Department of Microtechnology and Nanoscience

Wireless and Photonic System Engineering SSY085

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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: Contact Christian or 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. Real-time on-field football player tracking

Wireless technology is now being investigated to enhance the live experience in various sports. One idea is to equip the football players with small battery powered wireless transmitters. By receiving these signals from multiple positions around the arena, all player locations and movements can be accurately monitored and analyzed.

		
Transmitter placement	Possible receiver locations	Real-time tracking

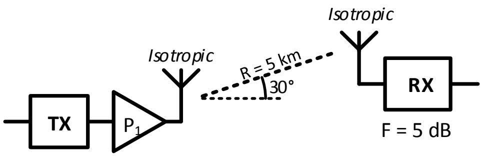
Your task is to design a wireless player tracking system for American Football based on the idea above. Your system should be able to simultaneously track up to 40 players with at least 25 position updates per second.

Your solution should include the design of the battery powered transmitters at the players and receivers around the arena, including choice of frequencies, modulation format, block diagrams, antennas, output power, etc. Use realistic assumptions where applicable.

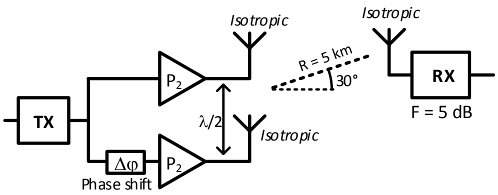
(30 points)

2. Phased array transmitter

The following 5.2 GHz wireless system should transfer 100 Mbit/s of data to a receiver which is located line-of-sight in a direction of 30° and 5 km distance compared to the transmitter. The system uses QAM-64 modulation with BER < 10^{-3}. Your task is to evaluate a traditional, and a phased array transmitter solution:



Case 1: Traditional transmitter



Case 2: Phased array transmitter

First, consider Case 1 with one isotropic transmitter.

a) How much transmit power (P_1) is needed to fulfil the specifications?

Now consider Case 2 with two phase controlled transmitters, separated by λ/2.

b) How should the phase shift, Δφ, be set to maximize the received power?
c) With this setting, how much transmit power is needed from each of the two amplifiers (P_2) to fulfil the specifications?
d) Compare the total transmit power: P_1 vs. $2\times P_2$. Why are they different/same?

(10 points)

3. Combined amplifiers

You have three EDFAs, with gains G_1=10 dB, G_2=12 dB and G_3=15 dB. The corresponding noise figures are F_{n1}=5 dB, F_{n2}=7 dB and F_{n3}=8 dB. If the amplifiers are cascaded (used in series) the total gain is obviously 37 dB. Calculate the maximum and minimum effective noise figure such a cascade can have.

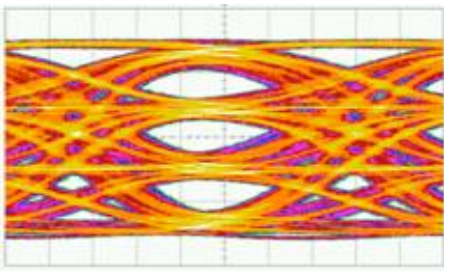
(10 points)

4. An MMF link

Within a datacenter a 50 m link is needed. The used wavelength is 850 nm, at which the fiber modal dispersion is around 1 ns/km and attenuation 2 dB/km. Assign 6dB for connector losses and splices, and another 5 dB in margin.
Directly modulated lasers with a bandwidth of 25 GHz and photodetectors with the same bandwidth are used. An average output power of 0 dBm is possible.

Calculate the highest datarate that can be achieved to reach a BER=10^{-9}, and whether the link is attenuation or dispersion limited. Make reasonable assumptions for the rise times. Consider two cases:

a) On-off-keying is used
b) 4-PAM is used.
Hint: 4-PAM needs approximately 3 times higher (optical) power than OOK for the same BER, since it can be seen as 3 OOK eye-diagrams stacked on top of each other (see figure).



A 4-PAM eye diagram

(10 points)

Solutions

1.

2. Phased array transmitter

a) *Output power, traditional system*

```matlab
% Basic data given in problem
f = 5.2e9; lambda = 3e8/f; R = 5000; Rb = 100e6;
F = 10^(5/10); % Receiver noise figure
Gt = 1; Gr = 1; % Isotropic transmit and receive antennas

% SNR requirement given by modulation and BER requirement
Ebn0= 10^(15/10); % 15 dB Eb/n0 required for BER = 1e-3 with QAM64 (see Modulation lecture, slide 29)
RbB = 6; % Spectral efficiency for QAM64
SNR = Ebn0*RbB;

% Calculate minimum power needed
B = Rb/RbB; T = 290; k = 1.38e-23;
Nin = F*k*T*B; % Noise power at receiver input
Pr = Nin*SNR; % Add SNR margin

% Calculate transmit power needed using Friis formula
P1 = Pr/(Gt*Gr*lambda^2)*(4*pi*R^2);
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Minimum transmit power, $P_1 = 3.78$ W = 35.7 dBm

b) *Phase difference*

With some simple trigonometric calculations, it is clear that the signal from the lower antenna has to travel a distance $d = \lambda/2\times\sin(30°)$ longer than the upper one, to reach the receiver. This corresponds to a phase difference of $\varphi = k\times d$, where k is the wave number: $k = 2\pi/\lambda$. When combined, this means that the $\Delta\varphi = +(2\pi/\lambda)\times\lambda/2\times\sin(30°) = \pi\times\sin(30°) = \pi/2 = +90°$ would be needed to make the signals align in the 30° direction.

c) *With this setting, how much transmit power is needed from each of the two amplifiers (P_2) to fulfil the specifications?*

When the signals are phase aligned, then their voltage contributions (E-field components) add in the receiver. Assuming a 50W reference impedance (will not change the end result), power and voltage are related by: $P = |V|^2/(2\times 50)$.

Since the received power and the distance is the same in both cases we have:

$P_r = x\times|V_1|^2 = x\times|V_2+V_2|^2 \rightarrow |V_2|^2 = \frac{1}{4}|V_1|^2$, where V1 and V2 are the voltages produced by the transmitters. This corresponds to $P_2 = \frac{1}{4}P_1 = 3.78/4 = 0.945$ W.

Each of the two amplifiers need to provide 0.945W.

d) *Compare the total transmit power: P_1 vs. $2\times P_2$. Why are they different/same?*

From the results in b) and c) clearly P_1 is twice as large as $2\times P_2$. So, the phased array solution allows the total power to be reduced, with no effect on the performance. The explanation is the fact that the phase alignment only works in the desired direction. In other directions the signals may cancel. So, effectively, the combined effect of the two transmit antennas is to direct the energy to the receiver. This is identical of replacing the isotropic antenna in Case 1 with a directive antenna. For two elements, there is a factor 2 (3dB) gain in directivity. This factor is called the array factor, and is added on top of the antenna gain characteristics of each antenna.

3. **Cascaded amplifiers**

If the amplifiers are used in order a,b,c, the total emitted noise power is proportional to

$((G_a F_{na}+F_{nb})G_b+F_{nc})G_c=G_aG_bG_c F_{n,eff}$

so that

$F_{n,eff}= F_{na}+F_{nb}/Ga+F_{nc}/(G_b G_a)$.

Thus the first amplifiers noise figure will dominate. Setting the amps in the order 123 will thus be best and have a lowest NF of
10^(5/10)+10^[(7-10)/10]+10^[(8-22)/10]=3.70=5.69 dB
and the order 321 will get the highest NF of
10^(8/10)+10^[(7-15)/10]+10^[(5-27)/10]=6.47= 8.11 dB

All other combinations will lie between these values (8.08 dB, 7.34 dB, 7.20 dB, 5.81 dB) for the respective (312, 231, 213,132)-orderings.

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4. **MMF link max data rate**

Make a rise time budget first. Assume Tx/Rx rise times are inverse bandwidths, i.e. 40 ps. The fiber rise time is 1000 ps/km*0.05 km=50ps. Total rise time is then sqrt(50^2+2*40^2)=75.5 ps, and if that amounts of 70 % of the symbol time slot, a rise-time-limited symbol rate of 0.7/0.0755=9.3 GHz. For OOK that is 9.3 Gb/s, for 4-PAM it is twice this, i.e. 18.6 Gb/s.

Now the power budget. Consider OOK first.
We require Q=6, for BER=10^{-9}, where $Q=I_1/(\sigma_0+\sigma_1)$, $I_1=2\ R\ P_{rec}$, P_{rec} is the *average* received power (which is equally splitted between 1s and 0s, hence the factor of 2), and R the responsivity. The thermal noise has the variance
$\sigma_1=\sigma_0=\sigma_T=\mathrm{sqrt}(4k_BTB/R_L)$. Hence $Q=RP_{rec}/\sigma_T$. The allowed thermal noise variance is then $\sigma_T^2=(R\ P_{rec}/Q)^2$ with the corresponding bandwidth given by
$B=(R\ P_{rec}/Q)^2R_L/(4k_BT)$.

The received optical power is 0 dBm minus 5 dB in margin, 6 dB in coupling losses and 2 dB/km•0.05 km=0.1 dB in fiber losses, giving -11.1 dBm=77.6 μW. With load resistance R_L=50 Ohm, a responsivity at 850 nm of R=0.68 A/W, and $k_BT=4.14\cdot10^{-21}$ J, we get
$B=(0.68\cdot77.6\cdot10^{-6}/6)^2\cdot50/(4\cdot4.14\cdot10^{-21})$=233 GHz
This is well beyond the bandwidth limited by the dispersion, so OOK is definitely dispersion limited.

For 4-PAM we use the same calculation, but insert 3 times lower optical power, i.e. 77.6/3=25.9 μW. This gives nine time lower bandwidth since the optical power scales with the square, i.e. 25.9 GHz. This is closer to, but still above, the dispersion limited bandwidth.

Thus the dispersion limited datarate is 9.3 Gb/s for OOK and twice that value, 28.6 Gb/s for 4-PAM