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Technical documentation of RF-COMLINK

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DISCLOSURE LIST

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CONTENT

1. Introduction

This document provides the technical information of the RF-COMLINK application dedicated to the link budget and data handling budget calculation.

2. Reference documents

RD 1 : Radio Frequency and Modulation Systems Part 1 Earth station and Spacecraft CCSDS 401.0-B-29
RD 2 : Bandwidth-Efficient Modulations CCSDS 413.0-G-3
RD 3 : ECSS-E-ST-50-05C_REV-2 Space engineering Radio frequency and modulation
RD 4 : ITU-R PROPAGATION MODELS SOFTWARE LIBRARY
RD 5 : Recommendation ITU-R P.618-12 : Propagation data and prediction methods required for the design of Earth-space telecommunication systems
RD 6 : Recommandation ITU-R P.372-14 : Radio noise
RD 7 : Odile Picon et coll. les Antennes, Théorie, conception et applications
RD 8 : CCSDS-130.1-G-2 TM Synchronization and Channel Coding – Summary of concept and rational Nov 2012
RD 9 : Memo O. Bompis du 3 Novembre 2008
RD 10 : CCSDS-131.3-O-1 DVB-S2 Coding & Modulation Standard use for High Data Rate TM link*s*
RD 11 : EVALUATION DE LA DEGRADATION DU G/T STATION DUE A LA PLUIE REF. DSO/RF/ITP-2017-0013946
RD 12 : CIC DATA EXCHANGE PROTOCOL V2.0 DCT/DA /PA - 2009.0021267
RD 13 : SIMU-CIC User manual CNES – DSO/DV/IF
RD 14 : IDM-CIC-V3 - XML model specifications
RD 15 : IEEE Standard Letter Designations for Radar-Frequency Bands IEEE Std 521™-2019
RD 16 : RF-COMLINK Modulation database DS/PF-2022.0010628
RD 17 : NOTE TECHNIQUE « TEMPERATURE ANTENNE POUR LA TM/TC » DSO/RF/ITP-2020.23084 du 19/05/2020
RD 18 : CCSDS 130-1g3 TM synchronization and channel coding Nov2012
RD 19 : CCSDS 131.31-O-1 CCSDS SPACE LINK PROTOCOLS OVER ETSI DVB-S2X STANDARD
RD 20 : CCSDS 413.0-G-3 CCSDS Bandwidth-efficient Modulations

3. Glossary

APSK : Amplitude and Phase-Shift Keying
AR : Axial Ratio
BER : Bit Error Rate
BPSK : Binary Phase-Shift Keying
CCSDS : Consultative Committee for Space Data Systems
CIC : Centre d’Ingenierie Concourante
CNES : Centre National d’Etudes Spatiales
CPM : Continuous Phase Modulations

CV : Convolutional
DVB : Digital Video Broadcasting
ECSS : European Cooperation for Space Standardization
EIRP : Equivalent Isotropic Radiated Power
GMSK : Gaussian Minimum-Shift Keying
GS : Ground Station
HKTM : HouseKeeping TeleMetry
IDM : Integrated Design Model
ISL : Inter Satellite Link
ITU : International Telecommunication Union
PCM/PSK/PM : Pulse-Coded Modulation/Phase-Shift Keyed/Phase Modulated
PLTM : Payload TeleMetry
PM : Phase Modulated
PSK : Phase-Shift Keying
QPSK : Quadrature Phase-Shift Keying
RF : Radio Frequence
RS : Reed Solomon
RSS : Root Sum Squared
RX : Receiver
SP-L/PM : Split-Phase Level/Phase Modulation
SRRC : Square Root Raised Cosine
TC : Telecommand
TC : Turbo Code
TCM : Trellis Coded Modulation
TM : Telemeasure
TX : Transmitter

4. General requirements

RF-COMLINK application is useable as a standalone software. For dynamic simulation, it uses files at CIC Standard Protocol **RD 12** provided by SIMU-CIC or IDM-CIC application (**RD 13** and **RD 14**)

It is possible to install the RF-COMLINK application without any administrator rights.

5. RF-COMLINK presentation

5.1. GENERAL PRESENTATION

RF-COMLINK is an application with

- An interface to provide all data needed for the link budget calculation
- A calculator computing and simulating the link budget
- An interface presenting the results of the link budget calculation as a budget table and as files and curves containing the results of the link budget for each time step of the simulation.
- A simulator providing the satellite memory state from files defining the payload data rate profile and the Ground Station visibilities.

RF-COMLINK application offers the possibility to define 3 types of RF links :

- Space-Earth link (Downlink budget for the Satellite Telemetry)
- Earth-Space link (Uplink budget for the Satellite Telecommands)
- Space-Space link (Intersatellite link)

RF-COMLINK application checks that the requirement concerning frequency allocations described in RD 3 is satisfied : RD 1 *Table 4.1: Frequency allocations to the Space Operation,Space Research and Earth Exploration services* reproduced Figure 5-1

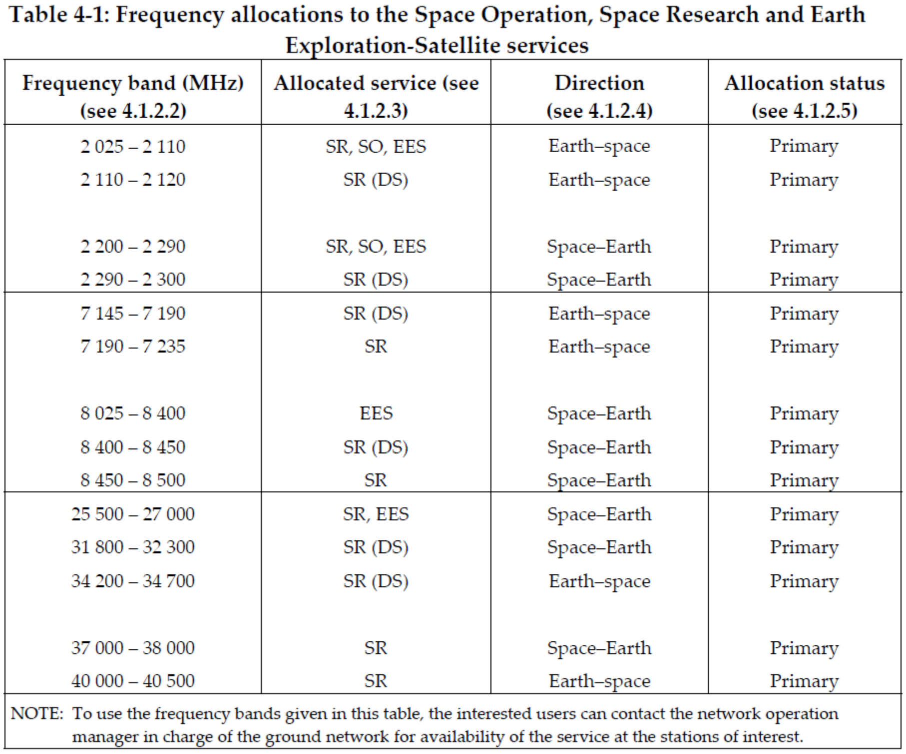


Table 4-1: Frequency allocations to the Space Operation, Space Research and Earth Exploration-Satellite services

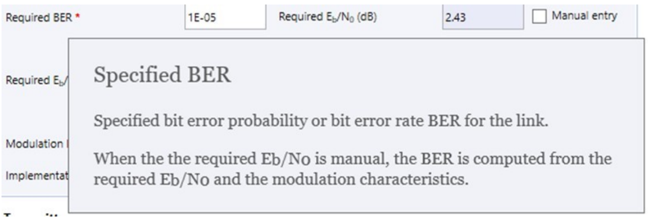
Frequency band (MHz) (see 4.1.2.2)	Allocated service (see 4.1.2.3)	Direction (see 4.1.2.4)	Allocation status (see 4.1.2.5)
2 025 – 2 110	SR, SO, EES	Earth–space	Primary
2 110 – 2 120	SR (DS)	Earth–space	Primary
2 200 – 2 290	SR, SO, EES	Space–Earth	Primary
2 290 – 2 300	SR (DS)	Space–Earth	Primary
7 145 – 7 190	SR (DS)	Earth–space	Primary
7 190 – 7 235	SR	Earth–space	Primary
8 025 – 8 400	EES	Space–Earth	Primary
8 400 – 8 450	SR (DS)	Space–Earth	Primary
8 450 – 8 500	SR	Space–Earth	Primary
25 500 – 27 000	SR, EES	Space–Earth	Primary
31 800 – 32 300	SR (DS)	Space–Earth	Primary
34 200 – 34 700	SR (DS)	Earth–space	Primary
37 000 – 38 000	SR	Space–Earth	Primary
40 000 – 40 500	SR	Earth–space	Primary

NOTE: To use the frequency bands given in this table, the interested users can contact the network operation manager in charge of the ground network for availability of the service at the stations of interest.

Figure 5-1 : Frequency allocations to the Space Operation,Space Research and Earth Exploration services (from RD2 table 4.1)

5.2. GENERAL USERS FUNCTIONS

All tab actions and parameters definitions are available when pointing the mouse over their location.



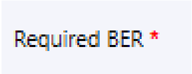
Required BER * 1E-05 Required E_b/N_0 (dB) 2,43 ☐ Manual entry

Specified BER

Specified bit error probability or bit error rate BER for the link.

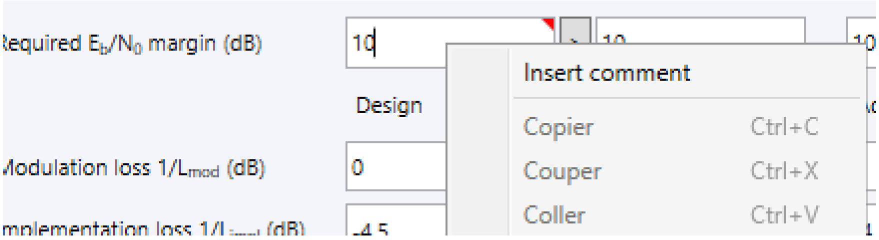
When the the required Eb/No is manual, the BER is computed from the required Eb/No and the modulation characteristics.

Parameters with a red star are mandatory to get a proper basic link budget



Required BER *

Comments can be added to each value by right clicking on the corresponding box. A red mark is shown if a comment has been added.

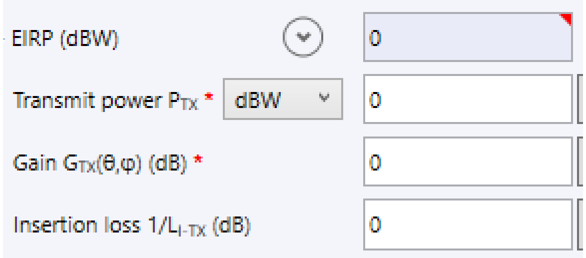


equired E_b/N_0 margin (dB) 10

odulation loss $1/L_{mod}$ (dB) 0

Some parameters can be directly provided or can be calculated from sub-parameters that can be displayed by clicking on the corresponding arrows

EIRP (dBW) * 55



EIRP (dBW) 0

Transmit power P_{TX} * dBW 0

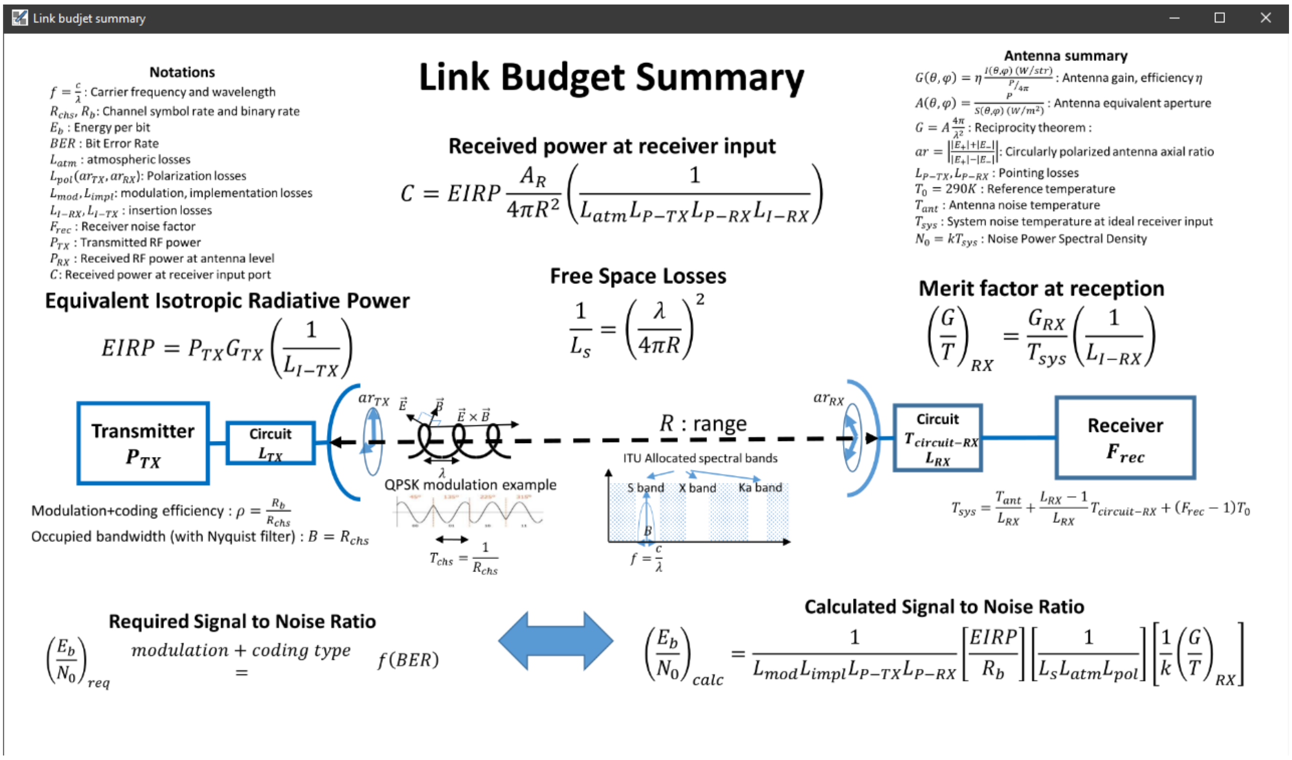
Gain $G_{TX}(\theta,\varphi)$ (dB) * 0

Insertion loss $1/L_{I-TX}$ (dB) 0

All parameters are gain parameters (losses shall be negative values)

5.3. LINK BUDGET SCHEMATIC

A link budget schematic tab can help the user to understand the provided link budget and used parameters



Link budjet summary

Link Budget Summary

Notations

$f = \frac{c}{\lambda}$: Carrier frequency and wavelength
R_{chs}, R_b: Channel symbol rate and binary rate
E_b : Energy per bit
BER : Bit Error Rate
L_{atm} : atmospheric losses
$L_{pol}(ar_{TX}, ar_{RX})$: Polarization losses
L_{mod}, L_{impl}: modulation, implementation losses
L_{I-RX}, L_{I-TX} : insertion losses
F_{rec} : Receiver noise factor
P_{TX} : Transmitted RF power
P_{RX} : Received RF power at antenna level
C: Received power at receiver input port

Received power at receiver input

$$C = EIRP\frac{A_R}{4\pi R^2}\left(\frac{1}{L_{atm}L_{P-TX}L_{P-RX}L_{I-RX}}\right)$$

Antenna summary

$G(\theta,\varphi) = \eta\frac{I(\theta,\varphi)\ (W/str)}{P/_{4\pi}}$: Antenna gain, efficiency η
$A(\theta,\varphi) = \frac{P}{S(\theta,\varphi)\ (W/m^2)}$: Antenna equivalent aperture
$G = A\frac{4\pi}{\lambda^2}$: Reciprocity theorem :
$ar = \left|\frac{|E_+|+|E_-|}{|E_+|-|E_-|}\right|$: Circularly polarized antenna axial ratio
L_{P-TX}, L_{P-RX} : Pointing losses
$T_0 = 290K$: Reference temperature
T_{ant} : Antenna noise temperature
T_{sys} : System noise temperature at ideal receiver input
$N_0 = kT_{sys}$: Noise Power Spectral Density

Equivalent Isotropic Radiative Power

$$EIRP = P_{TX}G_{TX}\left(\frac{1}{L_{I-TX}}\right)$$

Free Space Losses

$$\frac{1}{L_s} = \left(\frac{\lambda}{4\pi R}\right)^2$$

Merit factor at reception

$$\left(\frac{G}{T}\right)_{RX} = \frac{G_{RX}}{T_{sys}}\left(\frac{1}{L_{I-RX}}\right)$$

Modulation+coding efficiency : $\rho = \frac{R_b}{R_{chs}}$
Occupied bandwidth (with Nyquist filter) : $B = R_{chs}$

$$T_{sys} = \frac{T_{ant}}{L_{RX}} + \frac{L_{RX}-1}{L_{RX}}T_{circuit-RX} + (F_{rec}-1)T_0$$

Required Signal to Noise Ratio

$$\left(\frac{E_b}{N_0}\right)_{req} \overset{modulation + coding\ type}{=} f(BER)$$

Calculated Signal to Noise Ratio

$$\left(\frac{E_b}{N_0}\right)_{calc} = \frac{1}{L_{mod}L_{impl}L_{P-TX}L_{P-RX}}\left[\frac{EIRP}{R_b}\right]\left[\frac{1}{L_sL_{atm}L_{pol}}\right]\left[\frac{1}{k}\left(\frac{G}{T}\right)_{RX}\right]$$

6. Digital transmission

A digital link is defined by a transmitter chain generating a carrier signal $s(t)$ of frequency $\boldsymbol{f}$ modulated in amplitude and/or phase by a baseband signal $x(t)$.

$$s(t) = \mathcal{R}\left(x(t) * e^{2i\pi ft}\right)$$

The baseband signal $x(t)$ is built from a digital signal $x^*(t)$ built from a succession of symbols $a_k e^{i\theta_k}$ carrying the information, with a channel symbol period T_{chs} :

$$x^*(t) = \sum_{k=-\infty}^{k=+\infty} a_k e^{i\theta_k} \delta(t - kT_{chs})$$

The channel symbol rate $\boldsymbol{R_{chs}}$ expressed in symbols/s or Bauds is :

$$\boldsymbol{R_{chs}} = \frac{\mathbf{1}}{\boldsymbol{T_{chs}}}$$

The set of $\boldsymbol{M}$ discrete symbols used by the modulation is called the constellation.

A modulation with a constellation of $\boldsymbol{M}$ symbols can thus transmit $\boldsymbol{log_2 M}$ transmitted bits/symbol.

Coding can detect and correct transmission errors. It reduces modulation efficiency since some transmitted bits are reserved for detection/correction, but it improves the Bit Error Rate (***BER***) or probability that a received bit at the decoder output is wrong. Coding is characterized by its code rate (ratio between number of input bits k and output bits n :

$$\boldsymbol{\rho_{code}} = \frac{\boldsymbol{k}}{\boldsymbol{n}} < \mathbf{1}$$

The modulation/coding rate $\boldsymbol{\rho_{mod}}$ which is the ratio between the useful binary rate $\boldsymbol{R_b}$ (useful bits or information bits after detection/correction) and the channel symbol rate $\boldsymbol{R_{chs}}$ is thus

$$\boldsymbol{\rho_{mod}} = \frac{\boldsymbol{R_b}}{\boldsymbol{R_{chs}}} = \frac{\boldsymbol{k}}{\boldsymbol{n}} * \mathbf{log_2}\, \boldsymbol{M}$$

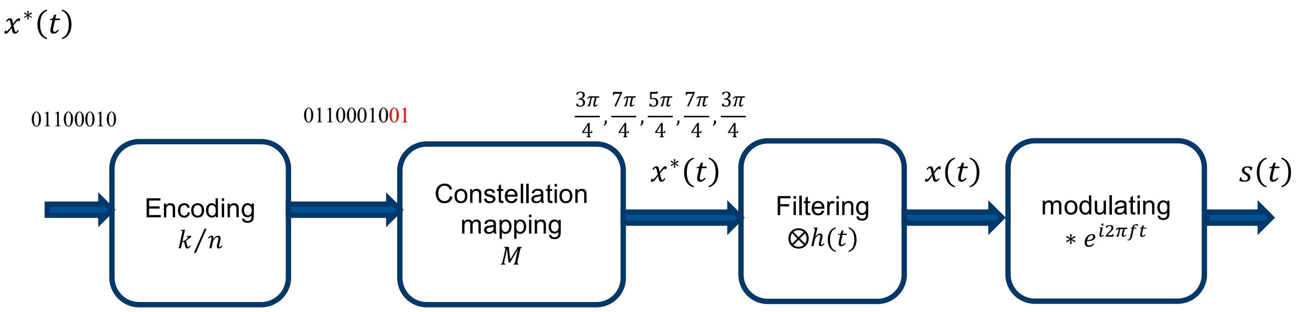
The modulated signal $s(t)$ occupies a certain bandwidth $\boldsymbol{BW}$ that can be reduced while being able to retrieve the symbols by filtering the samples of the input baseband signal $x^*(t)$ by a filter of impulse response $h(t)$:

$$x(t) = (h \otimes x^*)(t)$$

In this application, the transmission chain is thus split in 4 parts :

- Encoding function adding some redundant bits to the useful bit train to detect and correct errors
- Constellation mapping to map the coded bit chain to the constellation of symbols
- Filtering function providing the shape of the modulating baseband signal

- The modulating function creating the modulated signal from the baseband signal and the carrier



There are various solutions to implement these functions. A combination of solutions is called a modulation. A modulation is characterized by

- the Power Spectral Density (PSD) of the modulated signal $s(t)$, characterized in RF-COMLINK by (see **RD 16**)
    - the modulated signal PSD bandwidth at 99% power $\boldsymbol{B_{99\%}}$ to channel symbol rate $\boldsymbol{R_{chs}}$ ratio, $\boldsymbol{\beta_{mod}} = \frac{\boldsymbol{B_{99\%}}}{\boldsymbol{R_{chs}}}$
    - The maximum of the normalized modulated signal PSD $\boldsymbol{PSD_{max}}$ to channel period $\boldsymbol{T_{chs}}$ ratio $\boldsymbol{\alpha_{mod}} = \frac{\boldsymbol{PSD_{max}}}{\boldsymbol{T_{chs}}}$
- the function $\boldsymbol{BER}\left(\frac{\boldsymbol{E_b}}{\boldsymbol{N_0}}\right)$ relating the provided $\boldsymbol{BER}$ to the energy-per-bit $\boldsymbol{E_b}$ to noise Power Spectral Density $\boldsymbol{N_0}$ ratio.

The user can either define manually its modulation, or choose among a set of proposed modulation stored in the “MODULATION_DATABASE.txt” file describing modulation parameters $\boldsymbol{k/n}$, $\boldsymbol{M}$, $\boldsymbol{\beta_{mod}}$, $\boldsymbol{\alpha_{mod}}$, $\boldsymbol{BER@10^{-2}}$, $\boldsymbol{BER@10^{-4}}$, $\boldsymbol{BER@10^{-6}}$, $\boldsymbol{BER@10^{-8}}$ and provided with the application.

Available modulations are defined in “RF-COMLINK Modulation database.pdf” file provided with the application (see **RD 16**).

Modulation definition is not necessary for link budget calculation and is only used for occupied Bandwidth calculation and for required signal to noise ratio $\left(\frac{\boldsymbol{E_b}}{\boldsymbol{N_0}}\right)_{\boldsymbol{req}}$ calculation.

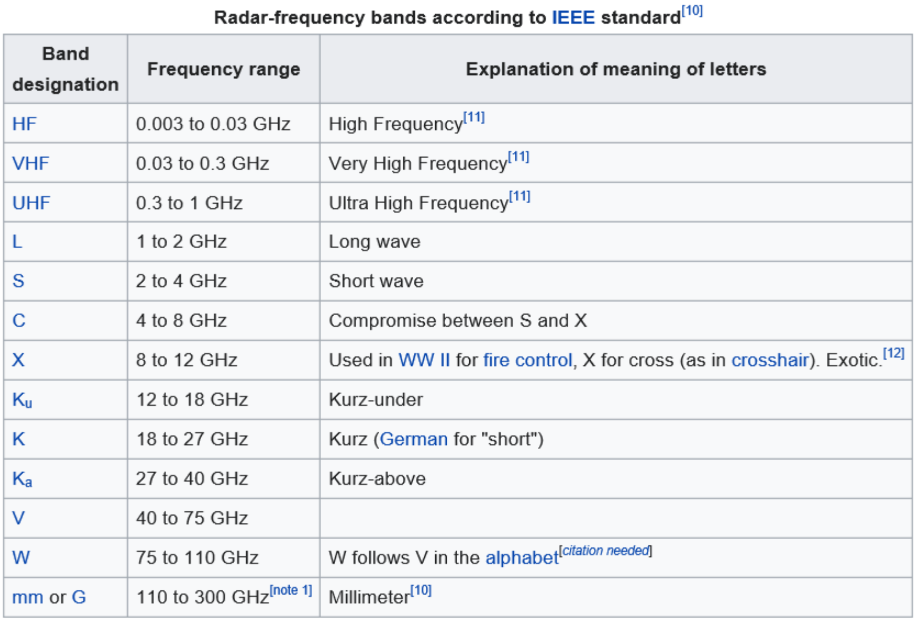
The modulation/coding spectral efficiency (b/s/Hz) is defined as

$$\boldsymbol{\eta_{mod}} = \frac{\boldsymbol{R_b}}{\boldsymbol{BW_{99\%}}}$$

7. General link parameters

The RF-COMLINK user can define :

- The link type (Earth-Space, Space-Earth or Space-Space
- The carrier frequency band letter (see IEEE standards **RD 15** and Figure 7-1)
- The carrier frequency $\boldsymbol{f}\ (\boldsymbol{Hz})$
- The modulation/coding type chosen among the modulations listed in the “MODULATION_DATABASE.txt” file
- Define its own modulation parameters
- The required information bit rate (useful bit rate) $\boldsymbol{R_b}\ (\boldsymbol{bits/s})$
- The specified Bit Error Rate $\boldsymbol{BER}$
- Ground Station location (Longitude $\boldsymbol{GS_{long}}$, Latitude $\boldsymbol{GS_{lat}}$, Height $\boldsymbol{GS_{height}}$)



Radar-frequency bands according to IEEE standard[10]

Band designation	Frequency range	Explanation of meaning of letters
HF	0.003 to 0.03 GHz	High Frequency[11]
VHF	0.03 to 0.3 GHz	Very High Frequency[11]
UHF	0.3 to 1 GHz	Ultra High Frequency[11]
L	1 to 2 GHz	Long wave
S	2 to 4 GHz	Short wave
C	4 to 8 GHz	Compromise between S and X
X	8 to 12 GHz	Used in WW II for fire control, X for cross (as in crosshair). Exotic.[12]
K_u	12 to 18 GHz	Kurz-under
K	18 to 27 GHz	Kurz (German for "short")
K_a	27 to 40 GHz	Kurz-above
V	40 to 75 GHz	
W	75 to 110 GHz	W follows V in the alphabet[*citation needed*]
mm or G	110 to 300 GHz[note 1]	Millimeter[10]

Figure 7-1 : Radio-frequency bands from RD 15

RF-COMLINK application computes the carrier wavelength $\boldsymbol{\lambda}\ (\boldsymbol{m})$:

$$\boldsymbol{\lambda} = \frac{\boldsymbol{c}}{\boldsymbol{f}}$$

For links between a Satellite and a Ground Station, RF-COMLINK provides a possibility to create a new Ground Station or to choose a pre-defined Ground Station from the “GROUND_STATION_DATABASE.txt” file providing a list of Ground Stations and their characteristic.

- When defining a new Ground Station, the user provides all the Ground Station parameters to achieve the link budget.
- When choosing a pre-defined Ground Station from the Ground Station database, RF-COMLINK provides all the Ground Station parameters and checks that the Ground Station parameters are compatible with the general link parameters.

The Ground Station database is a .txt file at CIC Standard protocol (**RD 12**) containing all the Ground Station parameters for all pre-defined Ground Stations :

- Acronym
- Frequency band
- Location
- Network
- Longitude
- Latitude
- Altitude
- Elevation min
- Antenna diameter
- EIRP design, favorable, adverse
- G/T design, favorable, adverse
- Gain RX design, favorable, adverse
- Pointing loss RX design, favorable, adverse
- Pointing loss TX design, favorable, adverse
- Axial ratio Rx design, favorable, adverse
- Axial ratio Tx design, favorable, adverse

RF-COMLINK calculates the modulation channel symbol rate $\boldsymbol{R_{chs}}$ from modulation/coding rate $\boldsymbol{\rho_{mod}} = \boldsymbol{log_2(M)} * \boldsymbol{\rho_{code}}$ and from required usebul binary rate $\boldsymbol{R_b}$.

$$\boldsymbol{R_{chs}} = \frac{\boldsymbol{R_b}}{\boldsymbol{log_2(M)} * \boldsymbol{\rho_{code}}}$$

RF-COMLINK calculates the modulated signal PSD bandwidth at 99% of power

$$\boldsymbol{B_{99\%}} = \boldsymbol{\beta_{mod}} * \boldsymbol{R_{chs}}$$

RF-COMLINK calculates the required signal to noise ratio $\frac{\boldsymbol{E_b}}{\boldsymbol{N_0}}$ by extrapolating the values from the modulation database with a logarithmic regression from the “Eb/N0@BER1E-x” characteristics of the modulation.

8. The link budget

A link budget consists of a presentation of the comparison between the calculation of the ratio $\left(\frac{\boldsymbol{E_b}}{\boldsymbol{N_0}}\right)_{\boldsymbol{calc}}$ between the Energy per bit $\boldsymbol{E_b}$ and the Noise Power Spectral density at ideal receiver input $\boldsymbol{N_0}$ and the required ratio $\left(\frac{\boldsymbol{E_b}}{\boldsymbol{N_0}}\right)_{\boldsymbol{req}}$ to comply with a bit error rate $\boldsymbol{BER}$ specified by the system.

- $\boldsymbol{E_b}$ $(\boldsymbol{J})$ is the average energy of a useful bit (or information bit).
- $\boldsymbol{N_0}$ $(\boldsymbol{W/Hz})$ is the monolateral Power Spectral Density of the noise at the ideal receiver input. In case of an AWGN channel (Additive White Gaussian Noise channel), the channel output $y(t)$ is

$$y(t) = x(t) + n(t)$$

with $x(t)$ the channel input and $n(t)$ a centered white gaussian processus of bilateral power spectral density $N_0/2$.

The link budget is also done to check that flux density at Earth level is compliant with ECSS constraints (RD 1).

8.1. REQUIRED SIGNAL TO NOISE RATIO

The $\left(\frac{\boldsymbol{E_b}}{\boldsymbol{N_0}}\right)_{\boldsymbol{req}}$ ratio required to meet a specified Bit Error Rate ($\boldsymbol{BER}$) depends on the type of modulation and coding used by the link.

For modulations defined in the “MODULATION_DATABASE.txt” file, RF-COMLINK application calculates the required $\frac{\boldsymbol{E_b}}{\boldsymbol{N_0}}$ ratio.

The user can define its own required $\frac{\boldsymbol{E_b}}{\boldsymbol{N_0}}$ ratio.

8.2. ANTENNA DIRECTIVITY, GAIN, EFFECTIVE AREA, RECIPROCITY THEOREM

8.2.1. ANTENNA DIRECTIVITY AND GAIN

Directivity of an antenna in a given direction $D(\theta,\varphi)$ is the ratio of the radiation intensity $I(\theta,\varphi)$ (W/str) radiated in a given direction (θ,φ) from the antenna to the total radiation intensity radiated by the antenna and averaged over all direction $\frac{P_{rad}}{4\pi}$

$$D(\theta,\varphi) = \frac{I(\theta,\varphi)}{\frac{P_{rad}}{4\pi}}$$

Hence,

$$\frac{\int_{4\pi} D(\theta,\varphi)d\Omega}{4\pi} = 1$$

Gain of an antenna $G(\theta,\varphi)$ is defined as

$$G(\theta,\varphi) = \eta * D(\theta,\varphi)$$

where η is the ratio of total radiated power over antenna input power, called antenna efficiency.

$D(\theta,\varphi)$ is the directivity pattern of the antenna

$F(\theta,\varphi) = \frac{D(\theta,\varphi)}{D_{max}}$ is the normalized radiation pattern of the antenna

8.2.2. EFFECTIVE AREA

The effective area of the antenna $A_{eff}(\theta,\varphi)$ in a given direction (θ,φ) is the ratio of the available power at receiving antenna input P_{ant} to the radiation density $S(\theta,\varphi)$ (W/m^2) of a plane wave incident on the antenna from that direction (θ,φ)

$$A_{eff}(\theta,\varphi)=\frac{P_{ant}}{S(\theta,\varphi)}$$

8.2.3. RECIPROCITY THEOREM

The reciprocity theorem links the antenna directivity with the antenna effective area :

$$A_{eff}(\theta,\varphi)=\frac{\lambda^2}{4\pi}D(\theta,\varphi)$$

8.2.4. TRANSMISSION EQUATION

For a transmission from a transmitting antenna of directivity $D_{TX}(\theta,\varphi)$ to a receiving antenna of effective area $A_{RX_{eff}}(\theta,\varphi)$ and directivity $D_{RX}(\theta,\varphi)$, the received power at antenna input can then be written as :

$$\begin{aligned}P_{ant} &= A_{RX_{eff}}(\theta,\varphi)*S(\theta,\varphi)\\ &=\frac{\lambda^2}{4\pi}D_{RX}(\theta,\varphi)*\frac{I(\theta,\varphi)*4\pi}{4\pi R^2}\\ &=\frac{\lambda^2}{4\pi}D_{RX}(\theta,\varphi)*\frac{P_{rad}D_{TX}(\theta,\varphi)}{4\pi R^2}\end{aligned}$$

$$P_{ant}=P_{rad}D_{TX}(\theta,\varphi)*\left(\frac{\lambda}{4\pi R}\right)^2*D_{RX}(\theta,\varphi)$$

8.3. RECEIVED POWER AND SIGNAL TO NOISE RATIO

The received power at receiver level $\boldsymbol{C}$ $(\boldsymbol{W})$ is the result of the general transmission formula (8.2.4) for a carrier signal of wavelength $\boldsymbol{\lambda}$

- Produced by a transmitter of Radio Frequency power $\boldsymbol{P_{TX}}$ $(\boldsymbol{W})$
- Attenuated by losses at emission $\boldsymbol{L_{TX}}$ (transmitter/antenna link for example)
- Transmitted by an antenna of gain $\boldsymbol{G_{TX}}$ in the direction of the receiver
- Propagating up to the receiver which is at a distance $\boldsymbol{R}$ $(\boldsymbol{m})$ from the emitter
- Attenuated during the propagation by propagation losses $\boldsymbol{L_{propa}}$(propagation losses) due to atmosphere (when any) and polarization
- Received by an antenna of gain $\boldsymbol{G_{RX}}$ in the direction of the transmitter
- Attenuated by losses at reception $\boldsymbol{L_{RX}}$ (antenna/receiver link for example)

$$\boldsymbol{C=\left[P_{TX}G_{TX}\left(\frac{1}{L_{TX}}\right)\right]*\left[\left(\frac{\lambda}{4\pi R}\right)^2\left(\frac{1}{L_{propa}}\right)\right]*\left[G_{RX}\left(\frac{1}{L_{RX}}\right)\right]}$$

This power is compared to the system noise Power Spectral Density at ideal receiver input $\boldsymbol{N_0 = kT_{sys}}$ ($\boldsymbol{k \approx 1.38E^{-23} J/K}$ Boltzmann constant), $\boldsymbol{T_{sys}}$ being the system noise temperature at ideal receiver input, including sky and ground noises seen from the receiving antenna, noise of emissions of penetrated medium (atmosphere), noise of antenna circuit, noise of transmission line between antenna and receiver, and noise of the receiver itself (receiver noise factor).

The received $\boldsymbol{\frac{C}{N_0}}$ ($\boldsymbol{Hz^{-1}}$) is then :

$$\boldsymbol{\frac{C}{N_0} = \frac{C}{kT_{eq}} = \left[P_{TX} G_{TX} \left(\frac{1}{L_{TX}}\right)\right] * \left[\left(\frac{\lambda}{4\pi R}\right)^2 \left(\frac{1}{L_{propa}}\right)\right] * \left[\frac{G_{RX}}{kT_{sys}} \left(\frac{1}{L_{RX}}\right)\right]}$$

Part of the useful signal can be lost during transmission process. These losses $\boldsymbol{L_{mod}}$ are called “modulation losses” (see §9.4.1).

Other implementation losses $\boldsymbol{L_{imp}}$ due to detection process and other implementation process (see §9.4.2) affect the transmission.

The ratio $\boldsymbol{\frac{E_b}{N_0}}$ is then computed thanks to:

$$\boldsymbol{\frac{E_b}{N_0} = \frac{1}{L_{imp}} * \frac{1}{L_{mod}} * \frac{\frac{C}{R_b}}{N_0}}$$

$$\boldsymbol{= \frac{1}{L_{imp}} \frac{1}{L_{mod}} \left[\frac{P_{TX} G_{TX} \left(\frac{1}{L_{TX}}\right)}{R_b}\right] * \left[\left(\frac{\lambda}{4\pi R}\right)^2 \left(\frac{1}{L_{propa}}\right)\right] * \left[\frac{G_{RX}}{kT_{sys}} \left(\frac{1}{L_{RX}}\right)\right]}$$

Apart from general losses, these values are the product of 3 terms related to :

- Transmission parameters P_{TX}, G_{TX}, L_{TX}
- Propagation parameters R, L_{propa}
- Reception parameters G_{RX}, L_{RX}, T_{sys}

The RF-COMLINK presentation is structured by these 3 set of parameters

The power flux at Earth level $\boldsymbol{\phi}$ (in dBW/m^2) is computed thanks to:

$$\boldsymbol{\phi = \frac{P_{TX} G_{TX} \left(\frac{1}{L_{TX}}\right)}{4\pi R^2} * \left(\frac{1}{L_{atm}}\right)}$$

The spectral power flux density at Earth level $\boldsymbol{PFD}$ (in dBW/m^2/Hz or dBW/m^2/4kHz) is computed thanks to:

$$\boldsymbol{PFD = \alpha_{mod} * \frac{(\phi)_{calc}}{R_{chs}} * BW = \frac{\alpha_{mod}}{R_{chs}} * \frac{P_{TX}G_{TX}\left(\frac{1}{L_{TX}}\right)}{4\pi R^2} * \left(\frac{1}{L_{atm}}\right) * BW}$$

With :

- BW = 4 kHz for a result in dBW/m^2/4 kHz
- BW = 1 Hz for a result in dBW/m^2/Hz
- α_{mod} = Maximum of normalized modulated signal PSD to symbol period ratio T_{chs}

8.4. DECIBEL UNITS FOR LINK BUDGET PRESENTATION

The link budget is presented as a sum of the different contributors. To do this, the Decibel unit will be used, transforming the signal to noise ratio calculation which is a product of terms into a sum of terms.

For a parameter P whose unit is $[U]$, we define the dBU unit as the unit of

$$P[dBU] = 10\log_{10}(P[U])$$

Examples :

$P_e = 2W = 3dBW$

$P_e = 2000mW = 33dBmW.$

dBmW are commonly written as dBm (dB for milliwatt). $1dBW = 30dBm$. For the received power (C), or power in general, the results could be presented in dBm.There are 30 dB of difference between a value in dBW and a value in dBm.

$P_e = 2W = 3dBW = 33\ dBm$

$G_e = 10000 = 40dB$

9. Link budget parameters

9.1. TRANSMISSION PARAMETERS

Transmission parameters are provided by the user.

For an Earth-to-Space transmission, transmission parameters can be provided by the user or can come from the selected ground station parameters (selected from the Ground Station database)

9.1.1. EQUIVALENT ISOTROPIC RADIATED POWER

RF-COMLINK user has the possibility to provide directly the Equivalent Isotropic Radiative Power of the transmitter $\boldsymbol{EIRP}$ value.

$$\boldsymbol{EIRP = P_{TX} G_{TX} \left(\frac{1}{L_{I-TX}}\right)}$$

RF-COMLINK can calculate the EIRP from defined sub-parameters $\boldsymbol{P_{TX}}$, $\boldsymbol{G_{TX}}$, and $\boldsymbol{L_{I-TX}}$

For Earth to Space links, the EIRP can be provided from a Ground Station selected from the provided .txt file of Ground Station database.

9.1.1.1. RF POWER

The Radio Frequency power provided by the transmitter (***Total provided RF Power*** $\boldsymbol{P_{TX}}$) shall be provided by the user

9.1.1.2. TRANSMITTER ANTENNA GAIN

The gain of the transmitter antenna (***Transmitter antenna Gain*** $\boldsymbol{G_{TX}}$) in the direction (θ, φ) of the receiver is directly provided by the user or calculated from an antenna pattern giving its characteristic function $F(\theta, \varphi)$, its directivity $D(\theta, \varphi)$ or its gain $G(\theta, \varphi)$ and its efficiency η, as a function of the emission direction (θ, φ)

$$D(\theta, \varphi) = 4\pi \frac{F(\theta, \varphi)}{\int_{4\pi} F(\theta, \varphi) d\Omega}$$

$$G(\theta, \varphi) = \eta * D(\theta, \varphi)$$

The antenna gain can be

- Either directly provided by the user (Manual setting)
- Either provided by the user as a radiation pattern MPM file (.txt file see § 12.1) giving $G(\theta, \varphi)$, $D(\theta, \varphi)$ or $F(\theta, \varphi)$ function of θ, φ
- Either calculated from a theoretical antenna type from a list and a formula giving its directivity (cf annex §12) and from its efficiency η

When the antenna gain is provided as a radiation pattern, the user shall provide the direction of the receiver (θ, φ)

When the antenna gain is provided as a radiation pattern, the radiation antenna pattern integral is computed to help the user knowing if the input file is a gain file or a directivity file. If the radiation pattern integral is 1 (0dB), the file is a directivity file and the user can define an antenna efficiency.

9.1.2. LOSSES AT EMMISSION

Losses at emission $\boldsymbol{L_{TX}}$ encompass two kind of losses :

- Insertion losses which represents the loss of signal power $\boldsymbol{L_{I-TX}}$ resulting from the insertion of a device in the transmitter to antenna transmission line
- Pointing losses which represents the loss of signal power $\boldsymbol{L_{P-TX}}$ resulting from antenna depointing wrt specified direction

We have

$$\boldsymbol{L_{TX} = L_{I-Tx} * L_{P-TX}}$$

9.2. PROPAGATION PARAMETERS

Propagation losses are the product of free space losses $\boldsymbol{L_s} = \left(\frac{\boldsymbol{4\pi R}}{\boldsymbol{\lambda}}\right)^{\boldsymbol{2}}$ depending on the distance $\boldsymbol{R}(\boldsymbol{t})$ between the transmitter and the receiver and the propagation losses $\boldsymbol{L_{propa}}$ including the attenuation $\boldsymbol{L_{atm}}$ due to the atmosphere and its content (rain, gaz, clouds…) and the polarization losses $\boldsymbol{L_{pol}}$.

$$\boldsymbol{L_{propa}} = \boldsymbol{L_{atm}} * \boldsymbol{L_{pol}}$$

9.2.1. TRANSMITTER/RECEIVER DISTANCE AND FREE SPACE LOSS

The distance between the transmitter and the receiver $\boldsymbol{R}(\boldsymbol{t})$ is

- Either given directly by the user
- Or provided by a .txt file at CIC standard protocol (**RD 12**) for a dynamic simulation

RF-COMLINK provides the free space losses $\boldsymbol{L_s}$:

$$\boldsymbol{L_s} = \left(\frac{\boldsymbol{4\pi R}}{\boldsymbol{\lambda}}\right)^{\boldsymbol{2}}$$

9.2.2. ATMOSPHERIC LOSSES

The atmospheric losses (or attenuations) $\boldsymbol{L_{atm}}$ is calculated using the CNES library "propa" (cf RD 4) providing the functions

- $Agaz$: Atmospheric gases attenuation in dB (ITU-R P.676-10)
- $Acloud$: Clouds attenuation in dB (ITU-R P. 840-6)
- $Arain$: Rain attenuation in dB (ITU-R P.618-12)
- $Iscint$: Scintillation in dB (ITU-R P.618-12)
- $Temperature$: Temperature (ITU-R P. 1510)
- WVC : Water vapour content (ITU-R P. 836-5)
- $rain - heigh$: Rain height (ITU-R P. 839-4)
- $rain - intensity$: Rain intensity in dB (ITU-R P. 837-6)
- TCC : Total Columnar content (ITU-R P. 840-6)
- $Nwet$: Wet term of refraction co-index (ITU R-P.453)

The calculation requires the elevation $Elev(t)$ of the satellite with respect to the ground station which is

- Either given directly by the user
- Or provided by a .txt file at CIC standard protocol (**RD 12**) for a dynamic simulation

Atmospheric losses include :

- Atmospheric gazes attenuation

$$A_{gaz}(dB) = Agaz(f, Elev, Temperature(GS_{lat}, GS_{long}), WVC((GS_{lat}, GS_{long}))$$

- Rain attenuation caused by a rainfall rate such that the probability to exceed it is p% at the considered location (or rain attenuation exceeded during p % of an average year)

$$A_{rain}(dB) = Arain\big(GS_{lat}, f, Elev, p, GS_{height}, rain - height\big(GS_{lat}, GS_{long}\big), rain - intensity\big(GS_{lat}, GS_{long}, 0.01\%\big), \tau\big)$$

p : Weather unavailability or rain attenuation from a calculated rainfall rate such that the probability to exceed it is p% at the considered location.
τ : tilt angle of the linearly polarized electric field vector with respect to the horizontal (for circular polarization use $\tau = 45°$)

- Clouds attenuation exceeded during p % of an average year

$$A_{cloud}(dB) = Acloud(f; Elev; TCC\big(GS_{lat}, GS_{long}, p\big))$$

$p =$ Total Columnar Content of liquid water exceeded during p% of an average year

- Scintillation standard deviation exceeded during p % of an average year

$$A_{Iscint}(dB) = Iscint(Nwet(GS_{lat}, GS_{long}); f; Elev; p; GS_{height}; \eta_r; D_{GS})$$

$p =$ Scintillation standard deviation exceeded during p% of an average year

$\eta_r; D_{GS}$: efficiency and diameter of Ground Station antenna

Total atmospheric losses (attenuation) are computed with the following formula (cf RD 5, Equ 63), with $p = \max(p, 1\%)$:

$$L_{atm}(dB) = A_{gaz} + \sqrt{(A_{rain} + A_{cloud})^2 + A_{Iscint}^2}$$

9.2.3. POLARIZATION LOSSES

Considered RF links in this application are circularly polarized (cf RD 1). Practically, propagation of the emitted Electro-magnetic field draws an ellipse in the plane orthogonal to the propagation. Transmitter antenna and Receiver antenna are characterized by their Axial Ratio $ar \geq 1$ defined as the ratio between the magnitude of the 2 orthogonal components of the electro-magnetic field (larger component over smaller component).

For perfectly circularly polarized antenna, $ar = 1$.

For linearly polarized antenna, $ar \gg 1$.

The user can provide the axial ratio of the Transmitter antenna $AR_{TX}(dB)$ and Receiver antenna $AR_{RX}(dB)$ in dB. For polarization losses calculations, linear values have to be taken into account (noted in minuscule ar_{TX} and ar_{RX}) with :

$$ar = 10^{\frac{AR}{20}}$$

The polarization losses L_{pol} is :

$$\frac{1}{L_{pol}} = \frac{1}{2}\left(1 + \frac{4ar_{TX}ar_{RX} + (ar_{TX}^2 - 1)(ar_{RX}^2 - 1)\cos 2\varphi}{(ar_{TX}^2 + 1)(ar_{RX}^2 + 1)}\right)$$

φ is the angle between axis of Transmitter radiation ellipse and Receiver radiation ellipse.

RF-COMLINK calculates the adverse polarization losses $\boldsymbol{L_{pol}}$ obtained with $\varphi = \frac{\pi}{2}$, the favorable case with $\varphi = 0$ and the design case with $\varphi = \frac{\pi}{4}$

9.3. RECEPTION PARAMETERS

Reception parameters are provided by the user.

For a Space-to-earth transmission, reception parameters can be provided by the user or can come from the selected ground station parameters (selected from the Ground Station database)

9.3.1. RECEIVER FIGURE OF MERIT

The user has the possibility to provide directly the receiver figure of merit.

$$\boldsymbol{\left(\frac{G}{T}\right)_{RX} = \frac{G_{RX}}{T_{sys}} * \left(\frac{1}{L_{RX}}\right)}$$

RF-COMLINK can calculate the receiver figure of merit from receiver antenna gain $\boldsymbol{G_{RX}}$, system temperature $\boldsymbol{T_{sys}}$ and implementation losses $\boldsymbol{L_{I-RX}}$ parameters.

9.3.2. RECEIVER ANTENNA GAIN

The gain of the receiver antenna (***Receiver antenna Gain*** $\boldsymbol{G_{RX}}$) in the direction (θ, φ) of the transmitter is directly provided by the user or calculated from an antenna pattern giving its characteristic function $F(\theta, \varphi)$, its directivity $D(\theta, \varphi)$ or its gain $G(\theta, \varphi)$ and its efficiency η, as a function of the emission direction (θ, φ)

$$D(\theta, \varphi) = 4\pi \frac{F(\theta, \varphi)}{\int_{4\pi} F(\theta, \varphi) d\Omega}$$

$$G(\theta, \varphi) = \eta * D(\theta, \varphi)$$

The antenna gain can be

- Either directly provided by the user (Manual setting)

- Either provided by the user as a radiation pattern MPM file (.txt file see § 12.1) giving $G(\theta, \varphi)$, $D(\theta, \varphi)$ or $F(\theta, \varphi)$ function of θ, φ
- Either calculated from a theoretical antenna type from a list and a formula giving its directivity (cf annex §12) and from its efficiency η

When the antenna gain is provided as a radiation pattern, the user shall provide the direction of the receiver (θ, φ)

When the antenna gain is provided as a radiation pattern, the radiation antenna pattern integral is computed to help the user knowing if the input file is a gain file or a directivity file. If the radiation pattern integral is 1 (0dB), the file is a directivity file and the user can define an antenna efficiency.

9.3.3. LOSSES AT RECEPTION

Losses at reception $\boldsymbol{L_{RX}}$ encompass two kind of losses :

- Insertion losses which represents the loss of signal power $\boldsymbol{L_{I-RX}}$ resulting from the insertion of a device in the antenna to receiver transmission line
- Pointing losses which represents the loss of signal power $\boldsymbol{L_{P-RX}}$ resulting from antenna depointing wrt specified direction

We have

$$\boldsymbol{L_{RX} = L_{I-RX} * L_{P-RX}}$$

9.3.4. SYSTEM NOISE TEMPERATURE

System noise temperature $\boldsymbol{T_{sys}}$ at ideal receiver input is the combination of

- the antenna noise temperature T_{ant} (noise from sources seen by the antenna) attenuated by the losses between antenna and receiver,
- the noise contribution of the feeder circuit between the antenna and the receiver
- the receiver additive noise temperature T_{rec}.

The user has the possibility to provide either directly the system noise temperature T_{sys} or the various contributors to T_{sys}.

In the case where the user provides the various contributors to $\boldsymbol{T_{sys}}$, he shall provide :

- $\boldsymbol{T_{circuit-RX}}$: the physical temperature of the feeder circuit between antenna and receiver
- $\boldsymbol{F_{rec}}$: the noise factor of the receiver yielding an additive noise temperature at the ideal receiver input $\boldsymbol{T_{rec} = (F_{rec} - 1)T_0}$ with convention temperature $\boldsymbol{T_0 = 290K}$.

System noise temperature $\boldsymbol{T_{sys}}$ at ideal receiver input is then :

$$\boldsymbol{T_{sys}} = \frac{\boldsymbol{T_{ant}}}{\boldsymbol{L_{I-RX}}} + \frac{\boldsymbol{L_{I-RX} - 1}}{\boldsymbol{L_{I-Rx}}} \boldsymbol{T_{circuit-Rx}} + \boldsymbol{T_{rec}}$$

9.3.4.1. ANTENNA NOISE TEMPERATURE

Noise from individual sources such as the Sun, atmospheric gases, the Earth's surface, etc., are usually given in terms of brightness temperature,T_b, proportional to source radiance at Radio frequencies ($hf \ll kT$). The antenna noise temperature at antenna input, T_{ant}, is the product of the antenna gain $G(\theta,\varphi)$ and the brightness temperature of the sources $T_b(\theta,\varphi)$ in the (θ,φ) direction :

$$T_{ant} = \frac{\iint_{4\pi} G(\theta,\varphi) T_b(\theta,\varphi) d\Omega}{4\pi}$$

The antenna noise temperature shall be provided by the user.

See **RD 17** for the calculation of this parameter.

9.3.5. RECEIVER FIGURE OF MERIT FROM GROUND STATION DATABASE

For a Space-earth link, the Ground Station data base can be used. It provides the Gain of the Ground Station antenna $\boldsymbol{G_{RX}}$ and the reference Ground Station figure of merit $\left(\frac{G}{T}\right)_{ref}$ at a reference satellite Elevation $\boldsymbol{El_{ref}}$ in clear sky conditions:

$$\left(\frac{\boldsymbol{G}}{\boldsymbol{T}}\right)_{\boldsymbol{ref}} = \frac{\boldsymbol{G_{RX}}}{\boldsymbol{T_{sky}}(\boldsymbol{clear - sky, El_{ref}}) + \boldsymbol{T_{station}}}$$

$\boldsymbol{El_{ref}} = 2°$ for X-band and above (>8GHz) links and $\boldsymbol{El_{ref}} = 5°$ otherwise

$\boldsymbol{T_{sky}}(\boldsymbol{clear - sky, El_{ref}})$ is the sky noise temperature in clear sky conditions at $\boldsymbol{El_{ref}}$ calculated from ITU-R P.618-12 and provided by CNES “propa” library (cf RD 4 T_{noise} function).

Station temperature $\boldsymbol{T_{station}}$ is the noise temperature of the Ground Station. It includes the noise temperature from the ground at station location and the station architecture performance (LNA noise factor, losses, ….) at elevation (El_{Ref}). It is retrieved thanks to precedent relation :

$$\boldsymbol{T_{station}} = \frac{\boldsymbol{G_{RX}}}{\left(\frac{\boldsymbol{G}}{\boldsymbol{T}}\right)_{\boldsymbol{ref}}} - \boldsymbol{T_{sky}}(\boldsymbol{clear - sky, El_{ref}})$$

Procedure described in **RD 11** is then followed to compute the Ground Station figure of Merit for the satellite Elevation El provided by the user (see propagation parameters §9.2.2)

$$\left(\frac{\boldsymbol{G}}{\boldsymbol{T}}\right)_{\boldsymbol{RX}} = \left(\frac{\boldsymbol{G}}{\boldsymbol{T}}\right)_{\boldsymbol{ref}} * \frac{\boldsymbol{T_{sky}}(\boldsymbol{clear - sky, El_{ref}}) + \boldsymbol{T_{station}}}{\boldsymbol{T_{sky}}(\boldsymbol{rainy - sky, El}) + \boldsymbol{T_{station}}}$$

Sky noise temperature in rainy sky conditions at elevation El, $T_{sky}(rainy - sky, El)$ is calculated from ITU-R P.618-12 and thanks to CNES “propa” library (cf RD 4 T_{noise} function) and from propagation parameters.

9.4. GENERAL LINK PARAMETERS

9.4.1. MODULATION LOSSES

Depending on the modulation choice, either all the transmitted power is used for data transmission or just a part of the transmitted power is used for data transmission, the remaining part of the power being used for the receiving process.

For example :

- For QPSK, BPSK, GMSK and 8PSK modulations, all the transmitted power is used for data transmission.
- For residual carrier transmission (SP-L/PM and PCM/PSK/PM), a part of the transmitted power is used on the residual central carrier (for SP-L/PM and PCM/PSK/PM) and the subcarrier harmonics (for PCM/PSK/PM).

Modulation losses refer to this implementation.

Modulation losses $\boldsymbol{L_{mod}}$ may only depend on the modulation index m which indicates by how much the phase (for PM signals) varies around its unmodulated level.

In case of BPSK (residual) (or SP-L/PM), modulation losses are equal to :

$$L_{mod} = \frac{1}{sin^2(m)}$$

In case of PCM/PSK/PM, modulation losses are equal to :

$$L_{mod} = \frac{1}{2.{J_1}^2(m)}$$

In other case (QPSK, BPSK (direct), GMSK, 4D-TCM-8PSK, 16APSK …) there is no modulation loss. Then, it can be considered that :

$$L_{mod} = 1$$

The user shall provide directly the modulation loss

9.4.2. IMPLEMENTATION LOSSES

Implementation loss $\boldsymbol{L_{impl}}$ (also named technological loss) account for distortion intermodulation, phase noise and other degradation introduced by real transmitter and difference between theoretical detection performance and the actual detection performance due to imperfections such as timing errors, frequency offsets, finite rise and fall times of waveforms.

10. Link budget

10.1. LINK BUDGET CALCULATION

Applying formula §8.3, RF-COMLINK computes

- $(\boldsymbol{C})_{calc}$, the calculated received power, especially for TC links (generally computed in dBm)
- $\left(\frac{C}{N_0}\right)_{calc}$, presented in dBHz
- $\left(\frac{E_b}{N_0}\right)_{calc}$, presented in dB
- required $\left(\frac{E_b}{N_0}\right)_{req}$, presented in dB
- margin between $\left(\frac{E_b}{N_0}\right)_{calc}$ and $\left(\frac{E_b}{N_0}\right)_{req}$
- power flux at earth level $(\boldsymbol{\phi})_{calc}$, in dBW/m^2
- power flux density at earth level $(PFD)_{calc}$, in dBW/m^2/Hz or dBW/m^2/4kHz

RF-COMLINK provides all files including the link budget values function of time, result of the satellite movement and orientation on its orbit, at CIC standard protocol (**RD 12**).

10.2. CALCULATION METHOD

The budget link can be seen as a sum (in dB) of contributors. In RD 1, the method of calculation is based on the knowledge of each contributor thanks to :

- its statistical distribution (UNIform, TRIangular or GAUssian).
- its Design value, noted D (D_k for contributor k)
- its Favorable value, noted F (F_k for contributor k), ($\mu + 3\sigma$ point)
- its Adverse value, noted A (A_k for contributor k) ($\mu - 3\sigma$ point)

It is important to note that, in dB, gain values are positives (except for negative gain for the antenna for example) and losses are negatives.

Knowing these parameters, it is possible to compute, for each contributor :

- its mean value, noted μ (μ_k for contributor k)
- its variance, noted σ^2 (σ_k for contributor k)

UNI : $\mu = (F + A)/2\,, \sigma^2 = (F - A)^2/12$
TRI : $\mu = (D + F + A)/3\,, \sigma^2 = \left((F - D)^2 + (A - D)^2 - (A - D)(F - D)\right)/18$
GAU : $\mu = (F + A)/2\,, \sigma^2 = (F - A)^2/36$

3 budget links are then performed :

The nominal case budget link :

$$X_{nominal} = \sum_{k=1}^{n} \pm D_k$$

There is a "+" sign if the contributor is part of the numerator of the budget link equation.
There is a "-" sign if the contributor is part of the denominator of the budget link equation.

The N sigma budget link :

$$X_{N-sigmas} = \sum_{k=1}^{n} \pm \mu_k - N. \sqrt{\sum_{k=1}^{n} {\sigma_k}^2}$$

Generally, N = 3.

The worst case RSS budget link :

$$X_{RSS} = \sum_{k=1}^{n} \pm D_k - \sqrt{\sum_{k=1}^{n} (A_k - D_k)^2}$$

In these case, the quantity X could be :

- $\frac{C}{N_0}$
- C (the received level, especially for TC link)
- $\left(\frac{E_b}{N_0}\right)_{calc}$
- Power flux at Earth level
- Power flux density at Earth level

10.3. LINK BUDGET PRESENTATION

Link budget presentation is extracted from CCSDS recommendation RD 1 at §4.1.2 TELECOMMUNICATIONS LINK DESIGN CONTROL TABLE

The link budget is presented in dB units.

The link budget includes

- An input table dedicated to general communications system operating conditions (cf §7 and RD 1 at §4.1.2)
- An input table recalling the modulation characteristics
- A table dedicated to transmission input parameters (cf §9.1 and RD 1 at §4.1.2)
- A table dedicated to propagation input parameters (cf §9.2 and RD 1 at §4.1.2)
- A table dedicated to reception input parameters (cf §9.3 and RD 1 at §4.1.2)
- A table dedicated to link budget (cf RD 1 at §4.1.2)

11. Data Handling budget

The user has the possibility to use a payload data generation profile providing the data flux function of time $\boldsymbol{R_{pl}(t)}$ $(\boldsymbol{bits/s})$ of the satellite payload.

The user has the possibility to define a maximum memory capacity $\boldsymbol{C_{mem,max}}$ $(\boldsymbol{bits})$ and an initial memory usage $\boldsymbol{C_{mem}(0)}$

RF-COMLINK provides a simulation of the memory load taking into account the data flux of the payload $\boldsymbol{R_{pl}(t)}$ $(\boldsymbol{bits/s})$, and the Ground Station visibility provided by IDM-CIC/Simu-CIC.

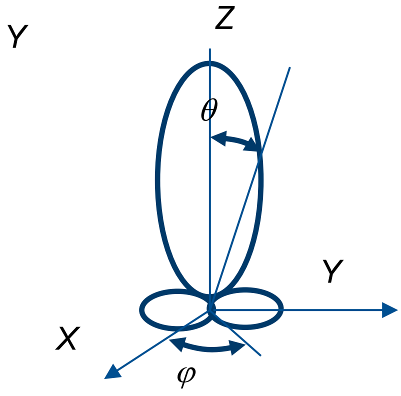
A “Payload telemetry_DATA_MEMORY_LOAD.txt” file and a “Payload telemetry_CUMULATED_DATA_DOWNLOADED.txt” file are provided.

12. Annex : Theoretical antenna radiation pattern

Ref : Odile Picon et coll. les Antennes, Théorie, conception et applications

12.1. CONVENTIONS

Z axis is the antenna symmetry axis



Relation between Directivity $D(\theta,\varphi)$ and normalized antenna radiation pattern $F(\theta,\varphi)$ is :

$$D(\theta,\varphi) = 4\pi \frac{F(\theta,\varphi)}{\int_{4\pi} F(\theta,\varphi)d\Omega}$$

For a given antenna, directivity at emission and reception are the same :

$$D_r(\theta,\varphi) = D_e(\theta,\varphi)$$

Antenna gain files shall be compatible with standard MPM files from the CIC protocol Standard **RD 12**. The data will be organized in 6 colons with the following definitions and conventions:

- Colon 1 : theta (θ) in degree $(-180 \leq \theta \leq +180)$
- Colon 2 : phi (φ) in degree $(0 \leq \varphi \leq 180)$
- Colon 3 : Right circular polarization gain G_+ in dB
- Colon 4 : Right circular polarization phase Φ_+ (in degree)
- Colon 5 : Left circular polarization gain G_- in dB
- Colon 6 : Left circular polarization phase Φ_- (in degree)

An exemple of such un file is given hereafter

CIC_MPM_VERS = 1.0
CREATION_DATE = 2020-03-01T13:44:14Z

```
ORIGINATOR = CIC
META_START
COMMENT labels Theta, Phi, Left circular polarization amplitude, Left circular polarization phase,Right circular polarization amplitude, Right circular polarization phase
USER_DEFINED_PROTOCOL = NONE
USER_DEFINED_CONTENT = ANTENNA_GAIN
USER_DEFINED_SIZE = 6
USER_DEFINED_TYPE = REAL
USER_DEFINED_UNIT = [deg, deg, dB, deg, dB, deg]
META_STOP

-180.00   0.00   -58.91856859   65.58659982   -10.28455546   33.77261637
-179.00   0.00   -57.90221853   54.33597922   -10.28228397   25.69095435
-178.00   0.00   -57.20207409   40.99947908   -10.28769747   17.99537886
-177.00   0.00   -56.64741444   25.54662854   -10.30135761   10.68767386
Etc….
```

Total antenna gain G is calculated as follow :

$$G = G_{+} + G_{-}$$

12.2. OMNIDIRECTIONAL ANTENNA

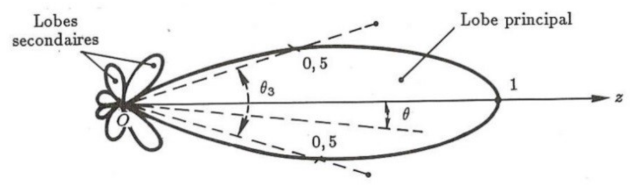
$$D(\theta, \varphi) = 1$$

12.3. GENERIC ANTENNA OF HALF POWER APERTURE θ_{3dB}

The characteristic function is

$$F(\theta, \varphi) = e^{-(\ln 2)\left(\frac{2\theta}{\theta_{3dB}}\right)^{2}}$$

$\theta = \frac{\theta_{3dB}}{2}$ is the angle at half power



The visualized radiation pattern is the directivity

$$D(\theta, \varphi) = 4\pi * \frac{F(\theta, \varphi)}{\int_{4\pi} F(\theta, \varphi) d\Omega}$$

12.4. UNIFORM CIRCULAR APERTURE

D : Diameter of the circular aperture

Valid for $\frac{D}{\lambda} \gg 1$ and $\theta \ll 1$

The E.M. field is constant over the aperture. The visualized radiation pattern is the directivity function :

$$D(\theta) = \left(\frac{\pi D}{\lambda}\right)^2 \left(\frac{2J_1\left(\frac{\pi D}{\lambda}\sin\theta\right)}{\frac{\pi D}{\lambda}\sin\theta}\right)^2 \text{ for } -\frac{\pi}{2} < \theta < \frac{\pi}{2}, \qquad D(\theta) = 0 \text{ elsewhere}$$

J_1 is Bessel function of the 1st order

12.5. DIPOLE

$$D(\theta) = \frac{3}{2}\sin^2\theta$$

12.6. WIRE ANTENNA OF LENGTH $n\lambda$

$$F(\theta) = \left(\frac{\cos(n\pi\cos\theta) - \cos n\pi}{\sin\theta}\right)^2$$

12.7. HALF WAVELENGTH ANTENNA

$$D(\theta) = 1.64\left(\frac{\cos\frac{\pi}{2}\cos\theta}{\sin\theta}\right)^2$$

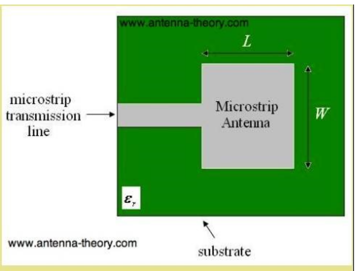
12.8. WIRE ANTENNA OF LENGTH $n\lambda$ WITH MASS PLATE

Twice the directivity of wire antenna of length $2n\lambda$

12.9. UNIFORM RECTANGULAIRE APERTURE L, l

$$F(\theta,\varphi) = \operatorname{sinc}\left(\frac{\pi L}{\lambda}\sin\theta\cos\varphi\right)\operatorname{sinc}\left(\frac{\pi l}{\lambda}\sin\theta\sin\varphi\right)$$

12.10. MICROSTRIP ANTENNA L, l



(a) Top View of Patch Antenna

$$F(\theta,\varphi) = \operatorname{sinc}\left(\frac{\pi L}{\lambda}\sin\theta\cos\varphi\right)\cos\left(\frac{\pi l}{\lambda}\sin\theta\cos\varphi\right)\sqrt{\cos^2\varphi + \cos^2\theta\sin^2\varphi}$$

12.11. HELIX ANTENNA

http://www.antenna-theory.com/antennas/travelling/helix.php

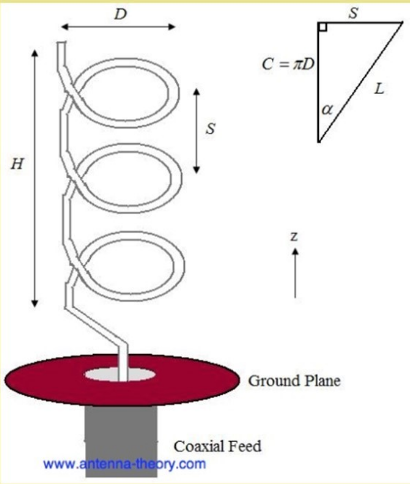


Figure 1. Geometry of Helical Antenna.

$$F(\theta) = \sin\left(\frac{\pi}{2N}\right)\cos\theta\,\frac{\sin\left(\frac{N\Omega}{2}\right)}{\sin\left(\frac{\Omega}{2}\right)}$$

$$\Omega = \frac{2\pi}{\lambda}S(\cos\theta - 1) - \pi\left(2 + \frac{1}{N}\right)$$

$$N = \frac{H}{S}$$

$$G_{max} = \frac{6.2\pi^2 D^2 NS}{\lambda^3}$$

$$HPBW(\mathrm{deg}) = \frac{65\lambda}{\pi D\sqrt{\frac{NS}{\lambda}}}$$

13. Annex : Modulation Database description

13.1. INTRODUCTION

This chapter presents the database of modulations provided with the RF-COMLINK application.

13.2. GENERAL DESCRIPTION OF THE MODULATION DATABASE

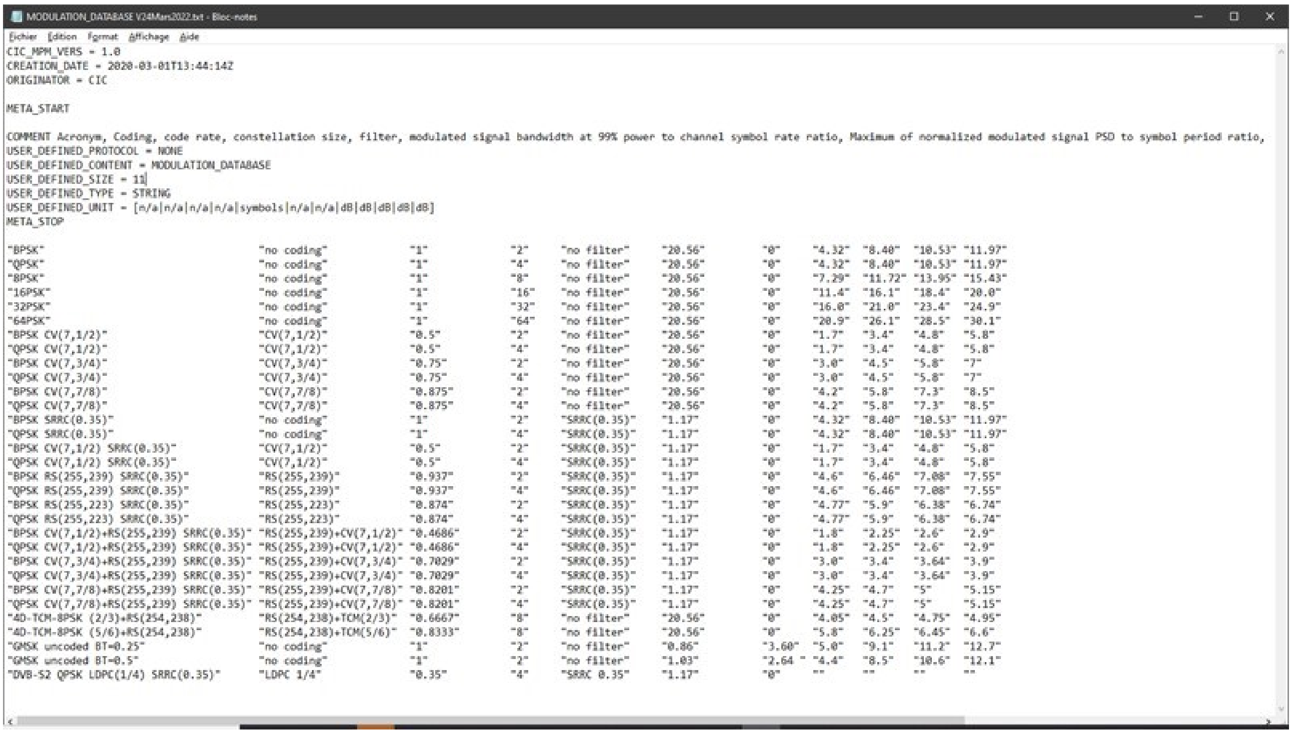
In RF-COMLINK application, a modulation is characterized by (see §6)

- its coding and code rate,
- its constellation size,
- the modulated signal filter,
- the modulated signal Power spectral density characterized by the modulated signal bandwidth at 99% power to channel symbol rate ratio and by the maximum of normalized modulated signal PSD to symbol period ratio,
- its BER function of $\frac{E_b}{N_0}$

BER function of $\frac{E_b}{N_0}$ for a modulation is described in a simplified manner as a discrete set of BER level, 10^{-2}, 10^{-4}, 10^{-6}, 10^{-8} and a logarithmic regression.

Modulations characteristics are provided in a database as a "MODULATION_DATABASE.txt" file with a header at CIC Standard protocol (**RD 12RD 12**), and with 11 colons :

1. Acronym (text)
2. Coding (text),
3. code rate ρ_{code},
4. constellation size M,
5. filter (text),
6. modulated signal bandwidth at 99% power $B_{99\%}$ to channel symbol rate R_{chs} ratio $\beta_{mod} = \frac{B_{99\%}}{R_{chs}}$,
7. Maximum of normalized modulated signal PSD to symbol period ratio T_{chs}, $\alpha_{mod} = \frac{PSD_{max}}{T_{chs}}$
8. Eb/N0@BER_1E-2
9. Eb/N0@BER_1E-4
10. Eb/N0@BER_1E-6
11. Eb/N0@BER_1E-8



```
CIC_MPM_VERS = 1.0
CREATION_DATE = 2020-03-01T13:44:14Z
ORIGINATOR = CIC

META_START

COMMENT Acronym, Coding, code rate, constellation size, filter, modulated signal bandwidth at 99% power to channel symbol rate ratio, Maximum of normalized modulated signal PSD to symbol period ratio,
USER_DEFINED_PROTOCOL = NONE
USER_DEFINED_CONTENT = MODULATION_DATABASE
USER_DEFINED_SIZE = 11
USER_DEFINED_TYPE = STRING
USER_DEFINED_UNIT = [n/a|n/a|n/a|n/a|symbols|n/a|n/a|dB|dB|dB|dB|dB]
META_STOP

"BPSK"                                  "no coding"             "1"           "2"    "no filter"    "20.56"       "0"     "4.32"  "8.40"  "10.53" "11.97"
"QPSK"                                  "no coding"             "1"           "4"    "no filter"    "20.56"       "0"     "4.32"  "8.40"  "10.53" "11.97"
"8PSK"                                  "no coding"             "1"           "8"    "no filter"    "20.56"       "0"     "7.29"  "11.72" "13.95" "15.43"
"16PSK"                                 "no coding"             "1"           "16"   "no filter"    "20.56"       "0"     "11.4"  "16.1"  "18.4"  "20.0"
"32PSK"                                 "no coding"             "1"           "32"   "no filter"    "20.56"       "0"     "16.0"  "21.0"  "23.4"  "24.9"
"64PSK"                                 "no coding"             "1"           "64"   "no filter"    "20.56"       "0"     "20.9"  "26.1"  "28.5"  "30.1"
"BPSK CV(7,1/2)"                        "CV(7,1/2)"             "0.5"         "2"    "no filter"    "20.56"       "0"     "1.7"   "3.4"   "4.8"   "5.8"
"QPSK CV(7,1/2)"                        "CV(7,1/2)"             "0.5"         "4"    "no filter"    "20.56"       "0"     "1.7"   "3.4"   "4.8"   "5.8"
"BPSK CV(7,3/4)"                        "CV(7,3/4)"             "0.75"        "2"    "no filter"    "20.56"       "0"     "3.0"   "4.5"   "5.8"   "7"
"QPSK CV(7,3/4)"                        "CV(7,3/4)"             "0.75"        "4"    "no filter"    "20.56"       "0"     "3.0"   "4.5"   "5.8"   "7"
"BPSK CV(7,7/8)"                        "CV(7,7/8)"             "0.875"       "2"    "no filter"    "20.56"       "0"     "4.2"   "5.8"   "7.3"   "8.5"
"QPSK CV(7,7/8)"                        "CV(7,7/8)"             "0.875"       "4"    "no filter"    "20.56"       "0"     "4.2"   "5.8"   "7.3"   "8.5"
"BPSK SRRC(0.35)"                       "no coding"             "1"           "2"    "SRRC(0.35)"   "1.17"        "0"     "4.32"  "8.40"  "10.53" "11.97"
"QPSK SRRC(0.35)"                       "no coding"             "1"           "4"    "SRRC(0.35)"   "1.17"        "0"     "4.32"  "8.40"  "10.53" "11.97"
"BPSK CV(7,1/2) SRRC(0.35)"             "CV(7,1/2)"             "0.5"         "2"    "SRRC(0.35)"   "1.17"        "0"     "1.7"   "3.4"   "4.8"   "5.8"
"QPSK CV(7,1/2) SRRC(0.35)"             "CV(7,1/2)"             "0.5"         "4"    "SRRC(0.35)"   "1.17"        "0"     "1.7"   "3.4"   "4.8"   "5.8"
"BPSK RS(255,239) SRRC(0.35)"           "RS(255,239)"           "0.937"       "2"    "SRRC(0.35)"   "1.17"        "0"     "4.6"   "6.46"  "7.08"  "7.55"
"QPSK RS(255,239) SRRC(0.35)"           "RS(255,239)"           "0.937"       "4"    "SRRC(0.35)"   "1.17"        "0"     "4.6"   "6.46"  "7.08"  "7.55"
"BPSK RS(255,223) SRRC(0.35)"           "RS(255,223)"           "0.874"       "2"    "SRRC(0.35)"   "1.17"        "0"     "4.77"  "5.9"   "6.38"  "6.74"
"QPSK RS(255,223) SRRC(0.35)"           "RS(255,223)"           "0.874"       "4"    "SRRC(0.35)"   "1.17"        "0"     "4.77"  "5.9"   "6.38"  "6.74"
"BPSK CV(7,1/2)+RS(255,239) SRRC(0.35)" "RS(255,239)+CV(7,1/2)" "0.4686"      "2"    "SRRC(0.35)"   "1.17"        "0"     "1.8"   "2.25"  "2.6"   "2.9"
"QPSK CV(7,1/2)+RS(255,239) SRRC(0.35)" "RS(255,239)+CV(7,1/2)" "0.4686"      "4"    "SRRC(0.35)"   "1.17"        "0"     "1.8"   "2.25"  "2.6"   "2.9"
"BPSK CV(7,3/4)+RS(255,239) SRRC(0.35)" "RS(255,239)+CV(7,3/4)" "0.7029"      "2"    "SRRC(0.35)"   "1.17"        "0"     "3.0"   "3.4"   "3.64"  "3.9"
"QPSK CV(7,3/4)+RS(255,239) SRRC(0.35)" "RS(255,239)+CV(7,3/4)" "0.7029"      "4"    "SRRC(0.35)"   "1.17"        "0"     "3.0"   "3.4"   "3.64"  "3.9"
"BPSK CV(7,7/8)+RS(255,239) SRRC(0.35)" "RS(255,239)+CV(7,7/8)" "0.8201"      "2"    "SRRC(0.35)"   "1.17"        "0"     "4.25"  "4.7"   "5"     "5.15"
"QPSK CV(7,7/8)+RS(255,239) SRRC(0.35)" "RS(255,239)+CV(7,7/8)" "0.8201"      "4"    "SRRC(0.35)"   "1.17"        "0"     "4.25"  "4.7"   "5"     "5.15"
"4D-TCM-8PSK (2/3)+RS(254,238)"         "RS(254,238)+TCM(2/3)"  "0.6667"      "8"    "no filter"    "20.56"       "0"     "4.05"  "4.5"   "4.75"  "4.95"
"4D-TCM-8PSK (5/6)+RS(254,238)"         "RS(254,238)+TCM(5/6)"  "0.8333"      "8"    "no filter"    "20.56"       "0"     "5.8"   "6.25"  "6.45"  "6.6"
"GMSK uncoded BT=0.25"                  "no coding"             "1"           "2"    "no filter"    "0.86"        "3.60"  "5.0"   "9.1"   "11.2"  "12.7"
"GMSK uncoded BT=0.5"                   "no coding"             "1"           "2"    "no filter"    "1.03"        "2.64 " "4.4"   "8.5"   "10.6"  "12.1"
"DVB-S2 QPSK LDPC(1/4) SRRC(0.35)"      "LDPC 1/4"              "0.35"        "4"    "SRRC 0.35"    "1.17"        "0"     ""      ""      ""      ""
```

Values can be omitted

13.3. MODULATION ACRONYM

A text for the modulation acronym

13.4. CODING

A text for the various codes implemented by the modulation

13.5. MODULATION CODE RATE

The modulation code rate ρ_{code} is the ratio of the length of uncoded word k over the length of coded word n. It is the product of code rates of individual codes implemented by the modulation.

If M is the size of the constellation and R_b is the (useful) information bit rate, the channel symbol rate is :

$$R_{chs} = \frac{R_b}{\log_2 M * \rho_{code}}$$

13.5.1. NO CODING

No error correcting is used

$\rho_{code} = 1$

13.5.2. CONVOLUTIONAL CODES

CV(K,n/k)

Length K, code rate $\rho_{code} = \frac{k}{n}$

13.5.3. REED SOLOMON

RS(n,k)

code rate $\rho_{code} = \frac{k}{n}$

13.5.4. TCM

TCM(n/k)

code rate $\rho_{code} = \frac{k}{n}$

13.5.5. LDPC

LDPC(n/k)

code rate $\rho_{code} = \frac{k}{n}$

13.6. CONSTELLATION SIZE

13.6.1. M-PSK

Constellation size : M

13.6.2. GMSK

Constellation size : $M = 4$

13.7. FILTER TYPE

Text for the type of filter for the pulse modulation

13.8. MODULATED SIGNAL POWER SPECTRAL DENSITY

A modulation is characterized by the Power Spectral Density $\Phi_{ss}(f)$ of the modulated signal $s(t)$. If f_c is the carrier frequency and $x(t)$ the modulating signal, the modulated signal Power Spectral Density $\Phi_{ss}(f)$ is half the complex modulating signal PSD offset by f_c :

$$\Phi_{ss}(f) = \frac{1}{2}\Phi_{xx}(f - f_c)$$

The database provides the modulated signal Power Spectral Density bandwidth at 99% power $B_{99\%}$ and the normalized Power Spectral Density maximum PSD_{max}.

The normalized Power Spectral Density is $\frac{\Phi_{xx}(f)}{\int_{f=-\infty}^{f=+\infty} \Phi_{xx}(f)\, df}$

$B_{99\%}$ is provided relatively to the channel symbol rate ratio R_{chs} through the modulation efficiency β_{mod}

$$\beta_{mod} = \frac{B_{99\%}}{R_{chs}}$$

$$\frac{\int_{f=f_c-\frac{B_{99\%}}{2}}^{f=f_c+\frac{B_{99\%}}{2}} \Phi_{xx}(f)df}{\int_{f=-\infty}^{f=+\infty} \Phi_{xx}(f)df} = 0.99$$

PSD_{max} is provided relatively to the channel symbol period T_{chs} through the ratio $\alpha_{mod} = \frac{PSD_{max}}{T_{chs}}$.

$$PSD_{max} = \max_f \frac{\Phi_{xx}(f)}{\int_{f=-\infty}^{f=+\infty} \Phi_{xx}(f)\, df}$$

13.8.1. NO FILTER

The PSD of a bi-phase pulse modulation without filtering is

$$\Phi_{xx}(f) = \sigma_s^2 T_{chs}\, sinc^2(\pi f T_{chs})$$

We have $\frac{\int_{f=-\frac{10.28}{T_{chs}}}^{f=+\frac{10.28}{T_{chs}}} \Phi_{xx}(f)df}{\int_{f=-\infty}^{f=+\infty} \Phi_{xx}(f)df} = 0.99.$

The modulated signal bandwidth at 99% power is then $B_{99\%} = \frac{20.56}{T_{chs}}$ and $\beta_{mod} = 20.56$

Maximum of normalized modulated signal PSD to symbol period ratio is $\alpha_{mod} = 1$ (0dB)

13.8.2. SRRC

Transfer function of SRRC filter is (see **RD 20**)

$$H_{SRRC}(f) = \begin{cases} \sqrt{\mathrm{T_{chs}}} \quad \text{for } |f|\mathrm{T_{chs}} < \frac{1-\alpha}{2} \\ \sqrt{\mathrm{T_s}} \sqrt{\frac{1}{2} + \frac{1}{2}\cos\left(\frac{\pi}{\alpha}\left(|f|\mathrm{T_{chs}} - \frac{1-\alpha}{2}\right)\right)} \quad \text{for } \frac{1-\alpha}{2} < |f|\mathrm{T_{chs}} < \frac{1+\alpha}{2} \\ 0 \quad \text{elsewhere} \end{cases}$$

$$\int_{f=-\infty}^{f=+\infty} |H_{SRRC}(f)|^2 df = 1$$

For $\alpha = 0.25$, we have $\int_{f=-1.103*\frac{1}{2T_{chs}}}^{f=+1.103*\frac{1}{2T_{chs}}} |H_{SRRC}(f)|^2 df = 0.99$,then $B_{99\%} = \frac{1.103}{T_{chs}}$ and $\beta_{mod} = 1.103$

For $\alpha = 0.35$, we have $\int_{f=-1.167*\frac{1}{2T_{chs}}}^{f=+1.167*\frac{1}{2T_{chs}}} |H_{SRRC}(f)|^2 df = 0.99$,then $B_{99\%} = \frac{1.167}{T_{chs}}$ and $\beta_{mod} = 1.167$

For $\alpha = 0.5$, we have $\int_{f=-1.268*\frac{1}{2T_{chs}}}^{f=+1.268*\frac{1}{2T_{chs}}} |H_{SRRC}(f)|^2 df = 0.99$,then $B_{99\%} = \frac{1.268}{T_{chs}}$ and $\beta_{mod} = 1.268$

Maximum of normalized modulated signal PSD to symbol period ratio is $\alpha_{mod} = 1$ (0dB)

13.8.3. GMSK

See **RD 20**, Table B-1 and Table B-2

- For BT=0.25, $\beta_{mod} = 0.86$
- For BT=0.5, $\beta_{mod} = 1.03$

For the normalized Power Spectral Density maximum, simulations give (see H. Guillon email)

- For BT=0.25, $\alpha_{mod} = 3.6$ dB
- For BT=0.5, $\alpha_{mod} = 2.64$ dB

13.9. BER PERFORMANCE

Bit Error Rate performance is given at 4 point : $BER = 10^{-2}$, $BER = 10^{-4}$, $BER = 10^{-6}$, $BER = 10^{-8}$

13.9.1. BPSK/QPSK, NO CODING

$$BER = \frac{1}{2} erfc\left(\sqrt{\left(\frac{E_b}{N_0}\right)_{req}}\right)$$

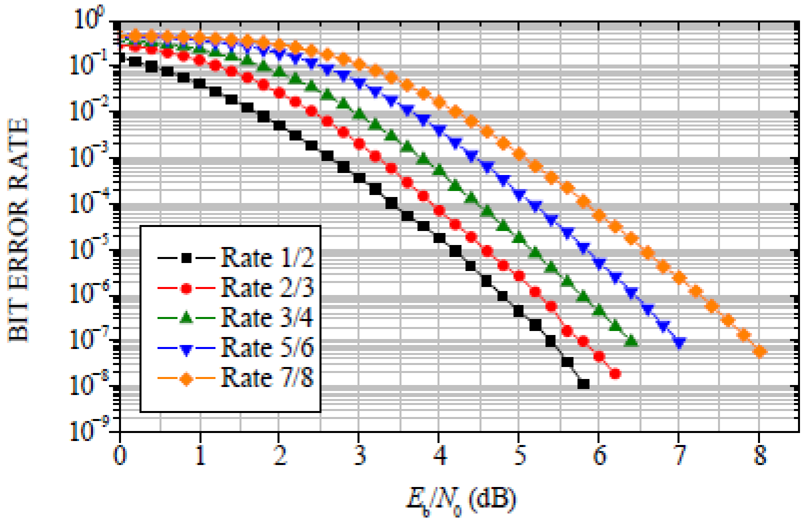
13.9.2. M-PSK, NO CODING

For M>2

$$BER = \frac{1}{\log_2 M} erfc\left(\sqrt{\log_2 M \frac{E_b}{N_0}} \sin\frac{\pi}{M}\right)$$

13.9.3. M-PSK, CV

See **RD 18**



NOTE – The performance of the original rate-1/2 code is reported for comparison.

Figure 4-10: Bit Error Rate Performance of the CCSDS Punctured Convolutional Codes

13.9.4. RS

See **RD 18**

Reed Solomon coding is (n, k).

m : number of bits per used symbol

$n = 2^m - 1 = k + 2E$ length of coded word, with k information symbols and $2E$ control symbols.

The code allows to correct $E = (n - k)/2$ errors. It adds at most E errors.

If it can be assumed that symbol errors occur independently with probability V_s at the RS decoder input, the RS decoder output symbol error probability P_s can be approximated by

$$P_s \approx V_s \sum_{i=E}^{i=n-1} \binom{n-1}{i} {V_s}^i (1 - V_s)^{n-i-1}$$

for $V_s \ll 1$,

$$P_s \approx \binom{\mathrm{n}-1}{\mathrm{E}} {V_s}^{E+1}$$

Moreover, we have $V_s = 1 - (1 - V_b)^m$ and $P_b \approx \frac{V_b}{V_s} * P_s$ where V_b is the bit error probability at the decoder input and P_b is the bit error probability at the decoder output.

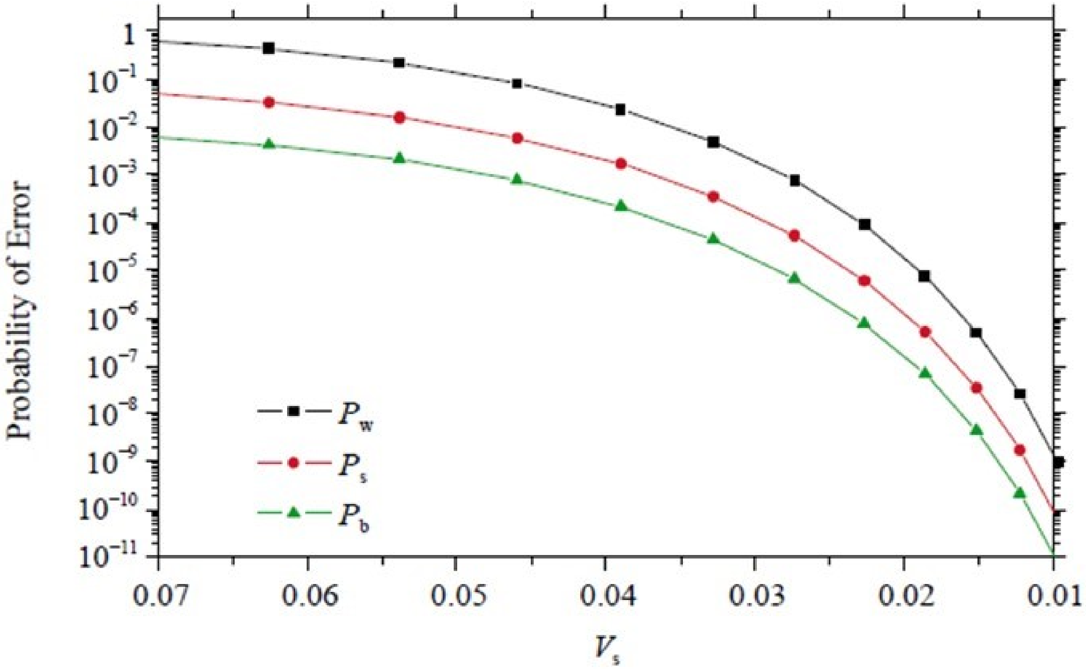


Figure 5-5: P_w, P_s, and P_b for the (255,223) RS Code with E=16

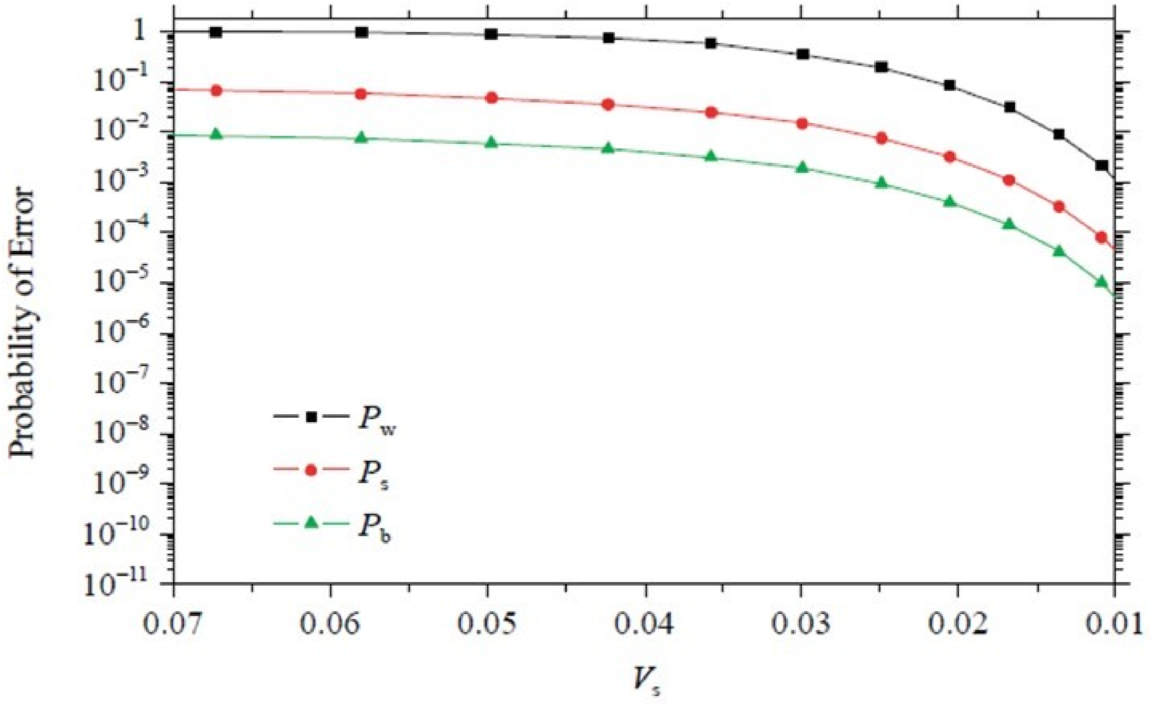
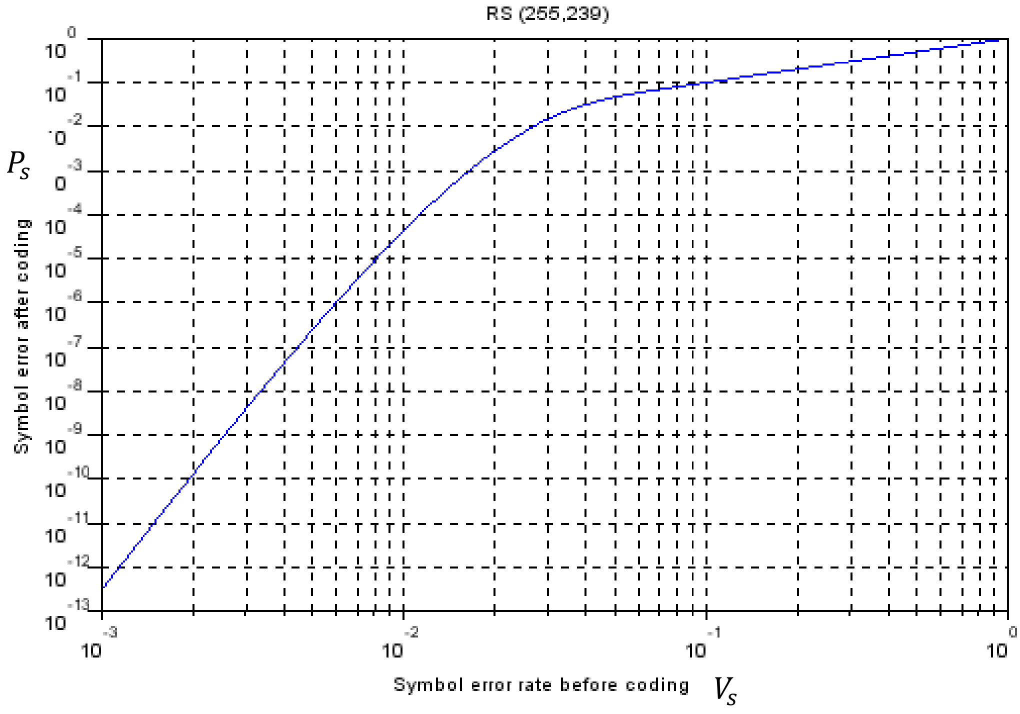


Figure 5-6: P_w, P_s, and P_b for the (255,239) RS Code with E=8



13.9.5. M-PSK, CV+RS

See **RD 18**

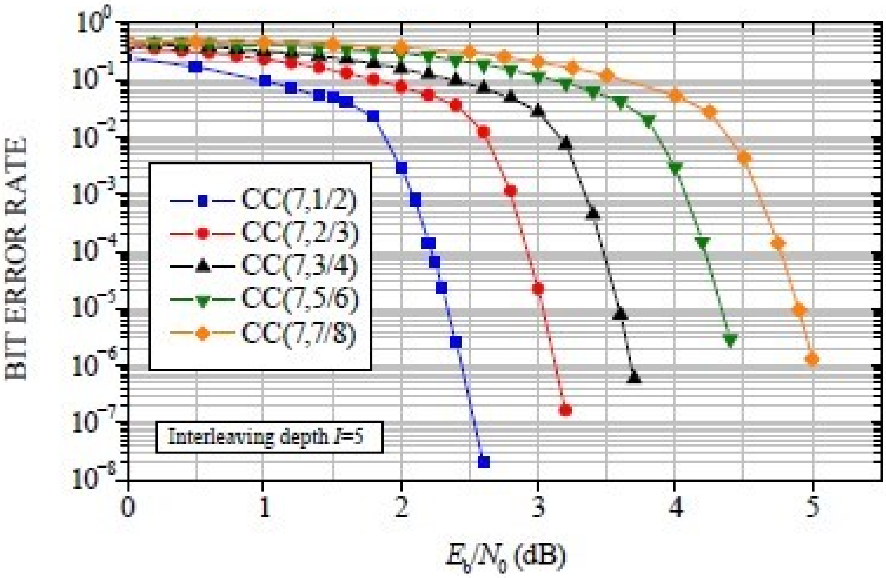


Figure 6-11: Bit Error Rate Simulated Performance of the CCSDS Concatenated Scheme with Outer E=16 Reed-Solomon Code (255,223) and Inner Punctured Convolutional Codes, Using Finite Interleaving with I=5

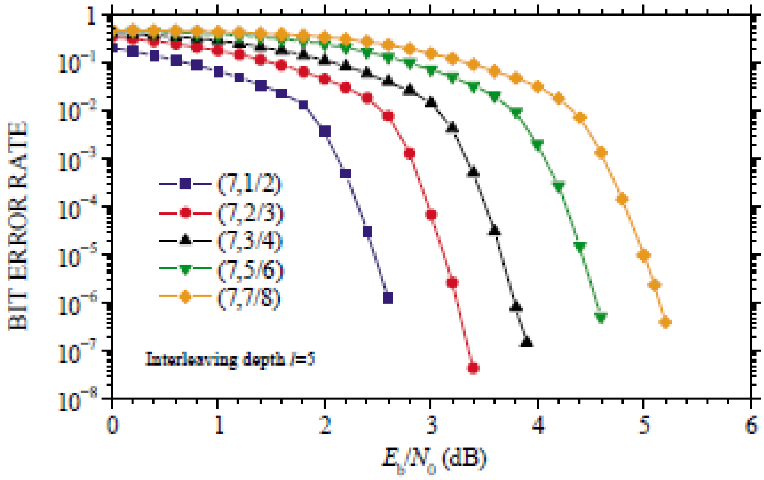


Figure 6-13: Bit Error Rate Simulated Performance of the CCSDS Concatenated Scheme with Outer E=8 Reed-Solomon Code (255,239) and Inner Punctured Convolutional Codes, Using Finite Interleaving with I=5

13.9.6. DVB-S2

(see **RD 19**)

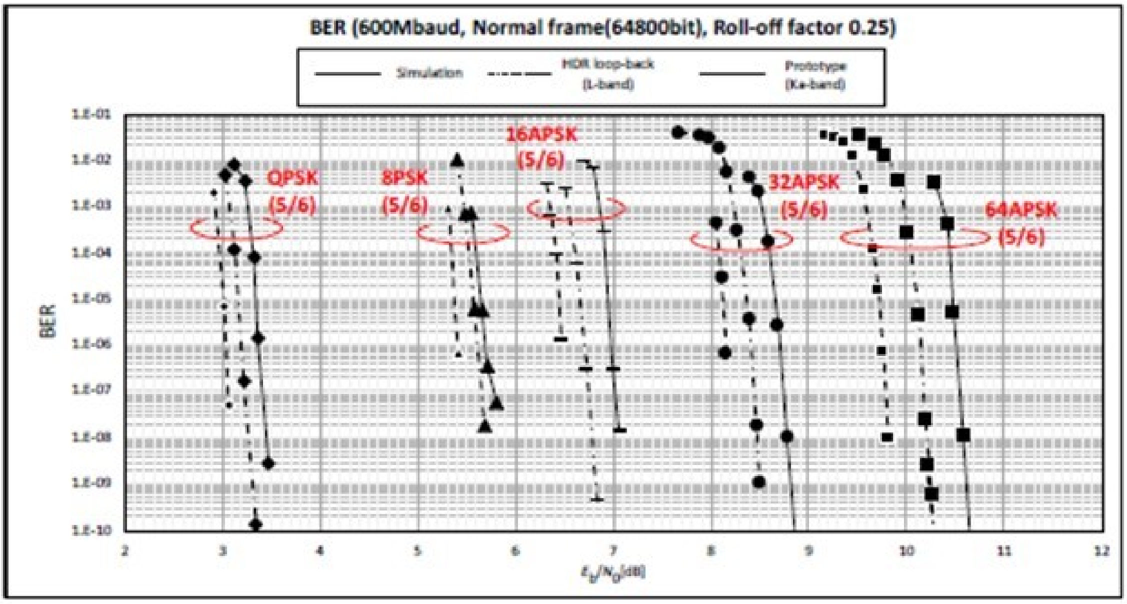


Figure H-4: BER Results for 0.25 Roll-Off

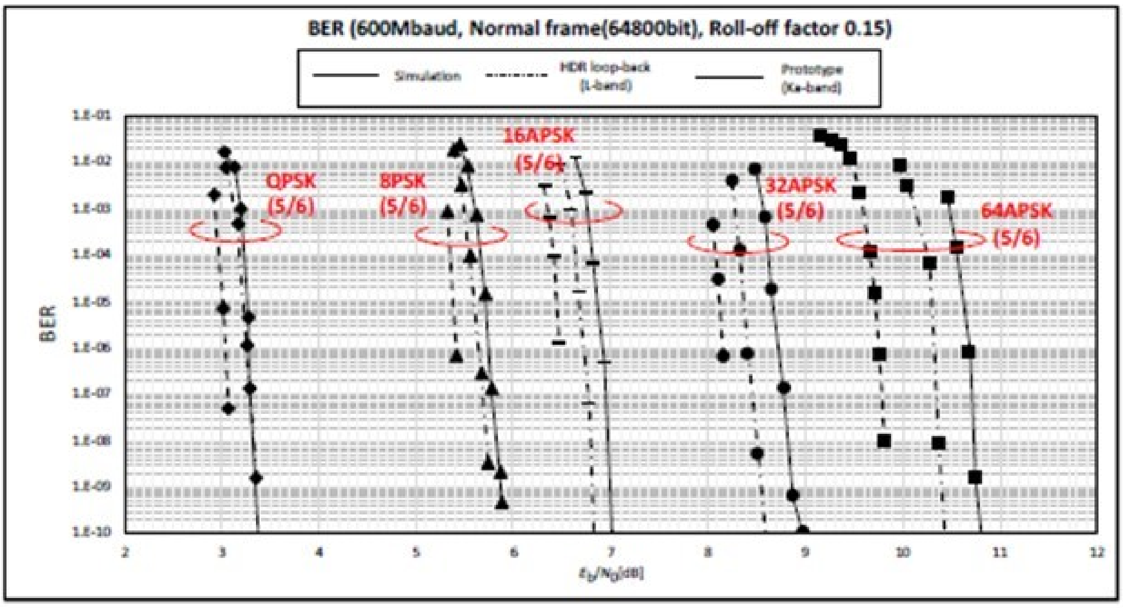


Figure H-5: BER Results for 0.15 Roll-Off