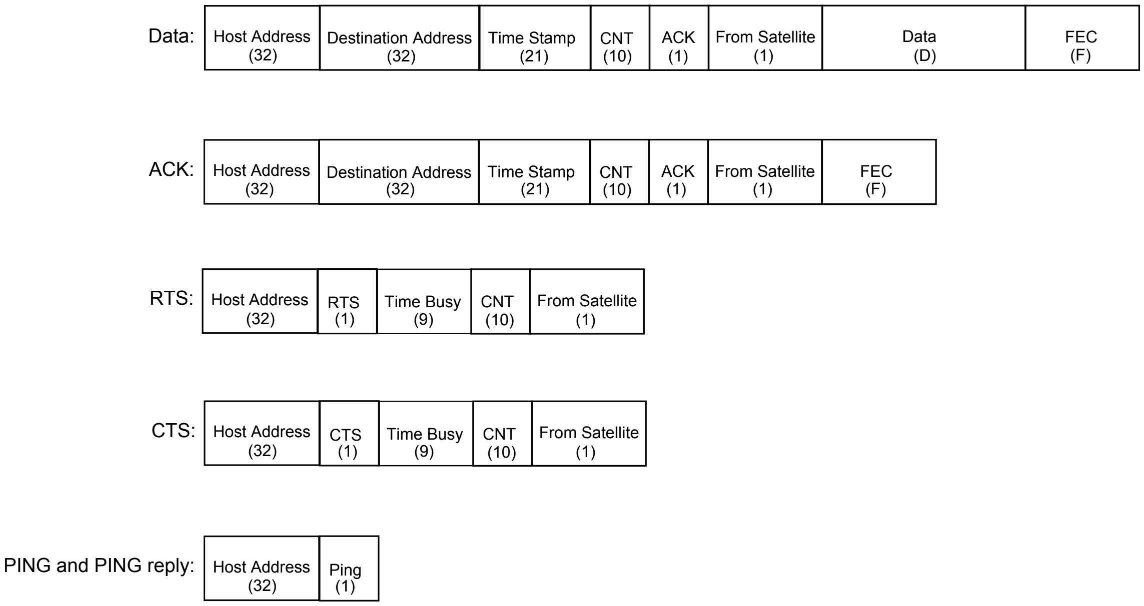


Figure 4.3 – Packet structures

- *Host Address* (32 bits) - Contains the address of the ground station that created the packet.
- *Destination Address* (32 bits) - Contains the address of the ground station to which the packet must be delivered.
- *Time Stamp* (21 bits) - This field stores the time of creation of the packet. It it used in calculations such as End-to-End (ETE) delay.
- *CNT* (10 bits) - The CNT field is the sequence number of the packet for a specific ground station.
- *ACK* (1 bit) - This field defines whether a packet is a Data packet or an ACK packet. If ACK=1 then it's an ACK packet and if ACK=0 it's a Data packet.
- *From Satellite* (1 bit) - This is an indication of whether the satellite transmitted the packet. A 1 indicates that the satellite has transmitted the packet. This is to prevent ground stations misinterpreting other ground stations as the satellite.
- *Data* (D bits) - The Data field will contain the actual data that is being transmitted. If a packet size of 1024 bits is chosen, this field will be $1024 - 256 - F$. The 256 bits are the header bits which includes the Host Address, Destination Address, Time Stamp etc. and F is the parity bits.
- *FEC* (F bits) - Since an FEC scheme is implemented, parity bits will be added to correct errors. The number of bits will depend on the FEC scheme implemented and how many bits the scheme can correct.

ACK packet

- The ACK packet’s structure is the same as the Data packet structure without the Data field. The size of an ACK packet is 512 bits.

RTS and CTS packets

- Both the RTS and CTS packets are 64 bits long and do not contain any parity bits for FEC.
- *Host Address* (32 bits) - Contains the address of the transmitter that sent out the RTS packet.
- *RTS* (1 bit) - This field indicates that this is an RTS packet and is only present in the RTS packet structure. RTS=1 means it is an RTS packet.
- *CTS* (1 bit) - This field indicates that this is a CTS packet and is only present in the CTS packet structure. CTS=1 means it is a CTS packet.
- *Time Busy* (9 bits) - The Time Busy field is populated by the transmitter sending the RTS packet and indicates how long data transfer is going to take.
- *CNT* (10 bits) - The CNT field is the sequence number of the packet.
- *From Satellite* (1 bit) - This is an indication that the satellite transmitted the packet.

Ping and Ping Reply packets

- The Ping and Ping Reply packets are both 64 bits long and do not contain any parity bits for FEC.
- *Host Address* (32 bits) - Contains the address of the transmitter that sent out the packet.
- *Ping* (1 bit) - This field indicates whether the packet is a Ping packet or a Ping Reply packet. Ping=1 indicates that it is a Ping packet and Ping=0 indicates it is a Ping Reply packet.

4.5 Modulation schemes

The choice of digital modulation scheme will significantly affect the characteristics, performance and resulting physical realisation of the communication system. There is no universal best choice of scheme but, depending on the natural characteristics of the channel, required performance and target hardware trade-offs, some schemes will prove a better fit than others. Consideration must be given to the data rate required, latency, available bandwidth and link budget. The physical characteristics of the channel will significantly affect the choice of optimum system. Please note for simplicity no pulse shaping filters are implemented in the modulation and demodulation of signals.

There are various techniques by which digital modulation can be accomplished. Modulating the frequency, amplitude or phase of the information bits of the carrier wave is the most basic known digital modulation techniques. The designation for each is,

- Varying amplitude (AM)→ OOK - On/Off Keying
- Varying frequency (FM) → FSK - Frequency Shift Keying
- Varying phase (PM) → PSK - Phase Shift Keying

More complex modulation schemes are available, each providing additional advantages but at the price of implementation complexity. In keeping with other applications, phase modulation gives the best results in satellite communications [12]. The major modulation schemes used in satellite communications are listed below,

- Binary Phase Shift Keying (BPSK)
- Quadrature Phase Shift Keying (QPSK)
- M-ary Phase Shift Keying (MPSK)
- Quadrature Amplitude Modulation (QAM)

All of these schemes are used in practice for specific satellite communication applications but the most widely used are BPSK, QPSK and 8PSK. Thus these were the choices to implement in the simulator. These three modulation schemes are described in further detail below.

4.5.1 BPSK

4.5.1.1 Data rate

BPSK is the most reliable modulation scheme used for wireless communication. This is because the only two symbols are far apart from one another, which means it can withstand a lot of noise. The baud rate of the system is chosen as 76 kBd, as described in Section 3.6. The data rate of the system is calculated by

$$C = R\log_2(M) \tag{4.5.1}$$

$$C = 76k\log_2(2)$$

$$C = 76\ kbps$$

where C is the data rate, R is the baud rate and M is the number of symbols used. Thus the BPSK system will be able to transmit at 76 kbps.

4.5.1.2 Modulation curve

The Bit Error Rate (BER) of a BPSK system can be derived from the Gaussian noise channel characteristics in the phase domain, as can be seen in Figure 4.4. Taking the integral over the cross-hatched area gives the probability of a bit error. The result will give the theoretical best BER for a BPSK modulation scheme. A BER graph, also known as a modulation curve, for BPSK was created with the BERTool in Matlab to show the theoretical BER of a BPSK system, Figure 4.5. The same tool was also used to create the modulation curve in the simulator.

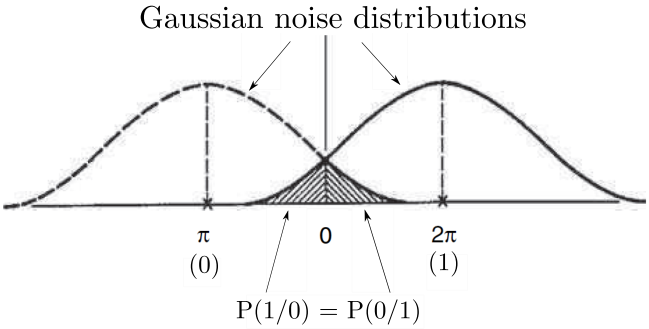


Figure 4.4 – Gaussian noise channel bit error region, [2]

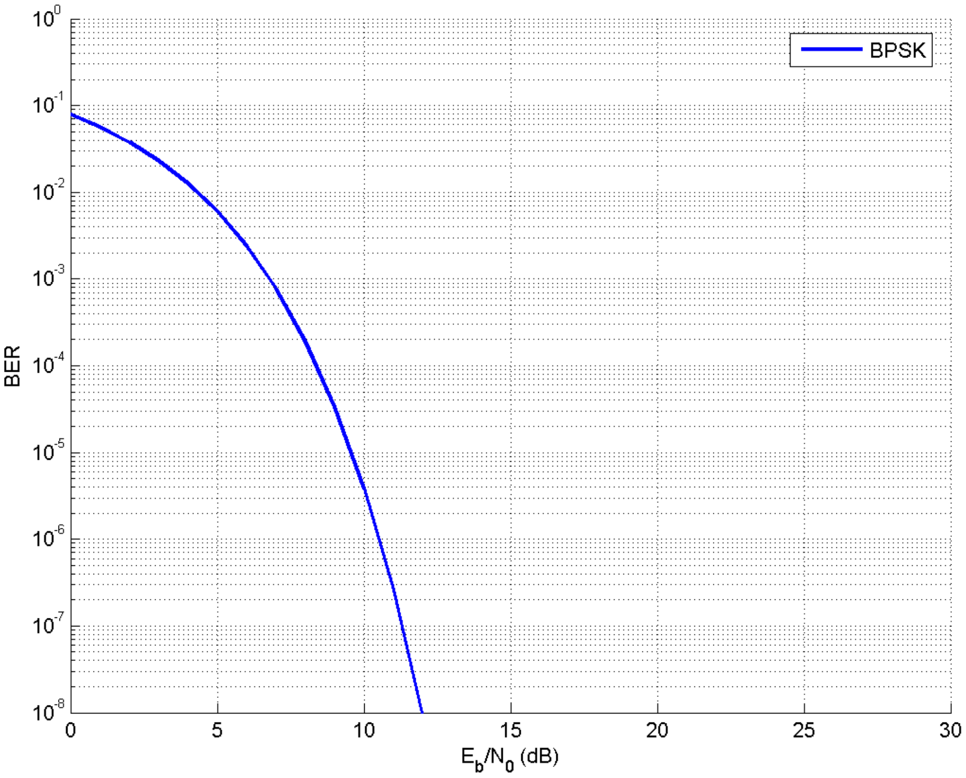


Figure 4.5 – BPSK modulation curve

4.5.2 QPSK

4.5.2.1 Data rate

Using the same bandwidth as a BPSK system, a QPSK system will have a data rate double that of BPSK. This is due to the input bit stream being converted into 2-bit symbols which are used to phase modulate the carrier wave. This makes QPSK a very efficient and reliable modulation scheme when compared against BPSK. Thus the number of symbols used, denoted by M, is four rather than two as with BPSK. Calculating the data rate for QPSK,

$$C = R\log_2(M) \tag{4.5.2}$$

$$C = 76k\log_2(4)$$

$$C = 152\ kbps$$

where C is the data rate, R is the baud rate and M is the number of symbols used. From the calculation above it can be seen that a QPSK system has double the data rate of a BPSK system.

4.5.2.2 Modulation curve

The BER for QPSK is almost the same as for BPSK. The in-phase noise component will affect only the in-phase signal component and the quadrature noise components will affect only the quadrature signal component. Thus for the same incoming data rate, both QPSK and BPSK have the same bit error rate performance in a given noise environment. The theoretical modulation curve for QPSK was created with BERTool and can be seen in Figure 4.6.

4.5.3 8PSK

4.5.3.1 Data rate

8PSK has three bits per symbol and requires a transmission bandwidth of $\frac{1}{3}$ of that of BPSK to transmit at the same data rate as BPSK. The phase state diagram for 8PSK is shown in Figure 4.7. Due to the increase in number of symbols, it is impossible to make the phase states orthogonal from each other. Thus additional power is needed to maintain the same overall performance as QPSK and BPSK. 8PSK needs twice as much power as BPSK or QPSK to achieve the same overall performance over the same link conditions. This is due to the fact that in 8PSK the phase differences between symbols decreases as seen on the phase state diagram. Thus if the the amplitude is increased by a factor of two, the distance between symbols is similar to that of BPSK or QPSK and hence give the same BER at the modulator output. 8PSK is an important modulation scheme in satellite communications, due to the extra

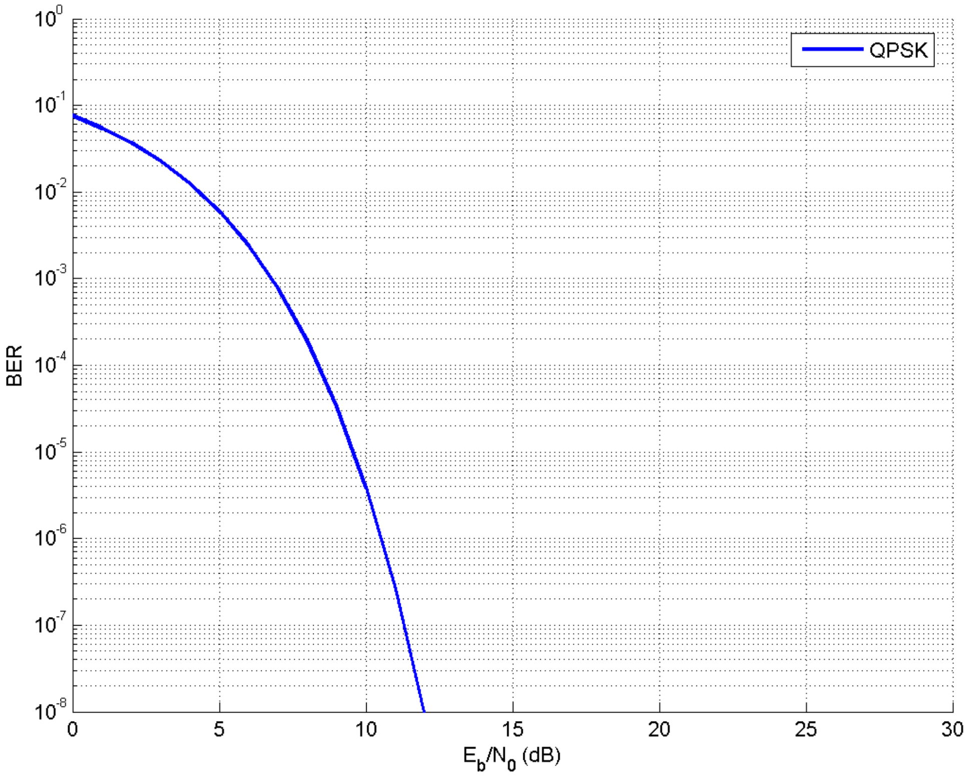


Figure 4.6 – QPSK modulation curve

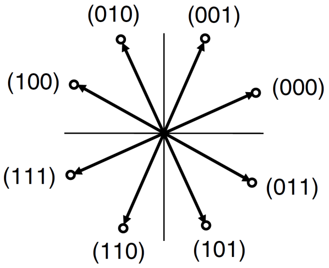


Figure 4.7 – 8PSK phase state diagram, [2]

bit in the symbols. This extra bit can be used for error correction coding, which can give up to a 3 dB coding gain. Calculating the data rate of an 8PSK system,

$$C = R\log_2(M) \tag{4.5.3}$$

$$C = 76k\log_2(8)$$

$$C = 228\ kbps$$

where C is the data rate, R is the baud rate and M is the number of symbols used. 8PSK has a higher data rate than that of BPSK and QPSK.

4.5.3.2 Modulation curve

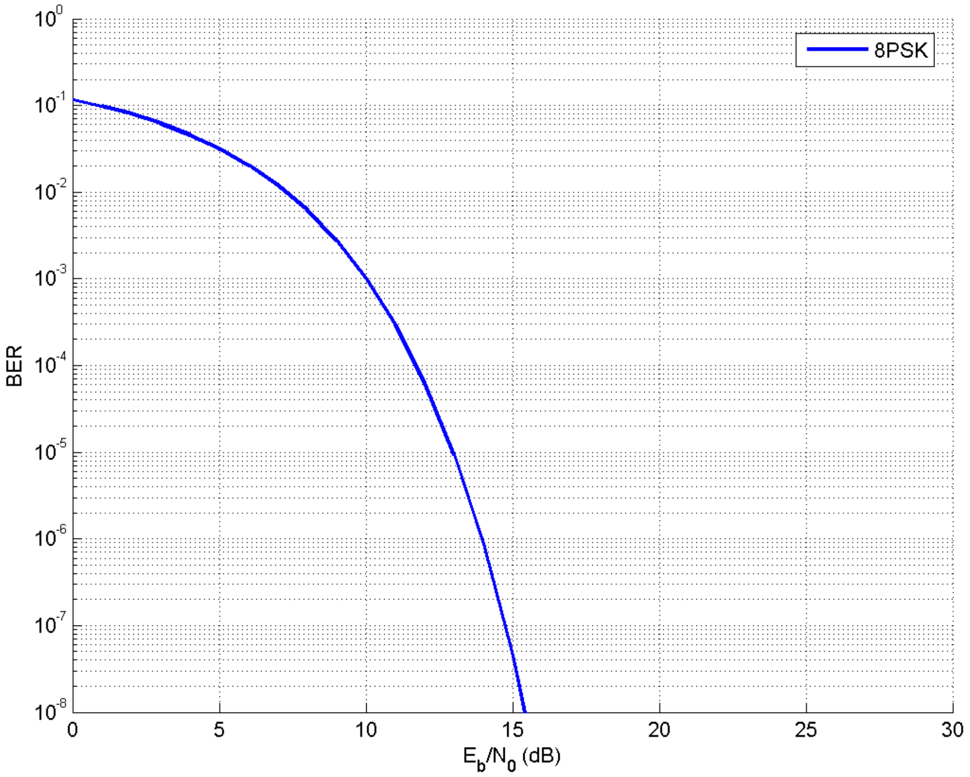


Figure 4.8 – 8PSK modulation curve

The modulation curve of 8PSK can be seen in Figure 4.8. Comparing 8PSK's modulation curve to that of BPSK or QPSK it can be seen that for 8PSK to achieve the same BER as QPSK or BPSK it will need more transmission power to increase the signal to noise ratio. For example, to achieve a BER of 10^{-6}, BPSK and QPSK need a signal to noise ratio of only about 11 dB, but an 8PSK system would need a signal to noise ratio of 14 dB. Thus the increased data rate of 8PSK comes at a price of higher transmission power.

4.6 Minimum BER for digital satellite networks

Any communication system must be designed to meet certain performance specifications. For digital transmissions, one of the most important specifications is the BER. The minimum BER performance requirement for a digital satellite communication system is 10^{-6}, [13]. In other words, for every million bits that are transmitted, only one will be received in error.

For any BER bigger than 10^{-6}, the incoming data will be discarded. Table 4.1 shows the minimum SNR required to achieve a BER of at least 10^{-6} for each modulation scheme.

Modulation Scheme	BER	Minimum SNR (dB)
BPSK	10^{-6}	11
QPSK	10^{-6}	11
8PSK	10^{-6}	14

Table 4.1 – Minimum SNR required to achieve a BER of at least 10^{-6} for BPSK, QPSK and 8PSK

BPSK and QPSK have both a minimum SNR very close to 11dB. For 8PSK modulation, a much higher SNR is required and this will decrease the amount of time during which communications can take place.

4.7 Receiver sensitivity

Receiver sensitivity is the minimum amount of power received that the receiver will be able to detect as a valid signal. It is a function of modulation scheme, minimum BER and noise figure. As mentioned in Section 4.6 the minimum BER for digital communications is 10^{-6}. Using the total background noise calculation, in Section 3.6.3, the noise floor can be expressed in dBm as,

$$N_{dBm} = 10\log(N_{tot} \times 1000) \tag{4.7.1}$$

$$N_{dBm} = 10\log(1.592 \times 10^{-12})$$

$$N_{dBm} = -118\ dBm$$

The result shows the noise floor level and it indicates how much noise is present in the system. Since we have set a minimum SNR for each modulation scheme, we have to add it to the noise floor value to get our receiver sensitivity. For BPSK and QPSK, 11dB will be added and for 8PSK, 14 dB will be added. For BPSK and QPSK the receiver sensitivity is

$$P_{sensitivity} = N_{dBm} + SNR_{min} \tag{4.7.2}$$

$$P_{sensitivity} = -118 + 11 = -107\ dBm \tag{4.7.3}$$

This means that a BPSK or QPSK system cannot receive any signal lower than -107dBm or 1.99×10^{-14} W, without serious increase in BER. For 8PSK

$$P_{sensitivity} = -118 + 14 = -104 \; dBm \tag{4.7.4}$$

And thus an 8PSK system will only be able to receive signals higher than -104dBm or 3.98×10^{-14} W, for acceptable BER.

4.8 Direct sequence spread spectrum

Spread spectrum is defined as a transmission technique in which a pseudo-noise code, independent of the information data, is employed as a modulation waveform to spread the signal energy over a bandwidth much greater than the original signal information bandwidth. At the receiver the signal is de-spread using a synchronized replica of the pseudo-noise code. The Code Division Multiple Access (CDMA) scheme that is studied here is taken from [3].

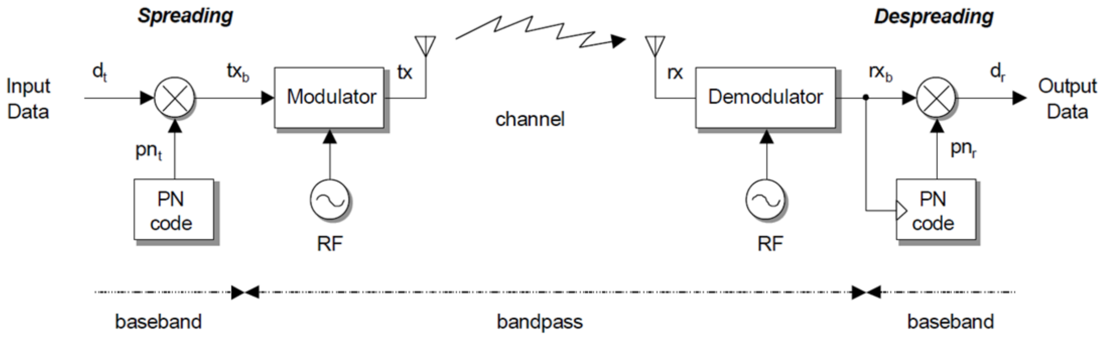


Figure 4.9 – Building blocks of a BPSK modulation DSSS system, [3]

There are two main types of spread spectrum techniques available. One is Frequency Hopping Spread Spectrum (FHSS) and the other one is Direct Sequence Spread Spectrum (DSSS). The latter one is chosen to be implemented, because of reasons to be explained later. Figure 4.9 shows the basic building blocks of a BPSK DSSS system which includes the spreading and de-spreading of the signal.

The input data can be any binary data d_t with a symbol rate of

$$R_s = \frac{1}{T_s} \tag{4.8.1}$$

and the pseudo-noise code pn_t with a chip rate of

$$R_c = \frac{1}{T_c} \tag{4.8.2}$$

4.8.1 Spreading

Referring to Figure 4.9, in the transmitter the binary input data d_t is directly multiplied by the pseudo-noise code pn_t and the result is the baseband signal

$$tx_b = d_t \times pn_t \tag{4.8.3}$$

Multiplying the binary input data d_t by the pseudo-noise code is effectively spreading the baseband bandwidth R_s of d_t to a baseband bandwidth of R_c.

4.8.2 De-spreading

The spread spectrum signal cannot be detected by a conventional narrowband receiver. At the receiver, the synchronized pseudo-noise code pn_r is multiplied by the received baseband signal rx_b . If the transmitter pseudo-noise code pn_t is the same as the pseudo-noise code at the receiver pn_r and they are synchronized, only then will the received signal be de-spread and the binary data recovered to produce d_r. If the wrong pseudo-noise code is used at the receiver, or if the receiver and transmitter's pseudo-noise codes are not synchronized, the multiplication of the received baseband signal rx_b by the receiver's pseudo-noise code pn_r will only lead to a further spreading of the received data rx_b.

4.8.3 Multiple access

In a DSSS system, all stations can transmit at the same time and every station has the total available bandwidth for transmission, but the SNR decreases as the number of stations increases.

Figure 4.10 is a simplified DSSS system with multiple stations transmitting at the same time. The multiplication of the received baseband spread spectrum signal rx_b by the pseudo-noise code pn_1 of station 1 only despreads the signal of station 1. Signals from other stations that are not despread produce noise N_u for station 1. Thus the more stations there are in the system, the more noise is produced.

Figure 4.11 shows what the received baseband spread spectrum signal will look like at the receiver. Note that as the number of stations increases, the noise also increases. As mentioned above, when station 1's signal is despread the other station's signals become noise as seen in Figure 4.12.

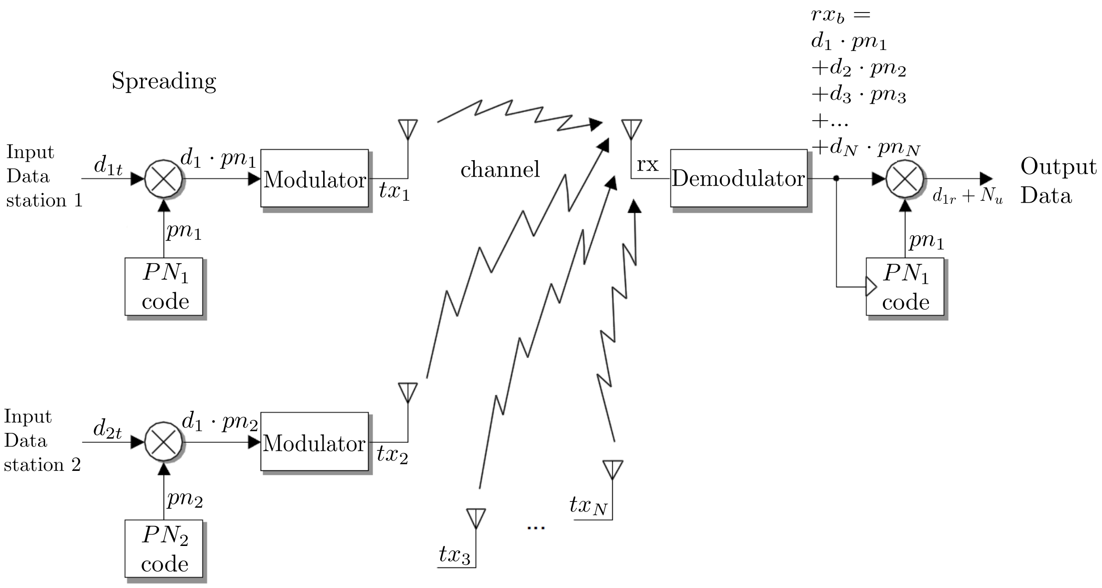


Figure 4.10 – Simplified DSSS system with multiple stations transmitting simultaneously, [3]

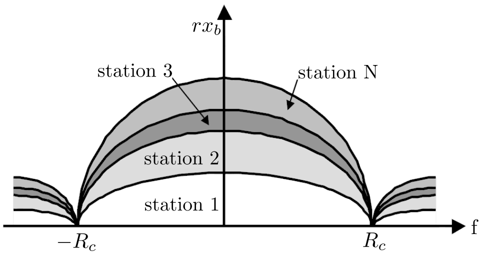


Figure 4.11 – Received baseband spread spectrum signal rx_b when multiple stations transmit simultaneously, [3]

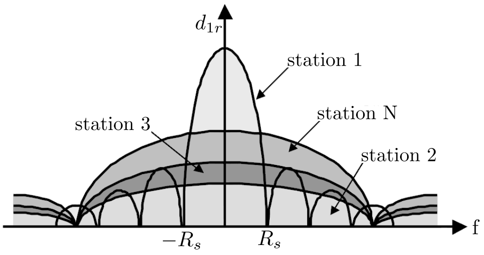


Figure 4.12 – Despread signal of station 1 with the other stations portrayed as noise, [3]

The noise produced by the other stations is added together. If there are too many stations transmitting at once, the noise will become too high and the despread signal will not be visible, because it is hidden beneath the noise. To overcome this a good set of pseudo-noise codes must be chosen. The set of pseudo-noise codes must have good autocorrelation for synchronization and low cross correlation (orthogonal codes) for low multiple access interference. Good codes to use are Gold codes, Kasami or Hadamard-Walsh codes. Another way to lower the amplitude of the noise each station produces is to use longer pseudo-noise codes. This will in effect spread the data even further, reducing the amplitude of the noise.

Longer pseudo-noise codes or higher chip rates will increase the processing gain. Processing gain is the amount, in decibels, that the amplitude of the signal will increase or decrease when the signal is spread or despread. The higher the processing gain the less noise each station will add to the system and thus the more stations that can be added. The processing gain is usually chosen as an integer value and it is calculated as follows

$$G_p = \frac{R_c}{R_s} \tag{4.8.4}$$

where R_c is the chip rate and R_s is the symbol rate.

Spread spectrum technology is a rather new technology implemented in satellite communications. It enables more than two stations to communicate at the same time. It also serves as encryption; if the receiver doesn't know the pseudo-noise code the transmitted signal cannot be despread. It also makes the transmitted signal very immune to interference and all the stations make use of the full bandwidth available.

4.9 Protocol overview

In wireless communications, the communication channel is shared among all the parties who want to communicate. This creates chaos if all stations want to communicate at the same time and therefore protocols were designed to make communications possible. These protocols, also know as the data transfer protocols, are made up of a set of rules that facilitate data communications. The protocols selected to be simulated are Round-Robin Polling, CSMA-CA and DSSS(CSMA-CA).

4.9.1 Round-Robin Polling

4.9.1.1 Description

In a satellite network with Round-Robin Polling, the satellite will poll each ground station in turn to enquire if the ground station has data to transmit. If the ground station has data, it will be allowed to transmit it. If the ground station has no data to transmit, the satellite polls the next ground station. If a ground station misses a turn, it has to wait for the next time the satellite polls it. But this can take quite some time if there are a lot of stations. The propagation delay in satellite systems also increases this waiting time.

A very big advantage of the Round-Robin Polling protocol is that there is less ground station generated noise present, because the ground stations don't contend for access to the channel.

4.9.1.2 Implementation

The Round-Robin Polling protocol will function as follow. Looking at Figure 4.13, the satellite sends out a Ping packet.

The intended ground station receives the packet and then immediately sends a Ping Reply packet. The function of the Ping Reply packet is to tell the satellite whether the ground station

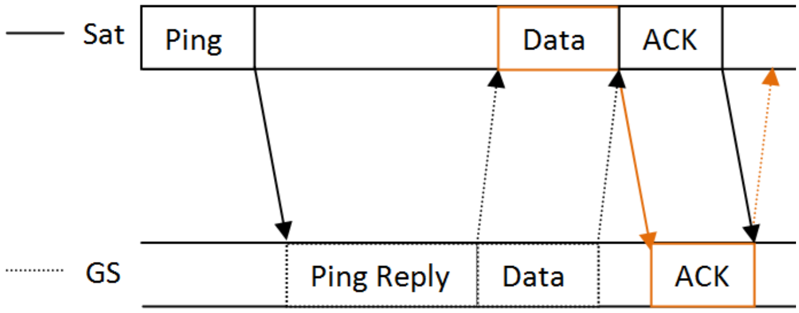


Figure 4.13 – Round-Robin protocol sequence diagram

has data to transmit. If the Ping Reply packet were not used the satellite would wait for the length of time a packet would take to transmit before pinging the next ground station. As the packet sizes become larger, these waiting times also become longer and thus the protocol becomes inefficient. Using a small Ping Reply packet removes this problem. If a ground station has data to transmit after it has received a ping, it sends out the Ping Reply packet to tell the satellite that it wants to transmit data. Then, directly after the Ping Reply packet, the ground station sends out the Data packet.

The satellite receives the Ping Reply packet sent from the ground station. It checks the Ping field to determine whether the ground station wants to transmit data. If the Ping field is set to 0 the ground station has no data to transmit and the satellite will send out a Ping packet to the next ground station. If the Ping field is set to 1, the satellite sets a timer and waits for the length of time it would take a packet to be transmitted from the ground station. If this timer expires and no Data packet has been received, the satellite pings the next ground station. If the satellite did receive a Data packet, it first checks in its buffer whether it has any Data packets to be delivered to the current ground station. If it has data to send to the ground station, it first sends out an ACK packet to acknowledge that it has received the Data packet and directly after that it transmits the Data packet found in its buffer. This Data packet is marked in orange in Figure 4.13. The satellite then starts a time out timer for the ACK packet it is waiting for.

Meanwhile the ground station is in receiving mode and waits for an ACK packet after it has sent out the Data packet to the satellite. The ground station then receives the ACK packet sent by the satellite and it marks the transmission as successful. It also receives the Data packet sent from the satellite. The ground station immediately replies with an ACK packet to the satellite. This ACK packet is marked in orange in Figure 4.13.

The satellite will receive the ACK packet and it marks the transmission as successful and removes the corresponding Data packet from its buffer. If the ACK packet was not received, the satellite would have timed out and would continue to ping the next ground station.

4.9.2 Carrier Sense Multiple Access with Collision Avoidance

4.9.2.1 Description

With CSMA-CA, a station that wants to transmit data senses the channel to determine whether the channel is busy. If the channel is available, a short RTS packet is transmitted. The RTS packet contains the source address and the length of the data packet it wants to transmit. If the satellite has received the RTS packet, it will reply with a Clear-to-Send (CTS) packet with the same information as in the RTS packet. All the stations that are able to receive data from the satellite will receive the CTS packet. The stations checks the contents, specifically the data packet length field, of the CTS packet and determine how long it will take a packet of that size to be transmitted. The stations then keep quiet during this estimated time. This is know as Virtual Carrier Sense (VCS). When the station that sent the RTS receives the CTS, it starts transmitting the data packet and waits for an acknowledgment of the packet. If no acknowledgment is received, the whole process is repeated. By doing this collisions are avoided, hence the name collision avoidance. The RTS and CTS packets are small compared with the data packets. Collisions between these shorter packets are less detrimental to system throughput than collisions between larger data packets would be.

4.9.2.2 Implementation

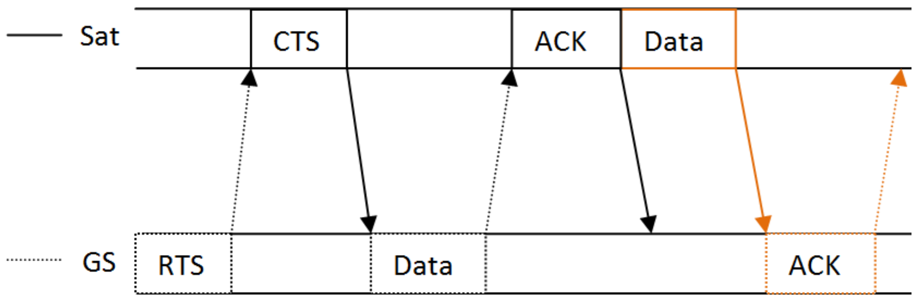


Figure 4.14 – CSMA-CA and DSSS(CSMA-CA) sequence diagram

As the satellite passes over a couple of ground stations, these ground stations will compete for channel access. A ground station senses the channel to determine whether any of the other stations that are in view are currently transmitting data. If not, the ground station sends out a short RTS packet, as seen in Figure 4.14. If the ground station senses that there are other ground stations transmitting data, it backs off for a random time between 1 and 10 seconds before sensing the channel again. All random integer numbers are selected from a uniform distribution. Depending on how many ground stations there are and how close to one another they are, these RTS packet won’t collide with one another. After sending out an RTS packet, the ground station keeps quiet for the amount of time it would take to transmit a CTS packet plus a random time between 1 and 10 seconds. This random time is added to prevent all the ground stations transmitting their next RTS packet at exactly the same time if a CTS is not received.

When the satellite receives an RTS packet, it transmits a CTS packet to all ground stations containing the time they should keep quiet for.

The ground stations that are in view of the satellite will receive the CTS packet sent by the satellite. All the ground stations then check the contents of the CTS packet received, specifically the Time Busy and Host Address fields. If the Host Address field is the same as the ground station's host address, it knows that its RTS got through to the satellite. That specific ground station will then transmit a Data packet to the satellite and will start a timeout timer. This timer will expire if no ACK packet is received and the ground station will compete for the channel access again. If the Host Address field doesn't match up to the ground station's host address, it keeps quiet for the amount of time indicated in the Time Busy field plus a random time between 1 and 10 seconds. When the ground station has kept quiet for the determined amount of time, it will sense the channel again before transmitting an RTS packet.

The satellite receives the Data packet sent by the specific ground station. The satellite then checks in its buffer whether it has any Data packets to be delivered to that ground station. If it does not have any, it transmits the ACK packet. If it has data to transmit to the ground station, it will transmit the ACK packet, and directly after that, it will transmit the Data packet. This Data packet is marked in orange in Figure 4.14.

When the ground station receives the ACK packet transmitted by the satellite, it marks the transmission as successful. It will then receive the Data packet transmitted by the satellite and replies with an ACK packet. This ACK packet is also marked in orange in the Figure 4.14. After the transmission of the ACK packet the ground station again competes for channel access.

The satellite marks the transmission as successful once the ACK packet is received. It also removes the corresponding Data packet in its buffer.

4.9.3 Direct Sequence Spread Spectrum Carrier Sense Multiple Access with Collision Avoidance

4.9.3.1 Description

Direct Sequence Spread Spectrum Carrier Sense Multiple Access with Collision Avoidance DSSS(CSMA-CA), functions in the same way as CSMA-CA, but with DSSS technology added.

4.9.3.2 Implementation

The underlying protocol in DSSS(CSMA-CA) is CSMA-CA. Thus the implementation is almost exactly the same, but with DSSS attributes added. Every ground station has its own pseudo-noise code and knows what the pseudo-noise code of the satellite is. Using these codes, every time a packet is transmitted, be it from the satellite or a ground station, the packet is transmitted using the corresponding pseudo-noise code. Thus less noise is generated in the system and there is less chance of packet collisions. The rest of the two protocols is exactly the same and they both rely on the CSMA-CA protocol for channel contention and data transmission.

4.10 Forward error correction

Wireless communication has become more popular over the last decade. Although there are many advantages to using wireless over fixed line systems, there is a major disadvantage, which is a high transmission error rate in a noisy environment. There is nothing we can do to stop transmission errors in wireless communications and they will be with us forever. Over the years we have learned how to deal with them. Some of the techniques and algorithms used to detect and correct errors will be discussed in this section.

4.10.1 Source of errors

There are two types of transmission errors in a wireless communication system, single bit errors and burst errors.

4.10.1.1 Single bit errors

Single bit errors are generated by noise in the system. The noise is modeled as a Gaussian process and is quantified in the SNR of the link. The noise is a random phenomenon, so there is no way of predicting or calculating when it will occur or which bit of data will be corrupted.

4.10.1.2 Burst errors

Burst errors are more common in wireless communication than single bit errors. Burst errors occur when a whole group of bits are corrupted at the same time. The source of burst errors can vary a lot, from other communication devices that are transmitting on the same frequency band to lightning and even faulty equipment. Having errors come in bursts, rather than single bit errors, has both advantages and disadvantages. One advantage is that data is usually transmitted in blocks and if a burst error occurs, only one or two blocks need to be retransmitted, say for example that a single bit error would occur once in every thousand bits. If the data block being sent is more than 1000 bits long, every data block will have to be resent if no error correction is used.

4.10.2 Error correction

On some systems, especially satellite systems, error correction coding is a necessity, due to the large propagation delays experienced. Error correction coding, or better known as FEC, is a bit more complex than the normal error detecting schemes. An error correction code is redundant data, or parity data that is added to a message, such that it can be recovered by a receiver even when a number of errors, up to the capability of the code being used, are introduced during transmission.

As with all things in life, there are certain limits to error correction coding. Although it is possible to make a code that corrects all errors in a message, Claude Shannon has shown that such a code will be infinitely long. This is known as the Shannon limit theorem [14]. How Shannon derived this is quite a lengthy and complex process, so it won't be discussed here.

There are many error correcting codes that can be used, including Hamming codes, cyclic codes such as BCH (Bose, Chaudhuri, Hocquenghem), Reed-Muller and Reed-Solomon and convolutional codes. Some of these codes perform better than others. One of the codes that comes close to the Shannon limit, as close as 0.0045 dB [15], is called Low Density Parity Check (LDPC) code.

4.10.2.1 LDPC

LDPC codes were first introduced by Gallager in his PhD thesis in 1960. However, because of the complexity of implementation they were forgotten for a very long time, until rediscovered fairly recently [16]. LDPC codes are a type of linear block code. To be more specific, a linear block code with the parity matrix H being sparse [17]. Being sparse means that it has many more zeros in the matrix than ones. Looking at the parity check matrix in Equation 4.10.1, with dimensions $m \times n$ for a (8×4) code. We can describe this matrix with two numbers, w_c and w_r, where w_c is the number of ones in each column and w_r the number of ones in each row.

$$H = \begin{bmatrix} 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 & 1 & 0 \end{bmatrix} \tag{4.10.1}$$

For a matrix to be a sparse, $w_c << n$ and $w_r << m$. The only way this can be achieved is when the parity matrix H is very large. For LDPC codes to come very close to the Shannon limit, they need a very large block length, up to 10^7. The decoding process is computationally expensive. As with other codes, optimally decoding an LDPC code is an NP-complete problem.

The reason why LDPC is not chosen to be implemented is because of the difficulty in determining how many errors it will be able to correct without implementing the complete LDPC scheme. The number of corrections is dependent on certain characteristics and computational methods at the LDPC receiver. To implement the LDPC scheme in a simulator is a time consuming process and a new thesis on its own.

The actual FEC algorithm is not implemented in the simulator. The FEC scheme is only implemented in principle. Meaning that the simulator will only correct a predetermined amount of bits depending on the scheme implemented. These predetermined bits are calculated beforehand and the ratio of packet size versus correctable bits are hardcoded into the simulator. Therefore, the decision was made to simulate the effect of a systematic code, such as BCH.

4.10.2.2 BCH

Since LDPC codes have been discarded as choice for the simulator, the next best FEC scheme is BCH. The BCH abbreviation stands for the discoverers; Bode and Chaudhuri in 1960 and, independently, Hocquenghem in 1959. BCH codes can correct multiple errors in a message and are a generalization of the Hamming code. A major advantage of BCH codes is that they can be decoded very easily with an algebraic method called syndrome checking. BCH codes are also highly flexible, allowing control over block length and error thresholds, thus a custom code can be developed to a given specification. In technical terms a BCH code is a multilevel cyclic variable-length digital error-correcting code used to correct multiple random errors. BCH codes work very well with multilevel phase-shift keying modulation whenever the number of levels is a prime number or a power of a prime number.

With BCH(n,k) codes, we can calculate

$$mt = (n - k) \tag{4.10.2}$$

parity bits from the input block of k bits using generator polynomial $G(x)$, [18]. We can correct combinations of t or fewer bit errors in the received block of n bits.

Then, at the transmitter side, the BCH(n,k) encoder calculates and adds mt parity bits to the block of k data bits. At the receiver, the BCH(n,k) decoder corrects any combination of t or fewer errors by using mt bits of parity information.

Table 4.2 shows some BCH error correcting capabilities taken from [5]. The BCH error correcting capabilities were calculated beforehand and, together with the capabilities taken from [5], BCH was implemented in the simulations.

Block length	Information bits	Number of correctable bits
7	4	1
15	11	1
15	5	3
31	26	1
31	16	3
63	57	1
63	36	5
63	7	15
127	120	1
127	78	7
127	8	31
255	247	1
255	155	13
255	9	63
511	502	1
511	268	29
511	10	121
1023	1013	1
1023	503	58
1023	11	255

Table 4.2 – Some BCH error correcting capabilities, from [5]

4.10.3 Coding gain

The effect of FEC is basically to improve the SNR of the link. The improvement in SNR is called the coding gain and is usually expressed in terms of decibels. A comparison of the coding gain of some FEC schemes is shown in Figure 4.15, as determined in [4]. Large coding gains can be created, but at the expense of longer codes. The code needs to be optimised so that the coding gain can be large enough to enable operation of the system at the least amount of transmitting power. Some balance must be achieved in the application.

4.11 Summary

- The antenna selected for the satellite is a high gain Yagi type and a Quadrifilar Helix will be used on the ground stations.
- 5 W and 10 W transmission power will be simulated.
- The modulation schemes chosen for simulation are BPSK, QPSK and 8PSK.
- The minimum BER is 10^{-6} which translates to a minimum SNR of 11dB for BPSK and QPSK. 8PSK has a minimum SNR of 14dB.
- The receiver sensitivity for BPSK and QPSK is -107dB, and for 8PSK,-104dB.
- The protocols to be simulated are Round-Robin Polling, CSMA-CA and DSSS(CSMA-CA).
- The FEC scheme chosen for the simulations is BCH.

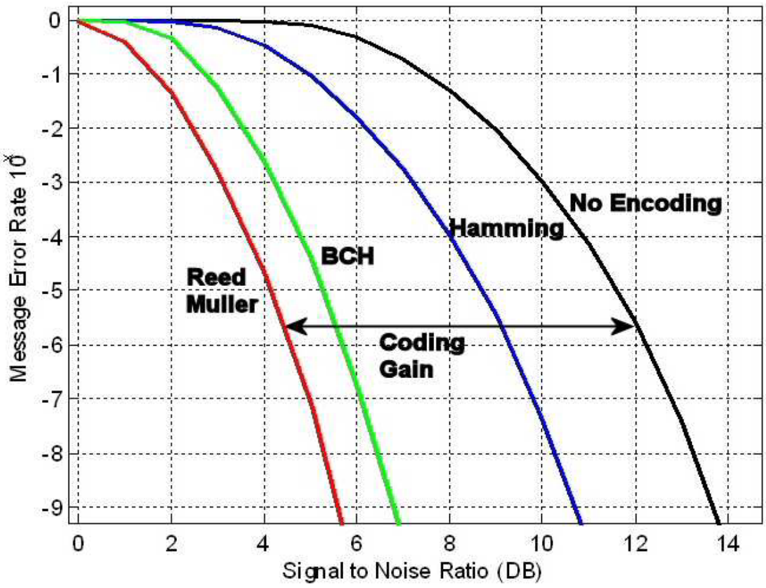


Figure 4.15 – Coding gain of various FEC schemes, [4]

4.12 Next chapter

In Chapter 5, different Opnet design aspects and performance simulation results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling are discussed.

Chapter 5

System Simulation

Some of the protocols chosen to be implemented are non-deterministic protocols. This makes it very difficult for the system to determine what the next state of the system will be. Thus one needs a simulator that can simulate these conditions and log the results for analysis.

5.1 Simulation requirements and platform selection

A simulation platform was needed to simulate a LEO satellite and its communication links to one or more ground stations. There was a long list of criteria the simulator had to adhere to. It had to be able to

- Track and simulate the orbit and orbit parameters of a satellite.
- Simulate antenna designs on both the satellite and ground stations.
- Implement and simulate different type of modulation schemes.
- Simulate the generation of network packets and the transmission of packets to and from the satellite.
- Simulate FEC capabilities.
- Monitor and save wireless channel parameters for later use.

These points were kept in mind during the platform selection phase. The first simulator was coded in Matlab [19]. It was discarded fairly quickly, due to the fact that the simulator needed to be a discrete event simulator and Matlab's simulations are in continuous time. This creates a problem if the computer's Central Processing Unit (CPU) becomes overloaded with work. If the CPU has a lot of data to process, it essentially slows down and this extends the time in which a set of instructions are processed. This makes it difficult to extract or calculate the correct time at which certain events occurred. Thus the focus shifted to a discrete event simulator which runs the simulation in discrete time events. The discrete event simulator manages the time issues and auto corrects for them so that the correct results and time are easily extracted or determined.

After doing research on discrete event simulators for wireless networks, two platforms stood out, Mixim [20] and Opnet Modeler [21].

Mixim is based on the Omnet++ [22] modeling framework created for mobile and fixed wireless networks (wireless sensor networks, body area networks, ad-hoc networks, vehicular networks, etc.). It offers detailed models of radio wave propagation, interference estimation, radio transceiver power consumption and wireless Medium Access Control (MAC) protocols.

The Omnet++ platform, which Mixim relies on, is an extensible, modular, component-based C++ simulation library and framework, primarily for building network simulators. Network is meant in a broader sense that includes wired and wireless communication networks, on-chip networks, queuing networks, and so on. Domain-specific functionality such as support for sensor networks, wireless ad-hoc networks, Internet protocols, performance modeling, photonic networks, etc., are provided by model frameworks, developed as independent projects. Omnet++ offers an Eclipse-based integrated development environment (IDE), a graphical runtime environment, and a host of other tools. There are extensions for real-time simulation, network emulation, alternative programming languages (Java, C#), database integration, SystemC integration, and several other functions.

The second simulator was coded on the Mixim platform. The development on this platform didn’t last long, due to a lack of documentation. The Mixim platform did not meet all the criteria, and the formulas used to calculate wireless channel parameters such as signal-to-noise ratio, thermal noise, interference noise were very vague. Also Mixim has no or poor documentation on its libraries, which makes it very difficult for the developer to use.

The third simulation platform chosen was Opnet Modeler. Opnet Modeler accelerates the research and development process for analyzing and designing communication networks, devices, protocols, and applications. A user can analyze simulated networks to compare the impact of different technology designs on end-to-end behaviour. Opnet includes a development environment to enable modelling of all network types and technologies. Listed below are some of the key features of Opnet Modeler,

- Fastest discrete event simulation engine among leading industry solutions.
- Hundreds of protocol and vendor device models with source code (complete Opnet Model Library).
- Object-oriented modeling.
- Hierarchical modeling environment.

- Discrete Event, Hybrid, and optional Analytical simulation.
- 32-bit and 64-bit fully parallel simulation kernel.
- Grid computing support for distributed simulation.
- Optional System-in-the-Loop to interface simulations with live systems.
- Realistic Application Modeling and Analysis.
- Open interface for integrating external object files, libraries, and other simulators.
- Integrated, GUI-based debugging and analysis.

Opnet has very good help documentation and online community based help where experts give their advice. It also supports satellite simulations, where a predefined satellite orbit file can be imported to a satellite object in the simulation. This satellite object will then follow the predefined orbit path during the simulation. The orbit file to be imported to Opnet must be of an ".sa" extension file type. Opnet recommends using the Satellite Tool-Kit (STK) software suite to create an orbit and export it to an ".sa" file.

In the STK software suite, the creation of the LEO satellite entails that the orbit parameters and other information regarding the satellite must be entered. The STK software also has an online database with orbit parameters of previously launched satellites. South Africa launched the SumbandilaSat in 2009 and the orbit file of SumbandilaSat was downloaded from the online database. The satellite's orbit path was then exported to the appropriate file type so that it could be used in the Opnet simulations. Taking all this into account, Opnet was chosen as the discrete event simulation platform to be used for the simulations, due to its vast functional capabilities.

5.2 Opnet

5.2.1 Opnet antenna designs

The antenna patterns for both the satellite and ground stations were designed with the Opnet antenna editor. The Opnet antenna editor enables an user to graphically create and modify an antenna pattern in a three dimensional space.

The ground station's antenna pattern, created in Opnet antenna editor, can be seen in Figure 5.1. As mentioned in Section 4.2, the ground station's antenna is a Quadrifilar Helix antenna design with a maximum antenna gain of 11dB. The graphical antenna pattern created is converted, within the Opnet platform, to a lookup table format where the simulation can look up the antenna gain value, given the angle between the transmitter and receiver. Because the antenna pattern table is manipulated graphically within the Antenna editor, it is inevitably somewhat imprecise. This can cause inaccurate results and has to be kept in mind when interpreting results.

The satellite's antenna pattern can be seen in Figure 5.2. The pattern was designed so that the value of θ is 54 degrees and the maximum antenna gain is 11dB, for reasons mentioned in Section 4.2. Please note that Figures 5.1 and 5.2, is not drawn to scale. For scaled images, please refer to Figures 4.1 and 4.2.

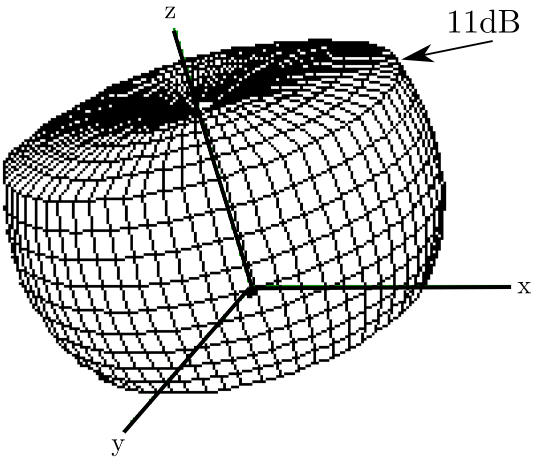


Figure 5.1 – Ground station antenna pattern created in Opnet antenna editor

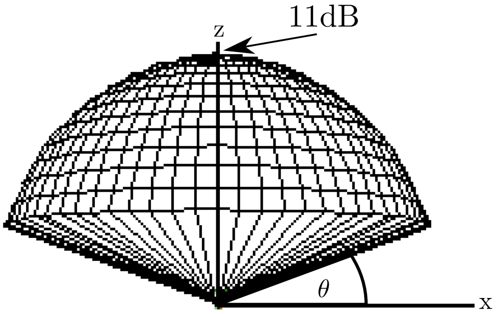


Figure 5.2 – Satellite antenna pattern created in Opnet antenna editor

5.2.2 Opnet modulation curves

A modulation curve characterizes the dependence of the BER of a radio transmission on the SNR. In the Opnet simulations, modulation curves are represented by a modulation table. A modulation table is a list that maps the SNR values to the BER values and this approximates a continuous modulation curve. These values are in the form of a lookup table. The simulator will match the BER value against the SNR value at the receiver. Because the modulation curve editor uses a graphical approach for defining a modulation curve, the results may be somewhat imprecise, but still fall within acceptable limits.

Modulation curves for BPSK, QPSK and 8PSK were created with Opnet modulation curve editor. Matlab's BERTool function was used to calculate theoretical modulation curves for the three modulation schemes. The theoretical data was then used to plot the modulation curves in the Opnet modulation curve editor. For purposes of example the BPSK modulation curve created in Opnet modulation curve editor can be seen in Figure 5.3. Please note that the curve is not in logarithmic form.

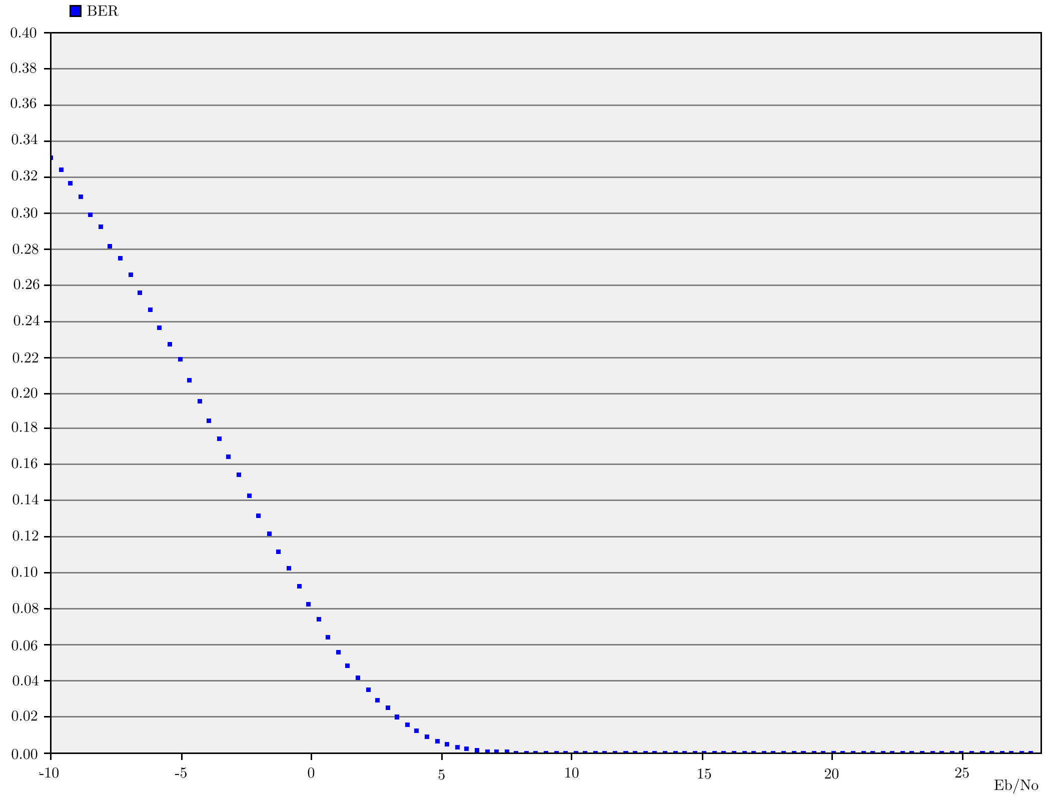


Figure 5.3 – BPSK modulation curve created in Opnet modulation curve editor

5.2.3 Opnet pipeline stages

The simulator utilises the following modules.

Satellite: This module represents the satellite and its functionality. It will follow a predefined orbit path and use the transceiver pipeline to establish communications between itself and ground stations.

Ground station: Represents the ground stations and their functionality.

Transceiver pipeline: The transceiver pipeline is a 14 stage process that is executed every time a packet is transmitted. The stages can be seen in Figure 5.4. The pipeline is divided into 6 stages for the transmitter and 8 stages for the receiver [23]. Each of the stages is a series of C/C++ code designed to simulate exactly what happens during transmission of a packet.

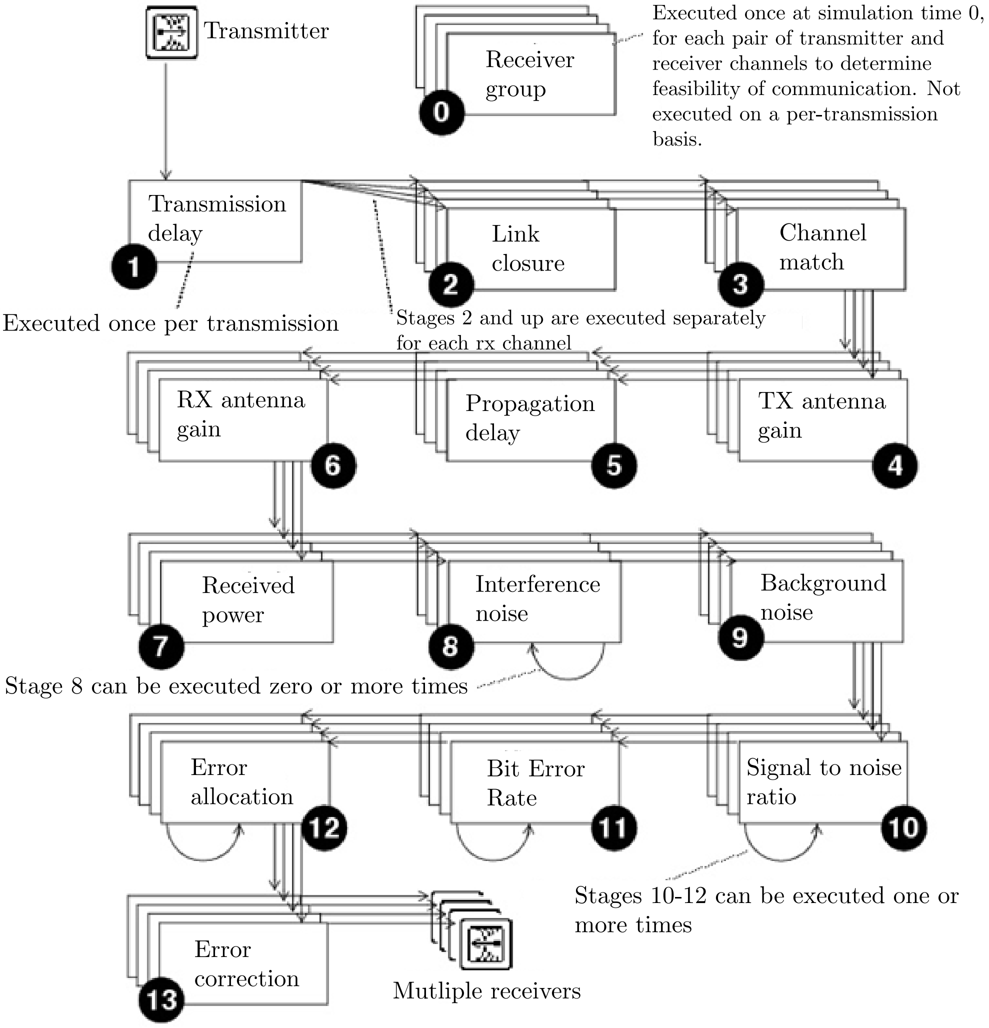


Figure 5.4 – Opnet transceiver pipeline stages

- **Stage 0 - Receiver Group:** This is the first stage in the transceiver pipeline and decides which receivers are able to receive the transmitted signal.
- **Stage 1 - Transmission Delay:** This stage calculates how long a packet takes to be transmitted. This is calculated by dividing the length of a packet by the data rate.
- **Stage 2 - Link Closure:** The link closure stage is implemented directly after the transmission delay stage. It eliminates some of the receivers by performing an LOS calculation. By using the positions of the ground stations on the earth and assuming a perfect

sphere (no mountains) for the earth, Opnet calculates whether communication is possible. If there is no way that a packet can reach a receiver, the packet is destroyed.

- **Stage 3 - Channel Match:** After it is determined that the transmitter can reach the receiver, the receiver must decide if it can decode the received signal. The channel match stage compares the characteristics of the transmitter and receiver. These include transmission frequency, modulation scheme, bandwidth, data rate and spreading-code (pseudo-noise code). If the transmission frequency doesn't match perfectly, the receiver decides whether there is an overlap of the bandwidth of the receiver and transmitter. If there is no overlap, the signal is ignored. If there is some overlap or when the frequency and bandwidth matches but other values don't match, the signal is considered as interference. The interference is later used in the noise stages. If all the characteristics of the transmitter and receiver match, the signal is marked as valid and proceeds to the next stage.

- **Stage 4 - Transmitter Antenna Gain:** The transmitter's antenna gain is calculated at this stage. A vector between the receiver and transmitter is used to determine the gain.

- **Stage 5 - Propagation Delay:** This stage calculates the time it takes a packet to travel from the transmitter to the receiver. The time is calculated by using the distance between the receiver and transmitter and the speed at which the signal propagates (speed of light). This is the last stage associated with the transmitter.

- **Stage 6 - Receiver Antenna Gain:** The receiver antenna gain is calculated in the same way as the transmitter antenna gain. A vector between the transmitter and receiver is created and from the vector the gain is calculated with the receiver's antenna pattern.

- **Stage 7 - Received Power:** After the receiver antenna stage, the received power is calculated. This stage has two functions, first it calculates the power for all incoming signals and secondly it determines which incoming signals are valid. The receiver locks on to a valid signal and sees all the other signals as interference. The received power then becomes the signal power in the signal to noise ratio stage.

- **Stage 8 - Interference Noise:** This stage is the first of two stages calculating the noise in the system. Interference noise is calculated from signals that cannot be decoded by the receiver. The channel match stage (stage 3), determines whether a signal is valid, invalid or interference. If a signal is valid it is decoded, if it is invalid it is ignored, or else the amount of noise the signal adds in the frequency band is calculated. This stage is executed for all signals that interfere with the valid signal.

- **Stage 9 - Background Noise:** Background noise takes urban, galactic and thermal noise into account. Three assumptions are made in this stage, the first assumption is that there is a constant ambient noise, the second is a constant background noise source and the third is that there is a constant thermal noise at the receiver. The noise is calculated using the power spectral density in the transmission band. The thermal noise is calculated by using Boltzmann's constant with a temperature of 290K. The noise is then multiplied over the entire bandwidth and is subject to the receiver antenna gain.

- **Stage 10 - Signal to Noise Ratio:** The signal to noise ratio is computed in this stage. The received power calculated in stage 7 is used as the signal power. The signal power is then divided by the sum of the interference noise and background noise. The signal to noise ratio is then converted to decibel scale. This stage is executed every time the background noise and interference noise are calculated.
- **Stage 11 - Bit Error Rate:** This stage finds a bit-error rate from the SNR and the modulation scheme used. Predefined modulation curves, Figures 4.5 to 4.8, are used as lookup tables. The SNR used in this stage is the effective SNR and is the SNR calculated in stage 10 plus the processing gain associated with the bandwidth and data rate.
- **Stage 12 - Error Allocation:** The BER calculated in the previous stage and the packet length are used to determine how many errors there are in the packet.
- **Stage 13 - Error Correction:** The last stage decides if the error correction code used is strong enough to correct the errors in the packet. The stage compares the number of errors in the packet with a limit set in the simulation. If there are more errors that the set limit the packet is marked as incorrect, else the packet is marked as correct.

When a packet has passed through all 14 stages it is marked as successfully delivered to the receiver. The ground stations and satellite make use of the transceiver pipeline for every packet transmitted. The transceiver pipeline is the core of the wireless simulation and without it communication is not possible.

5.3 Performance simulation

5.3.1 Packet size optimising

A simulator was built to determine the upper and lower bounds of the packet sizes to be used in the protocol simulations. The simulator consisted of a LEO satellite passing over one ground station. The simulation time simulated was 15 minutes, thus allowing only one pass over the ground station. The aim was to see how much data could be transferred in one pass. The ground station transmitted packets, one after the other, to the satellite. The satellite stored all the successfully received Data packets in its buffer and at the end of the simulations the number of packets in the satellite buffer was counted. A Data packet is considered delivered successfully when the ACK of that packet is received by the ground station. The packet sizes that were simulated are 1 kb, 2 kb, 4 kb, ..., 16 Mb. This is known as a set of packet sizes. The sizes may look unrealistic, but the upper and lower bounds had to be tested and the only way to do that was to make them, respectively very large or very small.

Not only was the packet size varied but the transmission power was also varied. The transmission power simulated was 1, 2, 3, ..., 10 W. So for every set of packet sizes, a simulation was run at a specific transmission power.

Thus for each one of the three modulation schemes, a full set of simulations was run, varying the transmit power and packet sizes. The FEC scheme implemented was BCH, as chosen in Section 4.10.2, and it was set to correct up to 10% of a packet. A packet with more than 10% errors was discarded. The results were exported to a text file where two Matlab scripts, 3d_line_plot.m and 3d_surf_plot.m, were used to plot Figures 5.5 to 5.10.

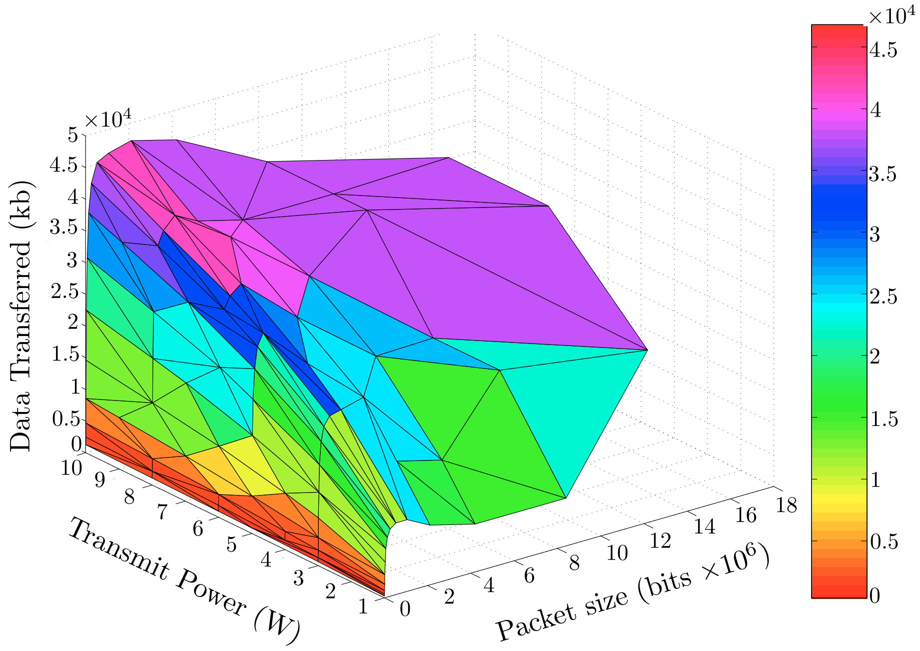


Figure 5.5 – Modulation: BPSK, Data rate: 76 kbps, BCH10%

Looking at the three dimensional plots, Figures 5.5, 5.7 and 5.9, it can be seen that the amount of data transferred successfully increases as the transmission power increases. And this is as expected. This is because if the transmission power is increased, the SNR at the receiver is higher and this accounts for better reception of a packet.

Now, looking at Figures 5.6, 5.8 and 5.10, a couple of interesting findings can be made. First, all of the modulation schemes have more or less the same Data Transferred versus Packet size curve shape. The only difference is that different modulation schemes peak at different packet sizes. For small packet sizes the data transferred is low, the reason being that more

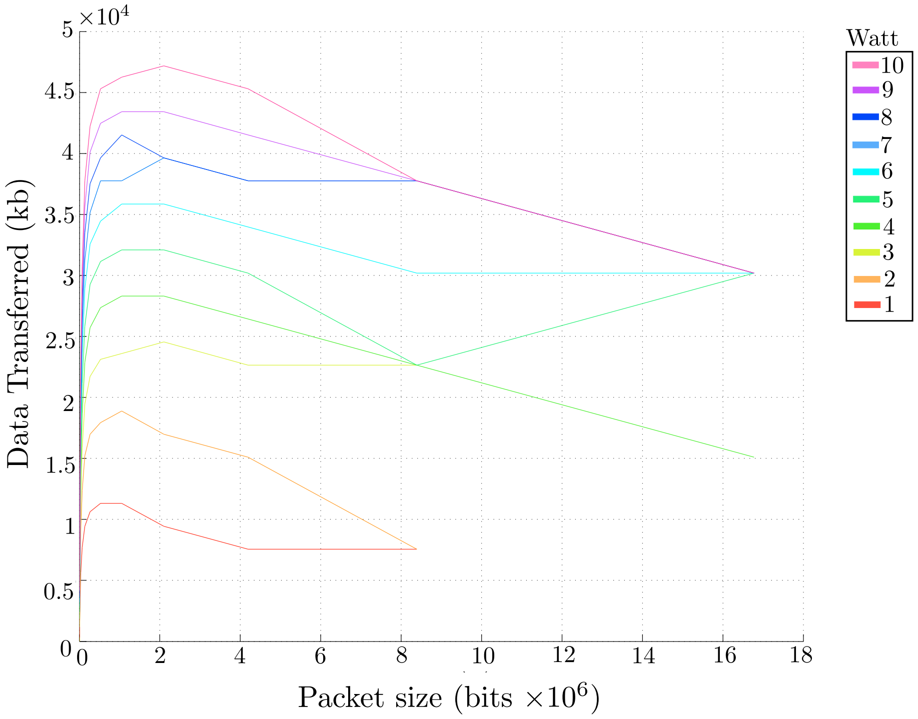


Figure 5.6 – Front view. Modulation: BPSK, Data rate: 76 kbps, BCH10%

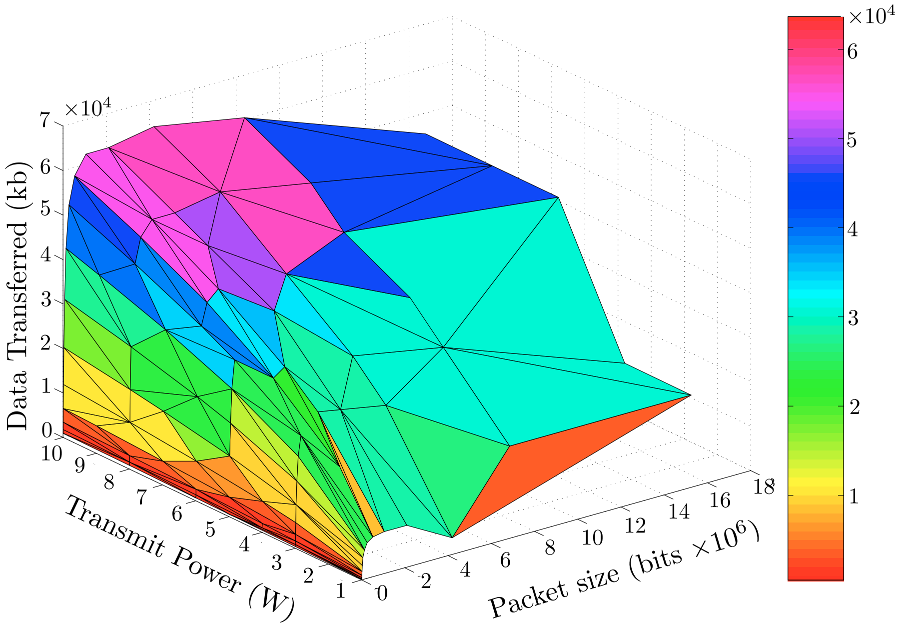


Figure 5.7 – Modulation: QPSK, Data rate: 152 kbps, BCH10%

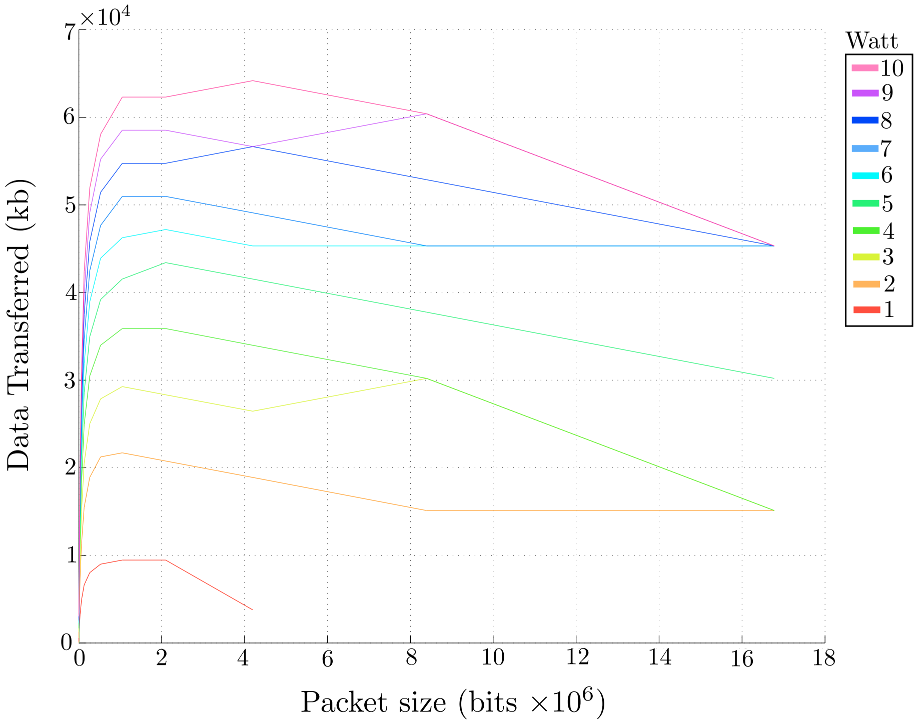


Figure 5.8 – Front view. Modulation: QPSK, Data rate: 152 kbps, BCH10%

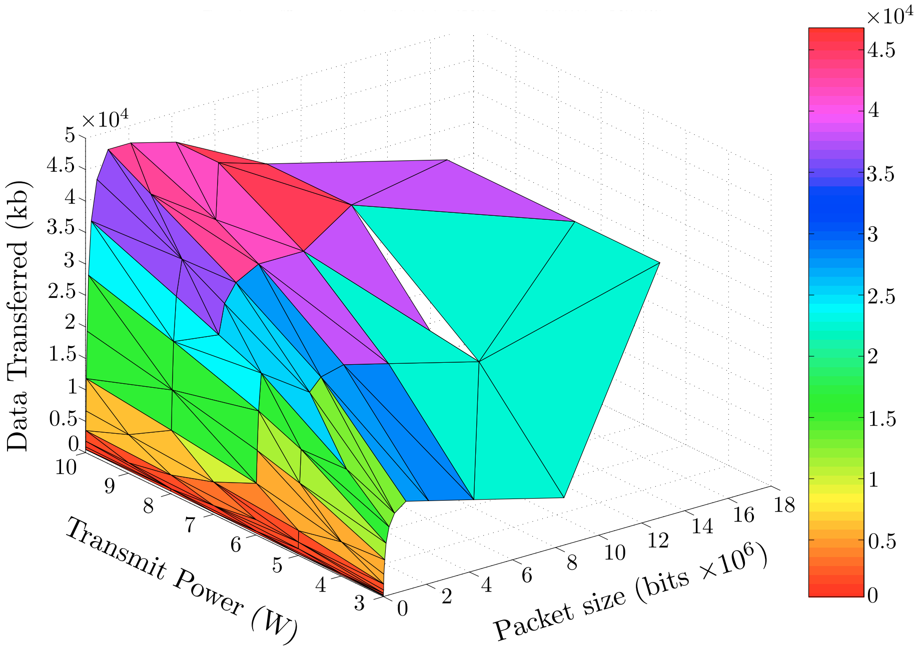


Figure 5.9 – Modulation: 8PSK, Data rate: 228 kbps, BCH10%

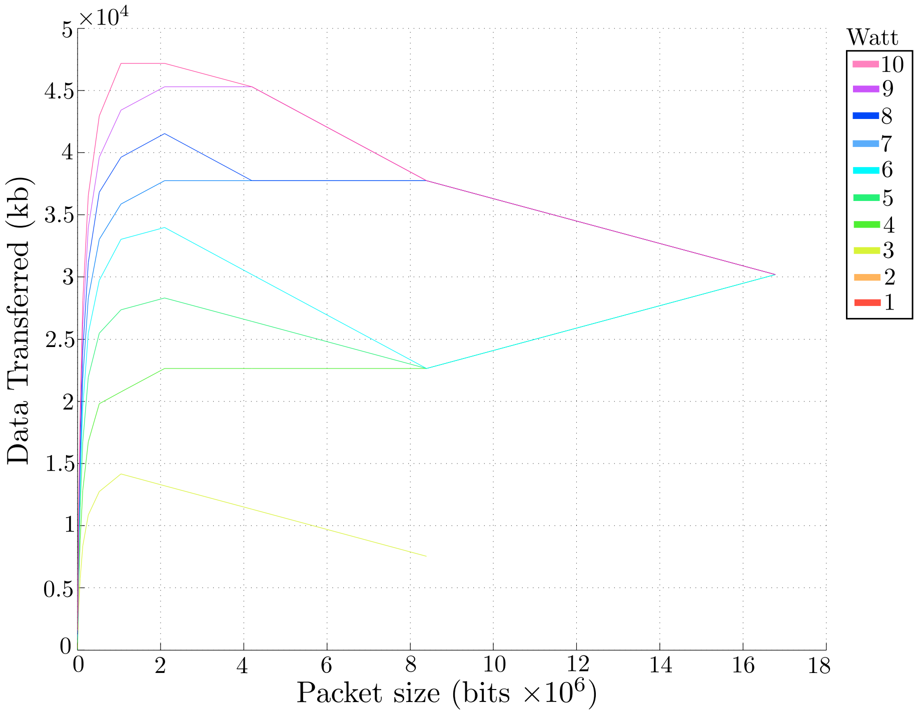


Figure 5.10 – Front view. Modulation: 8PSK, Data rate: 228 kbps, BCH10%

Data packets need to be transmitted to transfer a large amount of data. Thus transferring data with small packet sizes is not very efficient.

It can be seen that for all three modulation schemes the data transferred increases dramatically up to more or less a packet size of 1Mb. Being more specific, for BPSK the optimum packet size is 1 Mb if all the transmission powers are taken into account (Figure 5.6), and for QPSK it is also 1 Mb (Figure 5.8). For 8PSK it is 2 Mb, (Figure 5.10). Packet sizes bigger than 1Mb, become too large for the short time available in which to transfer data and thus decrease the amount of data transferred. It takes the slowest modulation scheme, BPSK transmitting a 1 Mb packet at 76 kbps,

$$\frac{1\ Mb}{76\ kbps} = 13.8\ seconds$$

to transmit a 1 Mb packet. If a 2 Mb packet were to be used it would take 27.6 seconds to transmit and during this long time the packet is more likely to be corrupted, and this shows in the results. Looking at the fastest modulation scheme, 8PSK transmitting a 1 Mb bit packet at 228 kbps takes only,

$$\frac{1\ Mb}{228\ kbps} = 4.6\ seconds$$

to transmit a 1 Mb packet. A 2 Mb packet takes 9.2 seconds and a 4 Mb packet 18.4 seconds. Thus any packet longer than 4 Mb for the 8PSK scheme takes too long to transmit and will decrease the amount of data transferred. But transmitting time isn't the only factor that comes into play, the minimum SNR of each modulation scheme has an effect on the results too. BPSK and QPSK have an 11 dB minimum SNR and 8PSK has a 14 dB minimum SNR. The higher the minimum SNR, the shorter the time frame in which communications can take place. Looking at Table 3.4 of the Matlab link budget calculations for the SNR values at different distances, it can be seen that the maximum SNR value is 17.8 dB at 5 W transmit power. With 10 W transmit power the maximum SNR value is calculated at 20.8 dB. Also looking at Figure 3.3 it can be seen that the SNR decreases exponentially as the distance increases linearly. Thus the minimum SNR of 14 dB significantly decreases the time in which communications can take place. With a shorter time to transfer packets, the size of the packets starts to play a big role. If the packet size gets too big it will be clipped if the SNR drops below 14 dB. Let us say for example, that three 2 Mb packets can be sent in the 8PSK time frame. The fourth packet starts transmitting and when 90% of the packet has been transmitted the SNR drops below 14 dB. The packet is discarded and time is wasted transmitting that packet. It is therefore better to transmit a smaller packet size so that more packets fit into the time frame available.

Another interesting observation is that QPSK has the highest amount of data transferred, between 60 and 70 Mb, with 10 W transmission power. Both BPSK and 8PSK have a peak data transfer between 45 to 50 Mb at 10 W. The reason for this is that BPSK and QPSK have the same error performance rate but QPSK has double the data rate of BPSK. Thus QPSK outperforms BPSK. 8PSK has an even higher data rate than that of BPSK and QPSK, but unfortunately it also has an higher bit error probability. Thus additional power is needed to maintain the same overall performance as QPSK and BPSK, as was mentioned in Section 4.5.3. 8PSK also has a smaller time frame in which communications can take place and this decreases the amount of data that can be transferred.

From the findings above, the upper limit of the packet sizes was chosen as 1 Mb. The following packet sizes were chosen to be simulated: 4 kb, 131 kb and 1 Mb bits. 4 kb is one of the smallest packet sizes and thus it was necessary to simulate this size. The 131 kb packet size was chosen as a middle size to see how packet sizes between 4 kb and 1 Mb would function in the system.

5.3.2 Round-Robin Polling

The simulators mentioned in Sections 5.3.2 to 5.3.4, were only built for testing purposes.

Three test simulators were built to test if the implementation of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling is working correctly. For the test simulators, the ground stations were placed close to one another. This was done to check the performance of each protocol under heavy load and to give every protocol the same configuration setup. For the actual simulations, discussed in Chapter 6, the ground stations are scattered across South Africa. All three test simulators ran for a simulated time of one day. Every protocol simulated was run ten times and every time the number of ground stations was increased by ten, until a maximum of one hundred stations was reached. The three simulators were run with a BPSK modulation scheme, transmitting at 76 kbps. The packet size chosen was 1 Mb. The FEC scheme implemented was BCH and it could correct errors up to 10% of the packet size. Only the throughput and efficiency were plotted in the results.

- Throughput is measured as the number of successfully delivered data bits divided by the simulation time. The successfully delivered bits are only the data packet bits, without the BCH bits, delivered to the satellite. The packet is marked as successful only when the ACK reply is received.
- The Efficiency is calculated as the successful data bits delivered divided by the total number of bits sent. The total number of bits sent includes all the overhead packet bits of the protocol in use. The successfully delivered bits are only data packet bits, without the BCH bits, delivered to the satellite. The packet is marked as successful only when the ACK reply is received.

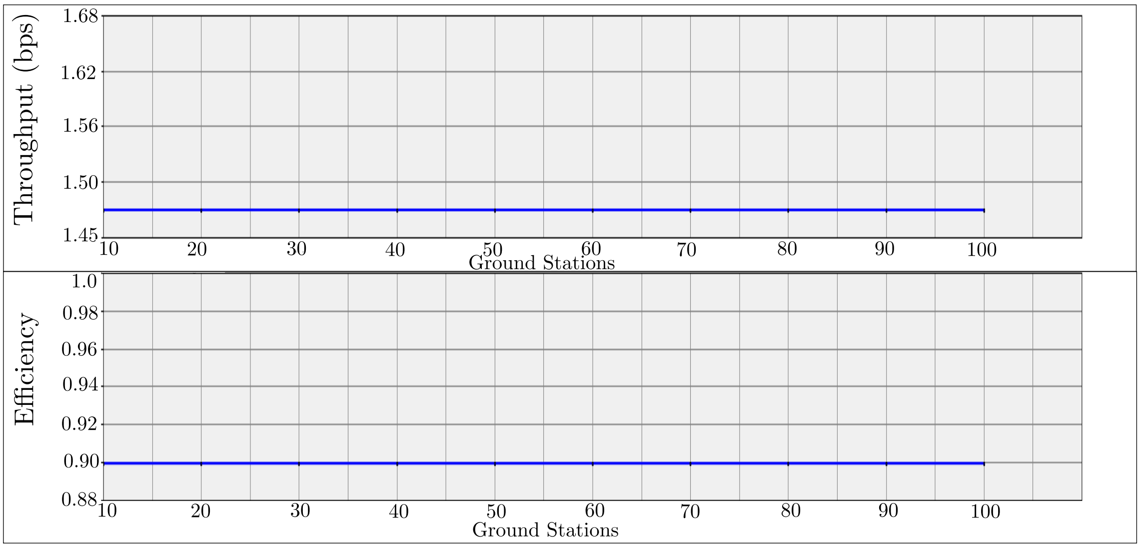


Figure 5.11 – Round-Robin polling performance testing results

The Round-Robin polling protocol's results can be viewed in Figure 5.11. As can be seen, Round-Robin's throughput is a flat straight line, even as the number of ground stations increases. This means that even as the number of ground stations increases the system keeps operating at a constant rate of performance. This is because Round-Robin Polling is a time division protocol, and this would only occur when the ground stations are close to one another. The time it takes to send out a Ping packet and receive a reply is very short. The calculation of the time for a BPSK modulation scheme with a data rate of 76 kbps to transmit a Ping packet and receive a reply is

$$t_{ping} = 2 \times \left(\frac{Packet\ size}{data\ rate} + t_p \right) \tag{5.3.1}$$

$$t_{ping} = 2 \times \left(\frac{64}{76k} + 7.436\ ms \right)$$

$$t_{ping} = 16.56\ ms$$

Thus it takes 16.56 ms to ping a ground station and it will take 1.656 seconds to ping a hundred ground stations. This is a very short time and each ground station will be pinged numerous times before it is out of view of the satellite. Thus even if a ground station misses a ping, it will be pinged during the next cycle or the cycle thereafter.

As expected, the efficiency of Round-Robin Polling is very high, at 90%. Since the satellite is in charge and controls the communications, there is much less noise in the system and no time or bits are wasted on competing for the channel. This results in a very high efficiency, even if the number of ground stations increases. Round-Robin has the highest throughput and efficiency of all three protocols simulated in these testing conditions. Please note that the throughput and efficiency changes when the ground stations are not close to one another and Round-Robin Polling does not have the best performance in the actual simulations, as shown in Chapter 6.

One important observation to mention is that it was found that when the simulation starts with no packets in the satellite's buffer, the throughput and efficiency graphs of all three protocols were not as expected. The reason is that when a packet is sent to the satellite, the satellite checks the received packet's Host Address field. It then looks in its buffer to check if there are any Data packets to be sent out to that specific ground station. If there aren't any Data packets in the satellite's buffer, the ACK is sent out for the received packet. But if there is a Data packet to send, the ACK is sent first and then the Data packet. Thus it is obvious that if the buffer of the satellite is not populated with packets when the simulation starts, the throughput will vary and not stay constant. So for all three test simulators the satellite's buffer was populated with Data packets to prevent this from happening. For the actual simulations, the satellite's buffer was not populated, to give more realistic results.

5.3.3 Carrier Sense Multiple Access with Collision Avoidance

Figure 5.12 shows the results of the performance testing on the CSMA-CA protocol. Looking at the throughput graph, it can be seen that the throughput increases gradually until 20 ground stations are reached and then the system starts to collapse exponentially. This means that a CSMA-CA system can handle up to 20 ground stations competing for access to the satellite before the system collapses.

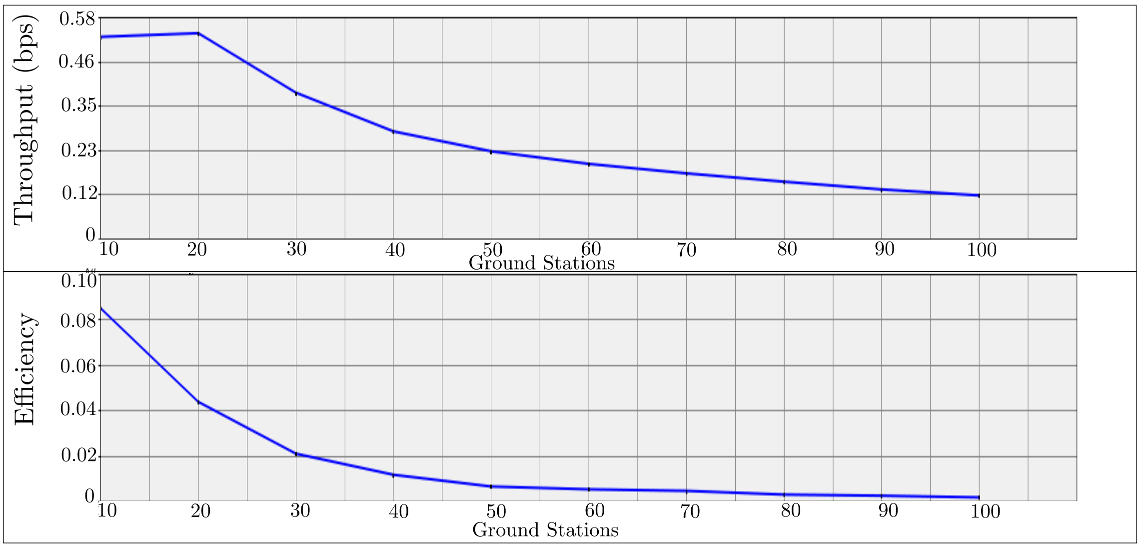


Figure 5.12 – CSMA-CA performance testing results

The reason for this is that the RTS packets start colliding with one another if there are more than 20 ground stations in the system. If an RTS packet eventually gets through and data is transmitted, stations that weren't in the satellite's view and did not receive the CTS packet start to interfere with the data transmission. With these testing conditions and all the ground stations placed next to each other, CSMA-CA has the lowest throughput performance of all the protocols tested.

The efficiency also decreases exponentially. From 10 stations to 20 stations the throughput increases, but the efficiency decreases. This is because, although the throughput is increasing by a small amount, the noise that the extra 10 stations add in terms of RTS packets and corrupted Data packets has a much greater negative effect on the efficiency than the rate at which the throughput increases. If more than 20 stations are added to the system the throughput drops and thus the efficiency drops.

5.3.4 Direct Sequence Spread Spectrum Carrier Sense Multiple Access with Collision Avoidance

The processing gain used in the simulations for the DSSS is set to 11 dB and every ground station has its own pseudo-noise code. The reason why 11 dB processing gain was chosen is that the Federal Communications Commission (FCC) has set a limit of 10 dB as the minimum processing gain on any device operating in the ISM band, [24].

Looking at the throughput graph in Figure 5.13, the throughput increases drastically up to 20 ground stations. After 20 ground stations, the throughput increases more slowly up to 40 ground stations. The reason for this is that the more ground stations are added, the more

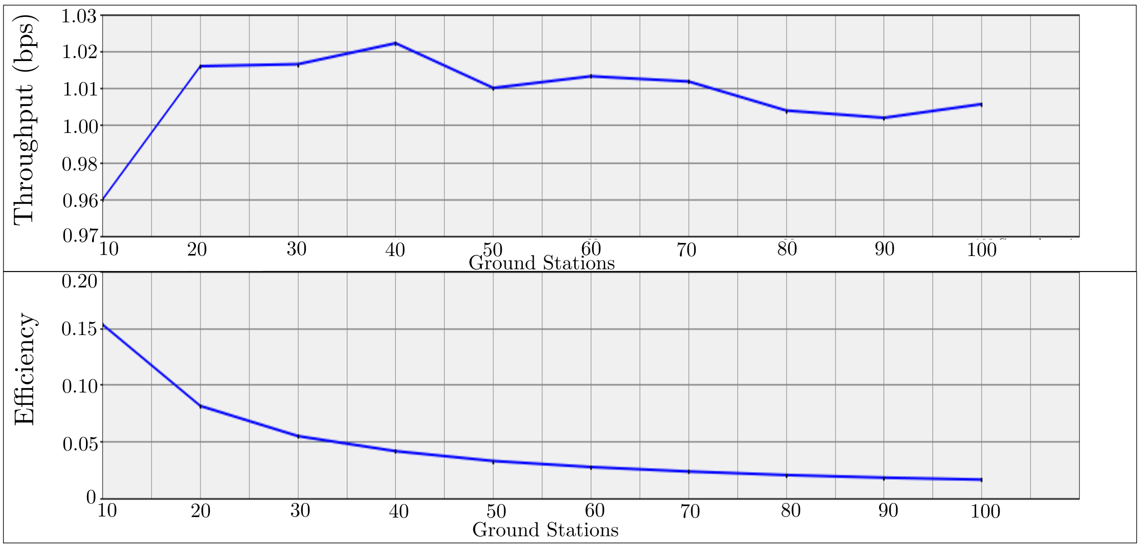


Figure 5.13 – DSSS(CSMA-CA) performance testing results

noise is added to the system, as mentioned in Section 4.8.3. The number of ground stations that can be added before the noise floor becomes so great that the despread signal can not be detected is directly dependent on the processing gain. For this setup with an 11 dB processing gain, the system can handle up to 40 ground stations before the noise becomes too great.

When more than 40 ground stations are added to the system the throughput starts to decrease. When a ground station receives a CTS packet, it checks the Time Busy field to see how long it should keep quiet for. The ground station then generates a random number between 1 and 10 and adds this to the total time, in seconds, it should keep quiet. The reason for this is to prevent all the stations from competing for the channel at the same time after keeping quiet for the requested amount of time. So, depending on the number of ground stations competing for the channel, the throughput will decrease. It can be seen in the throughput graph that the average throughput measured between 40 and 100 ground stations is decreasing.

With these testing conditions and the ground stations placed close to one another, DSSS(CSMA-CA) has the second highest throughput of the three protocols tested.

The efficiency decreases exponentially, as seen in Figure 5.13. The same is happening as in the case of CSMA-CA. The number of Data packets being delivered is far less than the overhead produced, in terms of RTS, CTS and ACK packets, in competing for the channel. The efficiency curves of CSMA-CA and DSSS(CSMA-CA) are almost identical and this is due to the fact that CSMA-CA is the main function of both protocols. The only difference is that the DSSS technology in the DSSS(CSMA-CA) protocol makes it possible to deliver more Data packets and thus DSSS(CSMA-CA) has the same efficiency curve as CSMA-CA but is a lot more efficient. DSSS(CSMA-CA) has the second highest efficiency with this test setup configuration.

5.4 Simulation environment configuration

The three simulators used to do performance simulations on the three protocols were modified, so that they could be used to do the actual simulations of the protocols. The setup and configuration of all three simulators is done in the same way so that results are consistent and can be compared against each other.

Each simulation will start with 10 ground stations, when the simulation is done another 10 ground stations will be added and the simulation will be run again. This will continue until 100 ground stations have been added. The ground stations are placed randomly within South Africa, as seen in Figure 5.14. The white lines seen in Figure 5.14 are the satellite's nadir ground tracks.

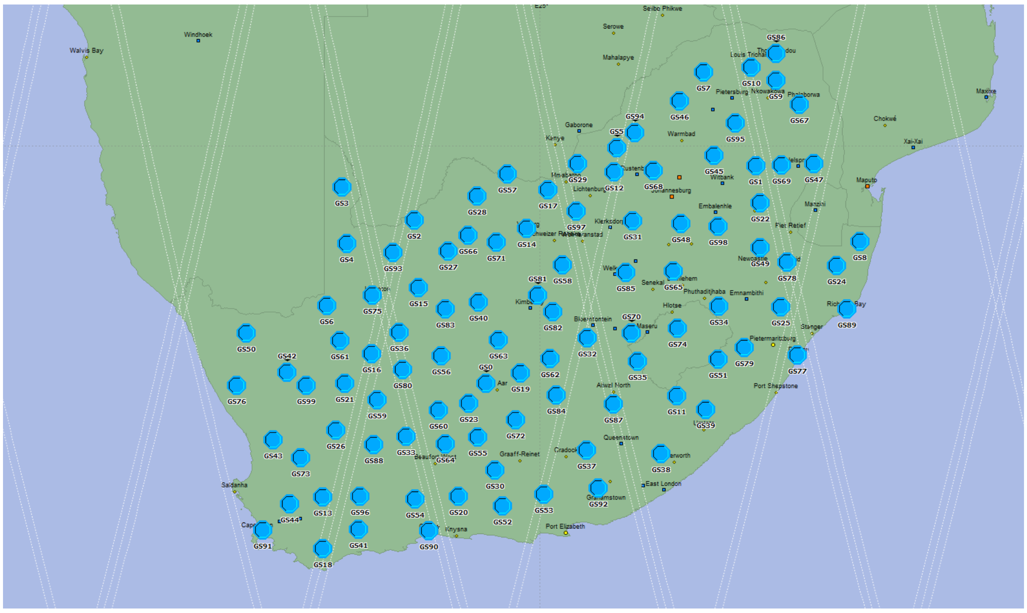


Figure 5.14 – Layout of 100 ground stations in South Africa

The simulations will be run for a simulated time of 2 weeks. The reason why 2 weeks is chosen is that after 2 weeks the satellite repeats its orbital pattern. Thus the results gathered from 2 weeks is enough to make an accurate prediction of what will happen if more than 2 weeks were simulated.

First all the packet sizes will be changed while the rest of the parameters are kept fixed. For every packet size simulation, 10 simulations will be run because of the number of ground stations to be added for every simulation. Then, when all the packet sizes have been simulated, the transmission power is changed and the packet sizes are varied again. When all the transmission powers have been simulated, the modulation scheme is varied and the simulations are run again. When all these simulations are done, the next protocol is simulated. Figure 5.15 shows the hierarchy in which the specific parameters were varied.

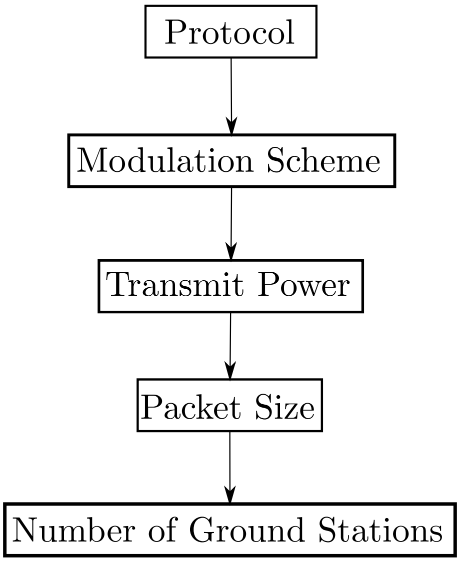


Figure 5.15 – Hierarchy of parameters varied in simulations

The simulations consist of the following parameters,

- Protocols: Round-Robin Polling, CSMA-CA, DSSS(CSMA-CA)
- Transmission power: 5, 10 W
- Modulation schemes: BPSK (76 kbps), QPSK (152 kbps), 8PSK (228 kbps)
- Packet sizes: 4 kb, 131 kb, 1 Mb
- Number of ground stations: 10, 20, 30, ... , 100

For the parameters above, a total of 540 simulations were run.

5.5 Summary

- The simulations are built in Opnet.
- Opnet has 13 pipeline stages that simulate the transmission of packets over wireless networks.
- The protocols implemented in the simulators are Round-Robin Polling, CSMA-CA and DSSS(CSMA-CA).
- The transmission powers to be simulated are 5 and 10 W.
- Modulation schemes to be simulated are BPSK (76 kbps), QPSK (152 kbps) and 8PSK (228 kbps).
- The optimum packet size for the modulation schemes is 1 Mb. The packet sizes chosen to be simulated are 4 kb, 131 kb and 1 Mb.

- The simulation will start with 10 ground stations. When the simulation is completed, 10 more stations will be added. This will continue until 100 ground stations have been added to the system.

5.6 Next chapter

In Chapter 6, the Opnet simulation results of the three protocols simulated, are discussed.

Chapter 6

Simulation Results

In this chapter the Opnet simulation results are discussed. The three protocols that were simulated are CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling.

Before the results can be discussed, some terminology needs to be defined,

- **Throughput** is measured as the successfully delivered data bits divided by the simulation time. The successfully delivered bits are only data packet bits, without the BCH bits, delivered to the satellite or the destination ground station. The packet is marked as successful only when the ACK reply is received.
- **Efficiency** is calculated as the successful data bits delivered divided by the total number of bits sent. The total number of bits sent includes all the overhead packet bits of the protocol in use. The successfully delivered bits are only the data packet bits, without the BCH bits, delivered to the satellite or the destination ground station. The packet is marked as successful only when the ACK reply is received.
- **Average End-to-End** (ETE) delay is the time delay between transmission of a packet and the packet's delivery at the destination. The time is logged when the delivered packet's ACK packet is received by the satellite. The average ETE delay is the only indicator of packets that have been delivered from host ground station to destination ground station.
- **Standard deviation** of ETE delay is exactly what the name says.
- **Undelivered packets** is the number of packets left in the satellite buffer when the simulation has been completed.

The uplink and downlink of the satellite and ground stations are not analyzed separately, all of the channels are seen as one big channel. So, for example, to calculate the efficiency, the number of bits transmitted successfully and the total number of bits transmitted are needed.

Thus every single bit that is transmitted is counted with a global counter, there are no separate uplink and downlink counters. The successfully transmitted bits are also counted with a global counter. If the satellite and/or a ground station was successful in the transmission, the global counter will be increased. This was done because it was found that when the uplink and downlink of the satellite and ground stations were analyzed separately not all factors that influenced the system were depicted in the results.

The results are discussed in a very specific way as seen in Table 6.1. There are a large number of graphs to interpret and arranging them in this way makes it easier to understand and interpret the results.

	BPSK (76 kbps)	QPSK (152 kbps)	8PSK (228 kbps)
4 kb	Figure A.1	Figure A.4	Figure A.7
131 kb	Figure A.2	Figure A.5	Figure A.8
1 Mb	Figure A.3	Figure A.6	Figure A.9

Table 6.1 – Arrangement of results for 5 W transmission power

	BPSK (76 kbps)	QPSK (152 kbps)	8PSK (228 kbps)
4 kb	Figure A.10	Figure A.13	Figure A.16
131 kb	Figure A.11	Figure A.14	Figure A.17
1 Mb	Figure A.12	Figure A.15	Figure A.18

Table 6.2 – Arrangement of results for 10 W transmission power

From Tables 6.1 and 6.2, when a packet size is chosen, and moving from left to right, the modulation scheme changes from BPSK to QPSK to 8PSK and thus the data rate increases. Choosing a modulation scheme and moving from top to bottom, the packet size increases from 4 kb to 131 kb to 1 Mb. Both of these two variables, data rate and packet size, can be combined into one variable called transmission time,

$$T_p = \frac{Packet\ size}{Data\ rate} \tag{6.0.1}$$

In some of the discussions below the transmission time T_p is used to help some of the findings. The figures referenced in Table 6.1 and 6.2 can be found in Appendix A.

6.1 Antenna design influence

As mentioned in Section 4.2, the Quadrifilar Helix antenna was used for the ground stations in the simulations. The satellite made use of a fixed, high gain, Yagi antenna. The idea was to run the simulations with these two types of antenna and if it were found that neither the ground stations nor the satellite could communicate with each other, then a different antenna design would be used. The other alternatives for the ground stations were a fixed high gain

Yagi antenna or a tracking Yagi antenna. The Quadrifilar Helix antenna was found satisfactory enough not to need to be replaced.

The other two ground station antennas were not simulated. It would be suggested that these two antennas be used in the following situations,

- The fixed, high gain, Yagi antenna could be used in situations were the transmission power is very low, below 5 W. A Yagi antenna can be designed with a higher gain than a Quadrifilar Helix. The higher the antenna gain, the lower the transmission power has to be to still have a functioning system. Using a fixed Yagi antenna will decrease the time frame a specific ground station will be in view of the satellite, but data transfer would definitely occur during this smaller time frame, which is better than using a Quadrifilar Helix, which would have no data transfer, due to the lower maximum gain.
- If cost is not a factor, then a high gain, tracking Yagi antenna can be used for the ground stations. This is the ideal solution for the system configuration. The Yagi antenna can be designed with a very high gain and the tracking system will enable the ground station to be in full view of the satellite, thus visible for a longer time frame than a fixed Yagi antenna.

The fixed, high gain, Yagi antenna option was not implemented in the simulations because the time frame that the ground station will be in view is smaller than that of the Quadrifilar Helix time frame. Thus less data would be transferred and this option was moved to the second choice of implementation.

The tracking Yagi antenna was discarded due to the higher cost of implementing such a system in real life.

6.2 Transmission power alternatives

As mentioned in Section 4.3, only 5 and 10 W transmission power was simulated. To compare the 5 and 10 W results with one another, each graph in the 5 W range will be compared to the corresponding graph in the 10 W range. For example, the 5 W, BPSK, 4 kb, BCH10% graph will be compared to the 10 W, BPSK, 4 kb, BCH10% graph. The throughput sub graph of the 5 W will be compared to the throughput sub graph of the 10 W etc.

6.2.1 Throughput

Only Figures A.1 and A.10 will be compared to each other. Figure A.1 is the 5 W, BPSK, 4 kb, BCH10% graph and Figure A.10 is the 10 W, BPSK, 4 kb, BCH10% graph. The reason for this is that comparing the other graphs with one another delivers the same findings as comparing only these two graphs. Thus the findings in these two graphs can be applied to the other graphs.

Comparing the 5 W throughput results (Figure A.1) to the 10 W results (Figure A.10), it can be seen that a system with 10 W transmission power has a higher throughput than a system with 5 W transmission. This is as expected. From the link budget analysis, it is easy to see that the higher the the transmission power the higher the received SNR will be. It is also found that the shapes of the different throughput graphs stay the same when transmission power is increased. This is due to the fact that nothing was changed on the protocol's implementation.

6.2.2 Efficiency

Comparing the efficiency sub graphs of Figures A.1 and A.10, it is noted that a 10 W system has a higher efficiency than a 5 W system. This holds true for all three protocols simulated. This is because of the increase in throughput when the transmission power is increased. The efficiency is calculated as the number of data bits successfully delivered divided by the total number of bits sent. Nothing was changed in the protocols, so the total number of bits sent stays the same even if the transmission power is increased. But, as the transmission power is increased the protocol's throughput increases, in other words more packets are delivered successfully. And this increase in throughput is why the efficiency increases when the transmission power is increased.

6.2.3 Average ETE delay

Comparing the Average ETE delay sub graphs of Figures A.1 and A.10, it is easy to see that a system with a lower transmission power has a higher average ETE delay than a system with a higher transmission power. The reason is that a system with a higher transmission power, has a higher throughput as mentioned above. A higher throughput translates to more packets being delivered successfully. As stated in the definitions in the beginning of this chapter, the Average ETE delay is the time delay from the time a packet is created until the packet is delivered at the destination. Now, if more packets are delivered successfully due to an increase in transmission power, the less time a packet has to wait in the transmitter's buffer before being transmitted. And this results in a decreased average ETE delay.

6.2.4 Undelivered packets

Looking at the undelivered packets sub graphs in Figures A.1 and A.10, it is found that as the transmission power increases, the number of undelivered packets also increases. The explanation is that the one satellite alone is servicing all the ground stations. This forms a multiple to one system and the satellite becomes the bottleneck. The satellite stores the received packets in its buffer to transmit them at a later stage.

The satellite can serve only one ground station at a time. This becomes a one to multiple system and again a bottleneck forms at the satellite. The lower the transmission power, the fewer packets are transmitted to the satellite and the fewer packets the satellite will have in its buffer at the end of the simulation. The higher the transmission power, the more packets are delivered and the more packets there will be in the satellite's buffer when the simulation ends. Thus the undelivered packets increase as the transmission power increases, due to the bottleneck created at the satellite.

6.2.5 Summary

By increasing the transmission power of a LEO satellite system, the throughput, efficiency and undelivered packet count increases as mentioned in Section 6.2.4. The Average ETE delay decreases as the transmission power is increased. Thus increasing the transmission power increases the overall performance of the system. It is suggested that the system be run with the highest possible transmission power of 10 W to obtain maximum system performance.

6.3 Varying the modulation scheme

In this section the results will be interpreted by keeping the packet size fixed and changing the modulation scheme. This is seen when moving from left to right, or visa versa, in Table 6.2 while keeping a fixed packet size.

The simulations were run for a transmission power of 5 W and 10 W. The results discussed in this section are for the 10 W simulations. It was found that by varying the modulation scheme, the system response of a 5 W and 10 W system is the same, keeping in mind that the throughput, efficiency etc. of a 10 W system is higher than that of a 5 W system due to the higher transmission power as explained in Section 6.2. Thus, to avoid duplication, only the 10 W results will be discussed in this section.

By changing the modulation scheme, the data rate is changed. By increasing the data rate, it can be seen that the time taken to transmit a packet decreases. Equation 6.0.1 shows the transmission time of a packet. Transmitting a packet faster can influence the systems performance quite considerably.

In addition, other characteristics such the minimum SNR required to achieve a BER of 10^{-6} changes as well. Referring to Section 4.6, Table 4.1, the minimum SNR needed to achieve a BER of 10^{-6} can be seen for all three modulation schemes.

6.3.1 Throughput

CSMA-CA

The CSMA-CA protocol makes use of RTS packets for channel contention. If more than one ground station is competing for the channel, there is a chance that these RTS packets will collide. The more ground stations there are competing for the channel, the more collisions will occur. This will continue until so many collisions take place that very few to no RTS packets get through to the satellite.

a) **Small packet sizes**

With the modulation scheme set at BPSK, the throughput performance of the CSMA-CA protocol is better than that of QPSK and 8PSK. The throughput drops slightly when the modulation scheme is changed to QPSK, which is rather unintuitive, due to the higher data rate of QPSK. The throughput drops even further when the modulation scheme is set to 8PSK.

The reason why the throughput drops when the modulation scheme is changed from BPSK to QPSK is the decrease in the time in which a packet is transmitted due to the increase in data rate. The faster a ground station can transmit packets, the more packets it can transmit in a given time interval. More packets means more noise in the system. A Data packet that is being transmitted is bombarded with more RTS packets by new ground stations that come into sight and that are not aware of the data transmission taking place. Consequently these RTS packets corrupt the Data packet being received and the receiver discards the packet. The channel contention must start all over again and time is wasted on transmitting overhead rather than essential data and this is why the throughput decreases.

The drop in throughput when moving from QPSK to 8PSK is mainly as a result of the smaller time frame available in which communications can take place due to the higher minimum SNR required by the 8PSK modulation scheme. The second reason is exactly the same as that in the shift from BPSK to QPSK mentioned above. Thus both these factors work against the 8PSK modulation scheme and bring down the throughput.

b) **Large packet sizes**

With larger data packets, the ratio of data transfer to overhead in the system is increased. In other words, the larger a packet is, the less time is spent on channel contention and more time on data transfer, thus increasing the throughput as can be seen when changing the modulation from BPSK to QPSK. With smaller packet sizes there is a decrease in throughput when changing from BPSK to QPSK.

The larger a Data packet is, the more errors can be corrected by the BCH scheme. More BCH bits means more RTS packets can collide with the Data packet before it is corrupted, since RTS packets are small. This also increases the throughput.

Another interesting finding is that the larger the packet sizes are, the better throughput performance the 8PSK modulation scheme has. Since the time frame is smaller with 8PSK, the ratio of data transfer to overhead is an important factor in increasing the throughput. 8PSK and BPSK have almost the same throughput when large packet sizes are used.

DSSS(CSMA-CA)

The DSSS(CSMA-CA) protocol functions in exactly the same way as the standard CSMA-CA protocol but with the added benefits of the DSSS technology, as mentioned before. The DSSS technology enables the system to tolerate more noise.

a) **Small packet sizes**

Examining the BPSK throughput performance, it is found that the throughput is already better than that of the standard CSMA-CA, due to the DSSS noise tolerance. Changing the modulation scheme from BPSK to QPSK, the throughput increases slightly. Then the throughput drops as the modulation scheme is changed from QPSK to 8PSK.

The slight increase in throughput when changing the modulation scheme from BPSK to QPSK is attributable to the increase in data rate. Unlike the CSMA-CA protocol, the DSSS(CSMA-CA) does not collapse as the data rate increases, because of the DSSS noise tolerance. It is also found that the throughput performance of the QPSK modulation scheme is the best, when compared to BPSK and 8PSK with the DSSS(CSMA-CA) protocol.

Changing the modulation scheme from QPSK to 8PSK, the throughput drops. This is due to the smaller time frame available for communications to take place in because of the increase in minimum SNR in the 8PSK modulation scheme. The throughput performance of the 8PSK modulation scheme is the worst, when compared to BPSK and QPSK with the DSSS(CSMA-CA) protocol.

b) **Large packet sizes**

As mentioned earlier, the larger the packet sizes are, the higher the ratio of data transfer to overhead. With the smaller packet sizes, there is a small increase in throughput when changing the modulation scheme from BPSK to QPSK. But with larger data packets, the increase in throughput from BPSK to QPSK is considerably higher. This increase has to do with the increase in the data transfer to overhead ratio and the increase in data transfer rate. Also, the larger a packet is, the more bits can be corrected by the BCH scheme.

Changing the modulation scheme from QPSK to 8PSK, the throughput decreases but not as much as with smaller packet sizes. Again the data transfer ratio helps quite a lot with the small time frame available when using 8PSK. The throughput drop is due to the smaller time frame available to communicate in.

Round-Robin Polling

Unlike CSMA-CA and DSSS(CSMA-CA), the Round-Robin Polling protocol is a centrally scheduled protocol. It also does not generate noise for channel contention as there is no competition between the ground stations for channel access. The satellite pings the ground stations in turn and if a ground station has data to transmit it will do so when requested.

a) **Small packet sizes**

With the modulation scheme set to BPSK, the Round-Robin Polling has the best throughput performance compared to QPSK and 8PSK Round-Robin Polling systems. Changing the modulation scheme to QPSK, the throughput drops. Setting it to 8PSK, the throughput drops even further.

The reason for the drop in throughput when changing the modulation scheme from BPSK to QPSK is due to the increase in data rate and effectively the decrease in packet transmission time. After a Data packet is transmitted, the satellite continues with the ping cycle. Thus the faster a packet is transmitted, the more ping cycles there will be. More ping cycles equals more time wasted on overhead and thus the throughput drops.

The drop in throughput moving from QPSK to 8PSK is due to the increase in data rate and the smaller time frame to communicate in due to the higher minimum SNR of 8PSK.

b) **Large packet sizes**

Using larger packet sizes with the Round-Robin Polling protocol increases the throughput. This can be seen when changing the modulation scheme from BPSK to QPSK. With smaller packet sizes, the throughput dropped in this instance, but with larger packet sizes, the throughput increases. This is because more time is spent on actual data transfer and less on the ping cycles. Please keep in mind that the larger the packet size is the longer a specific modulation scheme will take to transmit the packet.

Changing the modulation scheme from QPSK to 8PSK, the throughput drops as with the case with smaller packet sizes. But the throughput doesn’t drop as much as with smaller packet sizes. This is due to the increase in the ratio of data transfer to overhead due to the data rate increase and smaller time frame available for communications to take place in.

6.3.1.1 Summary

- **CSMA-CA:** CSMA-CA has the lowest throughput of all three protocols simulated due to system collapsing under low traffic load. The larger the packet sizes are, the better performance a CSMA-CA system has. The QPSK modulation scheme yields the highest throughput of all the modulation schemes simulated with CSMA-CA.
- **DSSS(CSMA-CA):** DSSS(CSMA-CA) has the highest overall throughput of the simulated systems. The high throughput is a result of the system being very noise tolerant and being a contention based system. The system performs at its best with large packet sizes and a QPSK modulation scheme.
- **Round-Robin Polling:** This protocol has the second highest throughput. As with the other two protocols simulated, using a QPSK modulation scheme and large packet size, the throughput is at a maximum.

6.3.2 Efficiency

Efficiency is calculated as the successful data bits delivered divided by the total amount of bits sent as discussed in the definition in the beginning of this Chapter.

CSMA-CA

CSMA-CA has the lowest efficiency of all three protocols simulated. This is due to the large overhead produced to compete for channel access and the low throughput achieved.

a) **Small packet sizes**

As the modulation scheme is changed from BPSK to QPSK, the efficiency decreases. The efficiency decreases even further when moving from QPSK to 8PSK.

As mentioned in the CSMA-CA throughput section, with small packet sizes the throughput drops slightly when changing from BPSK to QPSK. The amount of overhead produced in the system also increases. With these two factors affecting the system, the efficiency must decrease, as can be seen in Figures A.10 and A.13.

Varying the modulation scheme from QPSK to 8PSK, the efficiency decreases even more, as shown in Figures A.13 and A.16. This is also due to the drop in throughput and increase in overhead produced to compete for channel access.

b) **Large packet sizes**

The efficiency increases slightly when changing from BPSK to QPSK, see Figures A.12 and A.15. This is due to the increase in throughput. The system also spends more time on data transfer due to the larger packet size. The more time spent on data transfer, the less time is spent on channel contention and thus the efficiency increases.

The efficiency drops slightly when changing from QPSK to 8PSK, as can be seen in Figures A.15 and A.18. This is as a result of the drop in throughput of the system due to the small time frame available to communicate in, when using 8PSK.

DSSS(CSMA-CA)

DSSS(CSMA-CA) has the second highest efficiency of the three protocols simulated.

a) **Small packet sizes**

The efficiency of DSSS(CSMA-CA) stays almost exactly the same when changing the modulation scheme from BPSK to QPSK for small packet sizes, see Figures A.10 and A.13. This small increase is a consequence of the increase in throughput and overhead. QPSK has a higher data rate and thus more packets are transmitted in a given time. Also, more packets are being delivered because the system is capable of tolerating more noise. The overhead is also increased, due to the increased data rate. The ratio of data transferred to the overhead is such that they almost cancel each other out which leaves the efficiency only a slight margin to increase.

The efficiency drops to about half of BPSK and QPSK on the 8PSK modulation scheme, as seen in Figures A.13 and A.16. The reason for this big drop is the large drop in throughput, to only half that of BPSK and QPSK.

b) **Large packet sizes**

For larger packet sizes, the efficiency increases. Moving from BPSK to QPSK, (Figures A.12 and A.15), the efficiency increases due to the tremendous increase in throughput. The increase in throughput outweighs the increase in overhead and consequently the efficiency increases.

Moving from QPSK to 8PSK, the efficiency decreases, see Figures A.15 and A.18. The decrease is written to the higher minimum SNR of 8PSK compared to QPSK, thus a smaller time frame in which communications can take place.

Round-Robin Polling

Round-Robin Polling has the highest efficiency of all three protocols simulated. This is because Round-Robin Polling is a centrally scheduled protocol, whereas the other two are contention based. Thus there is no contention for channel access and the overhead produced is much lower.

a) **Small packet sizes**

For small packet sizes, the efficiency drops when moving from BPSK to QPSK. This is as mentioned before because of, the increase in number of ping cycles as the data rate increases. The ping cycles can be seen as overhead and as a result the efficiency decreases. These findings also hold true for changing the modulation scheme from QPSK to 8PSK, (Figures A.13 and A.16).

b) **Large packet sizes**

For large packet sizes the efficiency is best with a BPSK modulation scheme. This is due to the slow data rate, when less overhead is produced in terms of ping cycles. The amount of data transferred outweighs the amount of overhead produced by this slow data rate with a BPSK modulation scheme. Subsequently the efficiency is very high.

Moving from BPSK to QPSK, the efficiency decreases slightly, see Figures A.12 and A.15. Although the throughput increases, the amount of overhead produced due to the increase in data rate is high and, the efficiency decreases slightly.

Moving from QPSK to 8PSK, the efficiency drops slightly again, (Figures A.15 and A.18). The throughput also decreases and the increase in data rate generates more overhead. As a result, the efficiency decreases.

6.3.2.1 Summary

- **CSMA-CA:** The CSMA-CA protocol has the lowest efficiency of the three protocols. The efficiency increases slightly when a QPSK modulation scheme and larger packet sizes are used. The efficiency is low due to it being a contention based protocol and the fact that the system deteriorates very quickly with increased load.

- **DSSS(CSMA-CA):** DSSS(CSMA-CA) has the second highest efficiency. Using larger packet sizes and a QPSK modulation scheme increases the efficiency. Although the efficiency of DSSS(CSMA-CA) system is low, due to it also being a contention based protocol, the system doesn’t collapse as with CSMA-CA and the throughput is very high.

- **Round-Robin Polling:** Round-Robin Polling has the highest efficiency of the three protocols simulated. This is because Round-Robin Polling is a centrally scheduled protocol, whereas the other two are contention based. Thus there is no contention for channel access and the overhead produced is much lower. The efficiency of the protocol is at it best when using a QPSK modulation scheme and with large packet sizes.

6.3.3 Average ETE delay

The average ETE delay is the average time it would take a packet to be successfully delivered to the specified destination ground station. Both CSMA-CA and DSSS(CSMA-CA) are contention based protocols whilst Round-Robin Polling is centrally scheduled as mentioned before.

The contention based protocols have a disadvantage when it comes to the average ETE delay. For example, ground station 1 wins the channel contention by chance, and it transmits a Data packet, intended for ground station 3, successfully to the satellite. Ten minutes later the satellite passes over ground station 2 and ground station 3. Both of them are competing for channel access and by chance ground station 2 gets the channel access. Ground station 2 then transmits its data and ground station 3 misses out on communicating with the satellite. Ground station 3 has to wait a full orbit to compete for the channel and be served. This increases the ETE delay time of packets in the satellite buffer. And this happens for both the contention protocols simulated.

On the other hand, with the Round-Robin Polling protocol there is no contention for the channel because the satellite is in charge of who communicates. This attribute of the protocol has an advantage over the the contention based protocols. For example, the satellite pings ground station 1 and it transmits a Data packet, intended for ground station 3, successfully to the satellite. Ten minutes later ground station 2 and ground station 3 comes into view of the satellite. Now since the satellite pings all the ground stations in turn to transfer data, ground station 3 can't miss its turn to receive the Data packet sent by ground station 1.

To understand what has happened and to interpret the average ETE delay results, one has to take throughput and efficiency into account. Throughput and efficiency are only indicators of packets being delivered to either the satellite or a ground station. To calculate average ETE delay, the time a packet needs to travel from the host to the satellite and then to the is logged.

Please keep this in mind when interpreting the average ETE delay.

CSMA-CA

CSMA-CA has the worst average ETE delay of all three protocols simulated. This is the case for BPSK, QPSK and 8PSK. The explanation for this is evident in the throughput and efficiency graphs. The CSMA-CA protocol collapses after the number of ground stations increases to 20 and thus very few packets are delivered to the satellite. The packets on the satellite then have to wait for an indefinite time until the specific destination ground station has won the channel contention before a packet is delivered to that ground station. This increases the ETE delay time of every packet created and increases the average ETE delay. This holds true for all packet sizes.

DSSS(CSMA-CA)

a) **Small packet sizes**

For a BPSK or QPSK modulation scheme, and using small packet sizes, the average ETE delay of DSSS(CSMA-CA) is between those of CSMA-CA and the Round-Robin Polling protocol, (Figures A.10 and A.13). This is due to the fact that the DSSS(CSMA-CA) delivers more packets to the satellite than the CSMA-CA protocol.

With an 8PSK modulation scheme, the average ETE delay results change slightly, as in Figure A.16. The throughput of DSSS(CSMA-CA) drops quite drastically. This, in combination with the disadvantage of the contention based protocols, results in the average ETE delay decreasing.

b) **Large packet sizes**

The average ETE delay of a system with a BPSK modulation scheme and large packet sizes, is between CSMA-CA and Round-Robin Polling with CSMA-CA being the worst, (Figure A.12). The DSSS(CSMA-CA) has a very high throughput but has a higher average ETE delay than that of Round-Robin Polling. This is as a result of the packets being stuck on the satellite due to the contention based protocol characteristics.

With the modulation scheme set to QPSK, the throughput of DSSS(CSMA-CA) increases drastically. This drastic increase in throughput leads to a slight decrease in average ETE delay, meaning more packets are being delivered from the satellite to the destination ground stations than with the BPSK modulation scheme.

With a 8PSK modulation scheme, the throughput and efficiency decreases and thus the average ETE delay increases.

Round-Robin Polling

a) **Small packet sizes**

The average ETE delay of a Round-Robin Polling system with a small packet size is lower than that of the other two protocols simulated. This holds true for BPSK, QPSK modulation schemes, Figures A.10 and A.13. This is because BPSK and QPSK have a very good efficiency. The average ETE delay increases slightly when moving from BPSK to QPSK, due to the decrease in efficiency when moving from BPSK to QPSK.

Moving from QPSK to 8PSK, the throughput and efficiency of the Round-Robin Protocol decreases, which leads to an increase in the average ETE delay, see Figure A.16.

b) **Large packet sizes**

A Round-Robin Polling protocol with a BPSK modulation scheme has a very high efficiency and a low throughput, this indicates a system that does not transmit many packets but the packets are delivered and thus the average ETE delay is low, (Figure A.12).

Changing the modulation scheme to QPSK or 8PSK, the efficiency drops quite a bit and the throughput of both QPSK and 8PSK increases slightly, which increases the average ETE delay, (Figures A.15 and A.18). This is mainly due to the decrease in efficiency.

6.3.3.1 Summary

- **CSMA-CA:** CSMA-CA has the highest average ETE delay of the three protocols simulated. To decrease the average ETE delay of a CSMA-CA system, a QPSK modulation scheme with small packet sizes must be used.
- **DSSS(CSMA-CA):** The average ETE delay of a DSSS(CSMA-CA) is the lowest when using a QPSK modulation scheme. For a system with an 8PSK modulation scheme and any packet size, or a system with a packet size of 1Mb, DSSS(CSMA-CA) has a lower average ETE delay than Round-Robin Polling.
- **Round-Robin Polling:** Round-Robin Polling average ETE delay is at its lowest when using a QPSK modulation scheme.

6.3.4 Undelivered packets

The undelivered packet count is the number of packets left in the satellite's buffer when the simulation ends.

CSMA-CA

CSMA-CA has the lowest number of undelivered packets of the three protocols. This is as a result of the collapse of the system and almost no packets transmitted getting through to the satellite.

DSSS(CSMA-CA)

DSSS(CSMA-CA), on average, has the highest throughput of all the protocols and it has the highest undelivered packet count. This holds true for BPSK, QPSK and 8PSK with all the packet sizes simulated. The reason for this is because, as mentioned before, the satellite forms a bottleneck in the contention protocols. The satellite's download rate is much lower than its upload rate, due to the configuration, and this creates the bottleneck.

Round-Robin Polling

Round-Robin Polling has the second lowest undelivered packet count. This is true for BPSK, QPSK and 8PSK. This is because Round-Robin Polling has a better efficiency than DSSS(CSMA-CA). The reason why it's not lower than CSMA-CA is because of the CSMA-CA system collapsing and hardly any packets getting through to the satellite.

6.4 Influence of packet sizes on modulation scheme

In this section the modulation scheme will be kept constant and the packet size will be varied. This is seen as moving from top to bottom, or visa versa, in Table 6.2, while keeping the modulation rate fixed. Increasing the packet size and keeping the modulation scheme fixed decreases the transmission time of a packet, which influences certain characteristics of the protocols. Keeping the modulation scheme fixed, the BER vs SNR characteristics stay the same for every simulation run with different packet sizes.

6.4.1 Throughput

For a BPSK, QPSK or 8PSK modulation scheme, all three protocols simulated have an increase in throughput as the packet sizes are increased. This is also consistent with the packet size optimising simulations run in Section 5.3.1. The DSSS(CSMA-CA) protocol has the highest throughput on average, then Round-Robin Polling and lastly CSMA-CA.

The reason for the increase in throughput is that the ratio of essential data transferred to the overhead produced is reduced. Thus when data transfer takes place more time is spent on transferring data and less time on producing overhead.

6.4.2 Efficiency

As the packet sizes increase, the efficiency of all the protocols simulated increases. The Round-Robin Polling protocol has by far the best efficiency, then it is DSSS(CSMA-CA) and CSMA-CA has the worst.

The reason for the increase in efficiency is the same as that for the increase in throughput. The bigger the Data packets, the more data is transferred per packet and less time is spent on overhead. This in effect increases the efficiency.

6.4.3 Average ETE delay

As the packet size increases, the average ETE delay increases. The larger a packet size is, the longer it takes to be transmitted to the destination. Thus fewer packets can be delivered during a satellite pass. The other packets in the satellite's buffer have to wait for a full orbit before they can be delivered. This increases the delivery time of a packet and thus the average ETE delay increases.

6.4.4 Undelivered packets

The undelivered packet count decreases as the packet size increases. This is true for all protocols simulated. The reason is that the bigger the Data packets are, the fewer of them can be transferred in a period of time. And thus fewer of them are in the satellite's buffer when the simulation ends. It must be said that, although the undelivered packet count decreases as the packet size increases, focus must be put on the number of bits left in the satellite buffer. For example, if the undelivered packet count is 3 with the packet size at 4 kb, the totals number of bits left on the buffer is $3 \times 4096 = 12288$ bits. Compared to a undelivered packet count of 1 but with a packet size of 1 Mb, it is clear that the bigger packet size are the fewer packets are on board of the satellites buffer but this does not necessarily indicate that more data has been transferred.

6.4.5 Summary

By keeping a system's modulation scheme fixed and changing the packet size, the system's performance increases, regardless of which protocol is implemented, be it CSMA-CA, DSSS(CSMA-CA) or Round-Robin Polling. Packet sizes of 1 Mb is the highest packet size that can be used before system performance starts to decrease.

6.5 Summary

- The Quadrifilar Helix antenna proved sufficient enough and thus the Fixed Yagi or tracking antenna were not implemented in the simulations.
- It is suggested that the system be run with the highest possible transmission power of 10 W to get the maximum performance.
- The Round-Robin Polling protocol has the overall best efficiency performance because it is a centrally scheduled protocol and thus the ground stations do not make use of RTS packets to contend for channel access. The satellite controls channel access and less overhead is generated this way, increasing efficiency.
- The CSMA-CA system performs very poorly and would not be recommended if more than 10 ground stations are to be used.

- The DSSS(CSMA-CA) system has the overall best throughput performance and has the overall second best efficiency performance.

- The larger the packet size is of a specific configuration, the better the overall performance of that protocol. Thus it is recommended that as large a packet size as possible is used for every configuration, preferably 1 Mb. Packet sizes larger than 1 Mb takes too long to transmit and decreases system performance.

- The 8PSK modulation scheme performs very poorly overall due to the small time frame available in which communications can take place.

- The QPSK modulation scheme performs the best of all the modulation schemes simulated. BPSK and QPSK have the same minimum SNR, but QPSK has double the data rate which increases the QPSK's performance. The 8PSK has double the data rate of QPSK but it also has a much higher minimum SNR, which means that the QPSK modulation scheme outperforms 8PSK.

- There is no configuration of modulation scheme, packet size, transmission power etc. that is the best overall solution. The specific application's use and required characteristics needed must be taken into consideration. Then a suitable configuration must be chosen from the set of configurations presented that satisfies most of the needs of the application.

6.6 Next chapter

The next chapter is a summary and conclusion of this thesis.

Chapter 7

Summary and Conclusion

In conclusion of this thesis, the following remarks and conclusions are thought appropriate:

7.1 Motivation

The University of Stellenbosch and the CSIR both have projects that makes use of LEO satellite communications. These institutions do not make use of LEO constellations and each of them have a single LEO satellite orbiting the earth. Therefore, maximising the satellite channel utilisation is important. An investigation was done to maximise the intermittent, short communication slots. It was thought to be of great assistance should a realistic simulation tool be available to predict and optimise, LEO communication channel utilisation, for a specific application.

7.2 Summary of objectives and methodology

The work carried out under this project, had the following objectives:

- First, to overall define the limiting aspects of LEO satellite communications.
- Thereafter a systems design of a LEO satellite communication system to transfer very small data files or emails from rural settlements was investigated. The design included aspects such as antenna types, transmission power, packet structures and sizes, modulation schemes, physical limitations, protocols, error correcting coding etc.
- To implement the design in a discrete event simulator. The simulator was run and different variables of the system altered to observe the effect of each on the system.
- The results were interpreted to determine the effect of all these variables on each other and the effect on the system in terms of optimising. It would also determine the optimal

configuration for optimal LEO satellite communications, in terms of transfer of small data volumes.

7.3 Summary of results

- Three simulators were successfully built to simulate the three chosen protocols. Different variables of the simulators could be changed to determine the effect of each change on the system results.
- From the simulation results it was found that the Quadrifilar Helix antenna proposed in the design specifications should work very well. A fixed, high gain, Yagi antenna is recommended for systems with low transmission power. A tracking antenna would be the ideal solution for LEO satellite communications, should budget allow.
- Increasing the transmission power, increases the overall performance of the system; as expected. It is suggested that the system be run with the highest possible transmission power of 10 W to obtain maximum performance.
- Round-Robin Polling displayed the best overall efficiency in performance. Thus, if a system has to be selected in terms of efficiency only, Round-Robin Polling is the protocol to use. The performance of the Round-Robin protocol also stays constant with the increase in number of ground stations.
- The performance of a CSMA-CA system deteriorates rapidly under load and would not be recommended if more than 10 ground stations are to be used. The protocol's poor performance is due to the collisions of RTS packets for channel contention.
- The DSSS(CSMA-CA) system has the best overall throughput performance and the overall second best efficiency performance. This protocol would be recommended if maximised data transfer is the overall consideration.
- The larger the packet size of a system, the better the overall performance of that protocol. It is thus recommended to use as large a packet size as possible for every configuration, though preferably not bigger than 1 Mb. The larger the packet size, the more data is conveyed per packet transfer and thus less time is spent on overhead, increasing throughput and efficiency.
- The performance of the 8PSK modulation scheme is overall unsatisfactory because of the small time frame available in which communications can take place, where the Signal to Noise Ratio (SNR) is better than the required minimum BER of 10^{-6}. It would not be recommended that this modulation scheme be used at low transmit power. For this scheme the transmit power needs to be well above 10 W. This increase in transmission

power will increase the time frame available for communications to take place, thus improving the overall performance.

- The QPSK modulation scheme performs best of all the modulation schemes simulated. BPSK and QPSK have the same minimum SNR, but QPSK has double the data rate and outperforms BPSK for that reason. The 8PSK has a much faster data rate than that of QPSK, but also has a much higher minimum SNR, which results in the QPSK modulation scheme outperforming 8PSK. It is recommended that QPSK be used for a reliable and effective modulation scheme.
- The BCH FEC scheme works well enough but a more efficient scheme such as LDPC would increase the performance of the system. The actual code implementation was not part of the project objectives and the judgement was made on known performance comparison with BCH.
- There is no particular configuration of modulation scheme, packet size, transmission power etc. presenting the best overall solution for LEO satellite communications. The overall specific LEO satellite application must be considered and the characteristics required by that specific application. A suitable configuration must subsequently be chosen from the set of configurations available to satisfy most of the application requirements.
- However, the work carried out in the course of this project, provides a set of tools to assist with the design and configuration of an optimal LEO satellite system.

7.4 Contributions

This thesis makes the following contributions to the communication design process for LEO satellites:

- An in-depth analysis of the influence of important parameters on LEO satellite communications.
- A simulator built in Opnet to simulate the CSMA-CA protocol as applied to a LEO satellite network. Parameters such as packet sizes, modulation schemes, transmission powers, antenna types and FEC can be varied to evaluate the effect on system performance.
- A similar simulator for DSSS(CSMA-CA).
- A third Round-Robin Polling Opnet simulator with similar characteristics as the other two.
- Provision of guidelines in terms of parameter selection to satisfy particular applications.

- In summary, the set of tools developed as part of this work provides a valuable aid to enable pre-emptive systems design and decrease system performance uncertainties.

7.5 Suggestions for future work

The topic of this thesis can be extended and a lot more research and fine tuning can be applied to the current work. The following are suggested for future work:

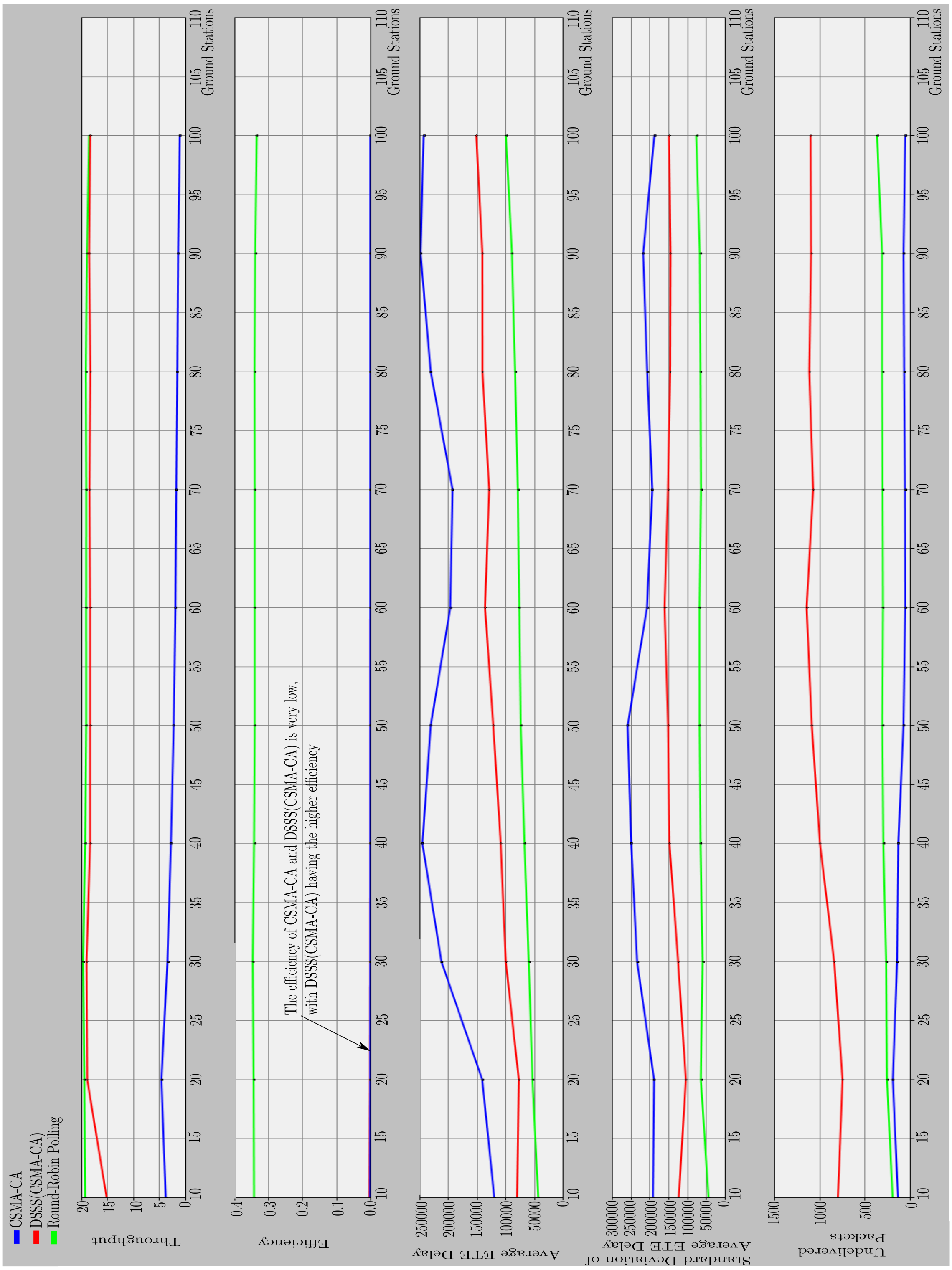
- A lot of work has gone into the three simulators. Further work can be done to improve coding, thus optimising the simulators so that they can be run in parallel on more than one computer to decrease simulation time.
- Implement a chosen configuration set on a physical testbed application to verify the results.
- Fine tune a specific configuration set to obtain a more accurate understanding of that configuration if needed. Add more satellites to current simulators to observe the effect on the system.
- Create an Adaptive Coding Modulation (ACM) simulator from the simulators provided.

7.6 Final Comment

With the increased number of users using telecoms, and the telecoms industry expanding at a fast rate, the value of computer simulations for modeling telecommunication systems cannot be over-emphasised. A set of tools was created to be used with a reasonable degree of confidence to simulate and predetermine the performance of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling as applied to LEO satellite communications.

Appendix A

Simulation Results



The efficiency of CSMA-CA and DSSS(CSMA-CA) is very low, with DSSS(CSMA-CA) having the higher efficiency

Figure A.1 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **5 W**, Modulation scheme **BPSK**, Packet size **4 kb**, FEC **BCH 10**%

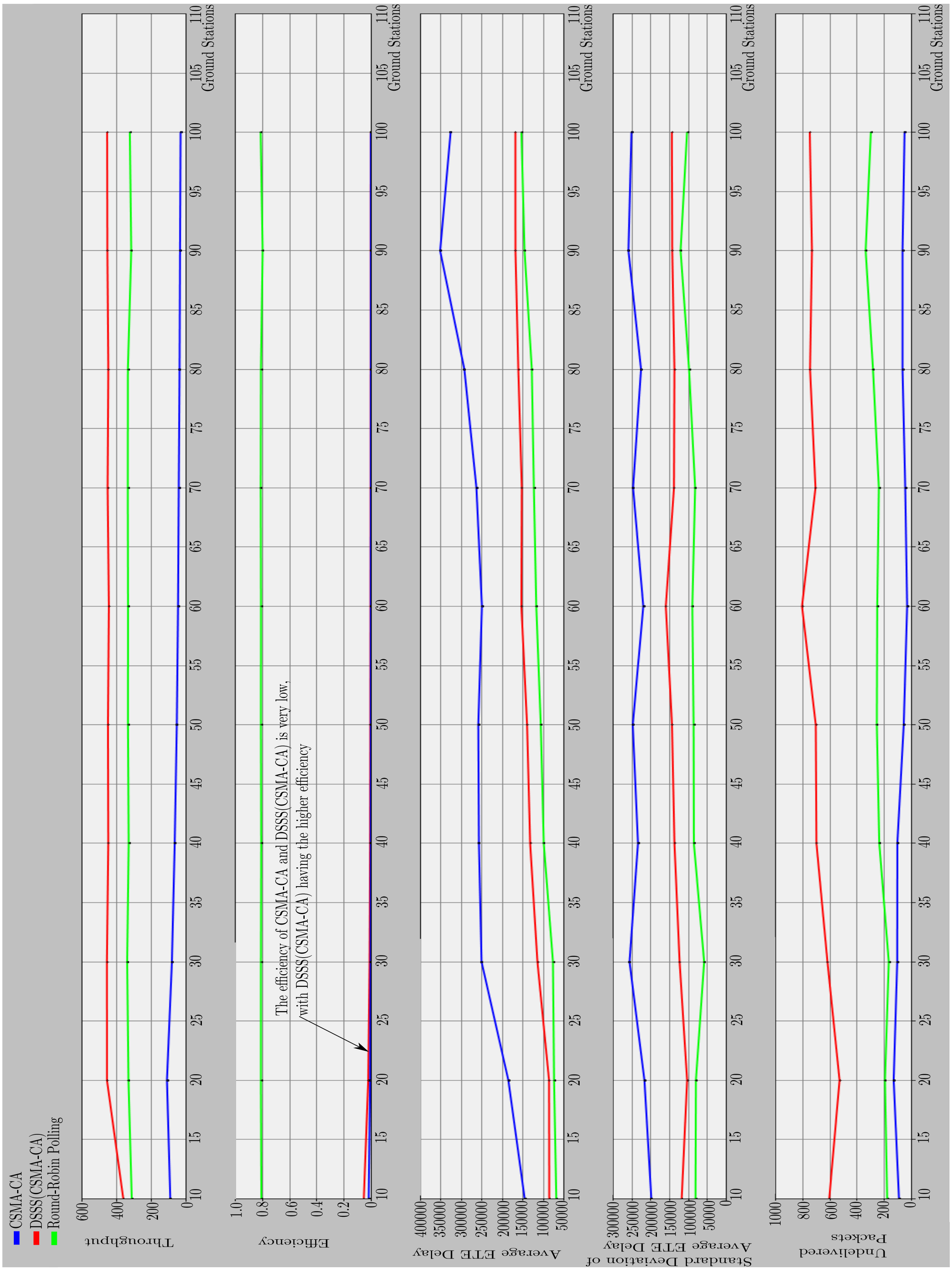


Figure A.2 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **5 W**, Modulation scheme **BPSK**, Packet size **131 kb**, FEC **BCH 10**%

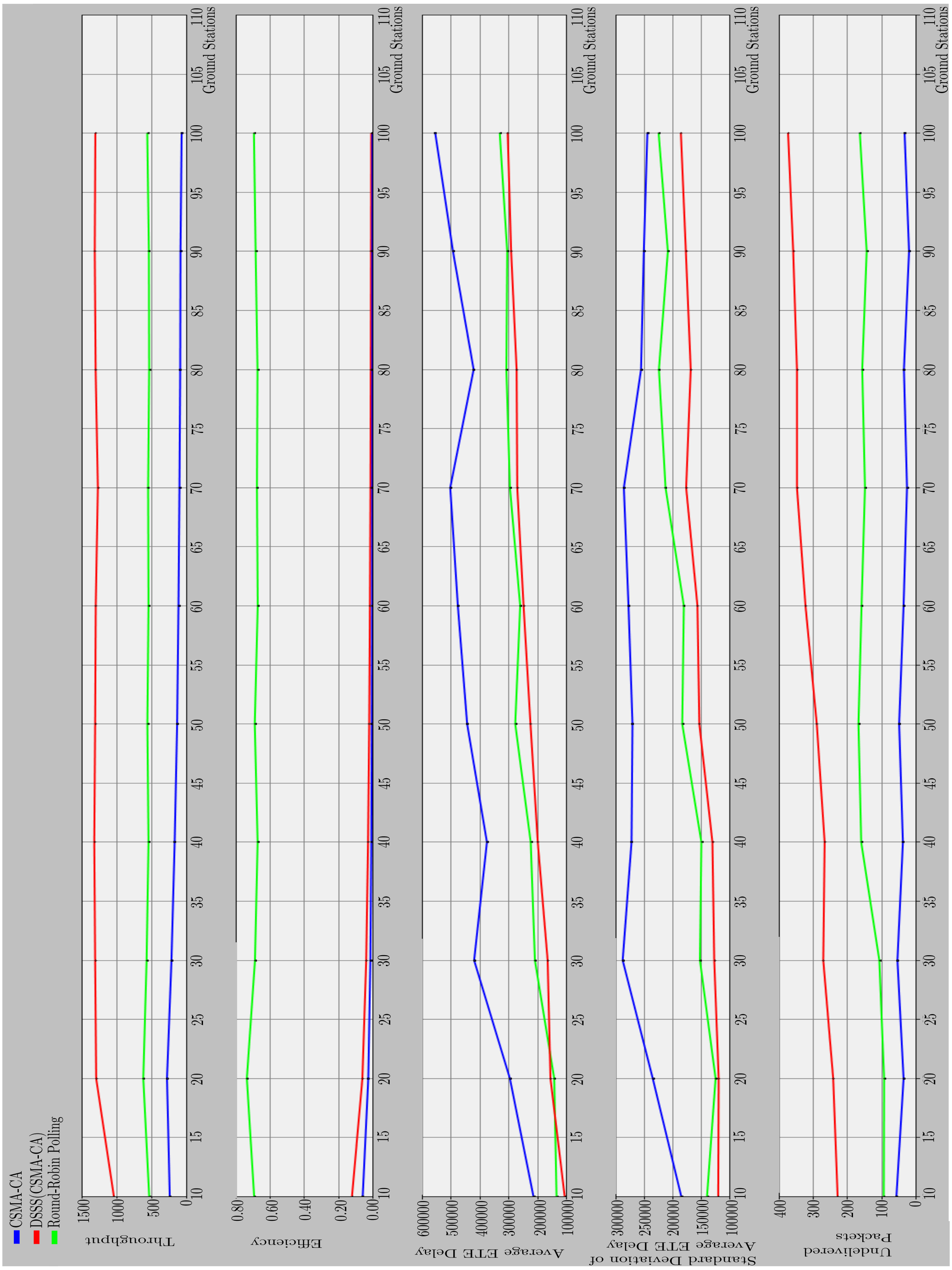


Figure A.3 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **5 W**, Modulation scheme **BPSK**, Packet size **1 Mb**, FEC **BCH 10**%

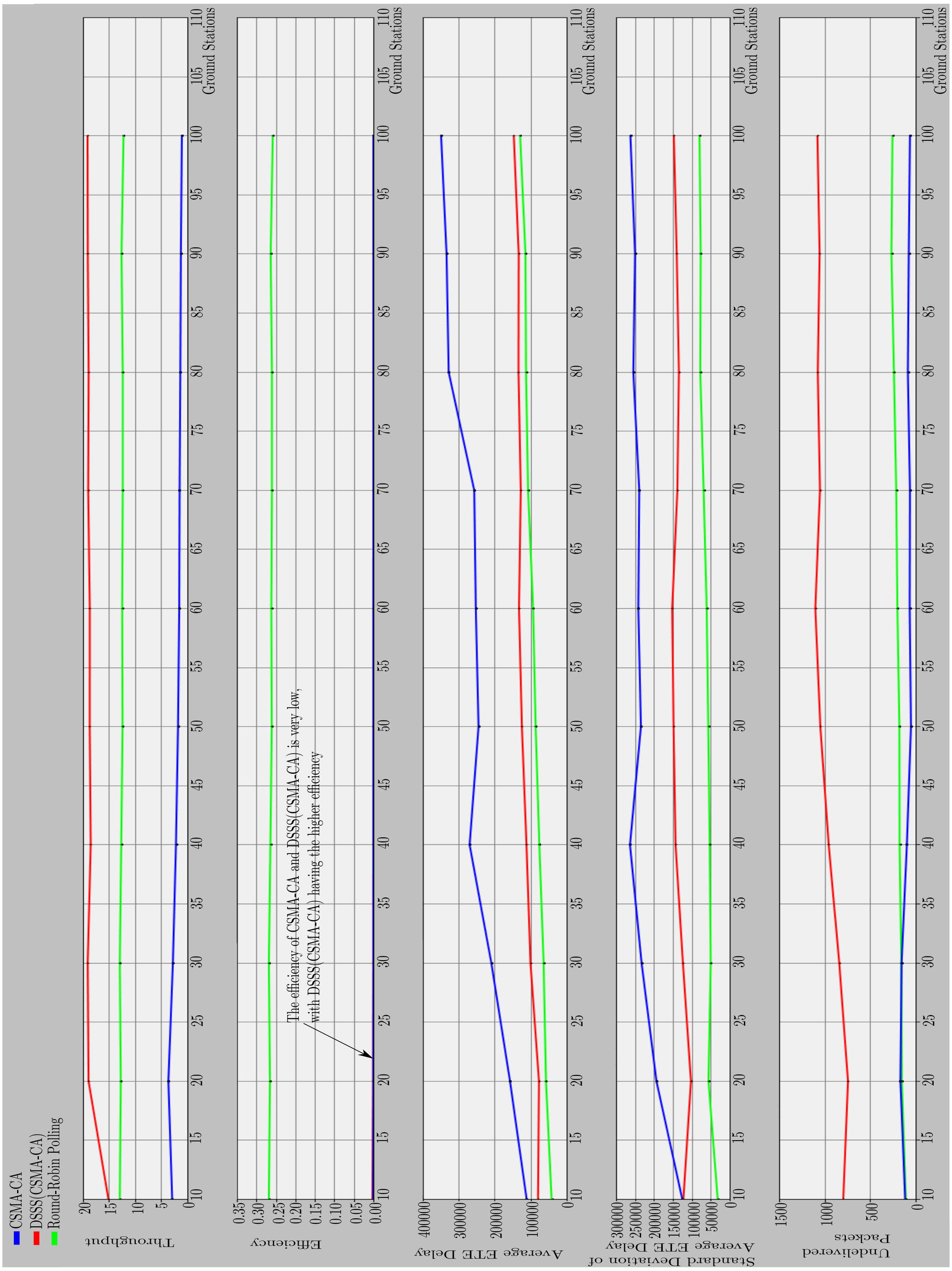


Figure A.4 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **5 W**, Modulation scheme **QPSK**, Packet size **4 kb**, FEC **BCH 10**%

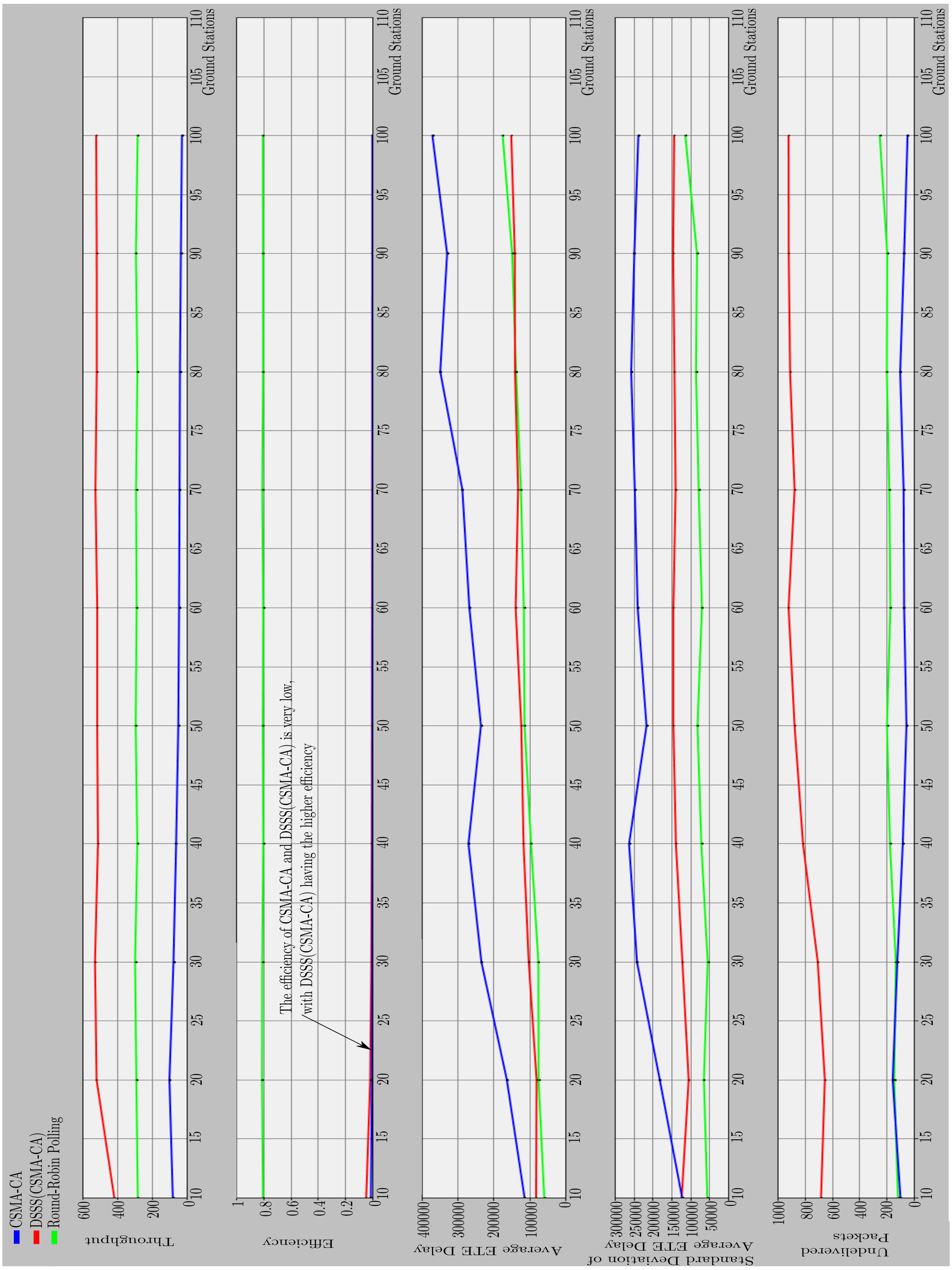


Figure A.5 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **5 W**, Modulation scheme **QPSK**, Packet size **131 kb**, FEC **BCH 10**%

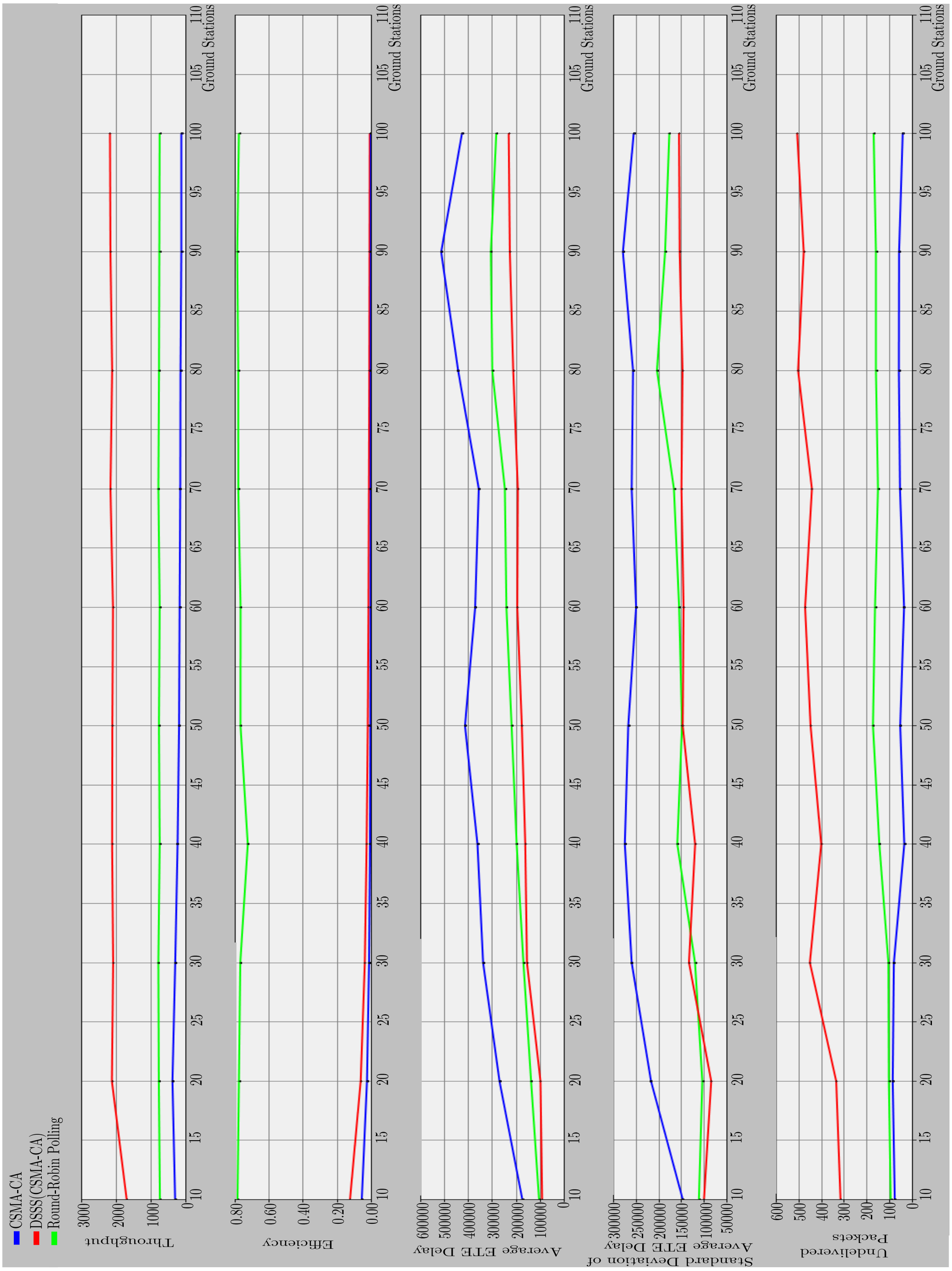


Figure A.6 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **5 W**, Modulation scheme **QPSK**, Packet size **1 Mb**, FEC **BCH 10**%

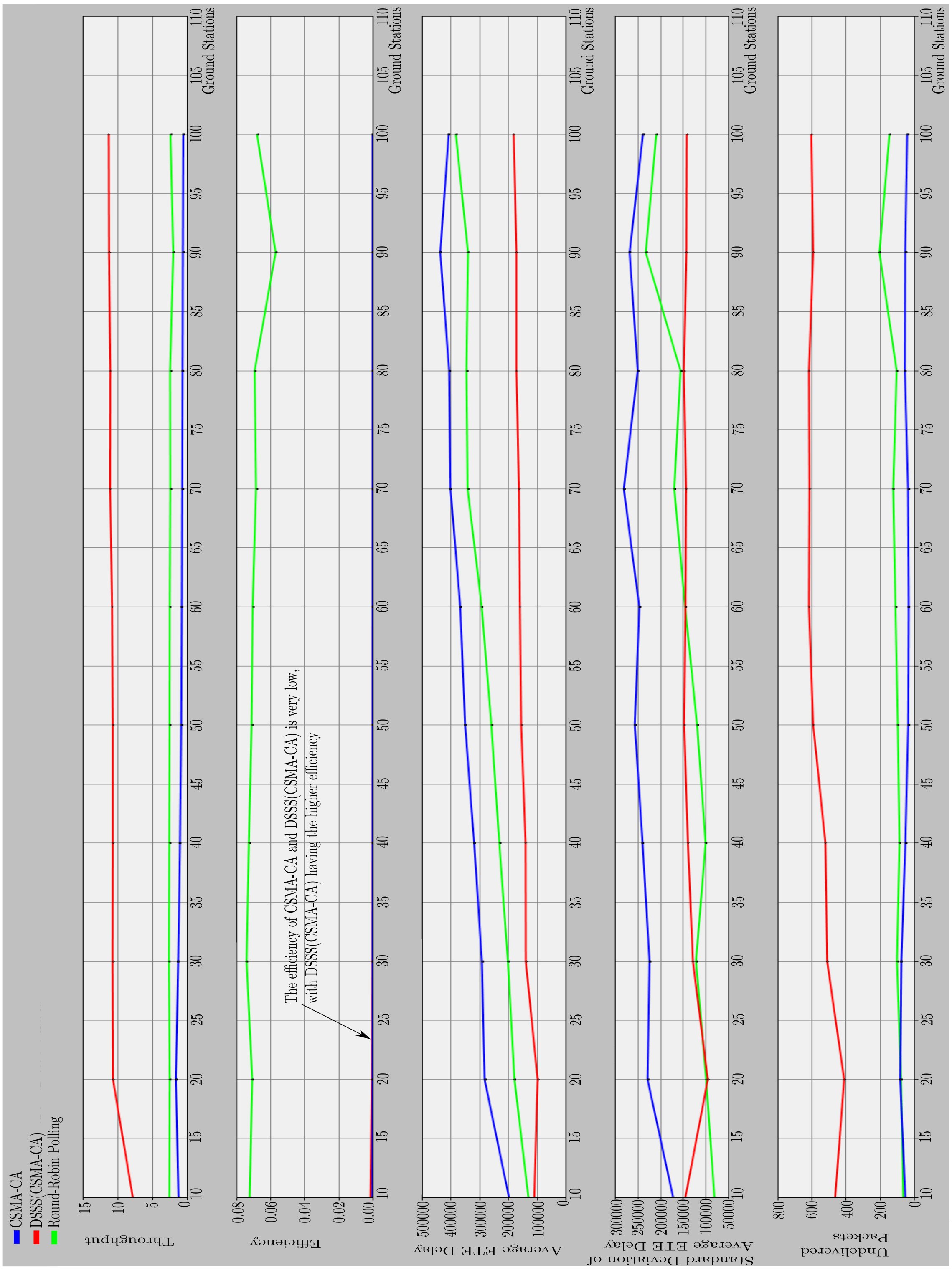


Figure A.7 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **5 W**, Modulation scheme **8PSK**, Packet size **4 kb**, FEC **BCH 10**%

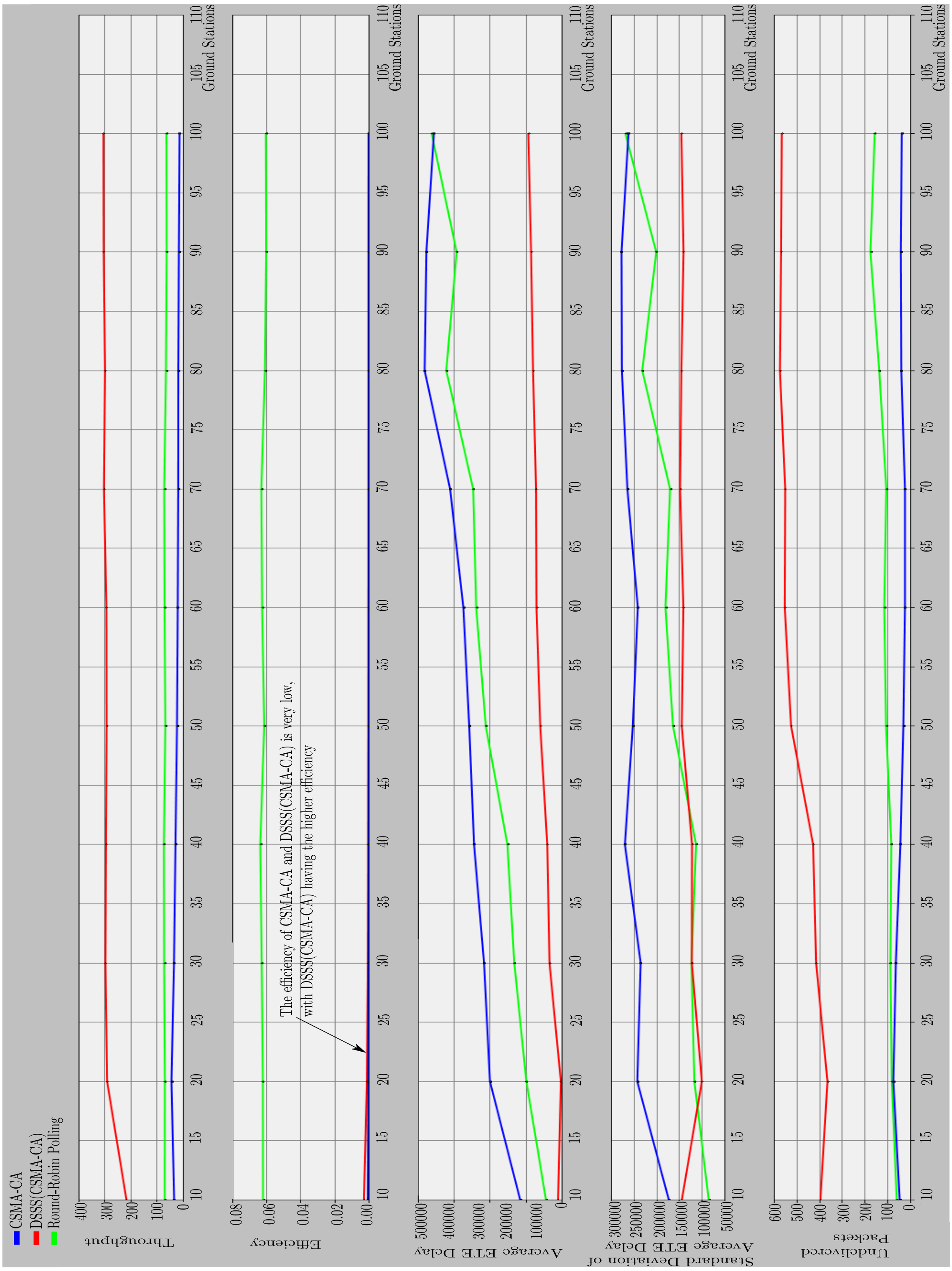


Figure A.8 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **5 W**, Modulation scheme **8PSK**, Packet size **131 kb**, FEC **BCH 10**%

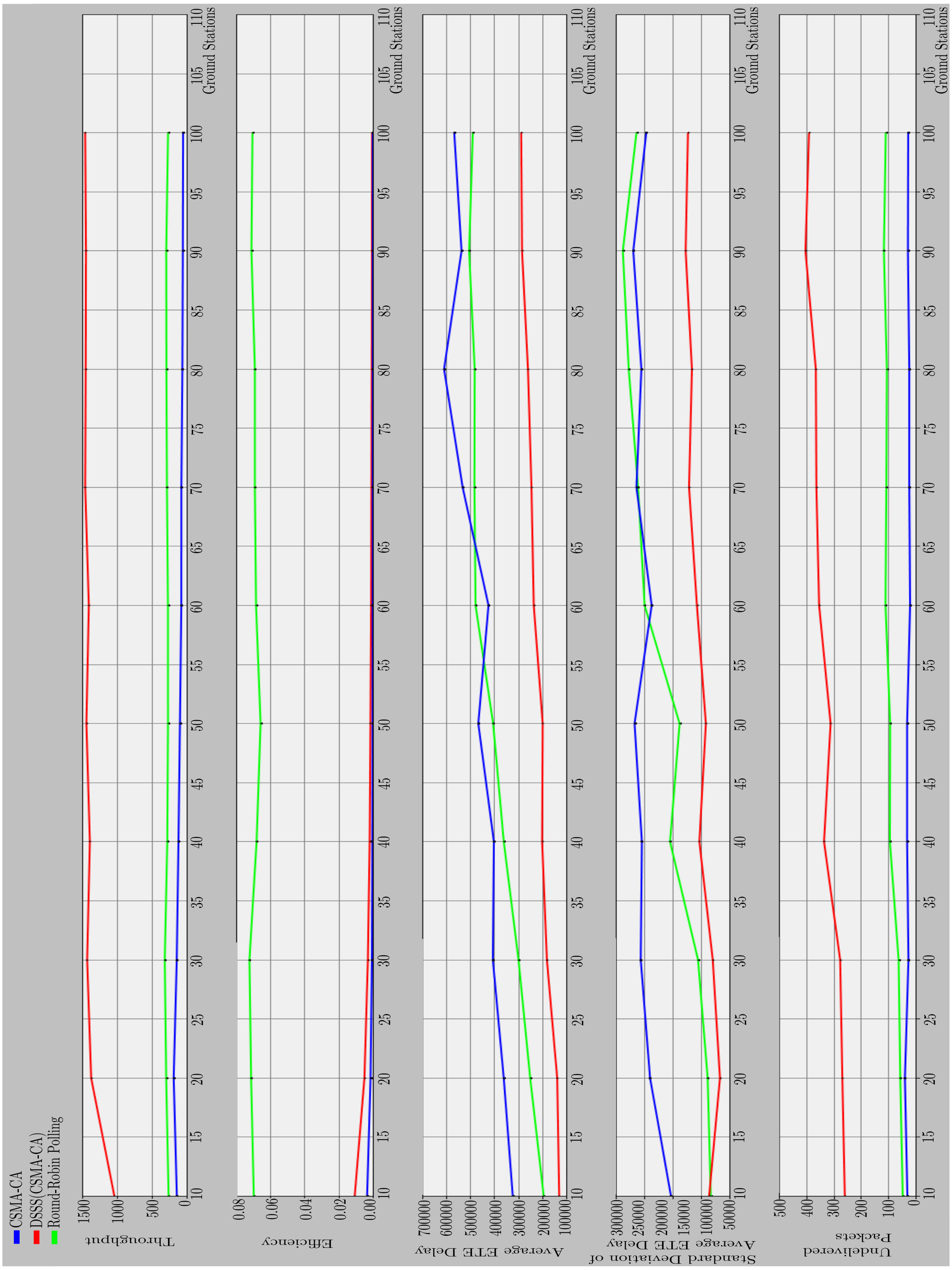
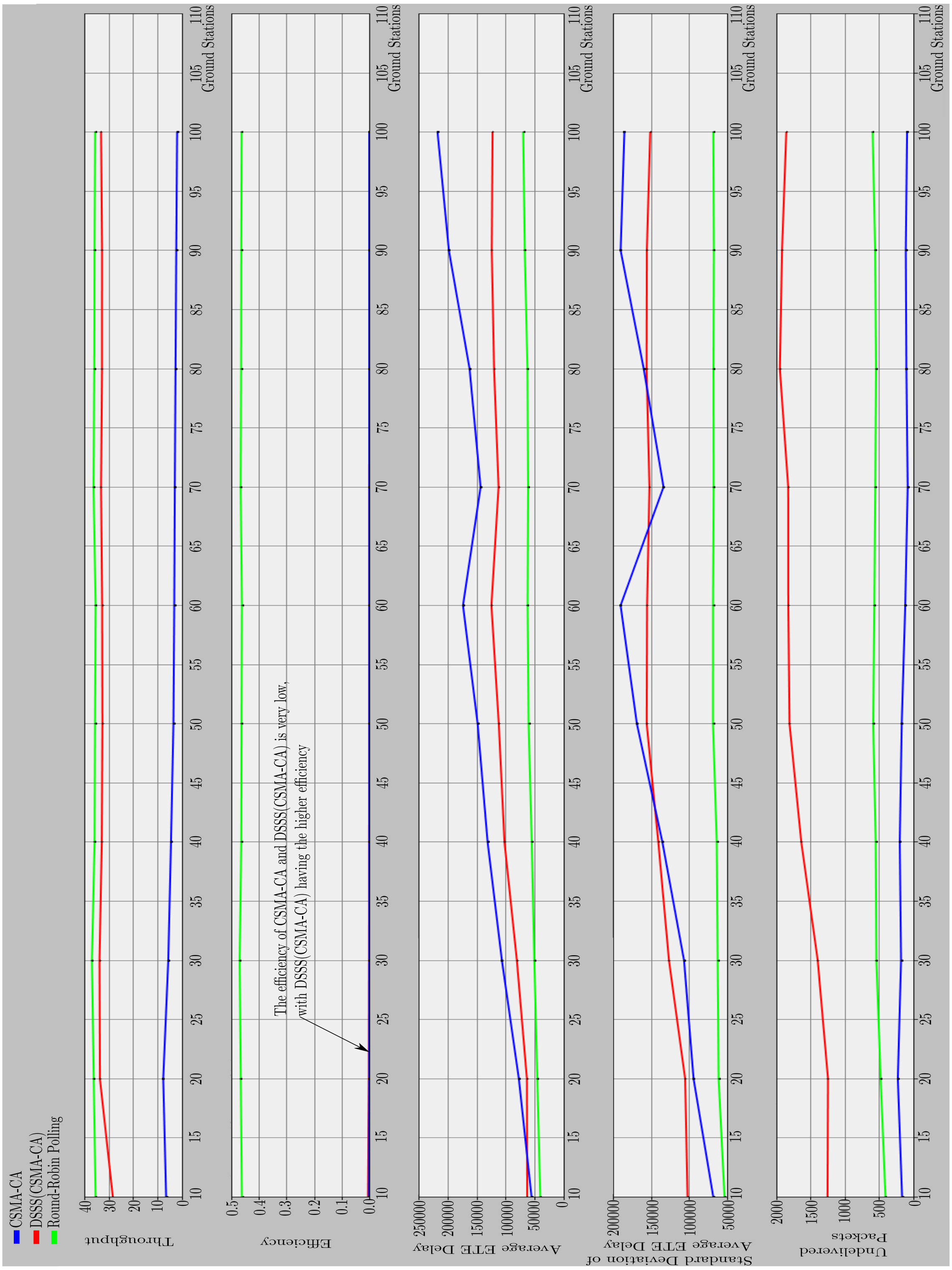
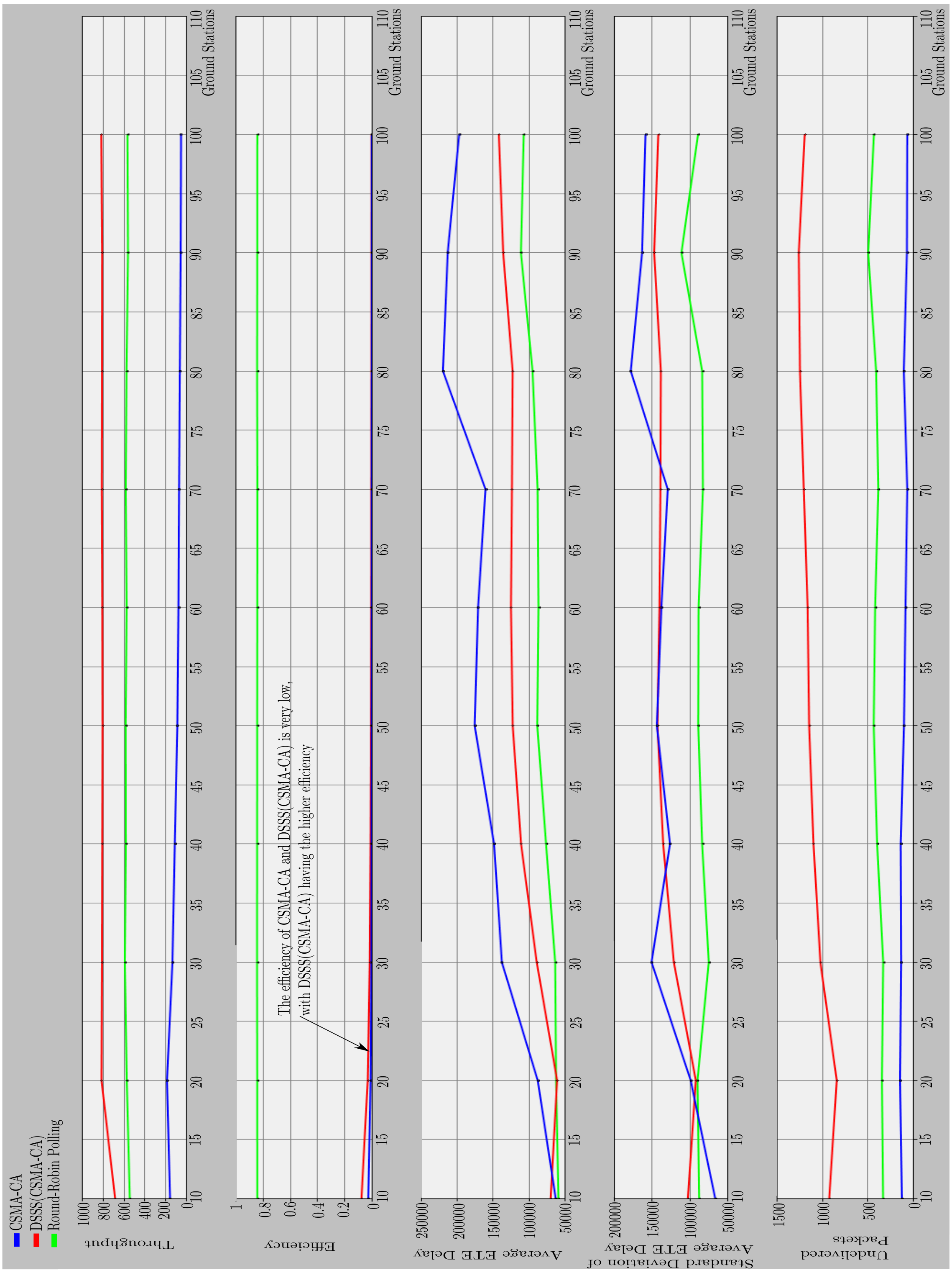


Figure A.9 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **5 W**, Modulation scheme **8PSK**, Packet size **1 Mb**, FEC **BCH 10**%



The efficiency of CSMA-CA and DSSS(CSMA-CA) is very low, with DSSS(CSMA-CA) having the higher efficiency

Figure A.10 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **10 W**, Modulation scheme **BPSK**, Packet size **4 kb**, FEC **BCH 10**%



The efficiency of CSMA-CA and DSSS(CSMA-CA) is very low, with DSSS(CSMA-CA) having the higher efficiency

Figure A.11 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **10 W**, Modulation scheme **BPSK**, Packet size **131 kb**, FEC **BCH 10**%

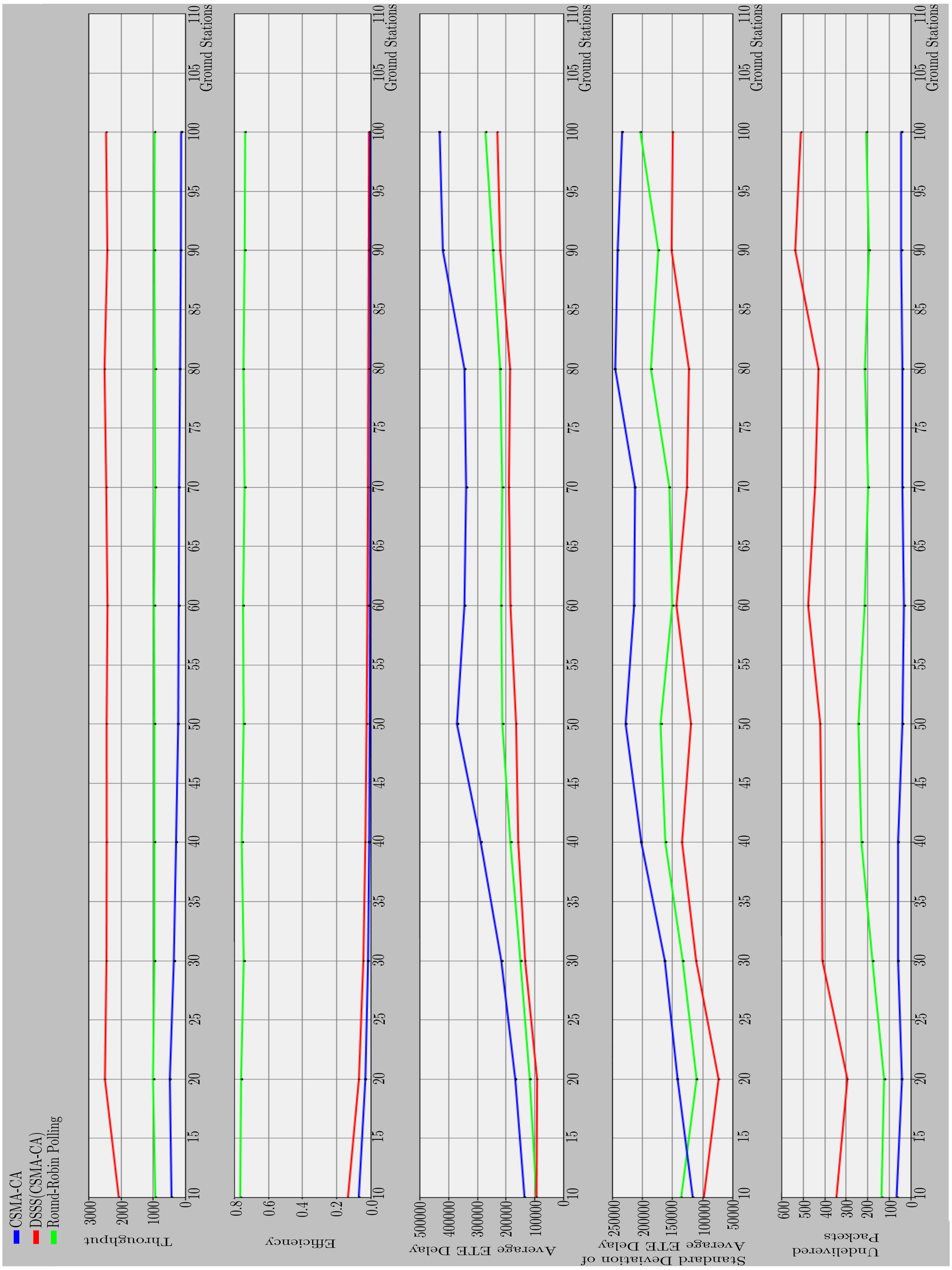


Figure A.12 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **10 W**, Modulation scheme **BPSK**, Packet size **1 Mb**, FEC **BCH 10**%

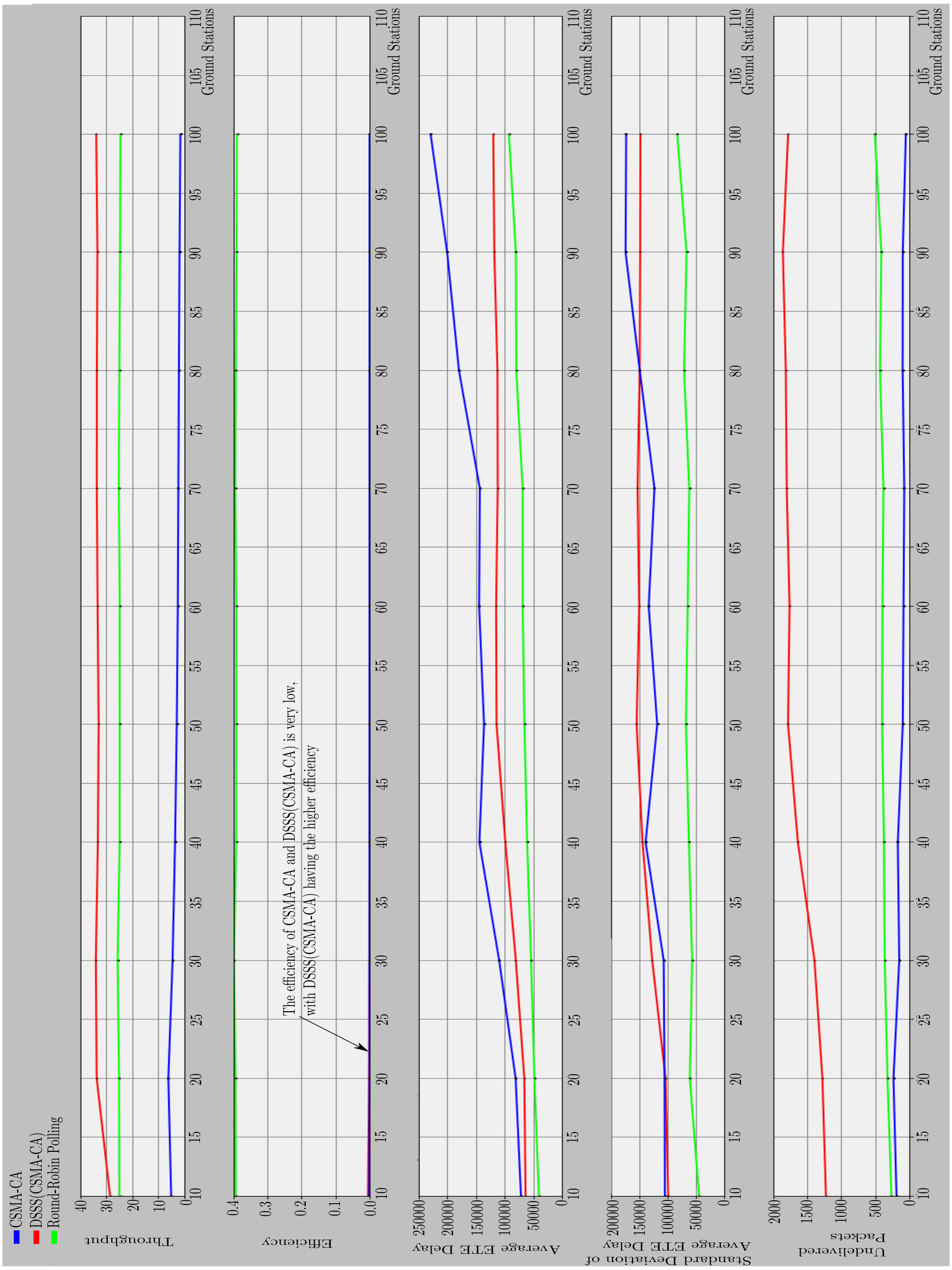


Figure A.13 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **10 W**, Modulation scheme **QPSK**, Packet size **4 kb**, FEC **BCH 10**%

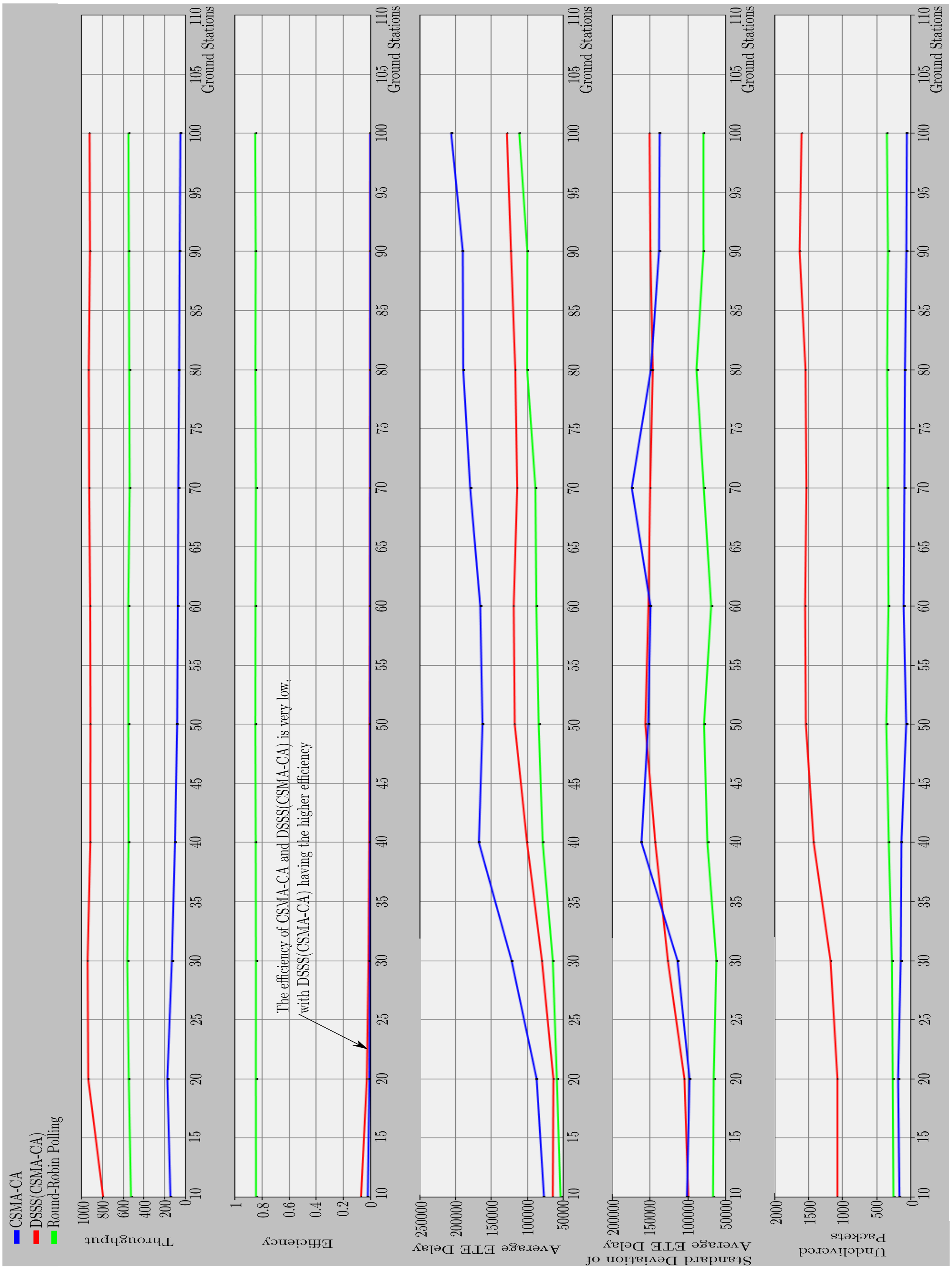


Figure A.14 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **10 W**, Modulation scheme **QPSK**, Packet size **131 kb**, FEC **BCH 10**%

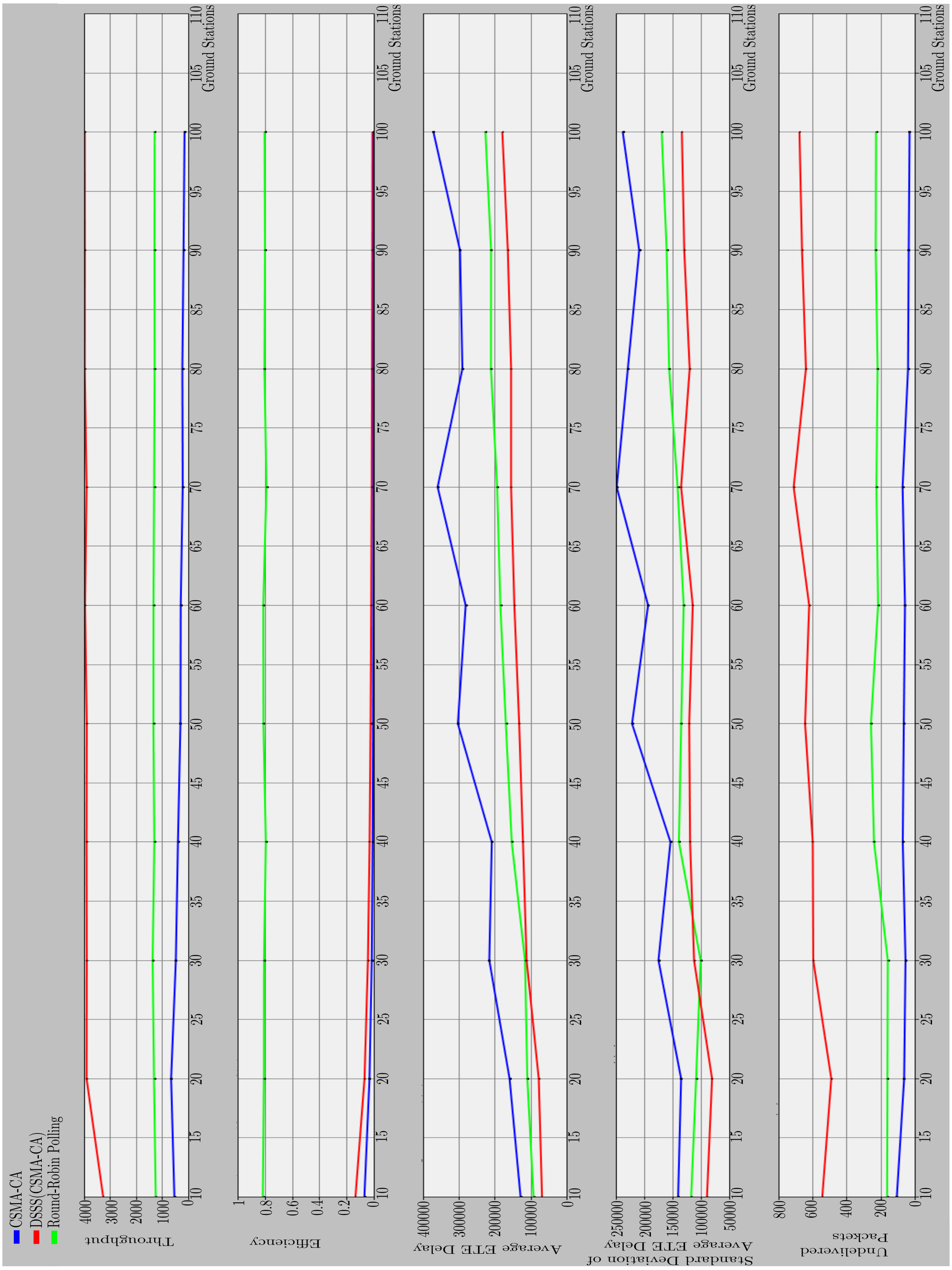


Figure A.15 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **10 W**, Modulation scheme **QPSK**, Packet size **1 Mb**, FEC **BCH 10**%

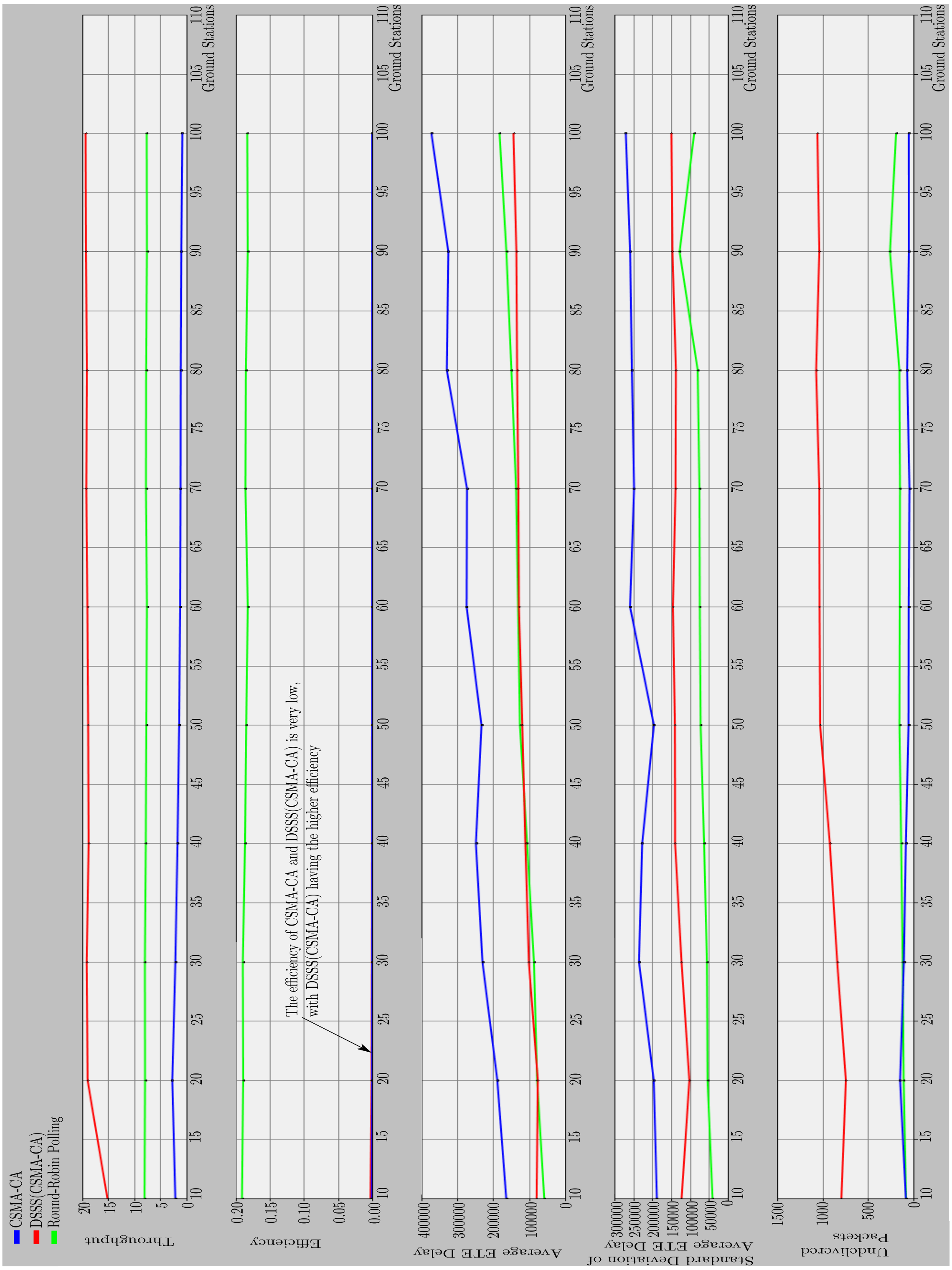


Figure A.16 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **10 W**, Modulation scheme **8PSK**, Packet size **4 kb**, FEC **BCH 10**%

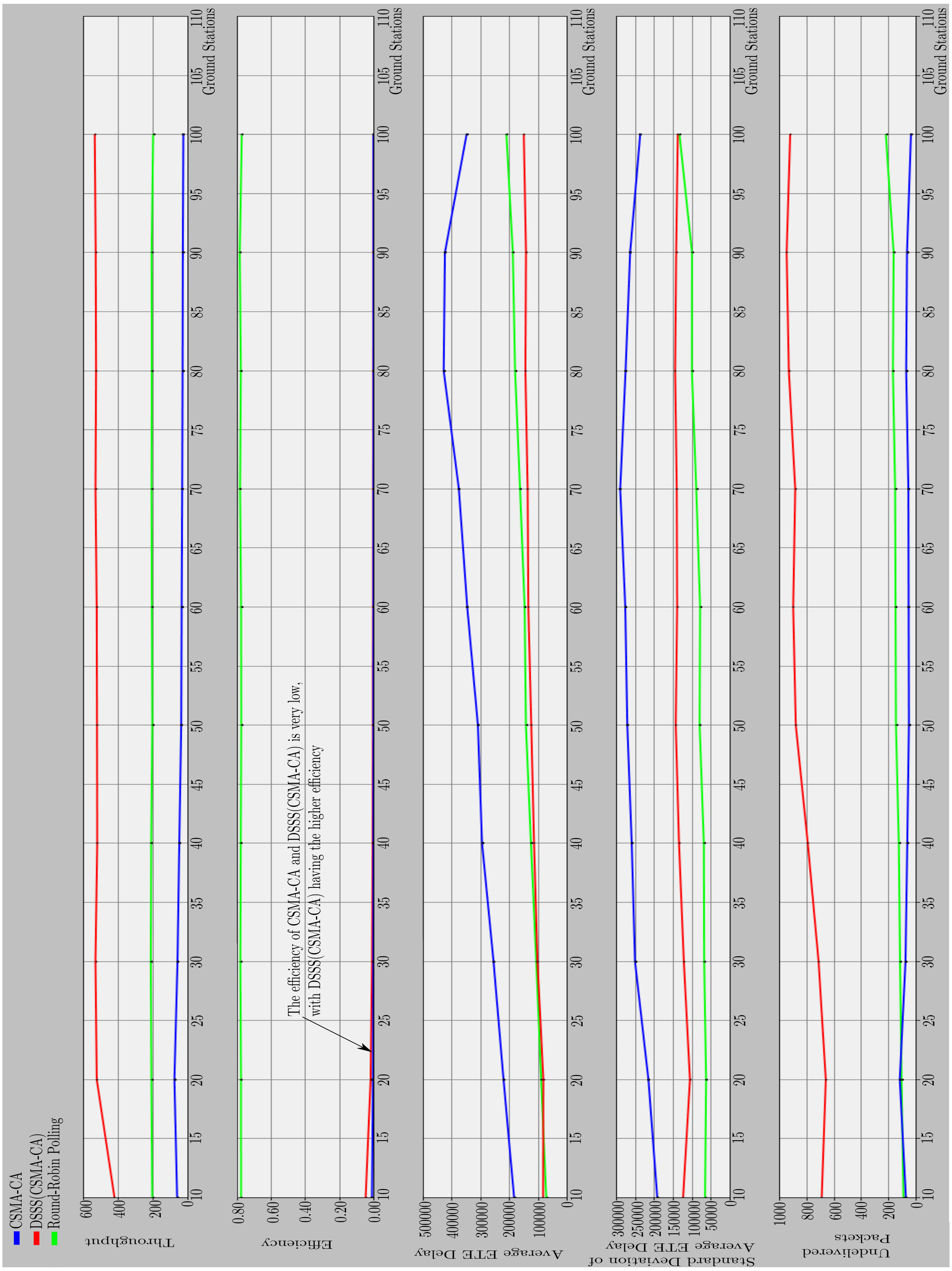


Figure A.17 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **10 W**, Modulation scheme **8PSK**, Packet size **131 kb**, FEC **BCH 10**%

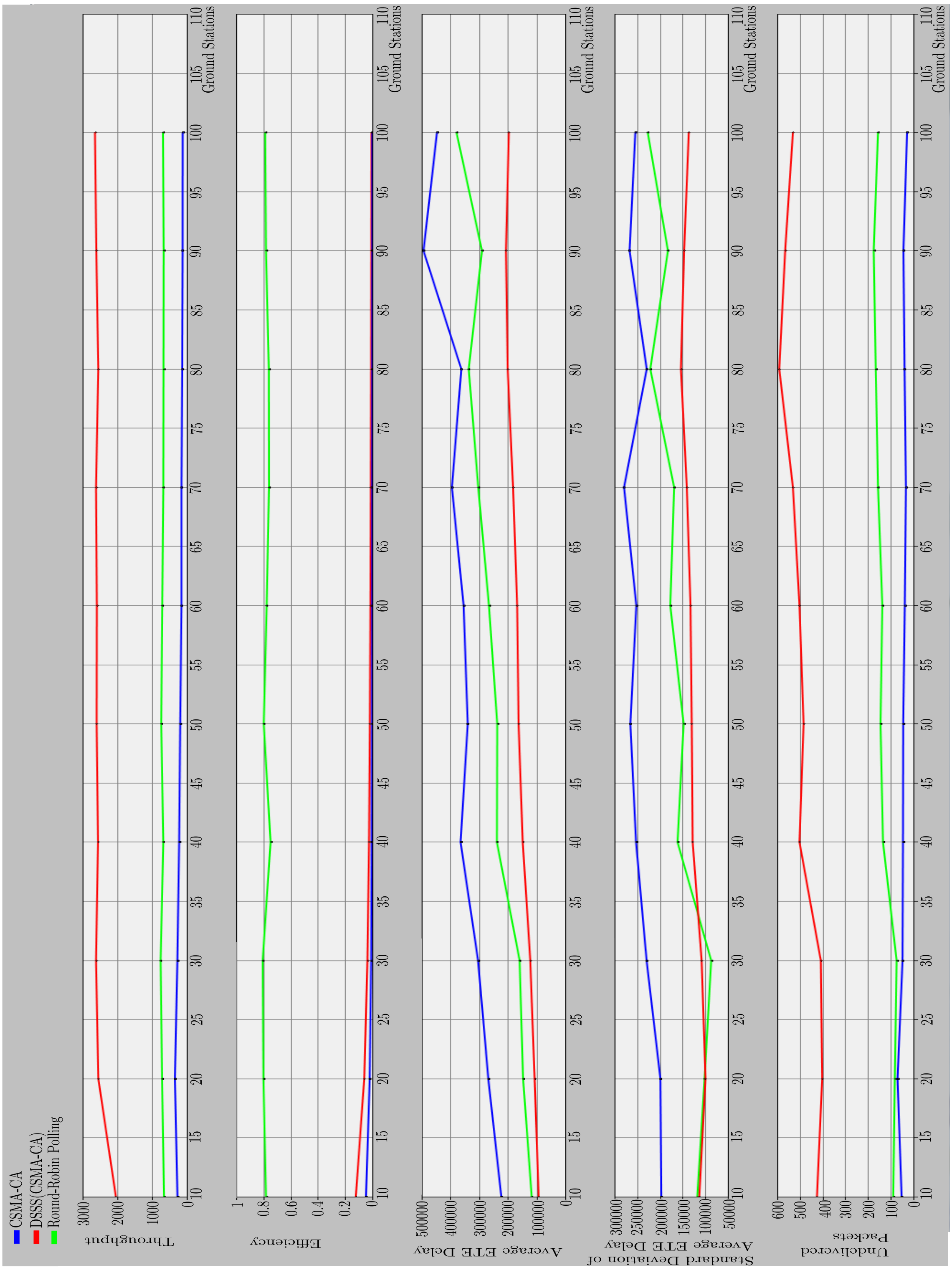


Figure A.18 – Results of CSMA-CA, DSSS(CSMA-CA) and Round-Robin Polling with the system attributes set as follows: Transmission power **10 W**, Modulation scheme **8PSK**, Packet size **1 Mb**, FEC **BCH 10**%

References

[1] SunSpace: Sunspace. November 2012.
Available at: `http://www.sunspace.co.za/home/`

[2] Lathi, P.B.: *Modern Digital and Analog Communication Systems*, vol. Third Edition. Oxford University Press, 1998.

[3] Meel, J.: *Spread Spectrum (SS) Introduction*. De Nayer Instituut, October 1999.

[4] Labuschagne, A.S.: *The Design of a Telemetry System for Grumeti Reserves*. Master's thesis, University of Stellenbosch, 2006.

[5] Castello, S.L..: *Error Control Coding*. Pearson, 1983-2004.

[6] Laboratory, E.S.: Sunsat. September 2003.
Available at: `http://research.ee.sun.ac.za/sunsat/`

[7] Cawood, A.: *Adaption, optimisation and simulation of the CSMA/CA protocol for a low eart orbit satellite UHF link*. Master's thesis, University of Stellenbosch, 2006.

[8] Bruce A. Campbell & Samuel Walter McCandless, J.: *Introduction to space sciences and spacecraft applications*. Gulf Publishing Company, 1996.

[9] Union, I.T.: Radiocommunication sector. November 2012.
Available at: `http://www.itu.int/net/about/itu-r.aspx`

[10] Louis J. Ippolito, J.: *Satellite Communications Systems Engineering*. Wiley, 2008.

[11] Tanenbaum, A.S.: *Computer Networks*, vol. 4. Pearson Education International.

[12] Salehi, J.G.P.M.: *Communications Systems Engineering*, vol. 2. Prentice Hall, 2002.

[13] Michael J. Miller, Branka Vucetic, L.B. (ed.): *Satellite Communications: Mobile and Fixed Services*. Kluwer Academic Publishers, 1993.

[14] Wolhuter, R.: *Advanced Telecoms Lectures 823 , Basic Error Correcting Coding*. The University of Stellenbosch, 2011.

[15] Sae-Young Chung, David Forney, G., Thomas Richardson, J. and Urbanke, R.: On the design of low-density parity-check codes within 0.0045 db of the Shannon limit. *IEEE Communications Letters*, vol. 5, no. 2, February 2001.

[16] MackKay, D.J.: *Information theory, Inference and Learning Algorithms*. Cambridge University Press, 2003.

[17] Leiner, B.M.: Ldpc codes - a brief tutorial. Helsinki University of Technology. April 2005.

[18] Malepati, H.: *Digital Media Processing, DSP Algorithms using C*. Elsevier, 2010.

[19] Matlab - the language of technical computing. October 2011.
Available at: `http://www.mathworks.com/products/matlab/`

[20] Mixim project. October 2011.
Available at: `http://mixim.sourceforge.net/`

[21] Network simulation. October 2011.
Available at: `http://www.opnet.com/solutions/network_rd/modeler.html`

[22] Omnet++. October 2011.
Available at: `http://www.omnetpp.org/`

[23] Banker, D.M.: *Modeling and Simulation of communications systems in Opnet*. Master's thesis, Air Force Institute of Technology, March 2000.

[24] Operation within the bands 902 to 928 MHz, 2400 to 2483.5 MHz, and 5725 to 5850 MHz. October 2011.
Available at: `http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=0f3b707131f3f93802718382fe17ee59&rgn=div8&view=text&node=47:1.0.1.1.16.3.234.31&idno=47`