Department of Microtechnology and Nanoscience

Wireless and Photonic System Engineering SSY085

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Teachers in charge:
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Aids: Open book examination. Any printed material and calculator of choice is allowed. Communication devices (computers, mobile phones etc.) are *not* allowed.

Examination checking: By appointment to Hans and Magnus

Convince yourself that you have understood the problem before you get started. Constructive and valuable gambits will also give points. If information is lacking in the description of the task, you must yourself introduce technical plausible assumptions. Make sure you clearly state such assumptions.
Grades: 3: ≥ 24, 4: ≥ 36, 5: ≥ 48

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1. 60 GHz short-range outdoor link

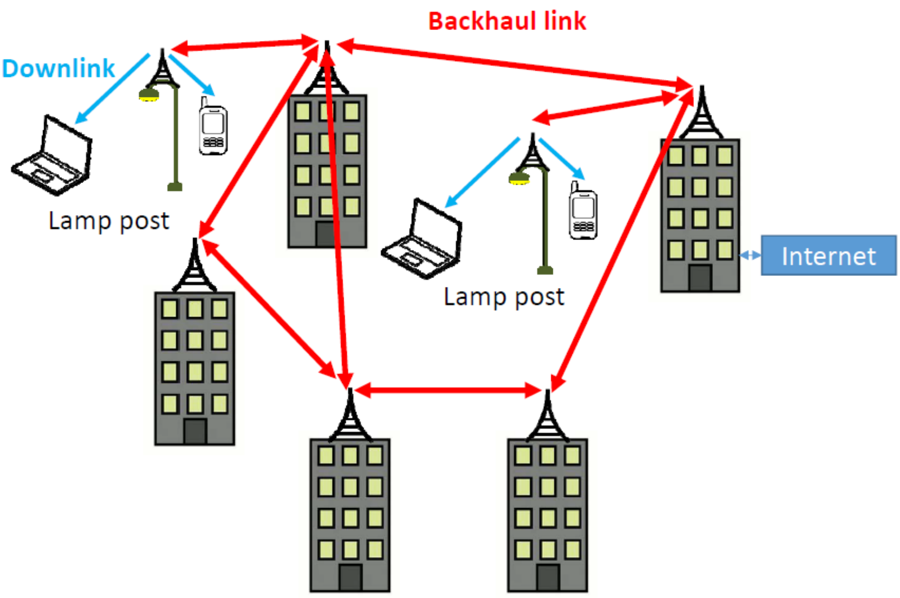
You should design a system for short-range 60 GHz outdoor wireless communication in a residential area, see below. The maximum distance between base stations in the backhaul link is set to 400 m. Apart from the backhaul link you should design the 100 Mbps downlink from base stations to mobile terminals. (To reduce the cost and complexity of the mobile units the 4G cellular system is used for uplink transmission.)

The downlink transmitter should use a phased array antenna with a steerable narrow *pencil-beam* directed towards the mobile unit. Hence, it is a line-of-sight system with a narrow beam, and Friis formula for free space propagation can be used. Assume that the phased array antenna has a directivity of $2.5 + 10\cdot\text{Log}_{10}(N)$ dBi, where N is the number of antenna elements.

The oxygen absorption at 60 GHz leads to an additional propagation loss of 16 dB/km. The Effective Isotropic Radiated Power (EIRP) is constrained by regulations to 43 dBm, and the peak transmitted power should not exceed 500 mW. The noise figure of the receivers are 10 dB.

To get full marks you must present block diagrams for both transmitter and receiver of backhaul link system, as well as block diagrams for transmitter and receiver of base station to mobile terminal downlink. Component parameters, antennas, frequencies, bandwidths, modulation formats etc. should be motivated considering signal and noise power levels, propagation effects, BER, portability, power consumption. Use realistic assumptions where applicable.

(30 points)



Problem 1. A 60 GHz short-range wireless communication system.

2. A short haul link

As a new employer at a large datacenter, you are assigned to design the inter-computer communication links. The used fiber is a GRIN MMF with a modal dispersion of 1 GHz per km and a loss of 2 dB per km. However in addition to the fiber losses the power budget shall also allow for coupling and connector losses, and margins amounting to 10 dB. The transmitter is a laser with 10 GHz of bandwidth and this values holds for the receiver as well. Assuming, OOK modulation, 0 dBm of transmitter power, a maximum transmission distance of 1 km, and rise time values equal to inverse bandwidths, what is the highest data rate this link can accommodate? Make additional assumption as required.

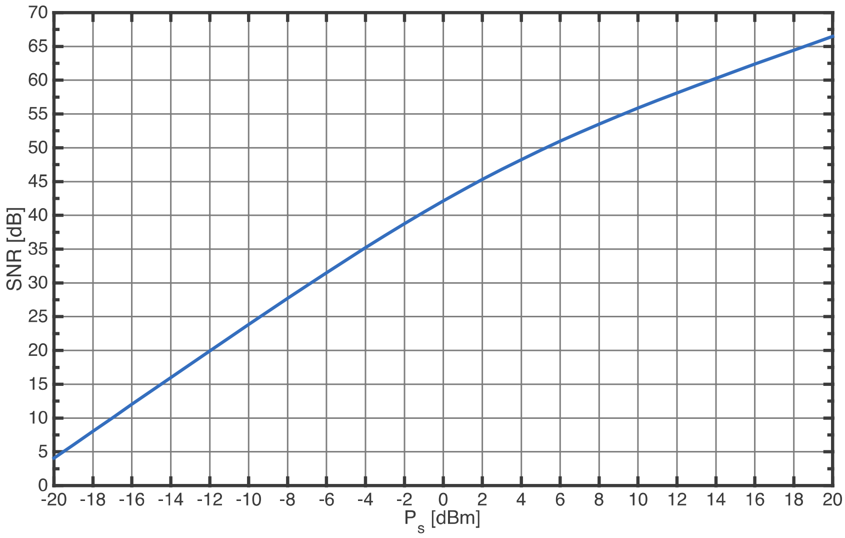
(10 points)

3. Photodetector responsivity

A new Silicon photodetector for 850 nm MMF transmission with a very high bandwidth of 40 GHz is characterized. The figure shows a fit to the measured (electrical) SNR vs. received optical power.

a) Which noise sources are present, and how can they be identified in this plot? (4 points)

b) Use the figure to estimate the responsivity and quantum efficiency of the photodetector. (6 points)



Problem 3. The measured photodetector SNR.

4. An optically amplified system upgrade

The fiber optical link from Gothenburg to Borås (70 km, attenuation 0.22 dB/km) has a single EDFA (NF=6 dB) at the receiver compensating for the fiber losses plus an extra 5 dB in filter and connector losses, and no other amplifiers. The optical signal to noise ratio (OSNR) at the receiver is 23 dB, dominated by signal-spontaneous beat noise.

The operator wants to increase the OSNR to at least 30 dB to allow for a data rate upgrade. The detector does not allow for a higher received signal power (it will saturate and distort the signal), so the idea is to use a 10 dB booster amplifier (NF=8 dB) before the fiber, and reduce the existing receiver EDFA gain with 10 dB. Is it possible to reach the desired 30 dB OSNR in this way?

(10 points)

Solutions

1.**Design of the backhaul link**

1. Determine minimum detectable input signal to the receiver.
    a. The bit rate R_b=1.0 Gbit/s.
    b. Choose QPSK digital modulation. Common bit error rate for QPSK $P_e=10^{-5}$.
    c. According to Table 9.5 bit energy/noise spectral density (E_b/n_0) is 9.6 dB for QPSK and $P_e=10^{-5}$. This relates to the signal to noise ratio at the output of the receiver S_o/N_o, bit rate R_b and band width B through eqn. 10.5

$$\frac{E_b}{n_0} = \frac{S_o}{N_o}\frac{B}{R_b}$$

    d. The bandwidth efficiency for QPSK is 2 bps/Hz (Table 9.5). Hence, for R_b=1.0 Gbit/s the receiver bandwidth B=500 MHz.

$$\frac{S_o}{N_o} = \frac{E_b}{n_0}2 = (9.6 + 3)\text{dB} = 18.24$$

    e. Minimum detectable input signal is then (eqn. 10.4)

$$S_{i,min} = kB[T_A + (F-1)T_0]\left(\frac{S_o}{N_o}\right)_{min}$$

    f. For an antenna with radiation efficiency e_{rad}=1, the antenna noise temperature T_A is equal to the brightness temperature T_b. Choose T_A=290 K to give some margin.
    g. The noise figure of the receiver is 10 dB.

$$S_{i,min} = k \cdot 0.5 \cdot 10^9[290 + (10-1)\cdot 290] \cdot 18.24 = 3.65 \times 10^{-10}\ W = -64.4\ dBm$$

2. Determine the antenna gain for line-of-sight propagation from Friis equation
    a. A highly directive parabolic antenna can be used for both transmitting and receiving the 60 GHz signal, thus $G_t=G_r=G$. Assume an aperture efficiency of 60% and a radiation efficiency of 100%.
    b. The transmitted power is limited to P_t=500 mW =0.5 W and the effective isotropic radiated power ($P_t \cdot G_t$) should not exceed 43 dBm=20 W.
    c. Apart from the radiation loss, we lose 16 dB/km·1 km=16 dB because of oxygen absorption.

$$P_r = P_t\frac{G^2\lambda^2}{(4\pi R)^2} - 16\ dB$$

    d. Assuming $P_r=S_{i,min}$, the first right term has to exceed -64.4+16=-48.4 dBm=$1.45\cdot 10^{-8}$ W.
    e. Starting from a parabolic antenna with a diameter d=20 cm, the area A=0.0314 m^2. The directivity can be calculated.

$$D = e_{ap}\frac{4\pi A}{\lambda^2} = 0.6\frac{4\pi \cdot 0.0314}{0.005^2} = 9470 = 39.8\ dBi$$

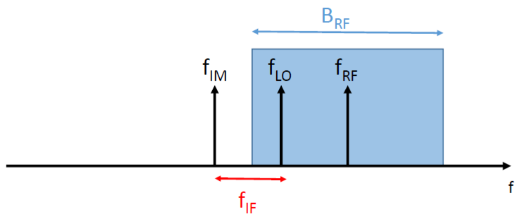
f. With this antenna gain the transmitted power becomes

$$\frac{1}{P_t} = \frac{9470^2}{1.45 \cdot 10^{-8}}\frac{0.005^2}{(4\pi \cdot 1000)^2} = 980$$

Hence, P_t=1.0 mW, which is far below the maximum value of 500 mW. The resulting EIRP=9.7 W=39.9 dBm, which is below the restriction on 20 W.

b. Block diagram for base station receiver.

a. The total gain of the receiver should be around 65 dB, which should be divided over an RF and IF frequency stage to avoid oscillations.
b. After the antenna we put a duplex filter to isolate the receiver and transmitter. The isolation should be at least 65+3 dB. It should have low insertion loss, which implies a not very sharp cut-off characteristic.
c. A low noise amplifier is used before the image rejection filter in order to that the insertion loss related to the sharp cut-off has less influence on the receiver noise figure.
d. The image, RF and LO frequencies are shown below. In order to that the signal of the image frequency should not be converted down to the intermediate frequency, the band width of the RF (image rejection) filter has to be smaller than four times the intermediate frequency, thus $B_{RF}<4 \cdot f_{IF}$. It is difficult to make an RF filter smaller than 5% (B_{RF}/f_{RF}), which gives us B_{RF}=3 GHz. Hence, f_{IF} should be larger than 750 MHz. If we want to prevent the out leakage of the LO signal as well, f_{IF} should be larger than 1.5 GHz. Let's choice f_{IF}=1.5 GHz, thus f_{LO}=58.5 GHz.



e. If we choose a first intermediate frequency of 1.5 GHz the fractional bandwidth of the IF band pass filter (B/f_{IF})=0.5/1.5=33%, which is very high. Maybe we should specify a lower bit rate or we should use a higher modulation format.

2. This is a simple rise time and power budget problem.

First the rise time budget: the tx/rx risetimes are 100 ps=0.1 ns each, and the fiber rise time is 1.0 ns for 1 km. This gives a system rise time of sqrt(1.0^2+2x0.1^2)=1010ps. Assuming a bitperiod of 4 times this is 4ns corresponding to 2.5 Gb/s.

For the power budget we can use the Q=6 criterion. For a thermally limited receiver, this gives $Q=6=RP_{rec} /(4\ kT\ B/ R_L)^{1/2}$, which we rewrite as $B=(R_L /4kT)(RP_{rec}/6)^2$. The received power is P_{rec}=0-2-10=-12 dBm=63.1e-6 W, the responsivity is (assume 100 % quant eff) R=q/hv=0.69 [A/W], T=300 K, RL=50 Ohms, gives B=160 GHz, which is way above the bandwidth limited by the dispersion.

Thus we are dispersion-limited to approximately 2.5 Gb/s, depending on the chosen criterion for dispersion tolerance.

3.

a) The SNR growth is 20 dB per decade for low powers, indicating thermal noise, and 10 dB/ per decade, indicating shot noise. Thus shot and thermal noise is limiting this receiver, depending on the power regime.

b) The responsivity is most easily obtained from the high power (shot-noise-dominated) regime, where we can neglect the thermal contribution, and $SNR=(R\ P_{rec})^2/(2qRP_{rec}\ B)=RP_{rec}/(2qB)$.
For example we read off the chart SNR=67 dB at P_{rec}=20 dBm=0.1 W, which gives $R=2qB\ SNR/P_{rec}$=0.64 [A/W], using B=40 GHz, and q for the electron charge. The quantum efficiency is, finally, R*hv/q=0.94=94%, where we used hv=2.34e-19 J for 850 nm photons.

4. Since the received signal power is the same in the two cases it is easiest to directly compare the received ASE powers. The total link losses that need to be compensated with amplifier gain is L=(5+70*0.22) dB=20.4 dB

Case a): The single EDFA-in-the receiver link:

Here $P_{ase,a} =G_a\ NF_a\ hv\ \Delta v/2$, where G_a=L=20.4 dB and NF_a=5 dB.

Case b): The dual EDFA link. The Tx EDFA has a gain G_1=10 dB, and the Rx EDFA must then amplify G_2=20.4-10=10.4 dB.

Here $P_{ase,b}=(G_1\ NF_1G_2/L+ G_2\ NF_2)\ hv\ \Delta v/2$ where NF_1=8 dB and NF_2=5 dB. Note that $G_1G_2/L=1$, or 0 dB.

The ratio between these noise powers will give the improvement in OSNR after the upgrade:
$P_{ase,a}/P_{ase,b}=G_a\ NF_a/(NF_1+G_2\ NF_2)=1/[(NF_1/(G_a\ NF_a))+G_2/G_a]$
where $NF_1/(G_a\ NF_a)$=8-20.4-5 dB=-17.4 dB=0.0182
and G_2/G_a=-10 dB=0.1
thus the improvement is 1/(0.0182+0.1)=8.46=9.3 dB. This is more than the required 7 dB, so the upgrade will work.