Department of Microtechnology and Nanoscience

Wireless and Photonic System Engineering SSY085

2010-10-18, 14.00-18.00

Teachers in charge:
Magnus Karlsson, phone 772 1590, email: magnus.karlsson@chalmers.se
Christian Fager, phone 772 5047, email: christian.fager@chalmers.se

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

Examination checking: Friday Nov. 5th, 12^{00} - 13^{00} in room A604 at MC2

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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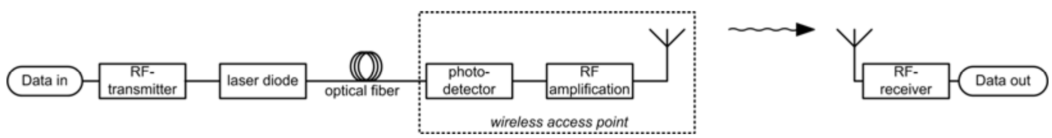
1. Radio over Fiber (RoF) systems are often used to extend the coverage of wireless systems in dense areas with a lot of end users by connecting simple multiple wireless access points through a fiber link, as illustrated in the schematic below.



Simple radio-over-fiber (RoF) downlink system.

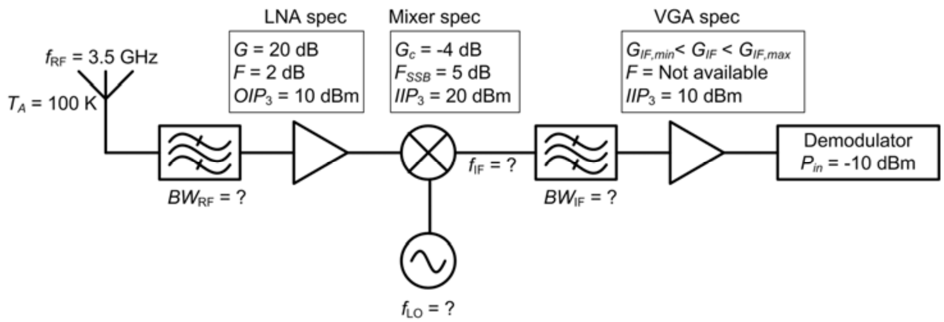
You should now use RoF technology to design a system for bi-directional distribution of mobile communication signals between one central unit and 10 wireless access points across the periphery of a large sports arena (500m × 500m).

The system should be designed to provide separate 5 MHz channels for up-link and down-link between each of the ten access points and the central unit. Regular mobile phones support the access points and need not to be included in the design.

To get full marks you must present block diagrams, component choices, and design calculations for the optical and microwave parts of the system. It is important to reduce the cost and energy consumption, so the power, amplification, and complexity in each block should be minimized. Use realistic assumptions where needed.

(30 points)

2. The figure below illustrates a 3.5 GHz super heterodyne receiver block diagram. The receiver will be used in an urban environment and should support a bitrate of 100 Mbit/s @ BER = 10^{-5} using 64-QAM modulation format.



a) Assign suitable values for the following parameters in the block diagram: f_{LO}, f_{IF}, BW_{IF}, BW_{RF}. All values must be carefully motivated. (3p)

b) Calculate the spurious free dynamic range of the receiver (you may assume lossless filters). Use this result to calculate the IF amplifier (VGA) gain variation required ($G_{IF,min}$ and $G_{IF,max}$) when the demodulator requires a fixed input power of 0 dBm. (4p)

c) Estimate the ratio between the maximum and minimum range between the transmitter and the receiver ($R_{\mathrm{max}}/R_{\mathrm{min}}$). The transmitter output power is fixed. (3p)

(10 points)

3. Multi-channel transmitters can be used reduce cost in cellular wireless systems. You should now consider a cellular wireless system in dense urban area with the following specifications:

Bitrate/channel: 10 Mbps (QPSK), BER < 10^{-5}
Outage probability: <5%
Receiver noise figure: 5 dB

How many channels can a single 1 GHz base station serve within a cell radius of 1 km if the total transmitted power is limited to 100 W? You may assume a base station antenna gain of 15 dB at a height of 20 m.

(10 points)

4. A 40 Gb/s OOK optical signal should be transmitted over an SMF with a loss of 0.2 dB/km. The transmitter supplies 0 dBm of (average) power. The receiver consists of a pin diode with responsivity R=0.8 A/W, and you require a BER<10^{-9}. What is the attenuation-limited distance if you use

a) no optical amplifiers at all, (5p)
b) a preamplified receiver, where an EDFA with a gain of 20 dB and a noise figure of 6 dB is used directly before the detector? (5p)

(10 points)

Solutions

Please note that these are our suggested solutions. Other solutions could be as good or better.

Solution to 2a.

BWIF: Rb/(spectral eff) = 100e6/log2(64) = 16 MHz -> Choose **BWIF = 20 MHz**
BWRF: Practical RF filters have bandwidths >~5%. Choose **BWRF** = 5%*fRF= **175 MHz**
fIF: The RF filter should block the image frequency, which is located at 2*fIF from fRF. If the RF filter is centered at 3.5 GHz, this means that 2*fIF > BWRF/2 -> fIF > BWRF/4 = 175 MHz/4 = ca 45 MHz. To keep some margin, we choose **fIF = 90 MHz**. This margin will also make sure that reverse leakage of the LO frequency through the mixer and LNA is blocked and not radiated back from the antenna.
fLO: The local oscillator frequency is selected as the difference between fIF and fRF = 3.5 GHz +/- 90 MHz. We choose **fLO = 3.41 GHz**.

Solution to 2b

```
% Solution presented as MatLab code
clear;
clc

%DRf = (P3/(No*SNR))^(2/3) is the equation we will use to calculate
DRf. We
%start out by findind No, SNR, and P3.

% RF filter
T1=0; %K Filter temp outside band.
% LNA
G2 = 100; % 20 dB
F2 = 10^.2; % 2 dB
P3_2 = 1e-2; % 10 dBm
T2 = (F2-1)*290; %
% Mixer
G3 = 10^-.4; % -4 dB
F3 = 10^.5; % 5 dB
P3_3 = 0.1*G3; % 20 dBm - 4dB (to get OIP3)
T3 = (F3-2)*290;% 337 K SSD noise temp
% VGA
GIF = 10; %(DRf will actually not depend on GIF)
P3_IF = 10^-2*GIF; % 10 dBm + GIF (to get OIP3)
%The IF amp. is considered noiseless.

% Filters have very high IP3 and do not need to be included in the
IP3
% calculations
P3 = (1/(P3_2*G3*GIF) + 1/(P3_3*GIF) + 1/(P3_IF))^(-1); %=0.0027*GIF
P3_dbm = 10*log10(P3/1e-3)

% We need to have an SNR  of 17.8 dB + 10*log10(6) dB (17.8 dB from
% eb/n0 and the factor 6 from spectral efficiency of QAM-64), se
Table 9.5 in Pozar
SNR_db = 17.8 + 10*log10(6)
SNR=10^(SNR_db/10);

Ta = 100;
```

```
B = 100e6/6; % B = Rb/spectral eff = 100 Mbit/s * 1/6 =16.7 MHz.
% Total noise power at receiver output:
No = 1.38e-23*17e6*((Ta + T2)*(G2*G3*GIF) + T3*(G3*GIF) + (T1 +
T2)*(G2*G3*GIF))
%(Which part is from the image frequency?)
%=6.84e-12*GIF

% Finally, the dynamic range calculation 3.108 in Pozar. Here GIF
will
% cancel out.
DRf = (P3/(No*SNR))^(2/3);
DRf_db = 10*log10(DRf)
```

%**=42 dB**

```
% This yields the following VGA gain range:
% Min power at input of VGA = No/GIF
% Power at VGA output = -10 dBm

Gain_max_db = -10 - 10*log10(No/GIF*1000) - SNR_db
```

%**=48 dB**

```
Gain_min_db = Gain_max_db - DRf_db
```

%**=6 dB**

```
% Assume propagation constant = 3
rmax_rmin = 10^(DRf_db/10/3)
```

%**≈25**

```
return
```

Solution to 3

```
% Solution presented as MatLab code
% Use the Hata-Okumura propagation model with the following
parameters
d = 1; % Cell radius
f = 1000; % Frequency
hb = 20; % Base station antenna height
hm = 2; % Mobile phone height

ch=0.8+(1.1*log10(f)-0.7)*hm-1.56*log10(f);
Lu_db = 69.55+26.16*log10(f)-13.82*log10(hb)-ch+(44.9-
6.55*log10(hb))*log10(d)

Ptx_dbm = 50; % Transmit power = 100W
Gtx_db = 15; % Transmit antenna gain

N0_dbm = 10*log10(1.38e-23*290*5e6*10^.5/1e-3) % Noise power at
receiver input (assume unity receive antenna gain for mobile)

snr_db = 9.6 + 3; % SNR = eb/no*Rb/B for QPSK modulation

out_marg_db = -10*log10(-log(1-.05)) % Outage probability margin
assuming Rayleigh fading environment (reasonable from the text, where
“dense” urban is stated.). prob_outage = 1-exp(-Pthr/P0), where P0 is
the nominal received power.

margin_per_user = Ptx_dbm + Gtx_db - Lu_db - N0_dbm - snr_db -
out_marg_db; % dB of margin per user
```

```
N = 10^(margin_per_user/10) % Use the margin to support N users
```

N = 18 users

Solution to 4

a)

This will be a thermal-noise-limited link, and the receiver sensitivity P_{rec} is obtained from Q=6, where $Q=I_1/(2\ \sigma_T)=2R\ P_{rec}/(2\ \sigma_T)=6$. In this case, $\sigma_T^2=4k_B\ T\ \Delta f\ /R_L$ = 1.32e-11 A^2, from which we get $P_{rec}=6\ \sigma_T\ /R=6(4k_B\ T\ \Delta f\ /R_L)^{1/2}/R$=-18.7 dBm. The allowed losses are thus 18.7 dB which corresponds to a link length of 18.7/0.2=93.5 km.

b)

Here signal-spontaneous noise will likely limit the link, and using P_{rec} to denote the average power in to the amplifier,the Q becomes $Q=I_1/\sigma_{s\text{-}sp}=2RGP_{rec}/(4\ R^2\ GP_{rec}\ S_{sp}\ \Delta f)^{1/2}=(P_{rec}/(F_n h\nu\Delta f/2))^{1/2}=6$, from which we find the sensitivity to be

$P_{rec}=18\ F_n\ h\nu\Delta f$.

By using $F_n=4$, $h\nu\Delta f$=5.12e-9 W, we get P_{rec}=-34.3 dBm, and the corresponding fiber length 34.3/0.2=171 km.

Check of noise powers: The s-sp noise power is $\sigma_{s\text{-}sp}^2=4\ R^2\ F_n h\nu\Delta f\ P_{rec}\ G^2/2$ = $(6RF_n h\nu\Delta fG)^2$=9.66e-11, which is almost 6 times the thermal noise, i.e. thermal noise is not completely negligible...

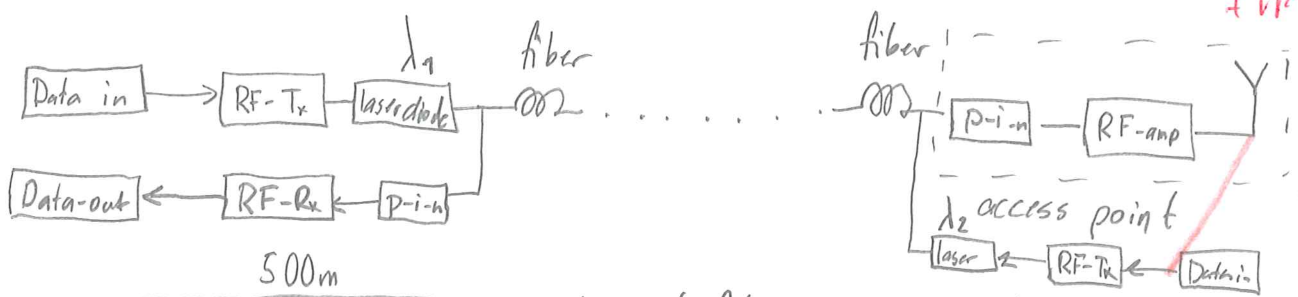
A more exact treatment accounts for the thermal noise as well in the expression for the Q, and can be shown to give

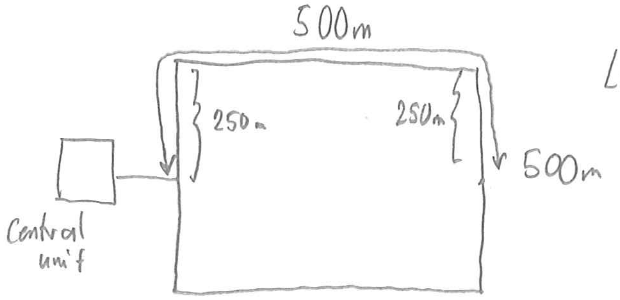
$P_{rec}=18\ F_n\ h\nu\Delta f+6\ \sigma_T\ /(RG)$ =-33.0 dBm, and the distance is then 165 km.

1. The access points are spread across the arena periphery. I assume that each wireless access point is connected to the central unit with an own fiber, down-link and up-link are transmitted over the same fiber using different frequencies for data from/to central unit.

The frequencies/modulation scheme are decided when designing the RF-transmitter. The fiber part is just making a link budget with RoF instead of free-space propagation model from the central unit to the access point. λ_1 used for uplink, λ_2 for downlink decided by lasers.

I design with one RoF link for each wireless access point that is the system below is used 10 times, one for each access point at the arena.





Longest fiber distance $L = 1km$

Design for this greatest fiber loss!

The frequency used for the design is $f = 900$ MHz (downlink), $f = 850$ MHz (up link) (for mobile phone users)

Each access point uses 5 MHz bandwidth for uplink/downlink.

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Downlink

First I need an estimate of how much power needs to be transmitted at the access point antenna.

ok

A mobile user is say at maximum R=100 m from the access point and the receiver needs a minimum amount of power.

Assume QPSK is used with BER $= 10^{-5}$ $\frac{E_b}{n_0} = 9,12$

$\Rightarrow$ SNR $= 18,24$ needed
$= 12,6$ dB

Data rate to mobile phone call $R_b = 50$ kbit/s $\Rightarrow B = 100$ kHz

If mobile phone antenna $T_A = T_0 = 290$ K and noise figure of mobile phone receiver $F = 3$ dB $= 2$

$\Rightarrow$ Noise power $= 10\log(kT_0 BF \cdot 1000) = -121$ dBm

Minimum received signal level -108 dBm $= 1{,}58 \cdot 10^{-14}$ W
(antenna in mobile phone has gain $G_r \approx 1$)

Using modified Friis equation with $N = 2{,}5$ $R_0 = 1$m

gives path loss $10\log\left(\frac{\lambda^2}{(4\pi R_0)^2} \frac{1}{(R/R_0)^N}\right) = -81$ dB

$f = 900$ MHz $\Rightarrow \lambda = 0{,}33$m

Add to this a fade margin of 20 dB (very many reflections inside arena)

yields total losses -101 dB

EIRP for antenna at access point -20 dBm

with omnidirectional antenna $P_t = -25$ dBm
$G_t = 5$ dB

This we need after the fiber!

Since RF-amp. in accesspoint say $G = 20$ dB $\Rightarrow P_{out} = -45$ dBm $= 3{,}16 \cdot 10^{-8}$ W from fiber link

RoF link

$P_{out} = P_{in}\, s_\ell^2 \alpha^2 R^2$ 2p

assume $R = 50\,\Omega$ no R is responsivity!

Fiber used is MMF with $\alpha = 1$ dB/km 1p — linear scale loss

Optical losses in 1km is 1dB $\Rightarrow \alpha = 0{,}8$ above 1p

Photodetector used is InGaAs with quantum efficiency $\eta = 0{,}8$ 2p

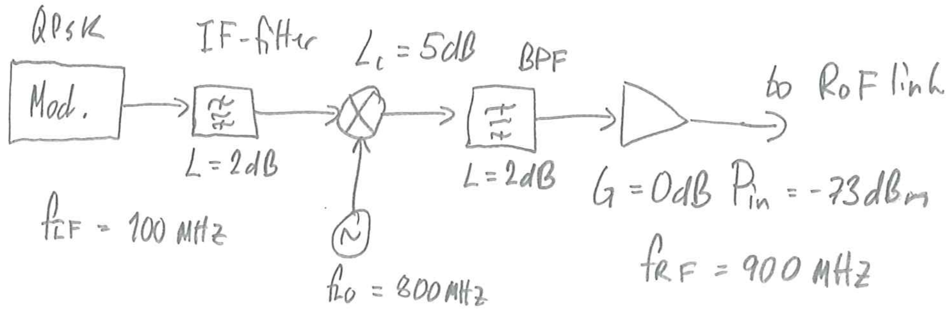
The laser used is of wavelength 1550nm (for downlink) 1p

$\Rightarrow$ Slope efficiency $s_\ell = \eta \frac{h\nu}{q} = 0{,}64$ W/A 1p

With P_{out} calculated $P_{in} = \frac{P_{out}}{s_\ell^2 \alpha^2 R^2} = \frac{3{,}16 \cdot 10^{-8}}{0{,}64^2 \cdot 0{,}8^2 \cdot 50^2}$ 1p

$P_{in} = 4{,}82 \cdot 10^{-11}$ W $= -73$ dBm so we have 28 dB link gain (which is maybe unrealistic) ? Yes!

This power needs to be delivered to fiber by RF-transmitter. Since down-link RF-frequency is 900 MHz a transmitter with up-conversion is required.



IF-filter $\begin{cases} f_c = 100 \text{ MHz} \\ \Delta f = 5 \text{ MHz} \end{cases} \Rightarrow \frac{\Delta f}{f} = 5\%$ OK!

↑ required BW

BPF $\begin{cases} f_c = 900 \text{ MHz} \\ \Delta f = 100 \text{ MHz} \end{cases}$ Upper sideband used $f_{RF} = f_{LO} + f_{IF}$
Lower sideband at 700 MHz rejected!

With the assumed values and calculations the amplifier need not be there, since enough power is most likely delivered directly from modulator.

Uplink

The mobile phone transmits 0,7 W = 28,5 dBm with modified Friis eq. $R_0 = 1m$ and $N = 2,5$ this yields with $R = 100m$

$$P_r = P_t \frac{G_t G_r \lambda^2}{(4\pi R_0)^2} \frac{1}{(R/R_0)^N} = 0.7 \cdot \frac{2^2 \cdot 0,35^2}{(4\pi \cdot 1)^2} \cdot \frac{1}{100^{2,5}} = 2,17 \cdot 10^{-8} W$$

$f = 850$ MHz $\Rightarrow \lambda = 0,35$ m $G_r = G_t = 2$ (omnidirectional antennas)

$P_r = -46,6$ dBm at access point, the system should also have 20 dB fade margin. Design for $P_r = -66$ dBm

With 20 dB amplification before fiber link $P_{in} = -46,6$ dBm at fiber.

Output power at central unit station after fiber (28 dB gain)

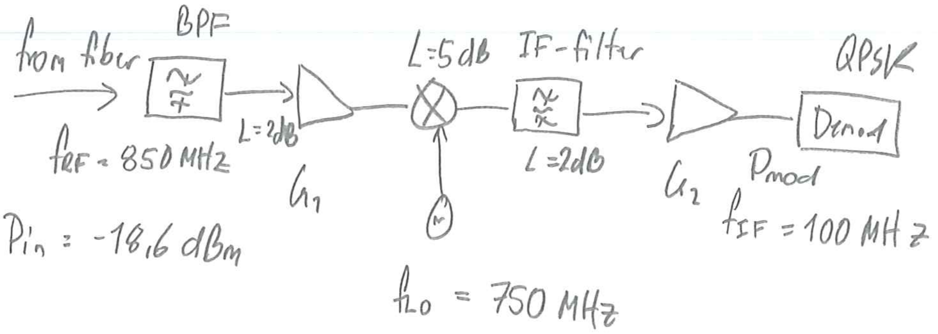
$$P_{out} = P_{in} S_e^2 \alpha^2 R^2 = 2,18 \cdot 10^{-8} \cdot 0,64^2 \cdot 0,8^2 \cdot 50^2 = -18,6 \text{ dBm}$$

+2p

This power must be detected by the RF-receiver! use $\lambda = 1500$ nm

Since a different laser wavelength is used for the up-link (to avoid crosstalk, S_e is slightly different and also α so this is an approximate result)

Use a receiver with a single down conversion step since not very much gain is needed.



Difference frequency is $f_{IF} = f_{RF} - f_{LO}$

Image frequency is at $f_{IM} = 650$ MHz

BPF $\begin{cases} f_c = 850 \text{ MHz} \\ \Delta f = 100 \text{ MHz} \end{cases}$ $\Rightarrow$ Image rejected!

IF-filter $\begin{cases} f_c = 100 \text{ MHz} \\ \Delta f = 5 \text{ MHz} \end{cases}$ $\frac{\Delta f}{f} = 5\%$

↑ required bandwidth

With filter losses 2+2 dB = 4 dB mixer conversion loss 5 dB

$\Rightarrow P_{mod} = -18,6 - 4 - 5 + G_{tot}$

Assume $P_{mod} = 0$ dBm $\Rightarrow G_{tot} = 27,6$ dB

Can be placed entirely on IF or spread as

$G_1 = 10$ dB $\quad G_2 = 17,6$ dB

The design given is for a worst case link from central-unit → access point

Should work if used 10 times for 10 access points!