UNIVERSITY OF WEST BOHEMIA

Faculty of Electrical Engineering
Department of Electronics and Information Technology

BACHELOR'S THESIS

Development of an algorithm for non-coherent ground station and omnidirectional antenna

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2022

ZÁPADOČESKÁ UNIVERZITA V PLZNI
Fakulta elektrotechnická
Akademický rok: 2021/2022

ZADÁNÍ BAKALÁŘSKÉ PRÁCE
(projektu, uměleckého díla, uměleckého výkonu)

Jméno a příjmení:	**Nikzad DEHGHANI**
Osobní číslo:	**E18B0230P**
Studijní program:	**B2612 Electrical engineering and informatics**
Studijní obor:	**Electronics and telecommunications**
Téma práce:	**Diverzitní kombinování signálů ze všesměrových satelitních pozemních stanic**
Zadávající katedra:	**Katedra elektroniky a informačních technologií**

Zásady pro vypracování

1. Describe the issue of omnidirectional satellite ground stations and data reception from small satellites.
2. Use network of the ground stations to simultaneous record of signals transmitted from selected satellite.
3. Prepare an algorithm for time synchronization of records, their demodulation and non-coherent diversity combining.
4. Evaluate processing gain of proposed diversity combining method and compare results with non-diversity single station reception.

Rozsah bakalářské práce:	**30 – 40**
Rozsah grafických prací:	**dle doporučení vedoucího**
Forma zpracování bakalářské práce:	**elektronická**
Jazyk zpracování:	**Angličtina**

Seznam doporučené literatury:

1. J. McGehee, „Multi-site spatially diverse demodulation of HF propagated signals," *MILCOM 2008 – 2008 IEEE Military Communications Conference*, San Diego, CA, USA, 2008, pp. 1-6, doi: 10.1109/MILCOM.2008.4753423.
2. VERTAT, I. Reference ground station – design document. Internal material of ESA project Ground segment as a service.
3. Documentation of SatNOGS ground stations. Available online (www.satnogs.org).

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Datum zadání bakalářské práce:	**8. října 2021**
Termín odevzdání bakalářské práce:	**26. května 2022**

L.S.

Západočeská univerzita v Plzni
Fakulta elektrotechnická

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V Plzni dne 8. října 2021

Abstract

A typical ground station consists of a high directional antenna placed on the antenna rotator. The solution has disadvantages like the high cost of antenna or low-reliability of antenna rotator, and the capability to track only one satellite at a time. It can be replaced by many omnidirectional ground stations with diversity combining to substitute the missing gain of the omnidirectional antenna. This bachelor thesis considers developing an algorithm for non-coherent signal combining from several omnidirectional ground stations due to the lack of antenna gain of these omnidirectional ground stations.

This concept due to the omnidirectional characters of individual ground stations without antenna rotators is capable of concurrently receiving more satellites at a time. If parallel signals from many of these ground stations in the same area are received, it is possible to process them into one stream to get a diversity gain (replacing antenna gain) and minimize the bit error rate for higher data rates.

The signal can be recorded from selected satellites with several SatNogs ground stations equipped with software-defined radio (SDR). However, concluding as to what the solution might be, beneficial, that this concept also can be used for existing online available software-defined receivers and can provide a much more efficient way to download data from many small satellites using low-cost public SDR stations. This thesis it be will, develop and simulate an algorithm for diversity combining in MATLAB and evaluate the performance of noncoherent stream combination. The algorithm will work according to hard decision demodulation and can be improved by switching to soft decision demodulation.

In the case of this thesis, the program will demodulate the symbol as a bit value of 0 or 1 in each stream and combine it into one result, but the soft decision of the demodulation can provide some measure of the probability that is 0 or 1 (e,g. by comparison of amplitudes of signaling frequency for bit value 0 to 1. The higher the value above 0.5, the higher probability that it is a bit value of 1. The lower the value below 0.5, the higher probability that it is a bit value of 0) to another improvement of diversity combinning. Diversity combining then makes a sum of probabilities from any number of the ground stations included and makes a hard decision whether it is 1 or 0.

Usage of diversity combining over many simple ground stations instead of one conventional ground can be a promising solution for the future, because the number of small satellites in space is dramatically increasing and ground station facilities must be increased and enlarged as well.

Keywords

Non-coherent signal combining, omnidirectional ground station, diversity combining, hard decision demodulation, soft decision demodulation.

Contents

List of Symbols and Abbreviations

Symbol	**Description**	**Unit**
C	Speed of light in vacuum	[km/s]
f	frequency	[Hz]
B	Bandwidth	[Hz]
k	Boltzmann‘s constant $(1{,}23 \times 10^{-23})$	[J/K]
T	Temperature	[K]
G	Gain	[dBm]
P	Power	[W]
λ	Wavelength	[mm,nm]
r	Radius	[m,km]
N_0	Noise power spectral	[J/Hz]
D_r	Data rate	[bits/s]
SNR	Signal to noise ratio	[dB]
σ	Standard deviation	[unit less]
t	Time	[s]

1 introduction to the problem

An omnidirectional ground station is capable of sufficiently receiving only a slow data rate due to a lack of antenna gain. Omnidirectional antennas are used to receive the Cube-Sat beacons, but these antennas do not allow higher data rates. However, their low gain can be compensated by the diversity gain of spatially distributed omnidirectional ground stations and by the coding gain of appropriate forward error correction codes. First of all, to make a better understanding of the topic, the research in this chapter is going to focus on :

- What is a ground station
- Ground station typical parts
- Commonly used bands for satellites communication
- Advantages of ground station
- Disadvantage of ground station

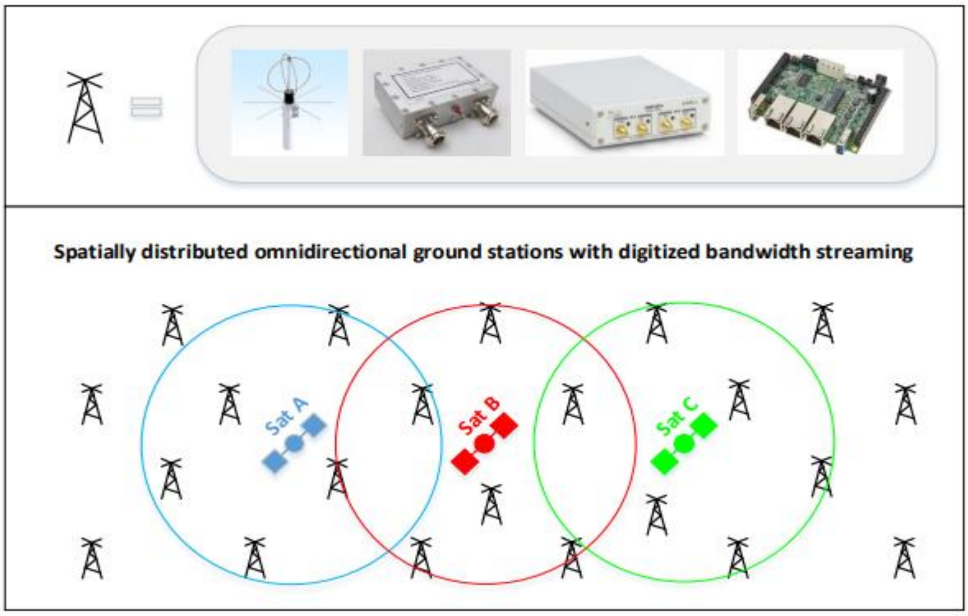

Figure 1:In the figure1 each ground station with the help of the internet will predict Station sites selection Doppler, processing Soft demodulation, Time synchronization Diversity combining, FEC decoding

1.1 The aim of the thesis

This thesis aim is to focus on the principles and the possible ways of writing the algorithm and demodulating signals for the non-coherent ground stations, by combining signals from several omnidirectional ground stations with the help of tools and software and simulations in MATLAB.

- The mathematical background of satellite communication will be illustrated in the thesis.
- Single output channel communication is being simulated with binary FSK (frequency shift keying) modulation. This type of communication is labeled as SISO (single input single output).
- Multiple output channels communication was simulated by the binary FSK and this type of communication is labeled as SIMO (single input and multiple outputs).
- Diversity combining of multiple output channels was simulated for different numbers of the ground station and BER (bit error rate) is calculated.
- Conclusions will be based on the results of the simulation for future realization of noncoherent diversity combining systems for small satellite signal reception.

2 What is a ground station?

A ground station, Earth station, or earth terminal is a terrestrial radio station designed for extraplanetary telecommunication with spacecraft (constituting part of the ground segment of the spacecraft system) or reception of radio waves from astronomical radio sources. Ground stations are located on the surface of the earth.[1]

Earth stations communicate with spacecraft by transmitting and receiving radio waves in the very-high frequency (VHF) or ultra-high frequency (UHF) or (S BAND), (X BAND), (Ku and Ka BANDS). When a ground station successfully transmits radio waves to a spacecraft (or vice versa), it establishes a telecommunication link.[1] In a telecommunications network, in a communication channel, a link connects two or more devices for data transmission.

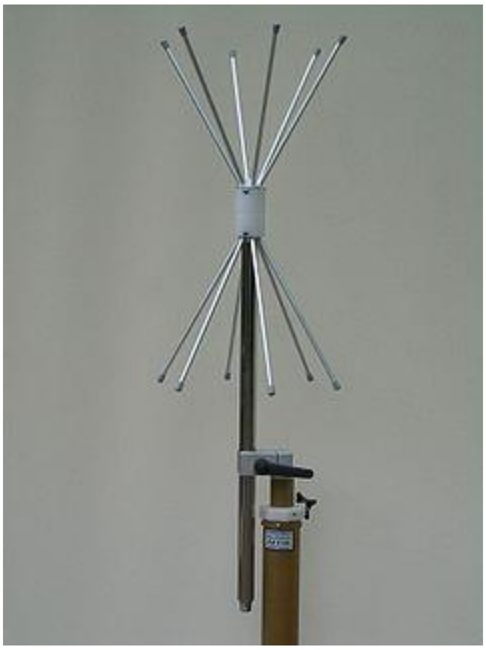

Figure 2: omnidirectional antenna of the ground station[2]

2.1 Ground station typical part

Typical parts which are used in the ground station are:

- High gain directional antennas (which consist of uplink and downlink)
- Antenna rotator (used to change the orientation, within the horizontal and vertical plane of a directional antenna)
- Power amplifier, which amplifies the transmitting signal

- Low noise amplifiers (amplifying the received signal)
- Filters (for separating an information-bearing signal from unwanted contaminations such as interference, noise, and distortion products.)
- Orbit prediction software

microwave transmission toward the satellite, involving a high-power signal is known as **Uplink.**
the corresponding receive direction, involving low-power signals is known as **Downlink.** All satellites are typically mounted on a pedestal. The antenna is an eye-catching, parabolic dish or some different type of highly directional antenna. The dish shape is designed to accurately direct and reflect incoming radio waves.

However, the main purpose of the antenna is to amplify the incoming signal without adding significant noise. The smaller antenna located at the focal point of the parabolic antenna is called the feed horn. The feed horn is used to gather the reflected signals from the dish and is transferred to a low noise block (LNB). The LNB amplifies and frequency converts the signal for further processing. Such as demodulation where the source signal is extracted from the received carrier wave, and eventually is visualized on a computer or television, etc.[3]

Figure 3: Ground station with rotator[4]

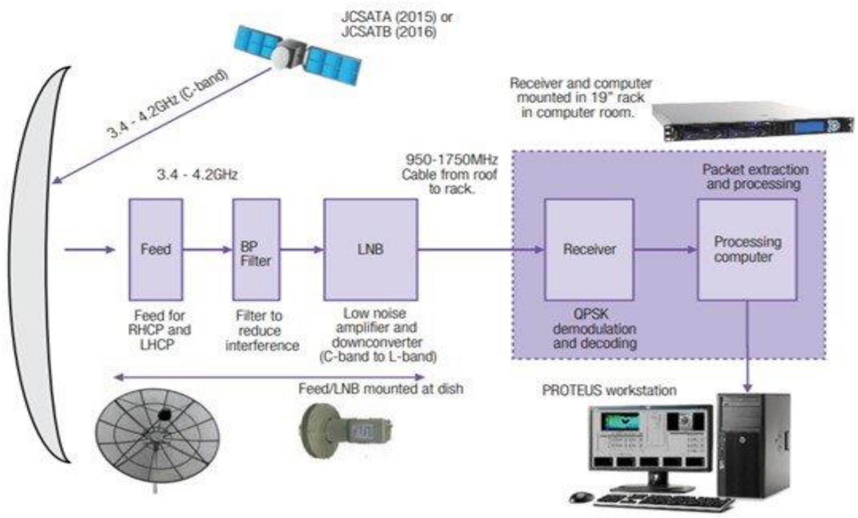

Figure 4:Block diagram of the typical ground station[3]

2.2 Commonly used bands for satellites communication

Variety of satellite frequency bands can be used, and designations have been developed so that they can be referred to easily. The higher frequency bands typically give access to wider bandwidths but are also more susceptible to signal degradation due to ‘rain fade’ (the absorption of radio signals by atmospheric rain, snow, or ice). New technologies are being investigated so that higher bands can be used.[5]

Commonly used bands for satellite communication:

- VHF _ Band (140-150 MHz)
- UHF_Band(400-450MHz)
- L – Band (1-2 GHz)
- S _ Band (2-4 GHz)
- C _ Band (4-8 GHz)
- X _ Band (8-12 GHz)
- Ku _ Band (12-18 GHz)
- Ka _ Band (26-40 GHz)

There is a variety of frequencies that can be used for satellite communication which is shown in figure 5.

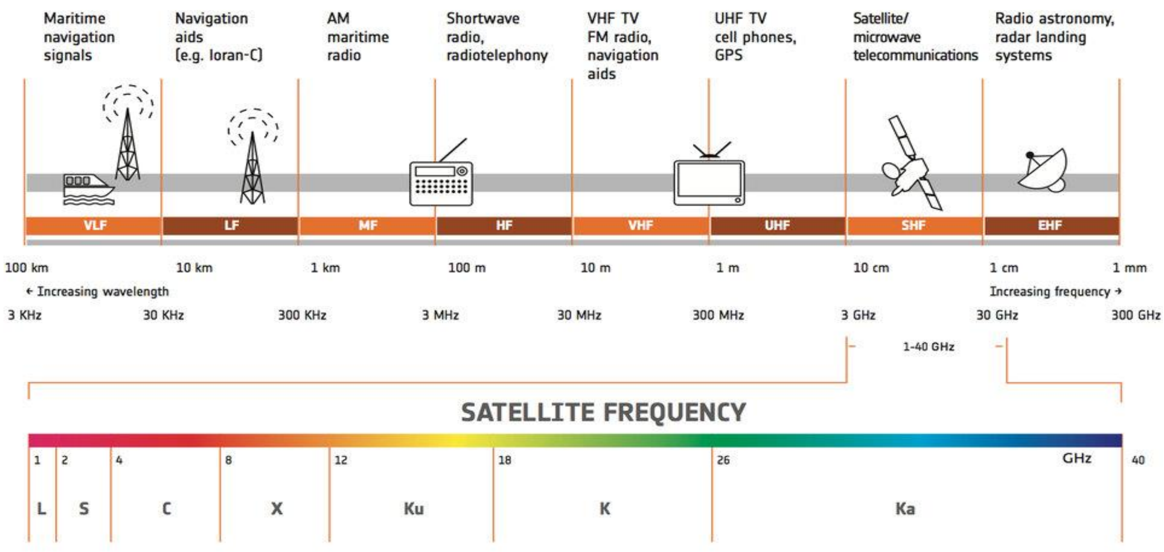

Figure 5: Sattelite communication frequency bands[5]

However small satellites use mainly UHF, sometimes also older band VHF or newer S-band.

2.3 Satellite communication and ground station advantages and disadvantages

There are numerous Advantages of satellite correspondences, where some of them are mentioned below:

- Through satellite transmission, coverage over the geographical area is quite large mainly for sparsely populated areas.
- High bandwidth
- Wireless and mobile communication applications can be easily established by satellite communication independent of location.
- It is used in a wide variety of applications such as global mobile communication, private business networks, long-distance telephone transmission, weather forecasting, radio/TV signal broadcasting, gathering intelligence in the military, navigation of ships and air crafts, connecting remote areas, etc.

- Security in satellite transmission is usually provided by the coding and decoding equipment.
- Ground station sites are easy to install and maintain.
- communication, is not restricted to LOS(line of sight)[picture]

Satellite correspondence has the accompanying disadvantages:

- High price of an antenna rotator
- High price of large high gain directional antennas
- Risk of antenna and rotator damage due to weather conditions like strong wind and risk of a functional outage if only one ground station is providing radio link with spacecraft the, capability of tracking only one satellite at a time, while the number of small satellites in space is rapidly increasing
- Design, development, investment, launch, and insurance of satellite requires higher costs.
- To reach the satellite from Earth, time can vary from several milliseconds for LEO (lower earth orbit) up to 320 milliseconds for GEO (geostationary earth orbit). This propagation delay can cause difficulties in real-time communication.
- Satellites are not easy to repair and maintain.
- Some circumstances like weather or sunspots affect the satellite‘s signal and can cause interference and make the proper operation of the satellite very difficult.
- It is required to be monitored and controlled on regular periods so that it remains in the orbit, once it has been launched.

3 SDR (Software processing of received signals)

Current ground stations use so-called SDR (software-defined radio) for the processing of the received signal. The software provides the ability to analyze and tune the receiver with different variations of frequencies, frequency bands, data rate, and baud rate and change in the signal-to-noise ratio (SNR) concerning the required instructions. SDR stands for Software Defined Radio and is a technology for radio communication. This technology is based on software-defined wireless protocols, as opposed to hardware-based solutions. This translates to supporting various features and functionalities, such as updating and upgrading through reprogramming, without the need to replace the hardware on which they are implemented. This hardware includes mixers, filters, amplifiers, modulators, demodulators, etc. This opens the door to the possibility of realizing multi-band and multi-functional wireless devices. SDRs play a vital role in wireless standard development due to their flexibility and ease of programmability. This is because most digital signal processing and digital front end, which includes channel selection, modulation, and demodulation, take place in the digital domain.[6]

Therefore, SDR only uses a simple RF tuner to down and up convert the signal and an ADC or DAC to do Analog to Digital and Digital to Analog signal conversion along with antennas, without needing many hardware components (see figure 6 for the structure of SDR) the rest of signal processing is done by software in computer or digital sisignalrocessors. This, in turn, makes SDR much more flexible and makes it easy to fix issues if a problem arises since most of the processing is done on the software rather than on the hardware.[7]

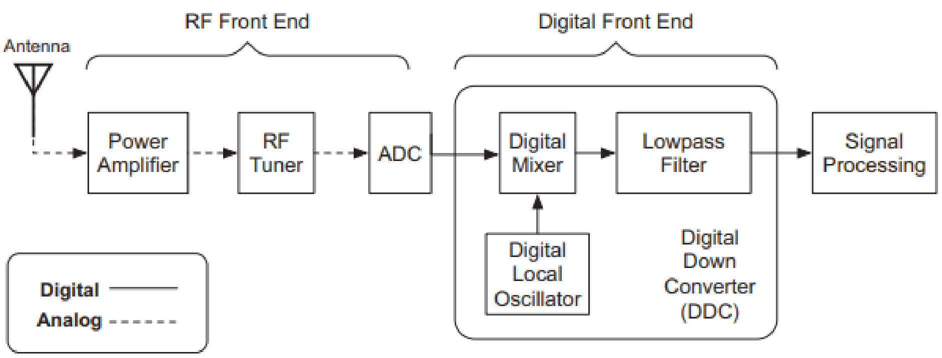

Figure 6: Block diagram of SDR receiver[6]

Some of this software are listed below:

- OpenWeb RX (web biased on SDR receiver)
- Web SDR
- AirSpy network
- Satnogs

(see figure 7).

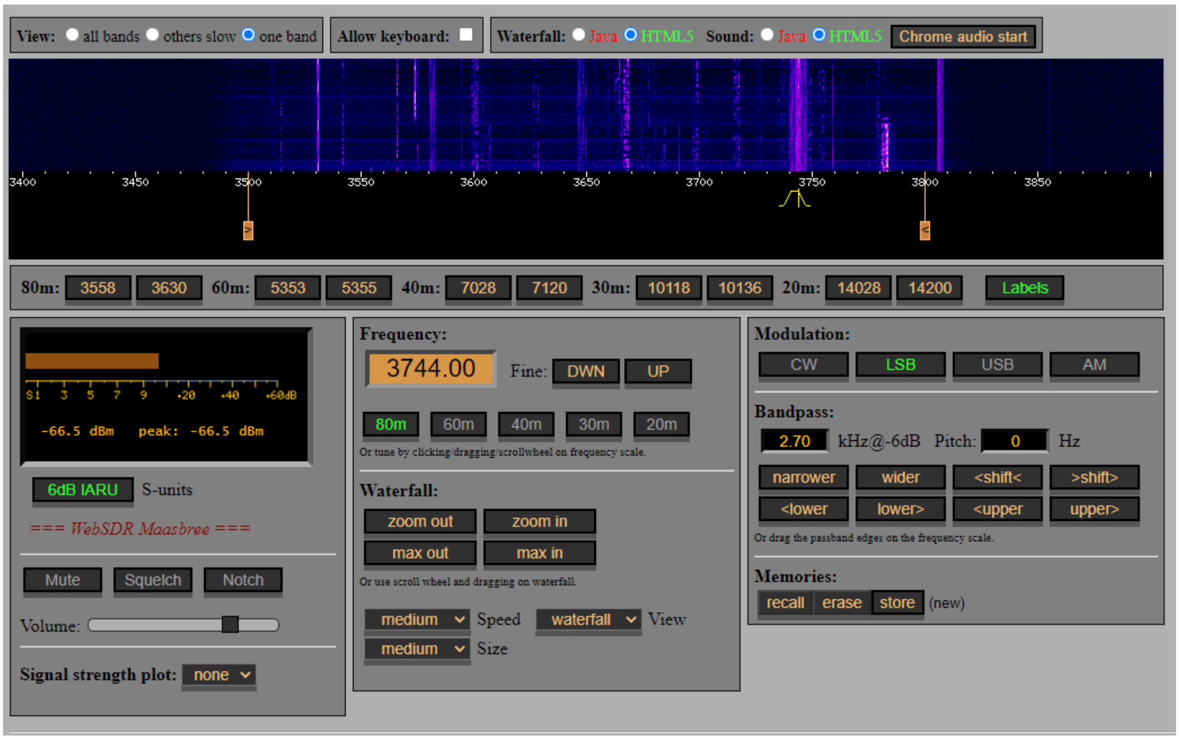

Figure 7: web SDR software configuration[8]

4 The idea of diversity combining

In current wireless communication systems, diversity combining is considered an important tool to enhance wireless link performance by alleviating the effects of radio channels' fading process.[10]

Diversity combining techniques are based on the redundancy of transmitted information. Destinations combine multiple copies of the same information signal received over different points of a domain such as time, frequency, and space. While time and frequency diversity can be achieved in single-antenna transmission systems, space diversity needs the use of multiple antennas that are spaced sufficiently far apart to obtain a diversity gain.[11]

On the receiver side, the used diversity combining technique plays an important role in the system performance. Three common diversity combining techniques are the selection combining (SC), the equal gain combining (EGC), and the maximal ratio combining (MRC). There is a trade-off between the performance and the complexity based on the selected diversity combining technique. These techniques are mainly used to increase the signal-to-noise ratio (SNR) of the received signal.[12]

In figure 7 the basic principle of diversity combining is shown.

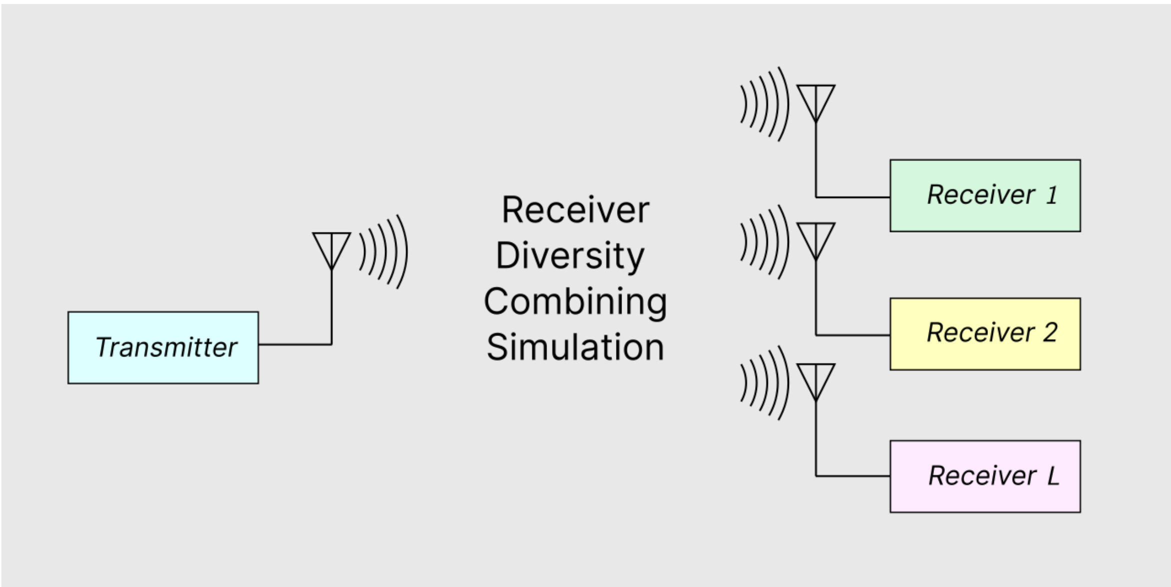

Figure 8: diversity combining[9]

5 Radio link budget

Link budgeting is an established method of analyzing performance in wireless and satellite communications. Link budgets are a design tool to predict signal-to-noise ratio (SNR) at a receiver given system parameters such as transmit power and antenna gain, and channel parameters such as propagation loss and interference. This predicted SNR is compared to a minimum required SNR to obtain a link margin. Equation 1 and Figure 8 represent a simplified link budget for wireless communications.[13]

$$P_R = P_T + G_T + G_R - L_{FS} - L_N \quad (1)$$

- P_R : received power (dBm)
- P_T : transmitter output power (dBm)
- G_T: transmitting antenna gain (dBi)
- G_R: receiver antenna gain (dBi)
- L_{FS}: free space loss or path loss (dB)
- L_N: miscellaneous signal propagation losses (these include fading margin, polarization mismatch, losses associated with the medium through which signal is traveling, other losses...) (noise factor) (dB)

Free space loss subscription L_{FS} can be determined by formula 2:

$$L_{FS} = 20\log(D) + 20\log(f) + 20\log\left(\frac{4\pi}{C}\right) \quad (2)$$

- D: maximum distance
- F: frequency
- C: speed of light in vacuum

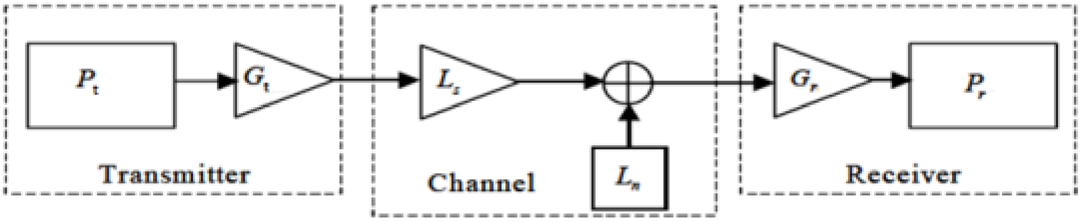

Figure 9: Block diagram representation of the link budget expressed in Equation 1 [13]

5.1 Radio link budget basics

The radio link budget is a summary of all the gains and losses in a transmission system. The radio link budget sums the transmitted power along with the gains and losses to determine the signal strength arriving at the receiver input which is described in figure 10. [14]

A good link budget is essential for a functioning link. Estimation of losses/gains in a radio link requires: [14]

- Suitable design
- Adequate choice of equipment

Every radio link contains some elements to be functional, which are: [14]

- Transmitting side (contains transmitting power, cable loss, antenna gain)
- Propagation side (FS(P)L, Fresnel zone)
- Receiving side (Antenna gain, cable loss, receiver sensibility)

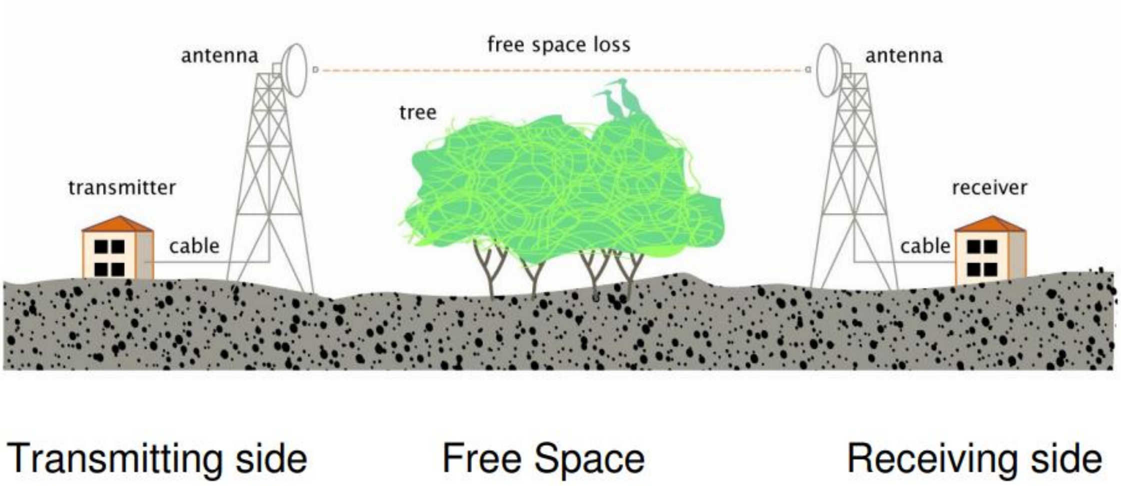

Figure 10: diagram of Radio link budget [14]

Once the link budget has been calculated (equation 1), then it is possible to compare the calculated received level with the parameters for the receiver, to discover whether it will be possible to meet the overall system performance requirements of signal-to-noise ratio, bit error rate, etc.

5.2 Signal to noise ratio (SNR)

Signal-to-noise ratio (often abbreviated as SNR or S/N) is a measure used in science and engineering that compares the level of the desired signal to the level of background noise. The signal-to-noise ratio, the bandwidth, and the channel capacity of a communication channel are connected by the Shannon–Hartley theorem. Signal-to-nose ratio is sometimes used informally to refer to the ratio of useful information to false or irrelevant data in a conversation or exchange.[15]

The Signal-to-noise ratio is defined as the ratio of the power of a signal (meaningful input) to the power of background noise (meaningless or unwanted input): [16]

$$SNR = \frac{P_{signal}}{P_{noise}} \quad (3)$$

where *P* is average power. Both signal and noise power must be measured at the same or equivalent points in a system and within the same system bandwidth. [16]

Because many signals have a very wide dynamic range, signals are often expressed using the logarithmic decibels scale. Based upon the definition of decibel, signal and noise may be expressed in decibels (dB). [16]

$$P_{signal} = 10log_{10}(P_{signal}) \quad (4)$$

And

$$P_{noise} = 10log_{10}(P_{noise}) \quad (5)$$

In a similar manner, SNR may be expressed in decibels as:[16]

$$SNR_{dB} = \frac{P_{signal}}{P_{noise}} = 10log_{10}(\frac{P_{signal}}{P_{noise}}) \quad (6)$$

Using the quotient rule for logarithms: [16]

$$SNR_{dB} = 10log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) = 10log_{10}\left(P_{signal}\right) - 10log_{10}(P_{noise}) \quad (7)$$

In formula 7, P is measured in units of power, such as watts (W) or milliwatts (mW), and a signal-to-noise ratio is a pure number. [16]

The signal and the noise must be measured the same way, for example as voltages across the same impedance. The root mean square can alternatively be used in the ratio: [16]

$$SNR_{dB} = 10log_{10}\left[(\frac{A_{signal}}{A_{noise}})^2\right] = 20log_{10}\left(\frac{A_{signal}}{A_{noise}}\right) = 2\left(A_{siganl,dB} - A_{noise,dB}\right) \ (8)$$

Also SNR can be determined by:

$$SNR = P_R[dBm] - P_N[dBm] \ (9)$$

- P_R = received power of the signal
- P_N = received power of noise

5.3 SNR to E_b/N_0

E_b/N_0 is defined as the normalized signal to noise ratio, or signal to noise per bit. E_b/N_0 is particularly useful when comparing the Bit error rate (BER) performance of different modulation schemes. E_b/N_0 is equal to the SNR divided by the "gross" link spectral efficiency in (bps/Hz), where the bits in this context are transmitted data bits, inclusive of error correction information and other protocol overhead. [17]

$$\frac{S}{N} = \frac{E_b f_b}{N_0 B} \quad (10)$$

- B = channel bandwidth
- f_b = channel data rate

E_b/N_0 in the form of dB: [17]

$$\frac{S}{N}[dB] = \frac{E_b}{N_0}[dB] + 10log_{10}\left(\frac{DR}{B_N}\right) \quad (11)$$

- N_0 = noise power specral density
- $DR = Data\ rate$
- $B_N = noise\ bandwidth$

The relation between bit energy Eb/No and symbol energy Es/No is reasonably straight-forward. For M-PSK/M-QAM modulation, the number of bits in each constellation symbol is:[18]

$$\frac{E_s}{N_0} = \frac{E_b}{N_0}log_2 M \quad (12)$$

- M = number of alternative modulation symbols
- E_s = energy per symbol (one symbol may represent multiple bits).

Plugging in the formula 12, the symbol error rate vs bit energy (SNR per bit, Eb/No) is given which is shown in figure 11. [18]

$$P_S, BPSK = \frac{1}{2}erf_c\left(\sqrt{\frac{E_s}{N_0}}\right) \quad (13)$$

$$P_S, 4PAM = \frac{3}{4}erf_c\left(\sqrt{\frac{2E_b}{5N_0}}\right) \quad (14)$$

$$P_S, 4QAM = \frac{1}{2}erf_c\left(\sqrt{\frac{E_b}{N_0}}\right) \quad (15)$$

$$P_S, 16QAM = \frac{3}{2}erf_c\left(\sqrt{\frac{4E_b}{10N_0}}\right) \quad (16)$$

$$P_S, 16PSK = erf_c\left[\sqrt{\frac{4E_b}{N_0}}\sin\left(\frac{\pi}{16}\right)\right] \quad (17)$$

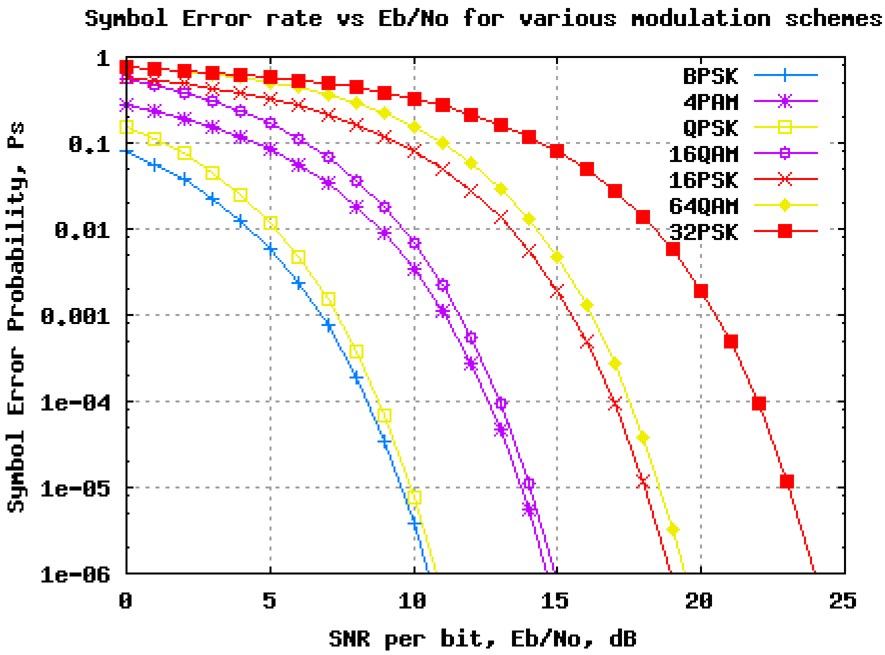

Figure 11: BER vs to E_b/N_0(dB) [18]

5.4 Noise power calculation

The major source of electrical noise in equipment arises from the random thermal motion of electrons in various resistive and active devices in the receiver. Thermal noise is also generated in lossy components of antennas, and thermal-like noise is picked up by the antennas as radiation. [19]

The available noise power from a thermal noise source is: [19]

$$P_N = kT_S B \ \ (J) \ (18)$$

Where:

- T_S : equivalent noise temperature in kelvin
- B : bandwidth (Hz)
- k : Boltzmann's constant $(1.23 \times 10^{-23}$ J/K)

The noise power per unit bandwidth is known as noise power spectral density,N_0.

Which is described below: [19]

$$N_0 = \frac{P_N}{B} = kT_S \text{ (J/Hz) } (19)$$

And the density is constant for all radio frequencies up to 300 GHz, and to maintain this possible carrier noise ratio the quality of communication needs the noise at the receiver must be reduced. [19]

5.4.1 Noise temperature and noise figure

Noise temperature provides a way of determining the thermal noise of the device in the receiver. The noise temperature is directly related to the physical temperature of the noise source but not equal to it. The noise temperature of various sources which are connected together in a cascade can be added directly to give the total noise.

The temperature at which a resistor at the component or system input would generate the same amount of noise measured at the output is called noise temperature. It goes back to the familiar kTB calculation for thermal noise power. Noise temperature is often used in calculating the overall noise figure of a system that includes an antenna at the input. [21] Noise temperature can be calculated from the formula 20:

$$Noise\ temperature\ in\ (K) = T_{REF} \times \left(10^{\frac{NF_{dB}}{10}} - 1\right)\ (20)$$

A noise figure is frequently used to specify the noise generated within the device. The noi-se figure is defined below:

$$NF = \frac{(\frac{Singal}{Noise})input}{(\frac{Signal}{Noise})output}\ \ (21)$$

Noise figure in dB:

$$Noise\ figure\ in\ (dB) = 10 \times log10\left(\frac{T_{noise}(K)}{T_{REF}(K)} + 1\right)\ (22)$$

The relationship between noise temperature and noise figure is (see figure12):

$$T_d = T_{REF} \times (NF - 1)\ (23)$$

Where T_{REF} is the reference temperature used to calculate the standard noise figure usually 290K.

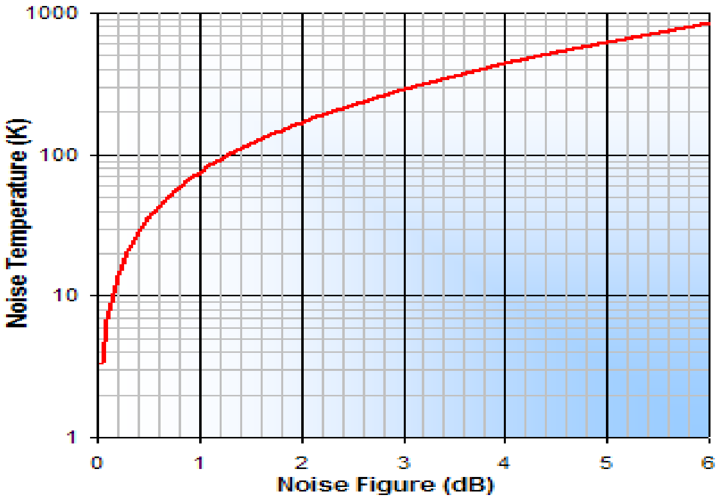

Figure 12:change of noise figure according to noise temperature [21]

The table of changes in the noise figure with respect to noise temperature is shown in table 1:

Table 1: calculation of NF (dB) with respect to noise temperature(K) [21]

NF(dB)	T_N (°K)	NF(dB)	T_N (°K)
0.1	7	2.1	180
0.2	14	2.2	191
0.3	21	2.3	202
0.4	28	2.4	214
0.5	35	2.5	226
0.6	43	2.6	238
0.7	51	2.7	250
0.8	59	2.8	263
0.9	67	2.9	275
1.0	75	3.0	289
1.1	84	3.1	302
1.2	92	3.2	316
1.3	101	3.3	330
1.4	110	3.4	344
1.5	120	3.5	359
1.6	129	3.6	374
1.7	139	3.7	390
1.8	149	3.8	406
1.9	159	3.9	422
2.0	170	4.0	438

5.4.2 Carrier to noise ratio

Carrier to noise ratio, also known as CNR and C/N is a signal-to-noise ratio of a modulated signal. In simple terms, it is a measure of the received carrier strength in relation to the strength of the noise received. [22]

In the receiver before demodulation, an RF amplifier and IF amplifier exists, if the overall gain of the receiver is G in (dBm), then noise power at the demodulation input is: [19]

$$P_N = kT_N BG \quad (24)$$

And if P_R is the signal power at the input to the receiver then signal power at the demodulation input is: [19]

$$C = P_R G \quad (25)$$

Hence carrier to noise ratio can be written as (for satellite channel link): [19]

$$\frac{C}{P_N} = \frac{P_R G}{kT_S BG} = \frac{P_R}{kT_s B} \quad (26)$$

Another way to define the carrier to noise ratio is: [19]

$$\frac{C}{N} = \frac{P_T G_T G_R (\lambda)^2}{kT_S B(4\pi R)^2} \quad (27)$$

Carrier to noise ratio in dB: [19]

$$\left[\frac{C}{N}\right] dB = 10\log\,(P_T G_T) - 20\log\left(\frac{4\pi r}{\lambda}\right) + 10\log\left(\frac{G_R}{T_S}\right) - 10\log\,(k) - 10\log(B) \quad (28)$$

For calculating carier to noise power specral density ($\frac{C}{N_0}$): [19]

$$\frac{C}{N_0} = \frac{P_T G_T G_R (\lambda)^2}{kT_S (4\pi r)^2} \quad (29)$$

Carier to noise power specral density ($\frac{C}{N_0}$) in dB:

$$\left[\frac{C}{N_0}\right] dB = 10\log(P_T G_T) - 20\log\left(\frac{4\pi r}{\lambda}\right) + 10\log\left(\frac{G_R}{T_S}\right) - 10\log(k)\ (30)$$

Carrier to noise ratio can be illustrated as an estimation of bit error rate (BER). In the design of telecommunication links the bit error rate (BER) is an important parameter that has to be estimated. For AWGN (additive wide Gaussian noise) channel there are well-known dependencies between bit error rate (BER) and energy per bit per spectra noise density (E_b/N_0). The relation between C/N_0 and E_b/N_0 is given by the equation 31:

$$\frac{E_b}{N_0} = \frac{C}{N_0 \times data\ rate}\ (31)$$

The relation between C/N_0 and E_b/N_0 is given by the equation 32 in dB:

$$\frac{E_b}{N_0}[dB] = \frac{C}{N_0}[dB] - 10log(Data\ rate)\ (32)$$

5.4.3 G/T ratio (gain/temperature)

G/T (dB/K) ratio is a figure merit that is widely used to specify the quality of an earth station, since we know the C/N ratio, in a satellite (the values of λ,R,B are specified) then it can be verified that C/N ratio is proportional to G_R/T_S. [19]

A professional earth station is required to have a G/T ratio of 40.7 dB/K at 4 GHz and 5-degree elevation angle and it is always required to specify the frequency and elevation angle because G_R varies as f^2 across the frequency band and T_S (system noise temperature) also depends on sky temperature. [19]

G/T defines the quality of the earth station.

5.4.4 System noise temperature (T_S)

The receiver system performance is determined by system noise temperature, T_S , which is also known as the effective input noise temperature of the receiver which is defined as the noise temperature of a noise source located at the input of a noiseless receiver, which would produce the same contribution to receiver output noise as internal noise of actual system itself. As an example: [20]

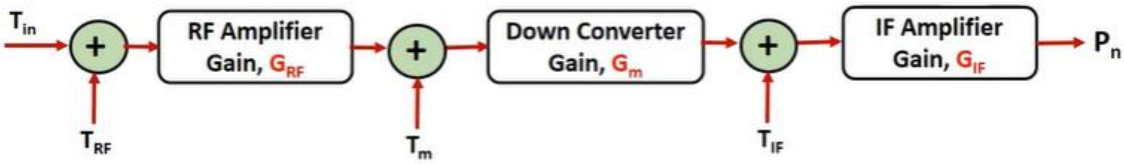

Figure 13:Equivalent receiver where each device is replaced by a single noise source [20]

- T_{in} = input noise temperature at the RF section
- T_{RF} = noise temperature for RF amplifier gain G_{RF}
- T_m =noise temperature for down converter gain G_m
- T_{IF} = noise temperature for IF amplifier gain G_{IF}
- P_n = total noise power

The expression for the total noise power at the IF output amplifier is the sum of all noise stages. Total noise power at the output of the IF amplifier is:

$$P_n = G_{IF}kT_{IF}B + G_{IF}G_mkT_mB + G_{RF}G_mG_{IF}kB(T_{in} + T_{RF})$$

This can be simplified to:

$$P_n = G_{IF}G_mG_{RF}kB[T_{RF} + T_{in} + \frac{T_m}{G_{RF}} + \frac{T_{IF}}{G_m + G_{RF}}]$$

With system noise temperature T_s, the noise power P_n at the output of the IF amplifier is:

$$P_n = G_{IF}G_mG_{RF}kBT_s$$

From the two equations above, equation 33 can be concluded:

$$T_s = \left[T_{RF} + T_{in} + \frac{T_m}{G_{RF}} + \frac{T_{IF}}{G_m + G_{RF}}\right] \quad (33)$$

from equation 33 it is concluded that the most important part of the ground station is the high-quality low noise amplifier with high gain and low noise figure to minimize the noise effect on the received signal. [20]

6 Bit error rate (BER)

A practical consideration that has so far received little attention is the correcting power of the coding required to do the job. In other words, if there is a need for a certain improvement in channel performance, how many bits must we be able to correct? [23]

The quality of a channel is often defined in terms of its bit error rate, or BER. This is a measure of how likely a bit is to be in error. [23]

6.1 The Gaussian Normal Function

While burst errors are unpredictable, random errors tend to occur as a result of predictable noise processes. For modeling purposes, noise in a communications channel is often assumed to be white, which simply means that, over the bandwidth of the channel, it has constant power at all frequencies. In other words, if we were to look at the noise on a spectrum analyzer over a suitable period of time, it would appear to be a flat line called the noise floor. The distribution of the noise is assumed to be Gaussian (or normal) which we've already seen and it adds to the signal in the channel (see figure 14). Taken together, this kind of interference is called AWGN or additive white Gaussian noise. The distribution of a signal can be found by creating a histogram of its magnitude over a suitable period of time. [23]

In the figure below is the normalized Gaussian distribution, centered about O. In this example, the x-axis is measured in standard deviations (**σ**) while the y-axis is in percent.

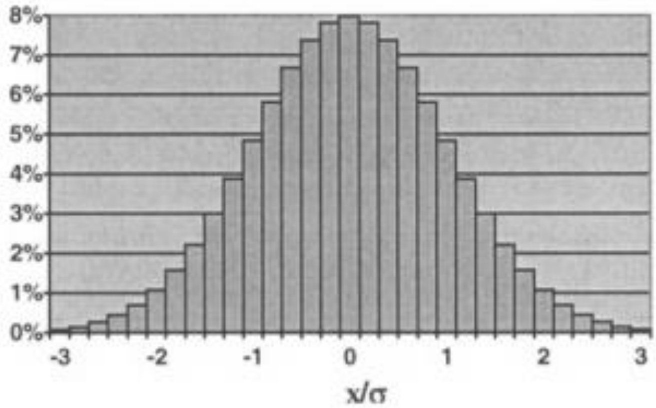

Figure 14: Gaussian (normal) distribution. [23]

The bars in the histogram have a width of one-fifth of **σ**. The equation for this curve is:

$$\frac{1}{\sigma\sqrt{2\pi}} \mathrm{e}^{\left(\frac{x^2}{2\sigma^2}\right)} \quad (34)$$

which has a unity area from -∞ to +∞. Suppose this plot was created by measuring the voltage of all the zeros at the receiver in a communications link. Adding up the area between ±1 comes to about 68%. This simply means that 68% of all zeros received will be within 10 of the correct **σ** position. Extending this idea, it's possible to see how likely a bit is to be received in error. [23]

6.2 Estimating the bit error rate (BER)

In Figure 10, two distributions are given, one centered on the origin and the other, on **x/σ = 3**. This means that the signal level for a one (whether volts or modulation space) is three times the standard deviation of the added noise. [23]

Clearly, it can be seen that there is a finite probability that a transmitted a zero will be interpreted as a one, and a transmitted one, as a zero. If the decision threshold is set at **x/σ = 1.5,** halfway between the centers of the two histograms, then the probability that zero is interpreted as a one will be the area under the zero histogram above the threshold point t (between **1.5** < **x/σ** < ∞) (see figure15). Because, in this case, the two distributions are the same, the probability that a one will be interpreted as zero is the same, ie., about $6^{1}/_{2}$%, For this channel, the BER is going to be about 0.066. [23]

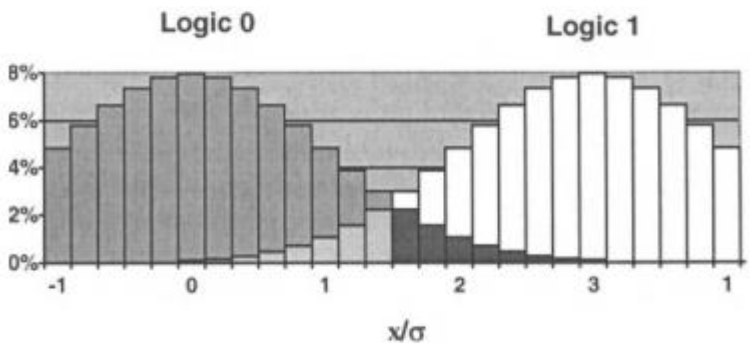

Figure 15: Error probability from two distributions [23]

Given $\left({P_{signal}}/{P_{noise}}\right)$ and an AWGN channel, it's possible to predict, near enough, what the BER will be. Given a typical modulation scheme, the BER can be estimated from:

$$BER = \frac{1}{2} e^{\left({-P_{signal}}/{2P_{noise}}\right)} \quad (35)$$

Equation 36 is for particular modulation, Where $\left({P_{signal}}/{P_{noise}}\right)$ is in dB. Coding gain is a term used to describe what the BER of a channel becomes after error control. [23]

7 Signals modulation

Modulation is the process of converting data into radio waves by adding information to an electronic or optical carrier signal. A carrier signal is one with a steady waveform with constant height, amplitude, and frequency. [24]

7.1 ASK and FSK and PSK modulation

There are three basic ways to modulate a sine wave radio carrier: modifying the amplitude, frequency, or phase. More sophisticated methods combine two or more of these variations to improve spectral efficiency. These basic modulation forms are still used today with digital signals. [25]

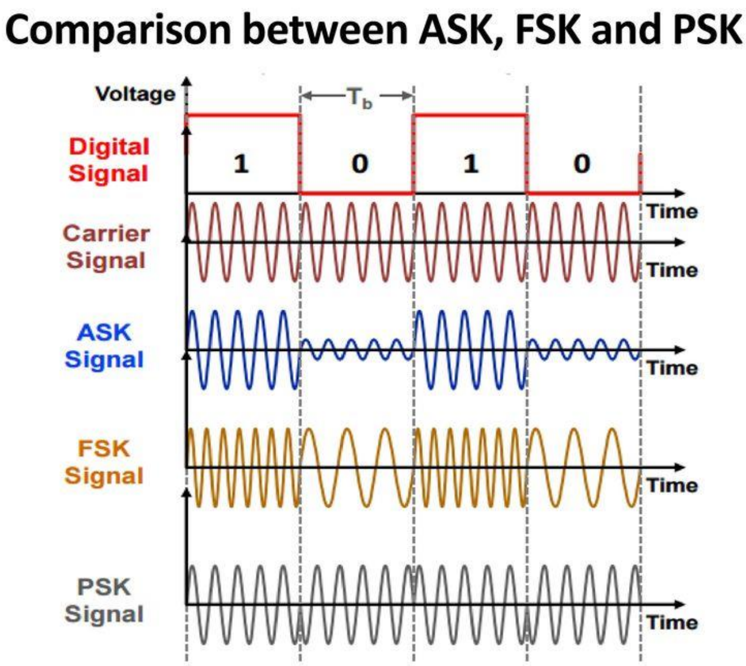

Figure 16: Three basic digital modulation formats are still very popular with low-data-rate short-range wireless applications: amplitude shift keying (ASK), and frequency shift keying (FSK), and phase shift keying (PSK). These waveforms are coherent as the binary state change occurs at carrier zero-crossing points. [26]

Figure 16 shows a basic serial digital signal of binary zeros and ones to be transmitted and the corresponding ASK and FSK and PSK signals resulting from modulation. There are two types of ASK signals. [25]

ASK produces sidebands above and below the carrier equal to the highest frequency content of the modulating signal. The bandwidth required is two times the highest frequency content including any harmonics for binary pulse modulating signals. [25]

Frequency shift keying (FSK) shifts the carrier between two different frequencies called the mark and space frequencies, or f_m and f_s *(Fig. 16)*. FM produces multiple sideband frequencies above and below the carrier frequency. The bandwidth produced is a function of the highest modulating frequency including harmonics and the modulation index. [25]

Which is:

$$m = \Delta f(t) \quad (36)$$

- Δf is the frequency deviation or shift between mark and space frequencies
- t, is the bit time interval of the data or the reciprocal of the data rate (1 bit per second)

Smaller values of m produce fewer sidebands. A popular version of FSK called minimum shift keying (MSK) specifies m = 0.5. Smaller values are also used such as m = 0.3. [25]

7.2 BPSK modulation (Binary Phase Shift Keying)

Binary phase-shift keying (BPSK), also known as binary-phase modulation, is a simple, popular digital modulation scheme. The symbol constellations are as far apart as possible, which is desirable for weak signal work. BPSK is also popular for its relatively simple spectrum-spreading capability. Thus BPSK finds application in weak signal communications, spread-spectrum, ranging and radar systems. [25]

Binary phase shift keying (BPSK), shifts the carrier sine wave 180° for each change in the binary state. BPSK is coherent as the phase transitions occur at the zero-crossing points. The proper demodulation of BPSK requires the signal to be compared to a sine carrier of the same phase. This involves carrier recovery and other complex circuitry. [25]

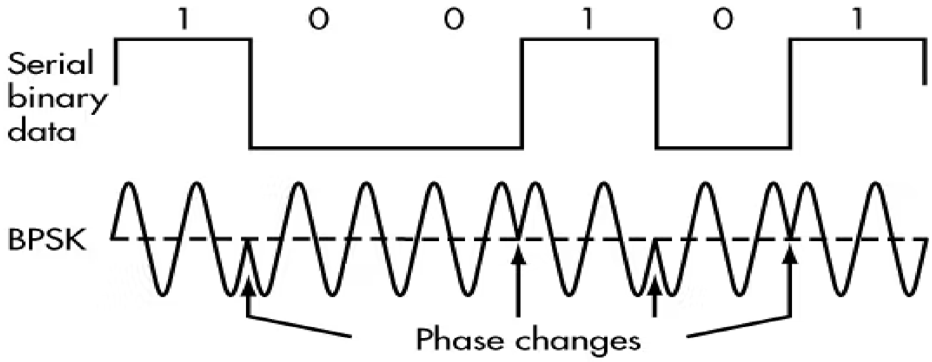

Figure 17: In binary phase shift keying[25]

Note a binary 0 is 0° while a binary 1 is 180°. The phase changes when the binary state switches so the signal is coherent. BPSK is very spectrally efficient in that you can transmit at a data rate equal to the bandwidth or 1 bit/Hz. (see figure 17)

7.3 Quadrature Phase Shift Keying (QPSK)

In a popular variation of BPSK, quadrature PSK (QPSK), the modulator produces two sine carriers 90° apart. The binary data modulates each phase, producing four unique sine signals shifted by 45° from one another. The two phases are added together to produce the final signal. Each unique pair of bits generates a carrier with a different phase. [25]
Look at the table 2:

Tabel 2: Carrier phase shift for each pair of bits presented[25]

Bit pairs	Phase (degrees)
0 0	45
0 1	135
1 1	225
1 0	315

Figure 18 illustrates QPSK with a phasor diagram where the phasor represents the carrier sine amplitude peak and its position indicates the phase. A constellation diagram in Figure 18 shows the same information. QPSK is very spectrally efficient since each carrier phase represents two bits of data. The spectral efficiency is 2 bits/Hz, meaning twice the data rate can be achieved in the same bandwidth as BPSK. [25]

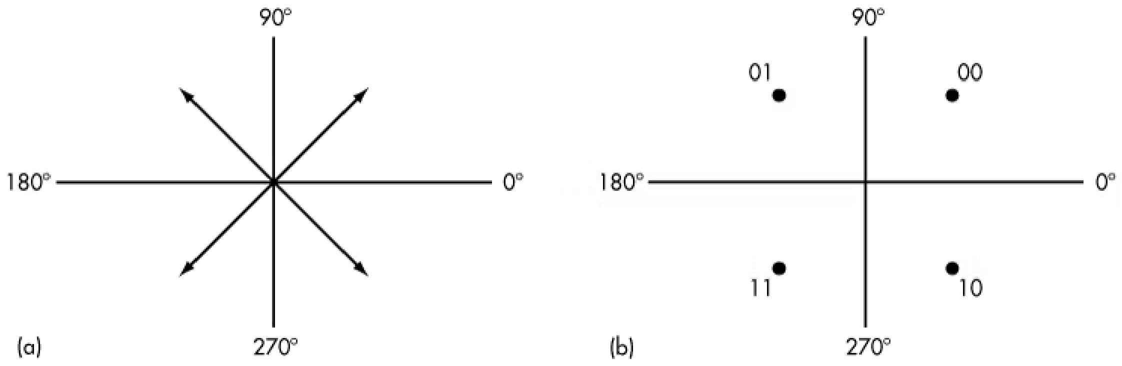

Figure 18: Modulation can be represented without time domain waveforms. For example, QPSK can be represented with a phasor diagram (a) or a constellation diagram (b), both of which indicate phase and amplitude magnitudes. [25]

8 Example of small satellite link budget

There is a satellite at 500 km altitude with 1 W RF power is equal to 30 dBi, which includes an omnidirectional antenna with a gain of 0 dB and frequency of 437 MHz, and a data rate of 19200 bit/s. On the ground station, there is an omnidirectional antenna with a gain of 0 dB, with low noise amplifier (LNA) gain of 30 dB and LNA noise of 1 dB, cable losses of 2 dB, and receiver noise of 5 dB. The estimate noise temperature of urban area for 430-440 MHz is 2000-3000 K (ITU recommendation). Calculate the power received at the radio link budget. (see figure 19 and 20)

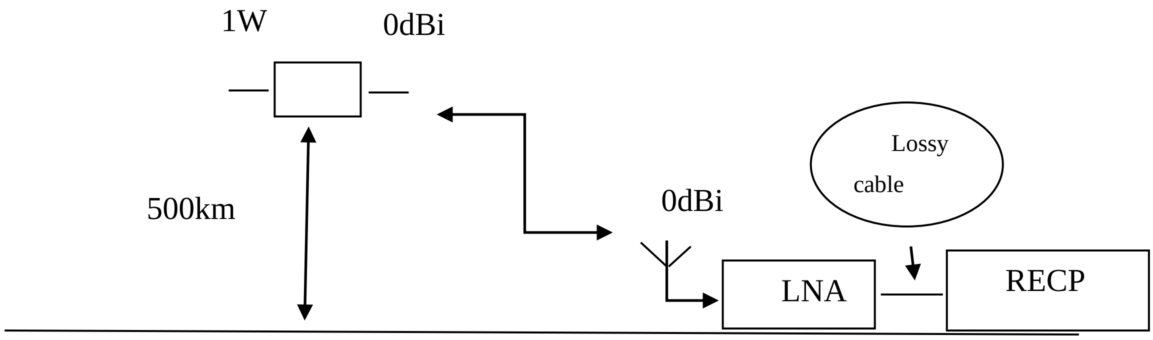

Figure 19

Solution:

According to formula 1, because the free space losses are dependent on the distance and frequency then we have to calculate the maximum distance of the satellite and the maximum distance is when the satellite is visible at zero elevation relative to the earth‘s surface, look at fig below:

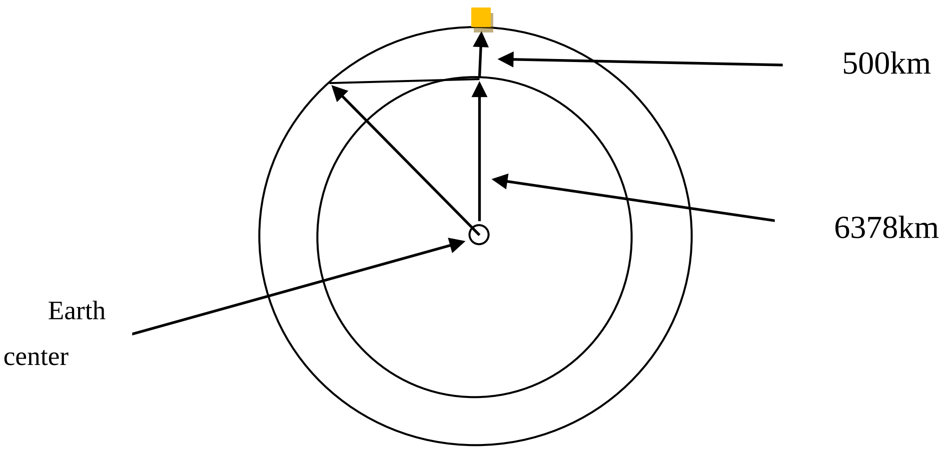

Figure 20: maximum distance of a satellite from Earth‘s center

The maximum distance can be determined by Pythagoras‘ formula so:

$$(6378 + 500)^2 = D^2 + 6378^2$$

So D is:

$$D = \sqrt{(6378 + 500)^2 - 6378^2} = 2574km$$

Now buy substituting the D in the formula 2, L_{FS} is:

$$L_{FS} = 20\log(2574000) + 20\log(4374000) + 20\log\left(\frac{4\pi}{299792458}\right) \approx 153.5dB$$

According to formula 1 the received power (received signal level) of the radio link budget is:

$$P_R = 30dBm + 0dBi + 0dBi - 153.5dB - 3dB = -126.5dBm$$

Where 3 dB is the margin.

Next, we need to calculate received the noise level at the LNA input, because we need the ratio between the power and the noise which is according to formula 11. Which the system temperature (T_S) and noise bandwidth (B_N) is needed to be calculated.

However, the noise bandwidth of the system is related to data rate because each modulation has some spectra efficiency. Spectral efficiency means how many bits per second is possible to transmit per 1Hz of bandwidth.

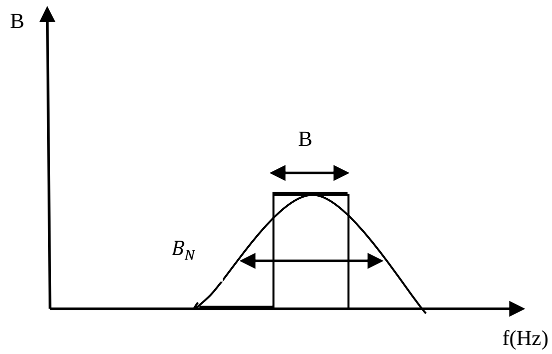

Figure 21

- B = required bandwidth for modulation
- B_N = equivalent noise bandwidth

According to figure 20, the receiver side has some real filters and it does not have a sharp frequency response, so there is a slow transient between passband and stopband.

So the bandwidth needs to be processed with respect to the modulation efficiency, and also some small amount of noise is coming from the outside of the band.

So the equivalent noise bandwidth (B_N) is slightly higher than the required bandwidth for modulation(B).

$$B_N = \frac{19200}{0.5} = 38400\ Hz$$

- For BFSK or GMSK is approximately 0.5 bps/Hz

Now for the system noise temperature with respect to formula 33:

$$T_S = T_{ANT} + T_{LNA} + \frac{T_{Cable}}{G_{LNA}} + \frac{T_{Receiver}}{G_{LNA} * a_{Cable}}$$

- T_{ANT} = temperature of the antenna (2000 K recommended by ITU)
- T_{LNA} = temperature of low noise amplifier
- T_{Cable} = temperature of lossy cables which generate some noise
- $T_{Receiver}$ = temperature of the receiver
- G_{LNA} = gain of low noise amplifier
- a_{Cable}= attenuation of cables

But in data sheets there is no noise temperature instead noise figure is given. According to formula 20, all the noise temperatures can be calculated.

$$T_{LNA} = 290\left(10^{\frac{1}{10}} - 1\right) = 75K$$

If the device is passive(cable) NF is equal to attenuation which over here is 2 dB.

$$T_{Cable} = 290\left(10^{\frac{2}{10}} - 1\right) = 170K$$

The noise figure of the receiver is relatively high (between 5 to 8 dB)

$$T_{Receiver} = 290\left(10^{\frac{5}{10}} - 1\right) = 627K$$

Hint: the calculation for the noise temperature can be done by an internet calculator, and the calculation here is just for understanding the steps.
And by substituting these values in the noise temperature equation:

$$T_S = 2000K + 75K + \frac{170}{1000} + \frac{627}{1000 * 0.63} \approx 2075K$$

Notice that the gain of LNA of 30 dB is relatively high (1000 amplification), according to:

$$G = 10log(g) \text{ (37)}$$

- G is the gain in dB
- g is the unitless gain

Due to high the gain of LNA, it is possible to neglect the noise added to cable and receivers. Now the values of noise temperature (T_S) and noise bandwidth (B_N) are calculated. By substituting these results in the received noise level formula (18):

$$N = k.T_s.B_n = 1.38 * 10^{-23} * 2075K * 38400Hz = -119.6\ dBm$$

Next step SNR (signal to noise ratio) can be calculated by the formula (9):

$$SNR = P_R[dBm] - P_N[dBm] = -126{,}5 - (-119.6) = \text{-6,9 dB}$$

This means the useful signal is weaker than the generated noise. Now from SNR is possible to calculate normalized signal to noise ratio, or signal to noise per bit (E_b/N_0) formula (11):

$$\frac{E_b}{N_0}[dB] = \frac{S}{N}[dB] - 10log_{10}\left(\frac{D_r}{B_N}\right) = -6.9 - 10log_{10}\left(\frac{19200}{38400}\right) = -3.9\ dB$$

So the quality of the signal is really low. according to figure10.

The normalized signal to noise ratio or signal to noise per bit (E_b/N_0), is -3.9 so with the omnidirectional ground antenna it is not possible to link due to extreme high bit error rate (demodulator has an almost random probability close to 0.5 if 0 or 1 is at the output). To stable the link with 10^{-5} of BER the higher value to (E_b/N_0) is demanded, which according to figure 10 will be around 12.5 dB.

So the gain of ground antenna (G_{ANT}) need to be increased by 16.4 dB, so 19200 bps data rate will work only with additional gain 16.4 dB of the ground station to get $(E_b/N_0) = 12.5dB$, by replacing the antenna gain in the received power formula.

Now it is possible to calculate that how fast the data rate can be transmitted for the omnidirectional antenna. So far we have the received power ($P_R = -126.5dBm$), and $(E_b/N_0) = 12.5dB$, which means SNR = 9.5 dB.

Now the new noise level needs to be calculated:

$$SNR = P_R[dBm] - N[dBm] \rightarrow 9.5 = -126.5 - N \rightarrow N = -126.5 - 9.5 = -136dBm$$

The noise bandwidth can be calculated:

$$N_{dBm} = 10 \times log_{10}\left(\frac{k \times T_S \times B_N}{0.001}\right) \rightarrow -136_{dBm} = 10 \times log_{10}\left(\frac{1.38 \times 10^{-23} \times 2075 \times B_N}{0.001}\right)$$

The noise bandwidth is $B_N = 870\ Hz$. Due to spectral efficiency and margin to equivalent noise bandwidth, 0.5 bps per 1Hz of bandwidth is used.

The data rate is:

$$D_r = B_N \times \eta_s = 870 \times 0.5 = 435\ bits/s$$

- η_s spectral efficiency of modulation
- B_N noise bandwidth of the channel

The margin was 3 dB and if the satellite is going to be in higher elevation ($10^{\circ}, 20^{\circ}$, ...), it means, shorter the distance and lower free space losses.

It is real that bitrates between 600-1200 bits/s can be received to omnidirectional antenna, but for higher data rates we need to add a gain of directional antenna or gain of diversiy combining of more omnidirectional ground stations.

9 Simulations of FSK modulation

The FSK communication system is simulated in Matlab software through an AWGN (Additive White Gaussian noise) channel and estimates the resulting bit error rate (BER). Compare the estimated BER to the theoretical value. (Matlab code)

For the first experiment, the Matlab example was used and later modified to noncoherent diversity combining.

Set the simulation parameters.

```
M = 2;          % Modulation order
k = log2(M);    % Bits per symbol
EbNo = [1 2 3 4 5 6 7 8 9 10 11 12 13];% Eb/No (dB)
Fs = 16;        % Sample rate (Hz)
nsamp = 8;      % Number of samples per symbol
freqsep = 10;   % Frequency separation (Hz)
```

Generate random data symbols.

```
data = randi([0 M-1],100000,1);
```

This code generates 100000 values from the range 0 to M-1. For the simulations with lower BER, longer data sets are demanded. In this case BER target will be 10^{-4}, so the 100000 lengths of data set is compromised between duration of the simulation and precision of BER.

Apply FSK modulation.

```
txsig = fskmod(data,M,freqsep,nsamp,Fs);
```

Pass the signal through an AWGN channel (a function in MATLAB).

```
rxSig  = awgn(txsig,EbNo+10*log10(k)-10*log10(nsamp),...
'measured',[],'dB');
```

Demodulate the received signal.

```
dataOut = fskdemod(rxSig,M,freqsep,nsamp,Fs);
```

Calculate the bit error rate (BER)

```
[num,BER] = biterr(data,dataOut);
```

Simulation is made in the range of Eb/No from 1 to 13 dB, random data signals are created, and FSK modulation is applied. A totally 50 receivers (ground stations) are simulated for diversity combining. The signal is created and passes through the AWGN channel and transmitted, the received signal gets demodulated, and the received bits of the signal are diversity combined, the BER can be calculated from the results of the diversity combining. The final result of the code is shown below (see figure 22):

```
close all;
clear all;

M = 2;          % Modulation order
k = log2(M);    % Bits per symbol
EbN0 = [1 2 3 4 5 6 7 8 9 10 11 12 13];      % Eb/No (dB)
Fs = 16;        % Sample rate (Hz)
nsamp = 8;      % Number of samples per symbol
freqsep = 10;   % Frequency separation (Hz)

for i=1:length(EbN0)
    data = randi([0 M-1],100000,1);
    txsig = fskmod(data,M,freqsep,nsamp,Fs);
    for s=1:50
        rxSig  = awgn(txsig,EbN0(i)+10*log10(k)-
10*log10(nsamp),...
    'measured',[],'dB');
dataOut(s,:) = fskdemod(rxSig,M,freqsep,nsamp,Fs);
diversityoutput(s,:)= mode(dataOut(1:s,:),1);
[i s]
[num,BER(i,s)] = biterr(data,diversityoutput(s,:)');
    end;
end;

semilogy(EbNo,BER(:,[1 3 7 10 20 50]));
legend('1 receiver','3 receiver','7 receiver','10 receiv-
er','20 receiver','50 receiver');
xlabel('Eb/No');
ylabel('BER');
axis([1 13 1e-4 1]);
```

In the code, on previous page, only the result of BER to Eb/N0 of only (1,3,7,…) receivers are shown in the fig below due to simplicity.

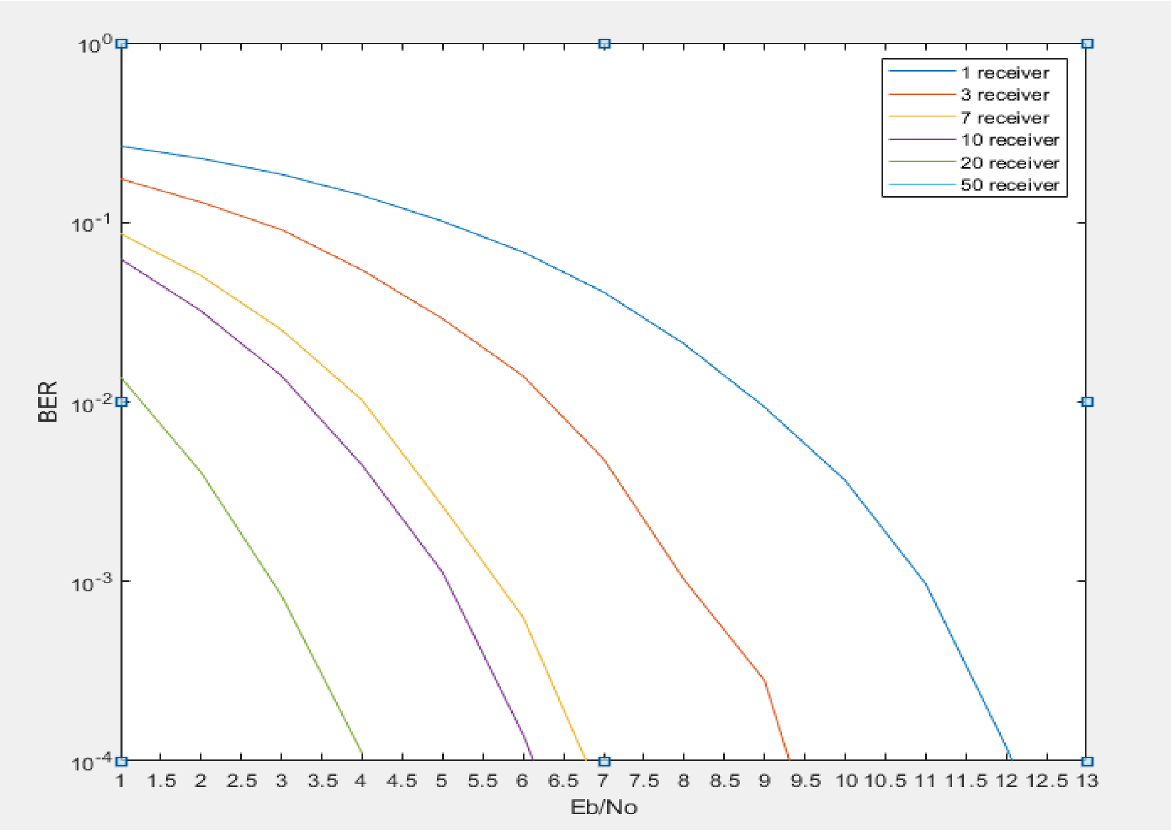

Figure 22: The change of BER with respect to E_b/N_0 regarding the numbers of receivers

As the chart illustrates, the number of ground stations has direct impact on lowering the BER which means the received result is likely correct and pretty close to the transmitted original signal and the difference of E_b/N_0 will decrease. (See table 3)

As the number of receivers increase the diversity combining gain[dB] will also increase. (See table 4)

For the SISO (single input single output) channel, the ground station requires E_b/N_0 equal to 12dB for 10^{-4} BER.

For the SIMO (single input multiple outputs) channel, figure 22 shows that even such a simple algorithm for diversity combining offers significant diversity combining gain.

Table 3: the difference of E_b/N_0 to the number of combined receivers

NUMBER OF COMBINED RECEIVERS	**1**	1 **TO 3**	**1 TO 7**	**1 TO 10**	**1 TO 20**	**1 TO** 50
$\boldsymbol{E_b/N_0}$	12	9.3	6.8	6.1	4	1.1

Table 4: the diversity combining gains up to 50 stations

Number of received signals	*3 stations*	*7 stations*	*10 stations*	*20 stations*	*50 stations*
The diversity combining gain[dB]	2.7	5.2	5.9	8	10.9

The previous simulation is the ideal case where all ground stations have the same signal quality, but in the real situation, the ground station will have a different signal quality.

Consider the case that there10 ground stations of 20, where 10 channels have a nominal value of E_b/N_0,2 of them have E_b/N_0 of -6 dB, 3 of them have E_b/N_0 -3dB, 2 of them have E_b/N_0 of 6 dB, 3 of them have E_b/N_0 3dB. Look at the figure 23:

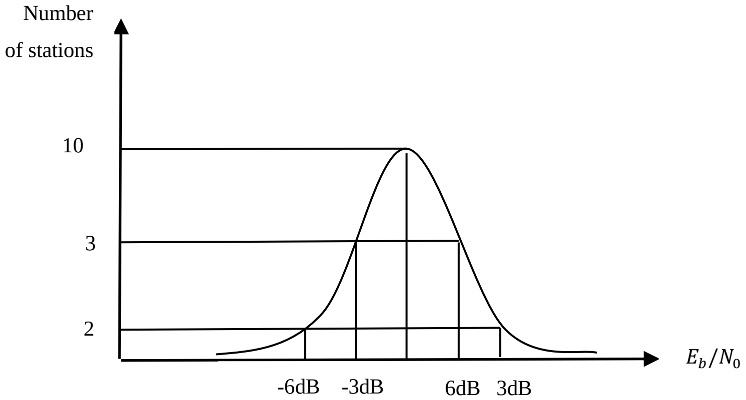

Figure 23

In this case for creating 20 channels, it needs five “for” loops in the previous algorithm. From 11 to 13, 13 to 15, 16 to 18 and 18 to 20 are the number of channels.

The diversity is from 1 to 20 and we save the result of all the receivers in one stream.

The result variations will define the channel quality.

The previous algorithm is modified on the next page.

```
close all;
clear all;

M = 2;          % Modulation order
k = log2(M);    % Bits per symbol
EbNo = [-6 -3 0 1 3 6];       % Eb/No (dB)
Fs = 16;        % Sample rate (Hz)
nsamp = 8;      % Number of samples per symbol
freqsep = 10;   % Frequency separation (Hz)

for i=1:length(EbNo)
    data = randi([0 M-1],100000,1);
    txsig = fskmod(data,M,freqsep,nsamp,Fs);
    for s=1:10
        rxSig  = awgn(txsig,EbNo(i)+10*log10(k)-10*log10(nsamp),...
    'measured',[],'dB');
dataOut(s,:) = fskdemod(rxSig,M,freqsep,nsamp,Fs);
[i s]
    end;
    for s=11:13
        rxSig  = awgn(txsig,EbNo(i)+3+10*log10(k)-10*log10(nsamp),...
    'measured',[],'dB');
dataOut(s,:) = fskdemod(rxSig,M,freqsep,nsamp,Fs);
[i s]
    end
     for s=14:15
        rxSig  = awgn(txsig,EbNo(i)+6+10*log10(k)-10*log10(nsamp),...
    'measured',[],'dB');
dataOut(s,:) = fskdemod(rxSig,M,freqsep,nsamp,Fs);
[i s]
     end
 for s=16:18
        rxSig  = awgn(txsig,EbNo(i)+6+10*log10(k)-10*log10(nsamp),...
    'measured',[],'dB');
dataOut(s,:) = fskdemod(rxSig,M,freqsep,nsamp,Fs);
[i s]
end
      for s=19:20
        rxSig  = awgn(txsig,EbNo(i)+6+10*log10(k)-10*log10(nsamp),...
    'measured',[],'dB');
dataOut(s,:) = fskdemod(rxSig,M,freqsep,nsamp,Fs);
[i s]
      end

 diversityoutput(1,:)= mode(dataOut(1:20,:),1);
 [num,BER(i,1)] = biterr(data,diversityoutput(1,:)');

end;

semilogy(EbNo,BER(:,[1]));
legend('20 receivers variations is channel quality');
xlabel('Eb/No');
ylabel('BER');
```

The result of channel quality in 20 receivers is shown in figure 24.

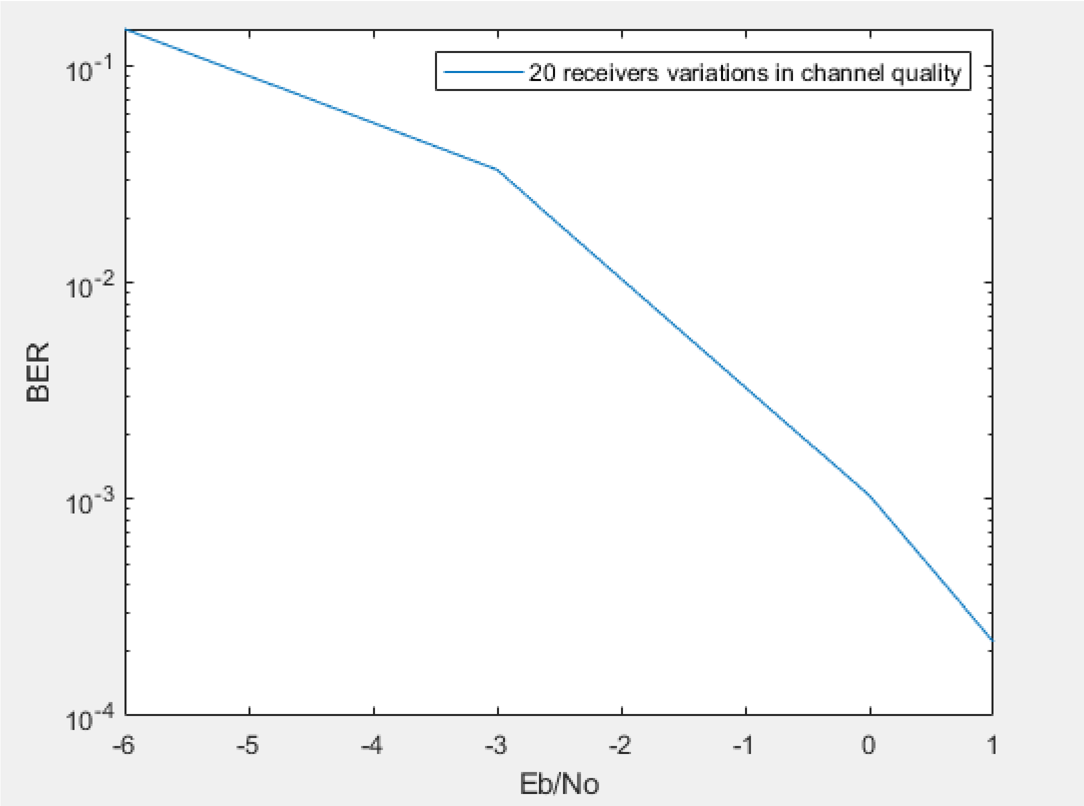

Figure 24: channel quality of 20 receivers

As it is illustrated, the channel quality for 20 receivers is the blue line, by comparing figure 24 with figure 22, for 20 receivers the BER is equal to 10^{-4} ,the value of E_b/N_0 is 4dB (in figure 22) which is the ideal case and in figure 24 the value of E_b/N_0 is close to 1dB which is a more realistic result. Even a low amount of this higher quality signal will improve the reception.

More important if the ground station (receiver) is closer to the satellite then better result can be achieved.

If we have low signal quality, it is a problem to find the proper delay of the streams, so time synchronization error needs to be covered in the following simulation. There are 8 samples per 1 modulation symbol in the time domain.

Based on the previous algorithm in each channel random shifting of the signal by 1 or 2 samples to the right or left can be simulated. There is a specific function in MATLAB for shifting samples to left or right which is;

```
Y = circshift(A,K)
```

circularly shifts the elements in array A by K positions and can be used in Passing the signal through an AWGN channel the previous algorithm in the form of:

```
        rxSig   = awgn(circshift(txsig,randi([-2
2],1,1)),EbNo(i)+10*log10(k)-10*log10(nsamp),...
     'measured',[],'dB');
```

Where A is “texing from” which is FSK modulation and K from generating data, is “randi” which is an original signal with random shifting from -2 up to +2 position with a vector dimension of 1 per 1 which are values (+2, +1, 0, -1, -2).

```
close all;
clear all;

M = 2;          % Modulation order
k = log2(M);    % Bits per symbol
EbNo = [-6 -3 0 3 4 6];       % Eb/No (dB)
Fs = 16;        % Sample rate (Hz)
nsamp = 8;      % Number of samples per symbol
freqsep = 10;   % Frequency separation (Hz)

for i=1:length(EbNo)
    data = randi([0 M-1],100000,1);
    txsig = fskmod(data,M,freqsep,nsamp,Fs);
    for s=1:10
        rxSig  = awgn(circshift(txsig,randi([-2
2],1,1)),EbNo(i)+10*log10(k)-10*log10(nsamp),...
    'measured',[],'dB');
dataOut(s,:) = fskdemod(rxSig,M,freqsep,nsamp,Fs);
[i s]
    end;
    for s=11:13
        rxSig  = awgn(circshift(txsig,randi([-2
2],1,1)),EbNo(i)+3+10*log10(k)-10*log10(nsamp),...
    'measured',[],'dB');
dataOut(s,:) = fskdemod(rxSig,M,freqsep,nsamp,Fs);
[i s]
    end
     for s=14:15
       rxSig  = awgn(circshift(txsig,randi([-2
2],1,1)),EbNo(i)+6+10*log10(k)-10*log10(nsamp),...
    'measured',[],'dB');
dataOut(s,:) = fskdemod(rxSig,M,freqsep,nsamp,Fs);
[i s]
     end
 for s=16:18
        rxSig  = awgn(circshift(txsig,randi([-2 2],1,1)),EbNo(i)-
3+10*log10(k)-10*log10(nsamp),...
    'measured',[],'dB');
dataOut(s,:) = fskdemod(rxSig,M,freqsep,nsamp,Fs);
[i s]
end
      for s=19:20
        rxSig  = awgn(circshift(txsig,randi([-2 2],1,1)),EbNo(i)-
6+10*log10(k)-10*log10(nsamp),...
    'measured',[],'dB');
dataOut(s,:) = fskdemod(rxSig,M,freqsep,nsamp,Fs);
[i s]
      end

 diversityoutput(1,:)= mode(dataOut(1:20,:),1);
 [num,BER(i,1)] = biterr(data,diversityoutput(1,:)');

end;
semilogy(EbNo,BER(:,[1]));
legend('20 receivers variations without perfect time synchronization');
xlabel('Eb/No');
ylabel('BER');
```

The result of the unperfect time synchronization of 20 receivers is shown below.

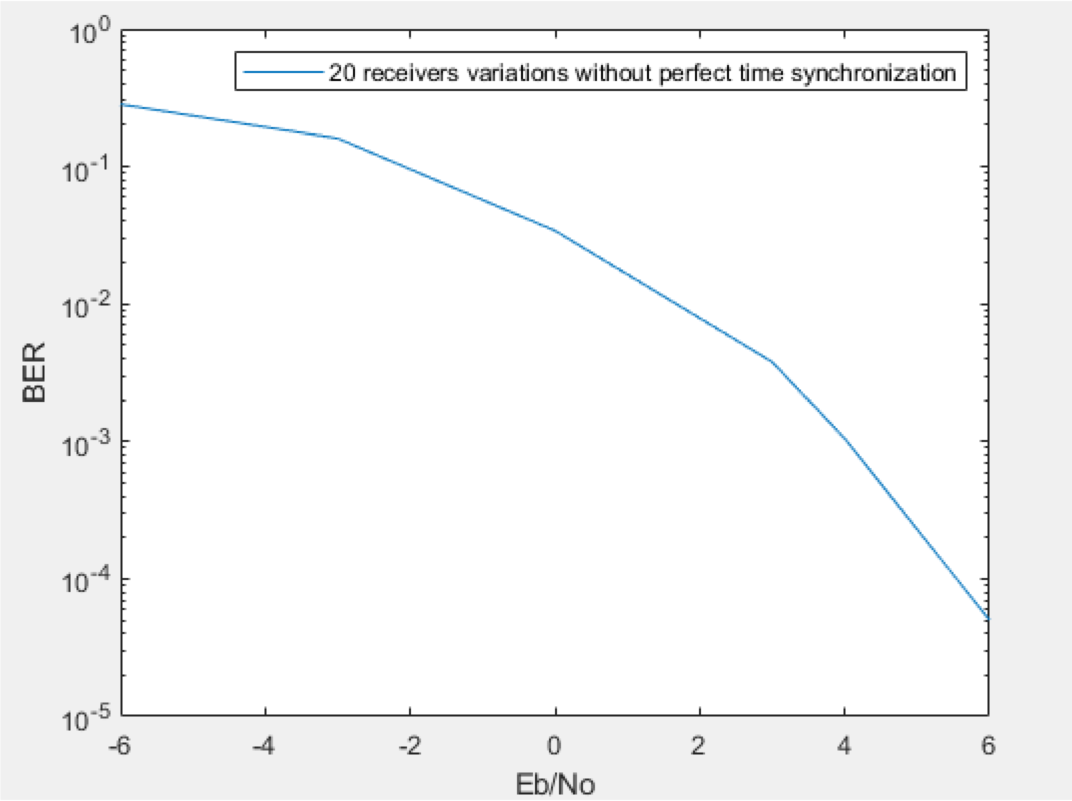

Figure 25: unperfect time synchronization of 20 receivers

Comparing the figure 25 with 22, for 20 receivers the BER is equal to 10^{-4} ,the value of E_b/N_0 is 4.2dB which is the ideal case and comparing to figure 24 for the same value of BER the E_b/N_0 is close to 1dB (perfect time synchronization and different signal qualities) and in figure 25 the same value of BER the E_b/N_0 is around 5dB which is worse compared to the previous results.

So, the quality of time synchronization of streams is significantly important for the performance of the diversity combining usage.

10 Conclusion

In the theoretical part of the thesis, the standard concepts of the ground stations and advantages and disadvantages, a simple calculation of link budget for small satellite communication systems, signal to noise ratio, and BER (bit error rate) were described, and the result of theoretical part shows that the antenna gain is important for reaching higher data rates.

An alternative solution in diversity combining system is proposed which provides interesting behavior which was shown and described in the simulation. The first simulation of FSK modulation reception was the ideal case of diversity combining where all the channels have the same signal quality and perfect synchronization. The second simulation of FSK modulation reception was shown with different quality of combined streams and perfect time synchronization. The third simulation of FSK modulation reception was shown with different quality of combined streams and nonperfect time synchronization.

All simulations show that the diversity combining of noncoherent ground stations with omnidirectional antenna will provide additional gain which replaces the missing gain of omnidirectional antennas. Such a network of omnidirectional ground stations can track more satellites in the same frequency band in comparison to the directional ground station.

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