RADIO SYSTEMS - ETIN15

Lecture no: 3

Narrow- and wideband channels

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WIDE-BAND CHANNELS

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- Delay (time) dispersion
- Narrow- versus wide-band channels



SHORT REVIEW



What do we know so far about propagation losses?





Two theoretical expressions for the deterministic propagation loss as functions of distance:

$$L_{|dB}(d) = \begin{cases} 20 \log_{10} \left(\frac{4 \pi d}{\lambda} \right), \text{ free space} \\ 20 \log_{10} \left(\frac{d^2}{h_{\text{TX}} h_{\text{RX}}} \right), \text{ ground plane} \end{cases}$$

There are other models, which we will discuss later.

We have discussed shadowing/ diffraction and reflections, but not really made any detailed calculations.

Statistical descriptions of the mobile radio channel



Now we are going to approach these variations from a statistical point of view.



RADIO SIGNALS AND COMPLEX NOTATION



Simple model of a radio signal

• A transmitted radio signal can be written

$$s(t) = A\cos(2\pi ft + \phi)$$
Amplitude Frequency Phase

- By letting the transmitted information change the amplitude, the frequency, or the phase, we get the tree basic types of digital modulation techniques
 - **ASK** (Amplitude Shift Keying)
 - FSK (Frequency Shift Keying) 🗸
 - **PSK** (Phase Shift Keying)

Constant amplitude

The IQ modulator



Take a step into the complex domain:

Complex envelope
$$\tilde{s}(t) = s_I(t) + j s_Q(t)$$

Carrier factor $e^{j2\pi f_c t}$ $s(t) = \operatorname{Re}\left[\tilde{s}(t)e^{j2\pi f_c t}\right]$

Interpreting the complex notation



Transmitted radio signal

$$F = \operatorname{Re}\left\{\tilde{s}(t)e^{j2\pi f_{c}t}\right\}$$
$$= \operatorname{Re}\left\{A(t)e^{j\phi(t)}e^{j2\pi f_{c}t}\right\}$$
$$= \operatorname{Re}\left\{A(t)e^{j(2\pi f_{c}t+\phi(t))}\right\}$$
$$= A(t)\cos(2\pi f_{c}t+\phi(t))$$

By manipulating the amplitude A(t)and the phase $\Phi(t)$ of the complex envelope (phasor), we can create any type of modulation/radio signal.

Example: Amplitude, phase and frequency modulation



A narrowband system described in complex notation (noise free)



It is the behaviour of the channel attenuation and phase we are going to model.



LARGE-SCALE FADING



Large-scale fading Basic principle



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Large-scale fading More than one shadowing object

Signal path in terrain with several diffraction points adding extra attenuation to the pathloss.



Large-scale fading Log-normal distribution

Measurements confirm that in many situations, the large-scale fading of the received signal strength has a normal distribution in the dB domain.



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Large-scale fading Fading margin



We know that the path loss will vary around the deterministic value predicted.

We need to design our system with a "margin" allowing us to handle higher path losses than the deterministic prediction. This margin is called a **fading margin**.

Increasing the fading margin decreases the **probability of outage**, which is the probability that our system receive a too low power to operate correctly.

Large-scale fading Fading margin (cont.)





The upper tail probability of a unit variance, zero-mean, Gaussian (normal) variable:

$$Q(y) = \int_{y}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) dx = \frac{1}{2} \operatorname{erfc}\left(\frac{y}{\sqrt{2}}\right)$$

The complementary error-function can be found in e.g. MATLAB

The Q(.)-function Upper-tail probabilities

Х	Q(x)	
4.265	0.00001	
4.107	0.00002	
4.013	0.00003	
3.944	0.00004	
3.891	0.00005	
3.846	0.00006	
3.808	0.00007	
3.775	0.00008	
3.746	0.00009	
3.719	0.00010	
3.540	0.00020	
3.432	0.00030	
3.353	0.00040	
3.291	0.00050	
3.239	0.00060	
3.195	0.00070	
3.156	0.00080	
3.121	0.00090	

Х	Q(x)
3.090	0.00100
2.878	0.00200
2.748	0.00300
2.652	0.00400
2.576	0.00500
2.512	0.00600
2.457	0.00700
2.409	0.00800
2.366	0.00900
2.326	0.01000
2.054	0.02000
1.881	0.03000
1.751	0.04000
1.645	0.05000
1.555	0.06000
1.476	0.07000
1.405	0.08000
1.341	0.09000

X	Q(x)
1.282	0.10000
0.842	0.20000
0.524	0.30000
0.253	0.40000
0.000	0.50000

Large-scale fading A numeric example

How many dB fading margin, against $\sigma_{F|dB} = 7$ dB log-normal fading, do we need to obtain an outage probability of 0.5%?

$$P_{\text{out}} = Q\left(\frac{M_{|\text{dB}}}{\sigma_{F|\text{dB}}}\right) = 0.5\% = 0.005$$

Consulting the Q(.)-function table (or using a numeric software), we get

$$\frac{M_{|dB}}{\sigma_{F|dB}} = 2.576 \Rightarrow \frac{M_{|dB}}{7} = 2.576 \Rightarrow M_{|dB} = 18$$



SMALL-SCALE FADING



Small-scale fading Ilustration shown during Lecture 1





Illustration of interference pattern from above



Reflector

Many reflectors ... let's look at a simpler case!

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Small-scale fading Two waves



At least in this case, we can see that the interference pattern changes on the wavelength scale.

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Small-scale fading Many incoming waves

Many incoming waves with





 $r \exp(j\phi) = r_1 \exp(j\phi_1) + r_2 \exp(j\phi_2) + r_3 \exp(j\phi_3) + r_4 \exp(j\phi_4)$

Small-scale fading Rayleigh fading



Small-scale fading Rayleigh fading – Fading margin



Fading margin $M = \frac{r_{\rm rms}^2}{r_{\rm min}^2}$ $M_{\rm |db} = 10 \log_{10} \left(\frac{r_{\rm rms}^2}{r_{\rm min}^2} \right)$

Probability that the amplitude r is below some threshold r_{min} :

$$\Pr(r < r_{\min}) = \int_{0}^{r_{\min}} pdf(r) dr = 1 - \exp\left(-\frac{r_{\min}^{2}}{r_{\max}^{2}}\right)$$

Small-scale fading A numeric example

How many dB fading margin, against Rayleigh fading, do we need to obtain an outage probability of 1%?

$$\Pr(r < r_{\min}) = 1 - \exp\left(-\frac{r_{\min}^2}{r_{\max}^2}\right) = 1\% = 0.01$$

Some manipulation gives

$$1-0.01 = \exp\left(-\frac{r_{\min}^2}{r_{ms}^2}\right) \Rightarrow \ln(0.99) = -\frac{r_{\min}^2}{r_{ms}^2}$$

 $\Rightarrow \frac{r_{\min}^2}{r_{ms}^2} = -\ln(0.99) = 0.01 \Rightarrow M = \frac{r_{min}^2}{r_{min}^2} = 1/0.01 = 100$
 $M_{|dB} = 20$

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Small-scale fading Doppler shifts





Receiving antenna moves with speed s_{RX} at an angle θ relative to the propagation direction of the incoming wave, which has frequency f_0 .

$$[c = speed of light = 3x10^8 m/s]$$

Frequency of received signal:

 $f = f_0 + v$

where the Doppler shift is

$$v = -f_0 \frac{s_{\text{RX}}}{c} \cos(\theta)$$

The maximal Doppler shift is

$$v_{\max} = f_0 \frac{s_{\text{RX}}}{c}$$

Small-scale fading Doppler spectrum



Incoming waves from several directions (relative to movement or RX)



All waves of equal strength in this example, for simplicity.

Spectrum of received signal when a f_0 Hz signal is transmitted.



Small-scale fading Doppler spectrum





Small-scale fading The Doppler spectrum



For the uncorrelated scattering with uniform angular distribution of incoming power (isotropic scattering), we obtain the Doppler spectrum by Fourier transformation of the time correlation of the signal:



$$S_{\rm D}(v) = \int \rho(\Delta t) e^{-j 2\pi v \Delta t} d\Delta$$

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for $-V_{\text{max}} < V < V_{\text{max}}$

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 $f_0 - v_{\rm max}$

This is the "classical" Doppler spectrum, a.k.a. the **Jakes'**

doppler spectrum.

 $f_0 + v_{\text{max}}$

Small-scale fading Fading dips





The larger the fading margin, the rarer the fading dips, and the shorter they are.

The length and the frequency of fading dips can be important for the functionality of a radio system.

Can we quantify these?

Small-scale fading Statistics of fading dips

Frequency of the fading dips (normalized dips/second)

Length of fading dips (normalized dip-length)



These curves are for Rayleigh fading and isotropic uncorrelated scattering (**Jakes' doppler spectrum**).

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Small-scale fading Rice fading



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COMBINING LARGE- AND SMALL-SCALE FADING

Large- and small-scale fading Combining the two

We will start using Alternative 1

We have seen examples of how we can compute the required fading margins, due to large- and small-scale fading, given certain criteria (e.g. outage probability).

If we have both types of fading, how do we combine them into a "total" fading margin? There are basically two options:

- 1) Calculate the fading margins separately and add them up.
- Derive the pdf (or cdf) of the total fading and calculate a single fading margin for both.

Alternative 1 is the simple solution, but it will overdimension the system a bit.

Alternative 2 is a much more complex operation.



NOISE- AND INTERFERENCE-LIMITED LINKS



Noise-limited system Fading margin and the link budget



 We use some propagation model to calculate a deterministic propagation loss.

Variations in the environment and movements will cause variations in the the propagation loss, which will propagate to the instantaneous received power.

To protect the receiver from too low received power, we add a fading margin.

Requirement for the receiver to operate properly.

Interference-limited system Interference fadning margin



In interference limited systems, we are preliminary interested in how far from the transmitter we can be, without receiveing too much interference.

Depending on the system design and requirements on quality, our receiver can tolerate a certain (C/I)_{min}.

Assuming fading on the wanted and interfering signal we can calculate a fading margin M_{IdB} required to fulfill som criterion on e.g. outage.

For independent log-normal fading, we can add the variances of the two fading characteristics and get a "total" lognormal fading with standard deviation: $\sigma_{tot|dB} = \sqrt{\sigma_{C|dB}^2 + \sigma_{I|dB}^2}$



DELAY (TIME) DISPERSION



Delay (time) dispersion A simple case



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Delay (time) dispersion A simple case



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Delay (time) dispersion One reflection/path, many paths



Delay (time) dispersion Bandwidth and time-resolution

Radio systems are band-limited, which makes our infinitely short impulses become waveforms with a certain width in time.



The time-width of the pulses is inversely proportional to the bandwidth.



NARROW- VERSUS WIDE-BAND

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Narrow- versus wide-band Channel impulse response

The same radio propagation environment is experienced differently, depending on the system bandwidth.



Narrow- versus wide-band Channel frequency response



Narrow- versus wide-band Let's not forget the time-dependence!

Measurement in hilly terrain at 900 MHz.

We need to take **absolute time** *t* into consideration, as the channel will change when things move.

The channel impulse response becomes:

 $h(t,\tau)$



[Liebenow & Kuhlmann 1993]

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Narrow- versus wide-band Doppler spectrum and delay

Since the channel at each delay τ is the result of different propagation paths, we can have different Doppler spectra for each delay.

This effect is shown by the scattering function:

 $P_{S}(v,\tau)$

(received power as function of doppler shift and delay)

Measurement in hilly terrain at 900 MHz.



Summary



NARROW-BAND CHANNELS

- Complex notation with amplitude, phase and complex envelope (phasor).
- Large-scale fading with log-normal distribution and calculation of fading margin.
- Small-scale fading with Rayleig and Rice distribution, calculation of fading margin.
- Received signal maximal Doppler shift, Doppler spectrum and time characteristics.
- Fading margin in the **link-budget** of noise limited systems.
- Fading margin and **maximal distance** for interference limited systems.

WIDE-BAND CHANNELS

- Instead of one (time varying) channel coefficient, we have an entire (time varying) impulse response
- Channel delay (time) dispersion and frequency selectivity
- Doppler spectrum as function of delay, i.e. the scattering function

There is **MUCH MORE** to learn about this – which many of you have done in in the Channel Modeling course (ETIN10)!