Designing a point-to-point link for high-speed backhauling

1. Introduction to the project

This paper discusses the design of a high-speed point-to-point link, specifically intended for backhauling applications. A backhaul network is defined as the portion of a hierarchical network that includes the intermediate links between the core network and the different peripheral subnets.

2. Project specifications

The project focuses on the creation of a complete link, which includes the following components and functionalities:

- **RF Transmitter (I/Q):** Must include real components with output power and linearity characteristics, including PA (Power Amplifier), Mix (Mixer), Drivers, and Antennas.
- **RF Receiver (I/Q):** Must include real components with linearity and noise characteristics, including LNAs (Low Noise Amplifiers), Mixes (Mixers) and Antennas.
- **Overall Link**: It must include baseband simulations (RX and TX) and the RF section.
- **Link Budget**: Must be calculated in "clear sky" condition with a margin of 4 dB.

The general specifications required for the link are as follows:

- **Band**: E-band, $71\text{-}76\ GHz\ /\ 81\text{-}86\ GHz$
- **Data Rate**: $100\text{-}300\ Mbps$
- **Modulation**: $64QAM - 512\ QAM$
- **Distance**: $1\ km - 2\ km$

The following specifications were chosen for the realization of the project:

- **Band**: E-band, $72\ GHz$
- **Data Rate**: $150\ Mbps$
- Modulation: $64\ QAM$
- Distance: $1\ km$
- Alpha (Roll-off Factor): 0.2
- bps (Bits per symbol): 6 (for $64QAM)$
- FEC (Forward Error Correction): $2/3$

A table is provided showing QAM modulation levels, bits/symbol, and incremental capacity gain. In addition, there is a graph of the Bit Error Rate (BER) for 64 QAM and different encoding values ($FECs$) and guard intervals, showing the $Eb/N0\ values$ needed for different BERs.

3. Components and link budget calculation

Antenna E-Band

The antenna model chosen is SB1-W800yyy with a diameter of 388 mm. The document includes a datasheet showing the characteristics of the "RFS E-Band Microwave Antennas" for back-hauling and front-hauling applications, mentioning ETSI Class 3 and FCC compliant 1ft and 2ft models.

BPF E-Band (E-Band Band Bandpass Filter)

The filter selected is the SWF-74305350-12-B1, a waveguide bandpass filter for the E-band (71-76 GHz). The parameters of interest are:

- Noise Figure: *2 dB*
- Insertion Loss: *2.0 dB*

E-Band amplifier

The amplifier chosen is Analog Devices' HMC8325 model, an E-band (*71-86 GHz) Low Noise Amplifier (LNA*). The parameters of interest are:

- Noise Figure: *3.6 dB*
- Gain: *21 dB*

Mixer

The mixer used is the TRF37X32 by Texas Instruments, a dual down converter with an integrated IF amplifier. The parameters of interest are:

- Noise Figure: *6.5 dB*
- **LO (Local Oscillator Level):** 21 dBm (although the datasheet shows *9.5 dB* for the noise figure, the value quoted in the table is *6.5 dB*).

BPF IF (Intermediate Frequency Bandpass Filter)

The IF filter is Mini-Circuits' BPF-A1340+ model, a bandpass filter from *1000* to *1800 MHz.* The parameters of interest are:

- Noise Figure: *0.84 dB*
- Insertion Loss: *0.85 dB* (at *1200 MHz*)

AMP IF (Mid-Frequency Amplifier)

The IF amplifier is Qorvo's TAT7460 model, a *75 Ohm RF amplifier*. The parameters of interest are:

- Noise Figure: *2.5 dB*
- Gain: *16.5 dB*

3.1. Parameter calculation with ADSim

The simulations with ADSim have made it possible to calculate the overall noise figure of the system, which turns out to be $8.17\ dB$. A detailed table shows the parameters of each stage (BPF, Mixer, Driver Amp, LNA) and the results of the analysis, including the Output Power ($58\ dBm$), Noise Figure ($8.17\ dB$), Output NSD ($-107.8\ dBm/Hz$), Output Noise Floor ($-47.8\ dBm$), SNR ($105.8\ dB$), and other linearity and power parameters.

3.2. Project idea and link architecture

The project idea provides for the transition from the baseband (in the Backend section) to the passband through an intermediate frequency of $1200\ MHz$. Next, the conversion to the Radio Frequency (in the Exciter section) and finally the transmission on the channel (in the Front-End section) takes place. On receive, the reverse process applies. The path of the antennas will be configured with distance and other specific parameters.

A representation of the RF air interface (Exciter and Front-End) shows the conversion chain up (UP CONVERSION) and down (DOWN CONVERSION), with the antenna path in the middle. This includes BPF, Mixer, RF Amp and LNA.

The overall design of the point-to-point link includes the transmitter with the RF section connected to the receiver diagram. The sections are named "modulation and transmission", "RF air interface" and "demodulation and reception".

3.2.1. Calculating the link budget

The link budget is used to balance the power received according to the power emitted, considering all the dissipative factors in the channel.

1. **Required bandwidth**: The required bandwidth is calculated as:

$$Band=(Rb/(bps\times FEC))*(1+\alpha)$$

With:

- $Rb=150\ Mbps$
- $bps=6$
- $FEC=2/3$
- $\alpha=0.2.$

$$Bandwidth=150\ Mbps/6\ bps*(3/2)*(1+0.2)=25\ Msps\times 1.5\times 1.2=45\ MHz$$

2. Path Loss: The wavelength

λ is calculated as $\lambda=c/f.$

- $f=72\ GHz$
- $c=3\times 108\ m/s$

We have $\lambda \approx 4.1667\times 10-3\ m$. The Path Loss is calculated as:

$$PathLoss=(\lambda/(4\pi\cdot distance))^2$$

For a distance of 1 km (1000 m):

$$PathLoss=(4.1667\times 10-3)^2/(4\pi\times 1000)^{2=1.0994e-13}$$

In dB:

$$PathLossdB=10log_{10}(PathLoss)=-129.59\ dB$$

3. Antenna Gain (Receive and Transmit):
    - Antenna diameter $= 0.388\ m$
    - Antenna Efficiency $\eta=0.5$

Antenna Area:

$$A=\pi\times(AntennaDiameter/2)^2$$

$$A=\pi\times(0.388/2)^2=0.1182\ m^2.$$

Gain in Reception:

$$ReceiveGain=((4\pi\cdot A)/\lambda^2)*\eta$$

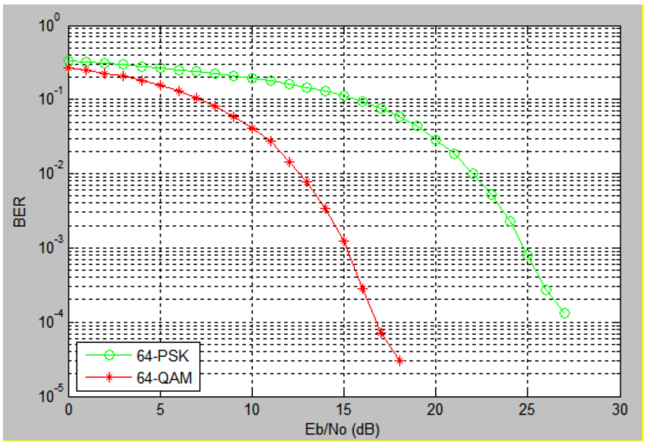
$$\mathrm{ReceiveGain}=((4\pi\times 0.1182)/(4.1667\times 10-3)^2)\times 0.5=4.2791\times 104.$$

In dB:

$$GuadagnoRicezione\_dB=10log_{10}(ReceiveGain)=46.314\ dB$$

It is assumed that the gain on reception is equal to the gain on transmission.

4. **SNR_0 (Signal-to-Noise Ratio at Demodulator Output):** Considering for a 64-QAM a *ratio* $E_b/N_0=17\ dB$ and a noise figure $F=8.17\ dB$, and a Clear Sky condition of $4\ dB$. The BER graph shows the trend of the BER as a function of E_b/N_0 *for 64-PSK and 64-QAM.*



$$(SNR_0)=(E_b/N_0)*(R_b/B)$$

- $R_b=150\ Mbps$
- $B=45\ MHz.$

$$Rb/B=150/45=3.33\ (SNR_0)$$

$$(SNR_0)=210.33$$

$$(SNR_0)dB=10\log_{10}(210.33)+4\ dB=23.22+4=27.229\ dB$$

5. System Temperature ($Tsys$):

$$Tsys=T_0*(F-1)$$

Assuming $T_0=290\ K$ (standard reference temperature) and $F=108.17/10=6.56$ (from the overall noise figure).

$$T_{sys=290}*(6.56-1)=290*5.56=1612.4\ K$$

$$Tsys=2079.3\ K$$

In dB/K:

$T_{sysdB}=10\log_{10(}T_{sys})=33{,}179\ dB/K.$

6. RX Antenna Parameter ***(GR/T_{sys}):***

$$(GR/T_{sys})dB=G_{dB}-T_{sysdB}$$

$$(GR/T_{sys})dB=46.314\ dB-33.179\ dB/K=13.134\ dB/K.$$

7. **Transmitting Power (*PT*)*:*** The formula for $PT\ in\ dB$ is given as:

$$PT_{dB}=-(GR/T_{sys})dB-GT_{dB}-L_{PATH}+SNR_{0dB}+10\log_{10}(k)+10\log_{10}(B)$$

Where k is Boltzmann's constant $(1.38\times10-23\ J/K)$.

$$10log_{10}(k)=10log_{10}(1.38\times10-23)=-228.6\ dBJ/K$$

$$10log_{10}(B)=10log10(45\times106)=76.53\ dBHz$$

The document calculates:

$$PT_{dB}=-(13.134)-46.314-(-129.59)+27.229-228.6+76.53=-54.700\ dB$$

$$PT=10-54.7/10=3.3888\times10-7\ W=-64.699541\ dBW$$

8. **Receiver Sensitivity (S_i):** Thermal Noise ($N_i=k\cdot T_0\cdot B$):

$$N_{idB}=10log_{10}(k)+10log_{10}(T0)+10log_{10}(B)$$

Assuming $T_0=290\ K$: $10log_{10}(290)=24.62\ dB/K$

$$N_{idB}=-228.6+24.62+76.53=-127.45\ dBm$$

Receiver sensitivity ($S_i=N_i\cdot F\cdot SNR_0$):

$$S_{idB}=N_{idB}+F_{dB}+SNR_{0dB}$$

Using values from the document:

$$S_{idB}=-187.45\ dB+8.17\ dB+27.229\ dB=-152.05\ dB$$

In Watts:

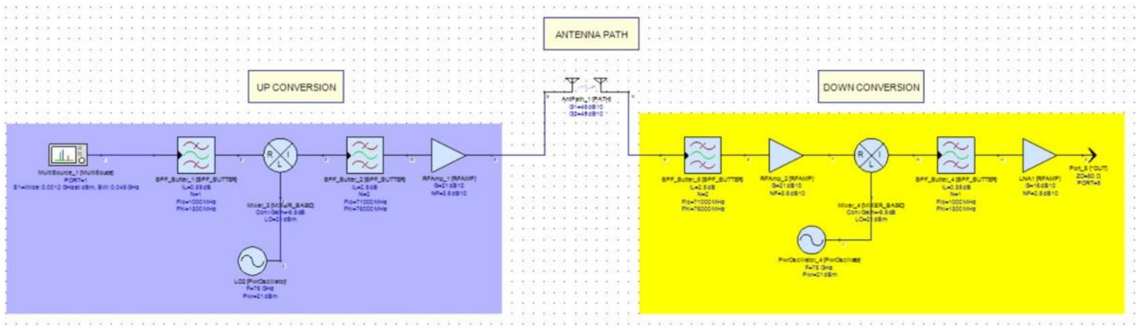
$$S_{iWatt}=10-152.05/10=6.2431\times10-16\ W=-162.045\ dBW.$$

If $S_{idB}=-152.05\ dB$ then $S_{iWatt}=10-15.205=6.23\times10-16\ W.$

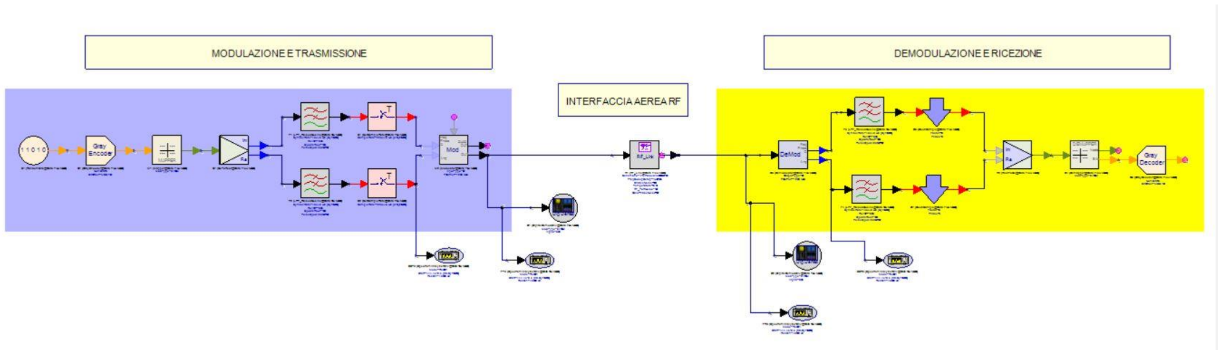
4. System architecture

Two distinct block diagrams are presented:

- The first highlights the "up conversion" and "down conversion" processes that characterize the air connection;



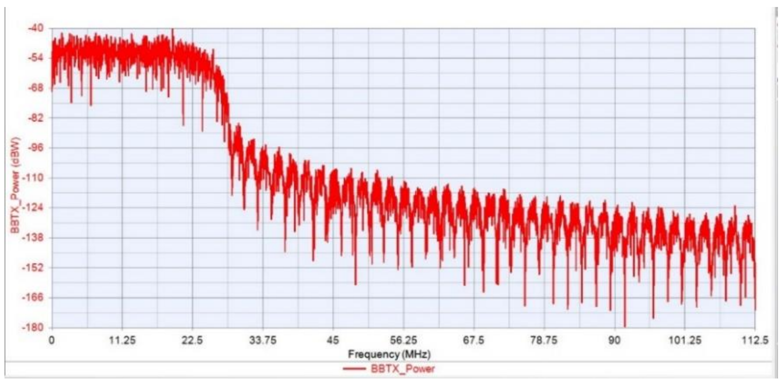
- The second provides a more complete view of the overall design, showing the transmitter with its RF section connected to the receiver schematic, which includes the "modulation and transmission" and "demodulation and reception" phases.



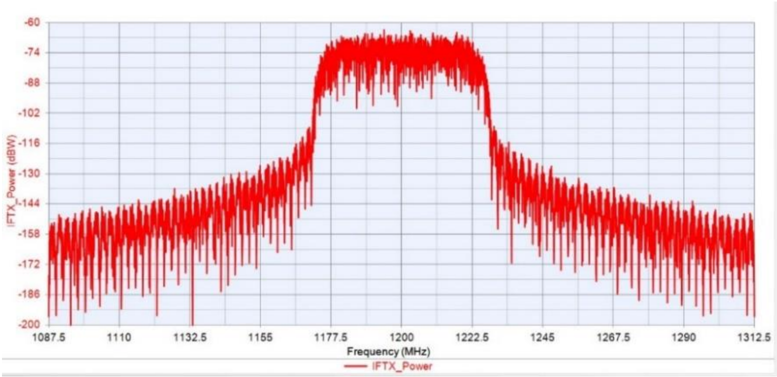
5. Simulation Charts

The paper presents several spectra and analyses obtained from the simulations:

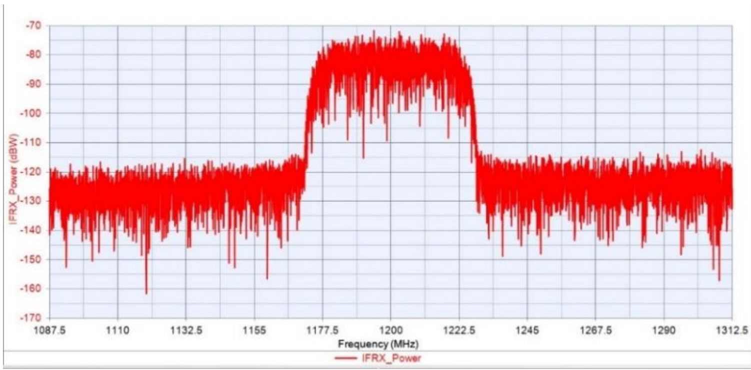
- **Baseband TX:** Shows the baseband spectrum being transmitted. You can see that the graph is centered on zero, so it displays half of the band.



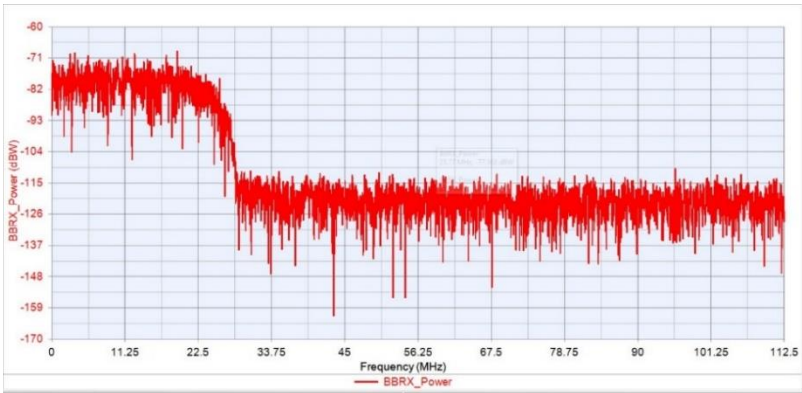
- **IF TX:** Transmitting intermediate-frequency spectrum, with a total bandwidth of 45 MHz, as predicted by the calculations.



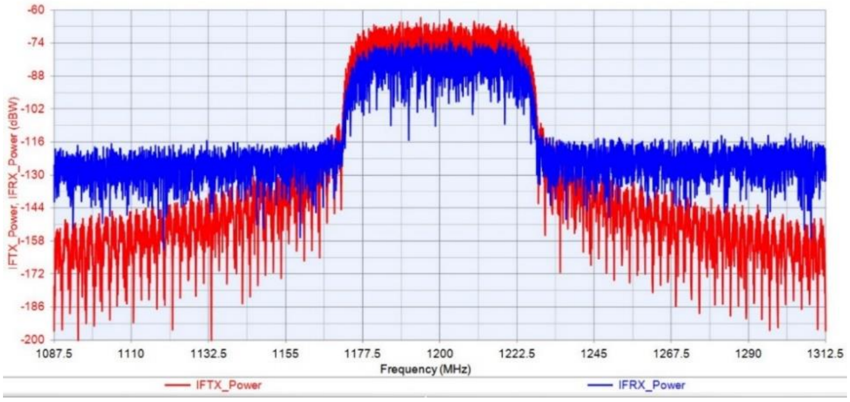
- **IF RX:** Receiving IF spectrum, also centered at 1200 MHz and with a bandwidth of 45 MHz, sized for the 1 km route and calculated losses.



- **Baseband RX:** Baseband spectrum after reception.



- **IF Graph Comparison:** Overlapping of the IF TX and IF RX spectra, allowing you to compare power levels and noise between intermediate frequency transmit and receive.



- **CNF:** Graph of the Carrier to Noise Figure (CNF) in dB, showing the trend of the CNF through the various stages of the system (BPF, Mixer, RF Amp, Antenna Path, LNA).