UNIK4230: Mobile Communications
Spring 2014

Per Hjalmar Lehne

per-hjalmar.lehne@telenor.com

Mobile: 916 94 909

Combating the Effect of Fading in Mobile Systems (Chapter 5)

6 March 2014

Agenda

- Introduction of fading
  - Effect of fading
- Diversity and types of diversity
- Combining techniques of diversity
- Equalizers

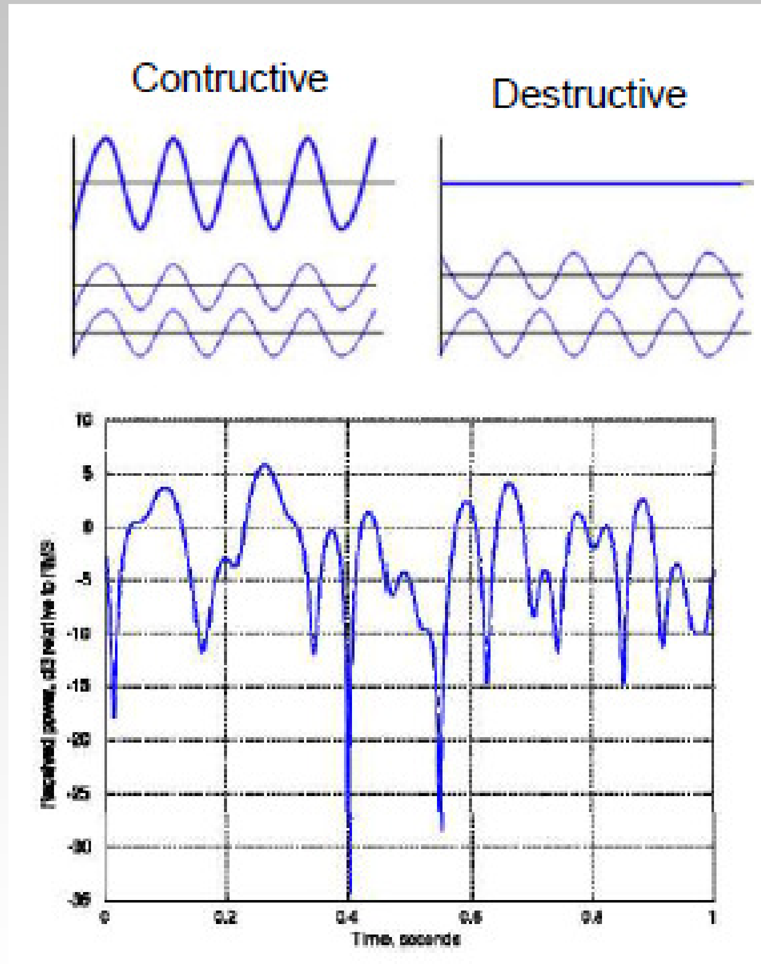
Agenda

- Introduction of fading
  - Effect of fading
- Diversity and types of diversity
- Combining techniques of diversity
- Equalizers

Introduction

- **Fading leads to-**
  - Quick signal variation (Rayleigh, short term)
  - Slow signal variation (lognormal, long term)
  - Inter-Symbol Interference (ISI)

- **Varies ways to combat fading-**
  - Micro diversity
  - Macro diversity
  - Channel equalizer



Effects of fading (I)

When signal varies, Signal-to-Noise Ratio (SNR) varies and Bit Error Rate (BER) varies over time.

- The total BER becomes larger than in a non-fading case with the same average power

For BPSK modulation (details in Lec 6 - Modulation), probability of error with and without fading becomes:

$$p(e) = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\gamma_0}\right) \quad , \quad \text{without fading}$$

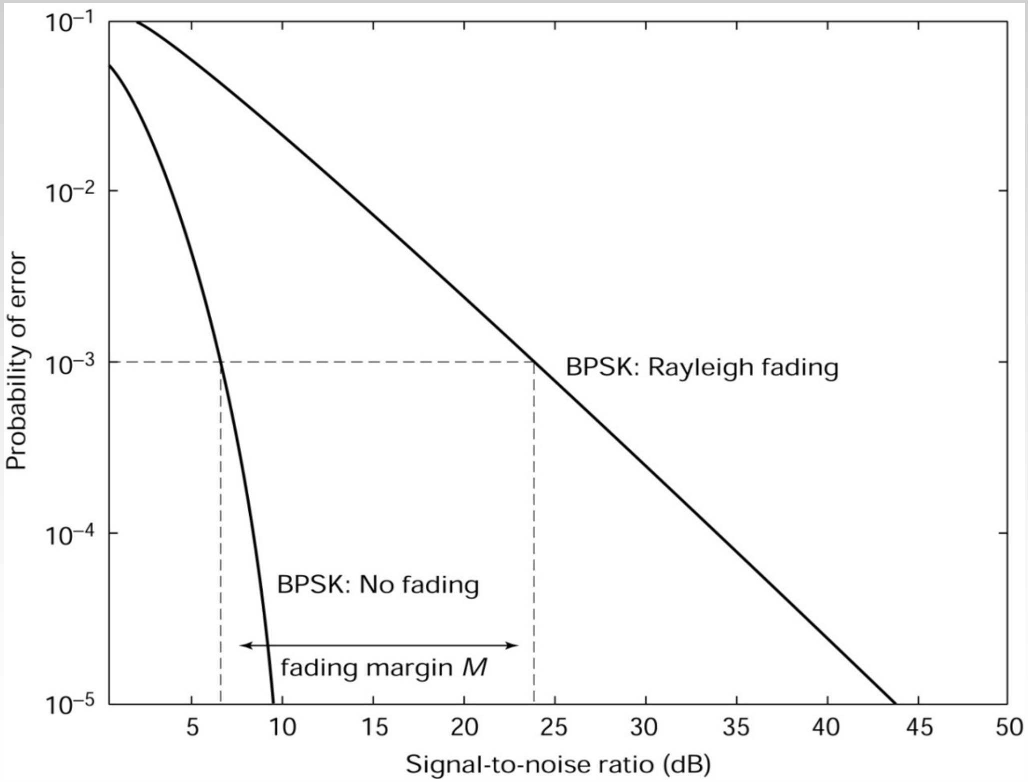
$$p_{fad}(e) = \frac{1}{2}\left[1 - \sqrt{\frac{\gamma_0}{1+\gamma_0}}\right], \quad \text{with fading}$$

Where γ_0 is the SNR

Effects of fading (II)

BER for BPSK-modulation without fading and with Rayleigh-fading

Fadw-margin M for BER=10^{-3} is 17 dB



Agenda

- Introduction of fading
  - Effect of fading
- Diversity and types of diversity
- Combining techniques of diversity
- Equalizers

Diversity (I)

Diversity means the combination of independent copies of the received signal, for example, by using multiple receiver antenna

The main idea is the probability that several independent versions of the signal has very low signal level at the same time is small.

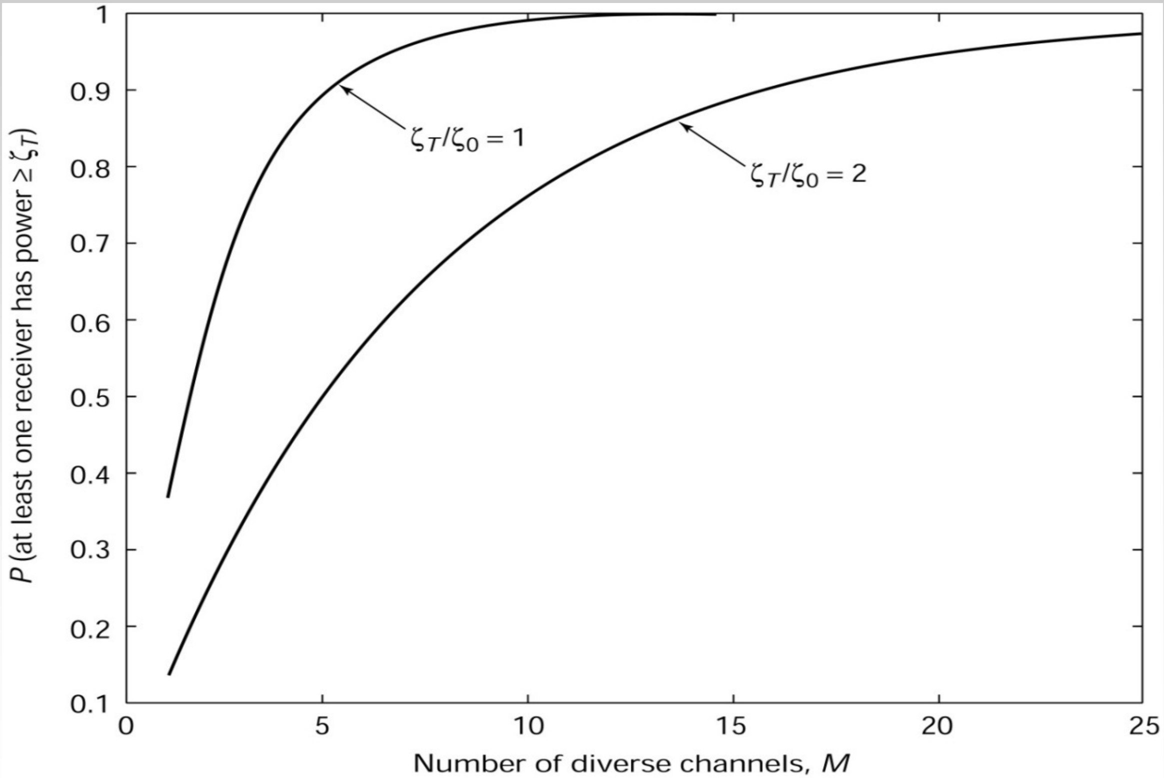
For example, the probability that M independent Rayleigh distributed signals at the same time is below a threshold value ζ_T is:

$$P_M(\zeta_T) = \left[1 - \exp\left(-\frac{\zeta_T}{\zeta_0}\right)\right]^M$$

where ζ_0 is the average power

Diversity (II)

The probability that at least one of M independent Rayleigh fading channels has power above ζ_T:



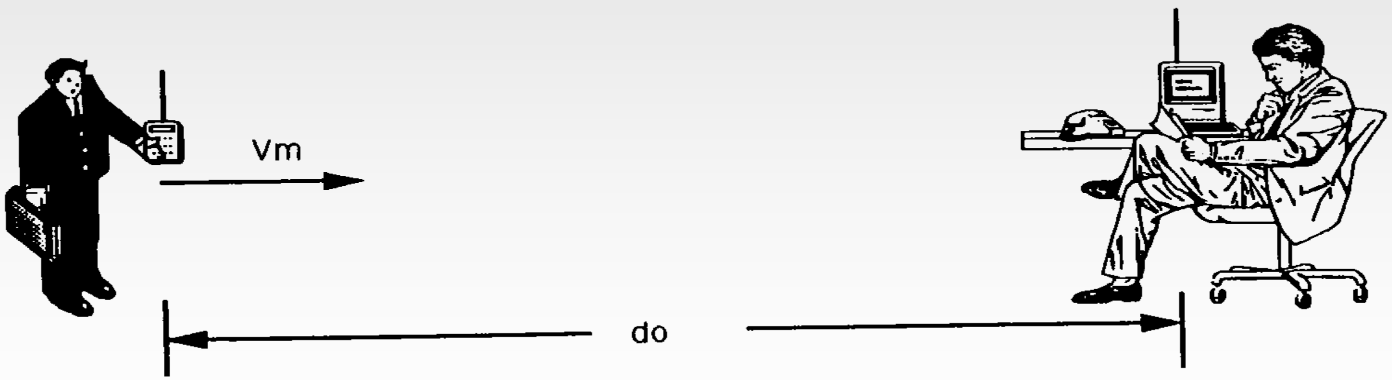
Other signal degrading effects

Random frequency modulation (FM) because of Doppler (chap. 2)

Co-channel interference (chap. 4)

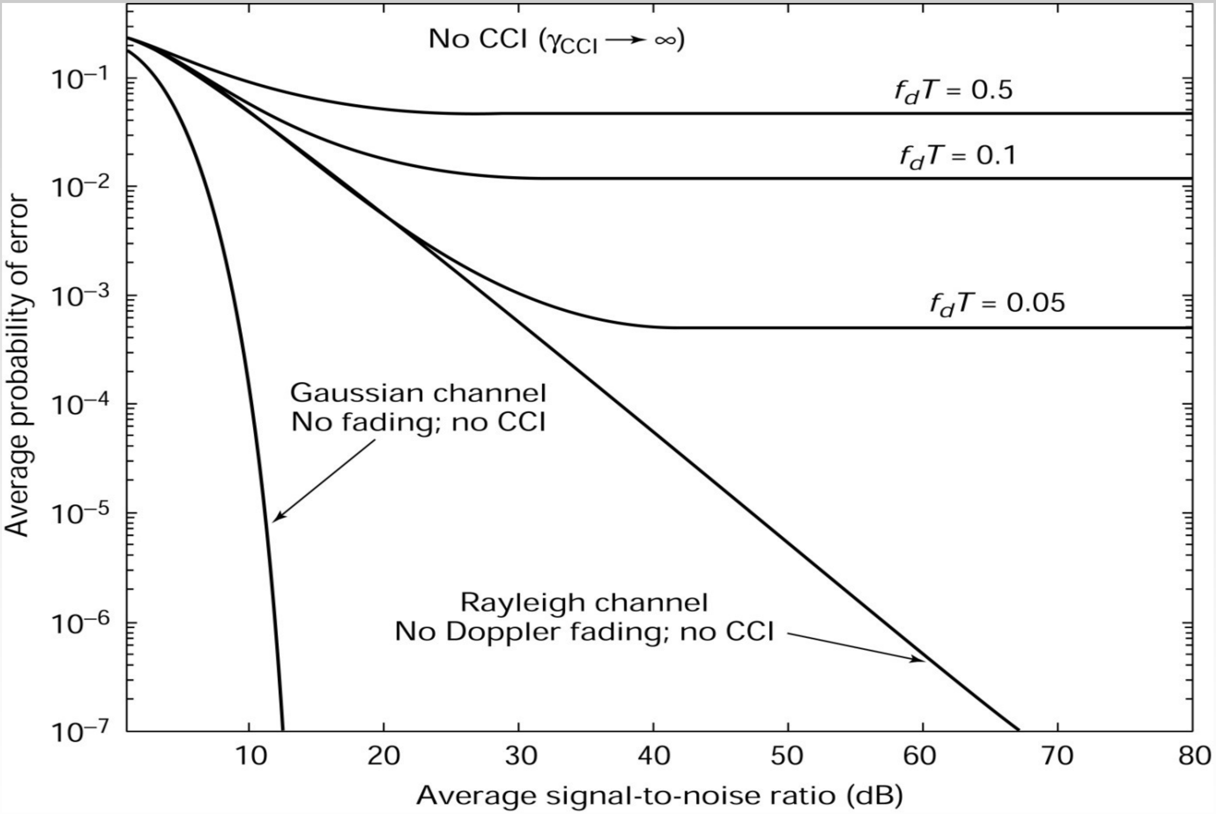
- Both these effects creates a «floor» for the BER. BER will not go below a certain value even with increased SNR

Intersymbol interference (ISI) because of frequency selective fading



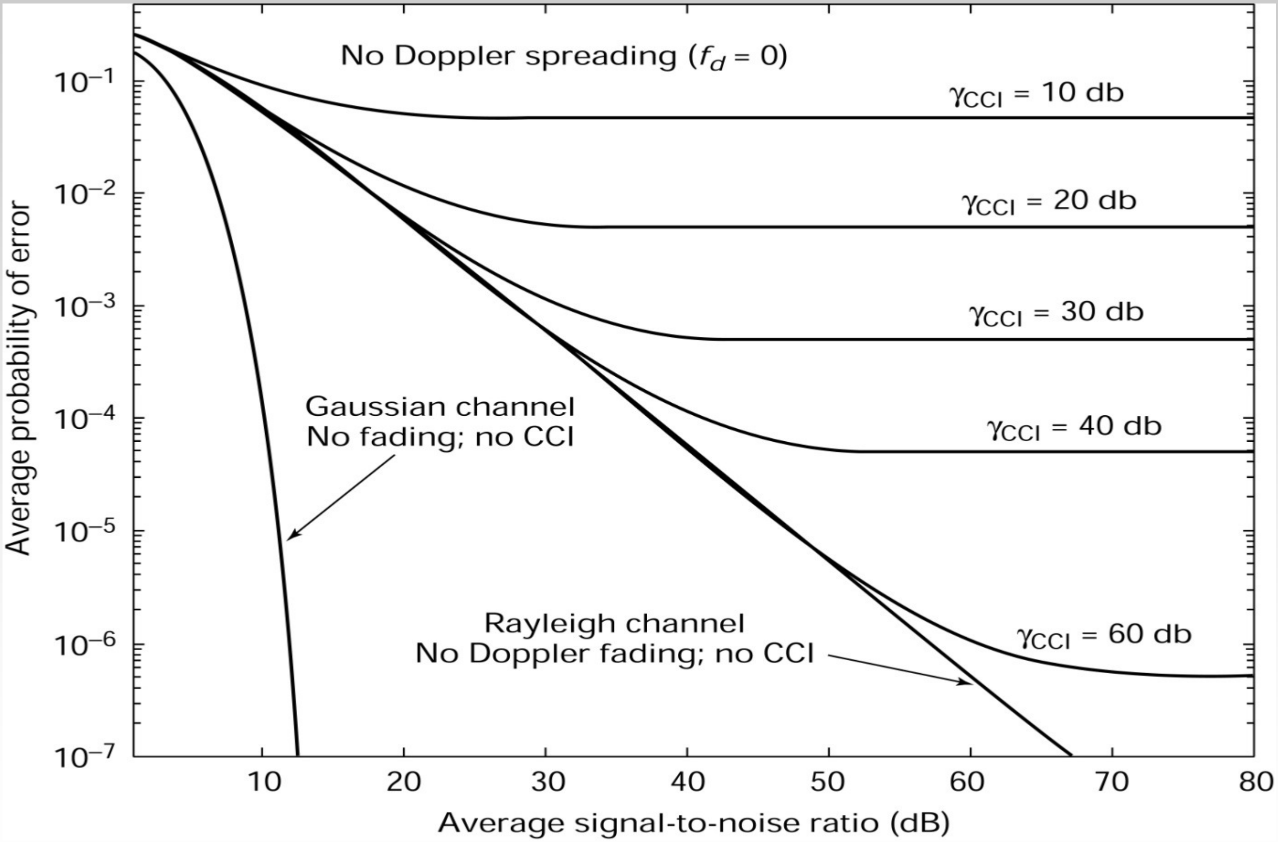
Signal degradation from Doppler

BER for different values of the product $f_D T$, wher f_D is maksimum Doppler-skift and T is the symbol length



Signal degradation from co-channel interference

BER for different values of the signal-to-interference ratio γ_{CCI}.



Types of diversity

Space diversity –

- Antenna separated in distance

Angular diversity –

- Antennas with different pointing directions

Frequency diversity –

- The same signal is transmitted at different frequencies

Polarization diversity-

- Antennas with different polarization (field orientation)

Time diversity –

- The same signal is repeated at different times

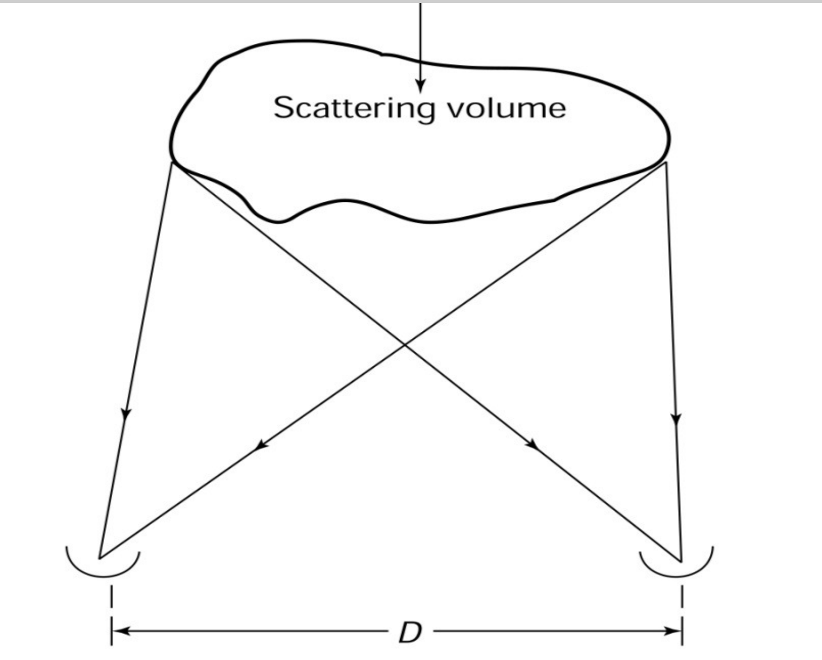
Multi-path diversity –

- Signals with different propagation paths are combined

Space diversity

Two or more antennas in different positions have uncorrelated fading patterns if separation is large enough

Required separation depends on the angle separation of the signal components



Extremes are:

- If multi-path components arriving with equal probability from all directions is necessary distance between two antennas $\lambda / 2$
- If all signal components arrive from the same direction space diversity will have no effect, no separation is large enough

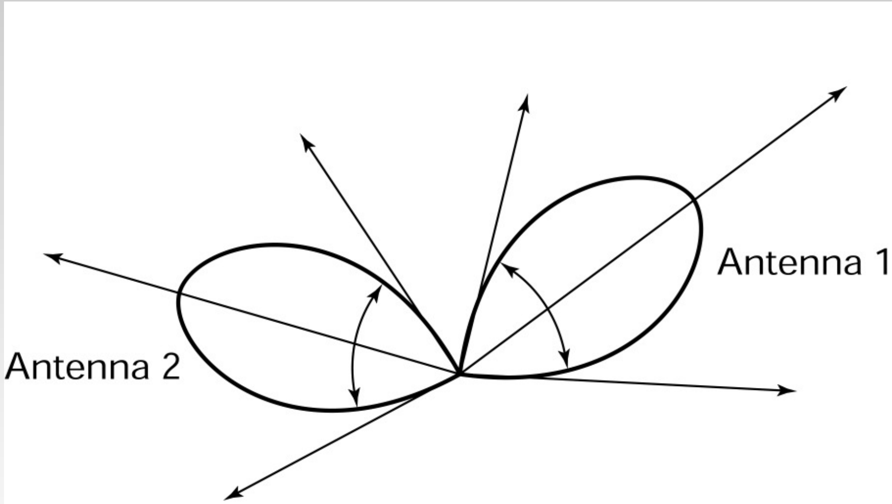
Space diversity at the base station

Angular diversity

The receiving antennas have different pointing direction.

Signal components arriving from different directions is normally uncorrelated

Angular diversity requires no physical distance between the antennas, and can therefore easier implemented on a mobile station



Frequency diversity

The same signal is sent on different frequencies, with so much distance that the signals are uncorrelated fading

The disadvantages of this method are:

- Bandwidth requirement is necessary to send several frequencies, and
- Complexity of the receiver must be able to receive on multiple frequencies simultaneously

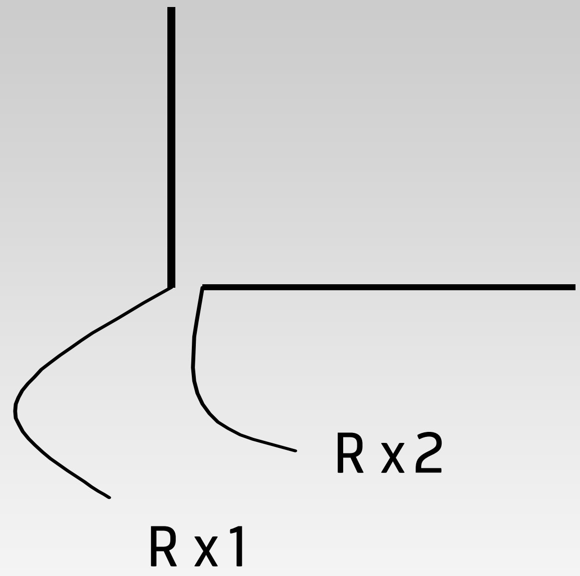
Polarization diversity

Signal at different polarization has uncorrelated fading

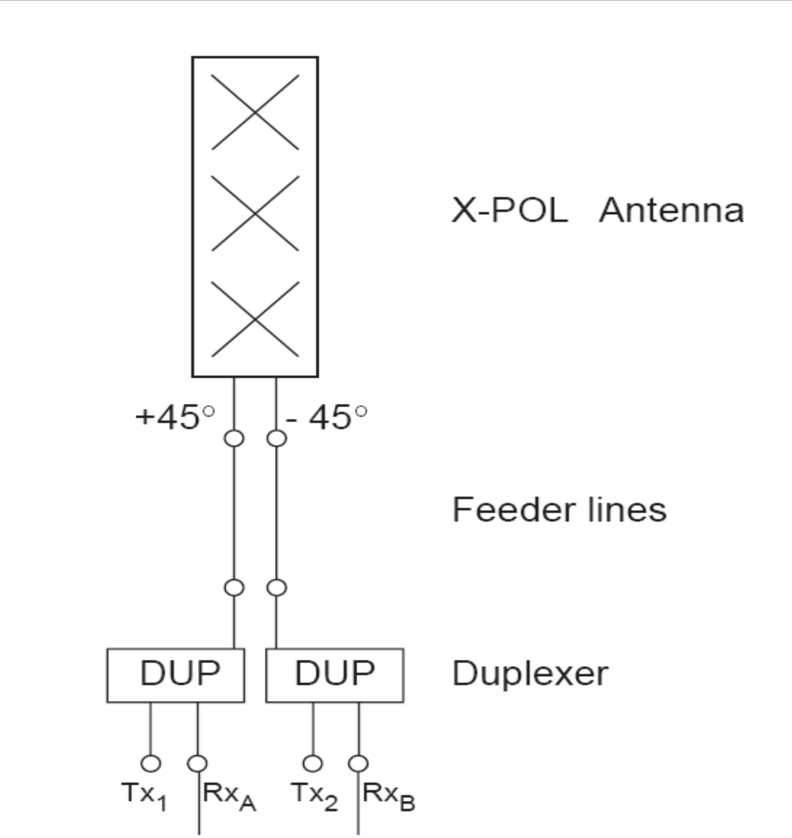
- For example vertical polarization & horizontal polarization

Exploits that the channel *depolarizes* the signal and that the signal received on different polarizations are fading uncorrelated

Disadvantage of this method is that a maximum of 2 uncorrelated polarization can exist (diversity order 2)



Polarization diversity at the base station



Source: Kathrein

Cross polar antenna used increasingly to save space

+/- 45° is normal

Time diversity

The same signal is sent several times, with a difference that exceeds the channel coherence time

The advantage of the method, compared with the other methods mentioned, is that only one antenna is required

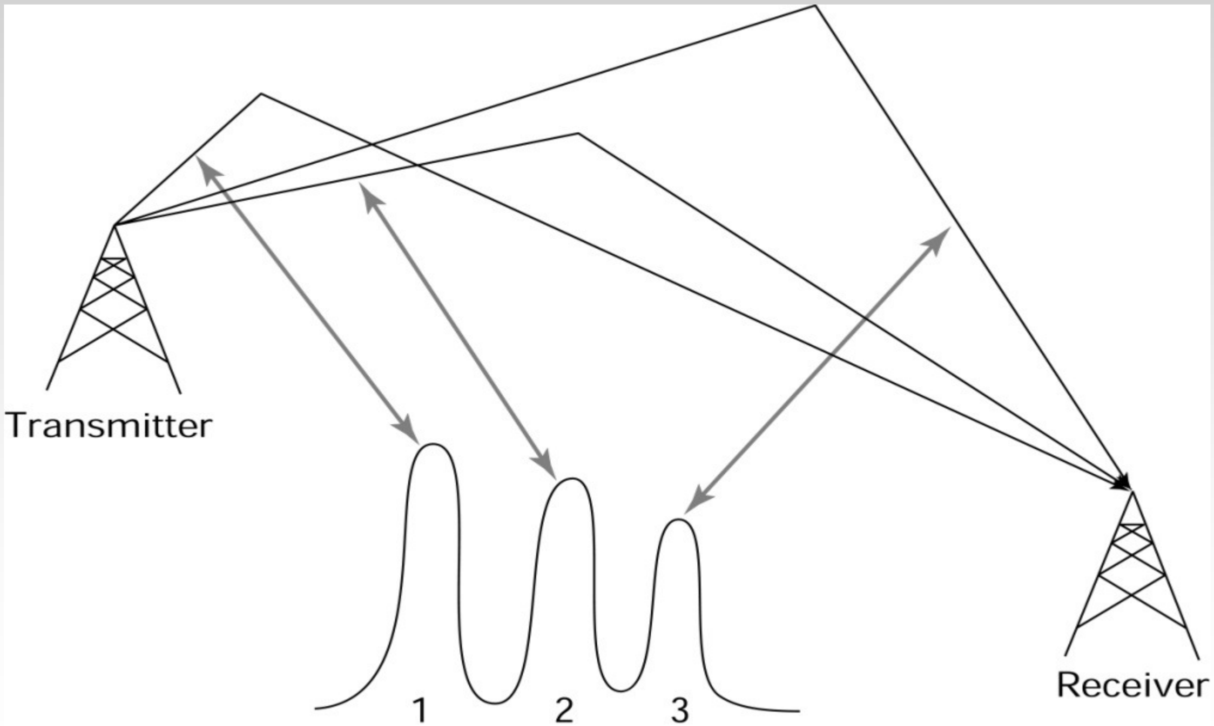
The disadvantage is the high memory requirements in the receiver for temporary data storage

Error correcting coding can be viewed as a form of time diversity

Multipath diversity

If multi-path components have a large enough separation that the can be distinguished from each other, they can be combined in the receiver

This is used in RAKE receivers, which are widely used in CDMA systems (Chapter 6 – course book)



Agenda

- Introduction of fading
  - Effect of fading
- Diversity and types of diversity
- Combining techniques of diversity
- Equalizers

Combining techniques for diversity

Selection combining (SC)

- Selects all times the strongest signal (branch)

Maximum-ratio combining (MRC)

- Adds all branches with different weight based on SNR

Equal-gain combining (EGC)

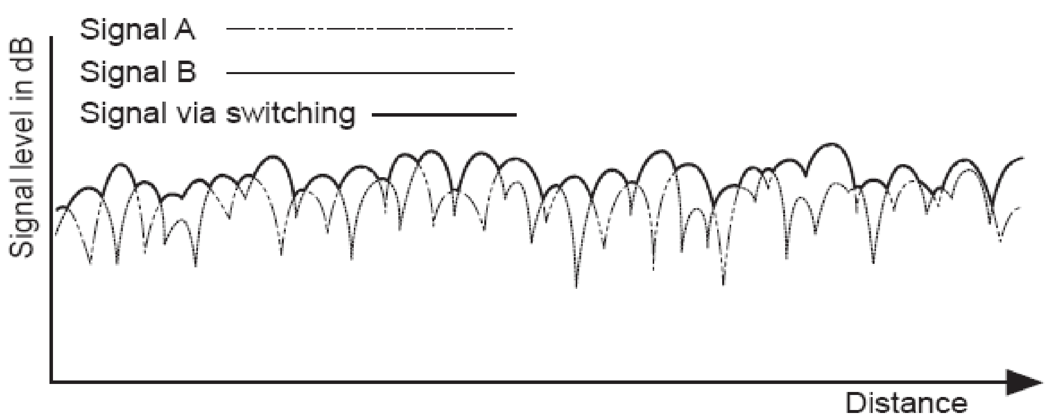
- Adds all branches of equal weight

Selection combining (SC)

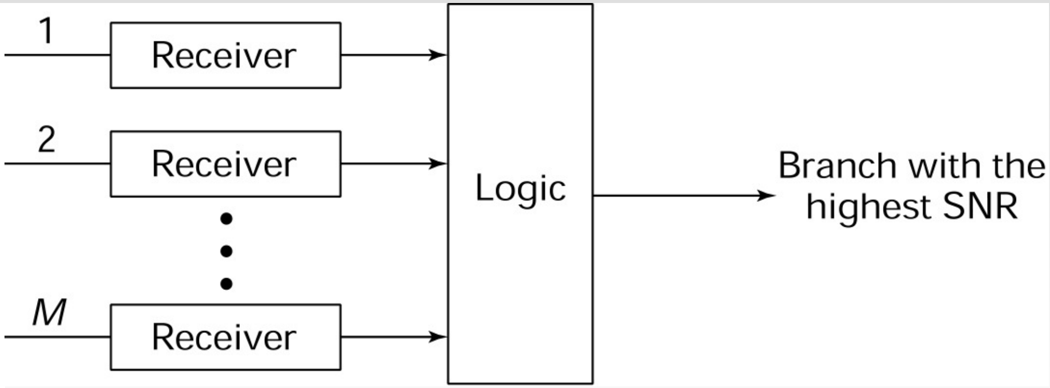
Choose the diversity branch with the strongest SNR

Possible solution to avoid continuous testing of all branches:

- Use same branch until it goes below a given threshold value, and only then test all the stuff and select the strongest.



Source: William C.Y. Lee, Mobile Communications Design Fundamentals

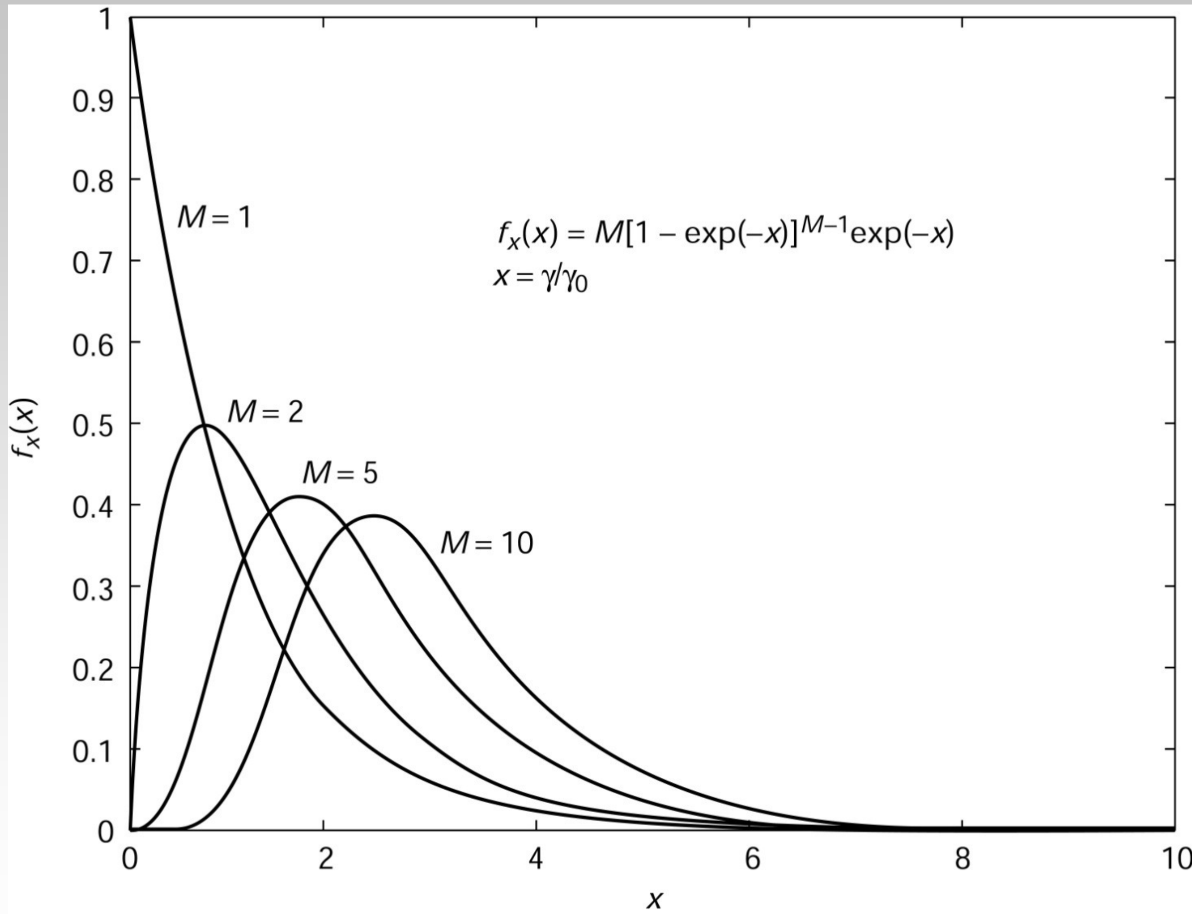


Selection combining (SC)

Average improvement using selection diversity:

$$\frac{\gamma_{se}}{\gamma_0} = \sum_{n=1}^{M} \frac{1}{n}$$

Probability density function for γ_{se}/γ_0.

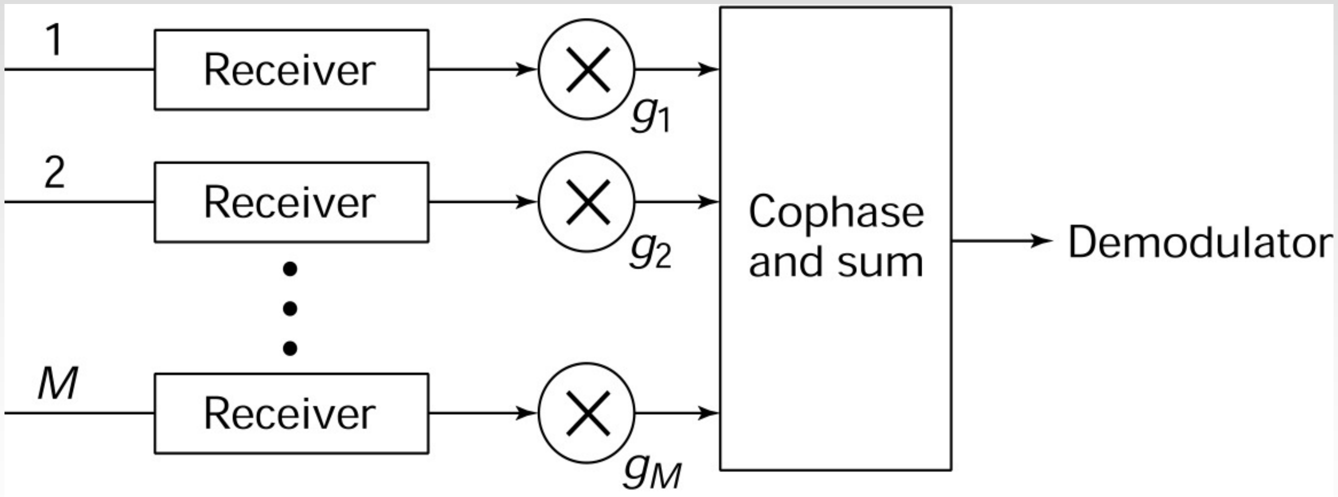


Maximum-ratio combining (MRC)

Scales all the branches by a factor g_n that is proportional with SNR of each branch

This is an optimum way to combine the signals

- More complex than selection combining

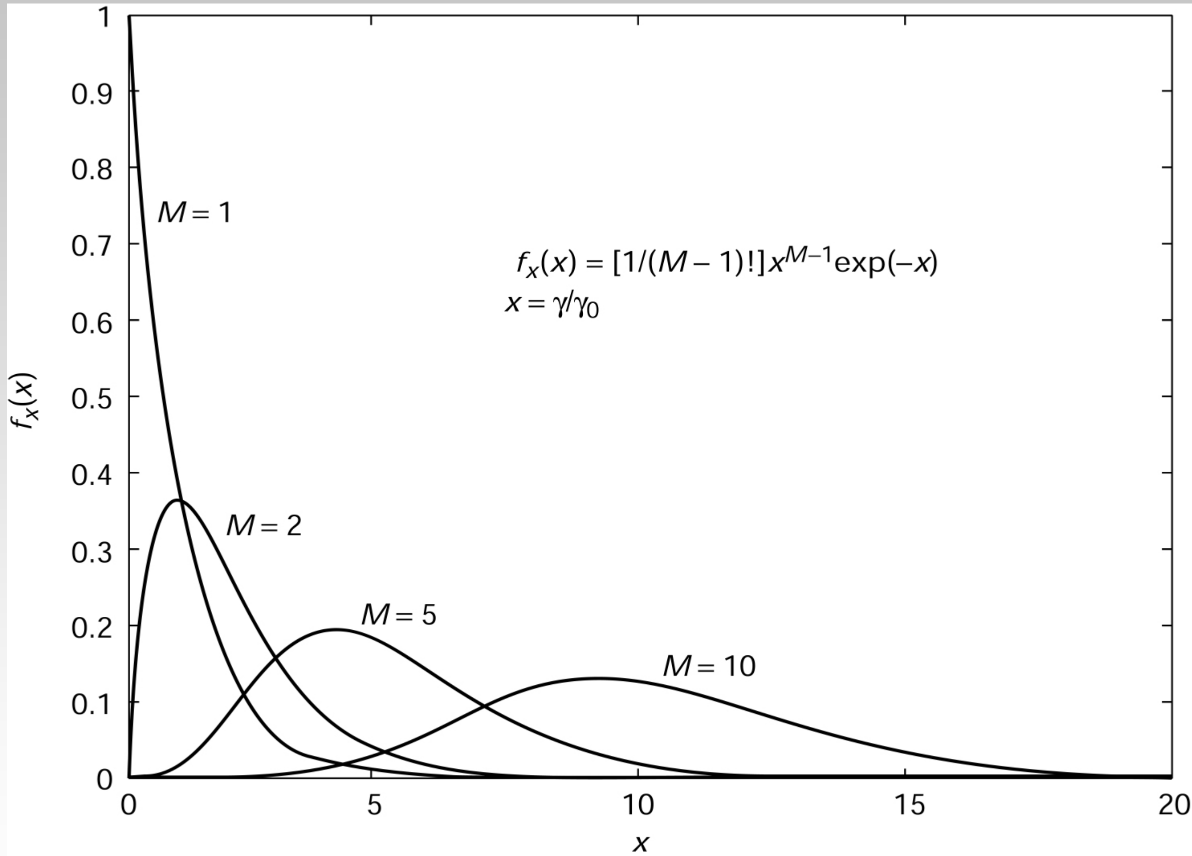


Maximum-ratio combining (MRC)

Average SNR by using MRC is:

$$\gamma_{MR} = \sum_{n=1}^{M} \gamma_n = M\gamma_0$$

Probability Density Function for γ_{MR}/γ_0



Equal gain combining (EGC)

Scales all branches with the same weight

Performance is worse than the MRC, but better than SC

Less complex than MRC

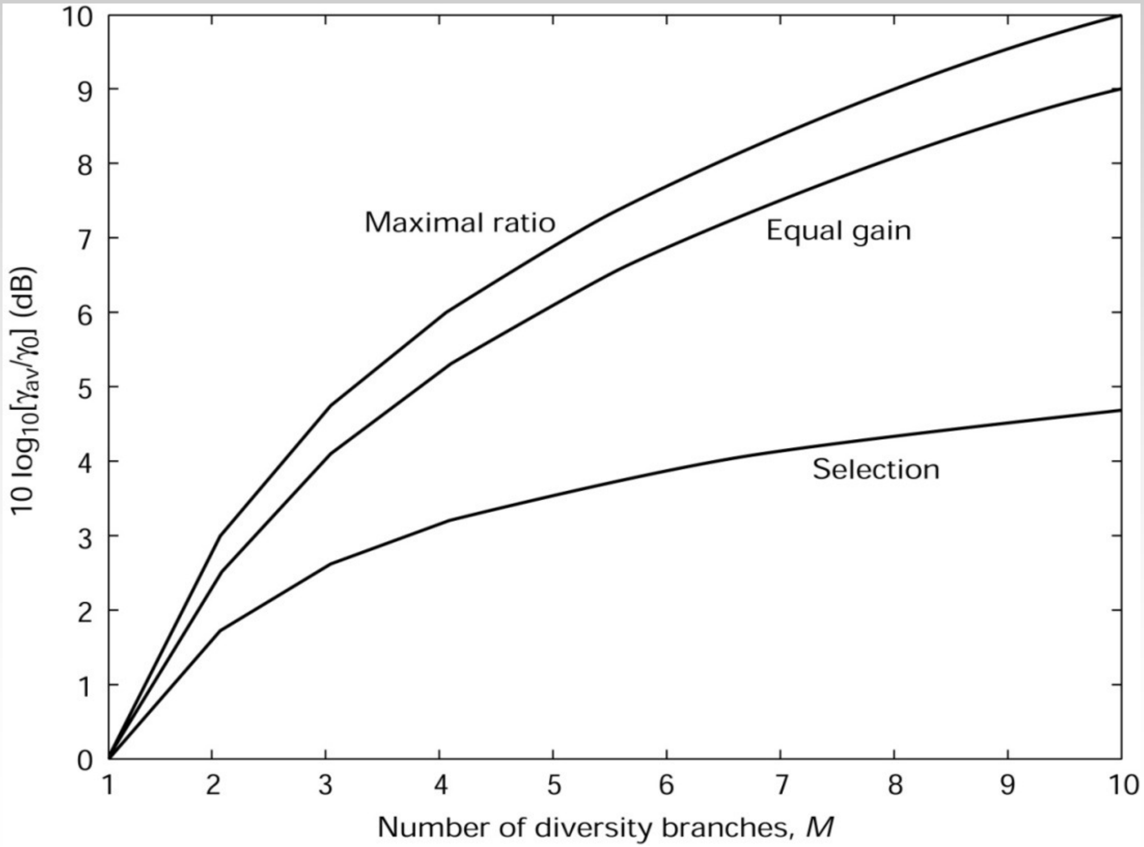
Performance between SC and MRC,

- The average SNR by using EGC is:

$$\gamma_{EC} = \gamma_0 \left[1 + \frac{\pi}{4} (M - 1) \right]$$

Comparing diversity methods:

All results are for an assumption of uncorrelated branches, with a correlation equal to ρ, performance is reduced approx. a factor √(1-ρ)2



Performance improvement – BER with diversity

Average BER for a diversity method can be found using the following expression:

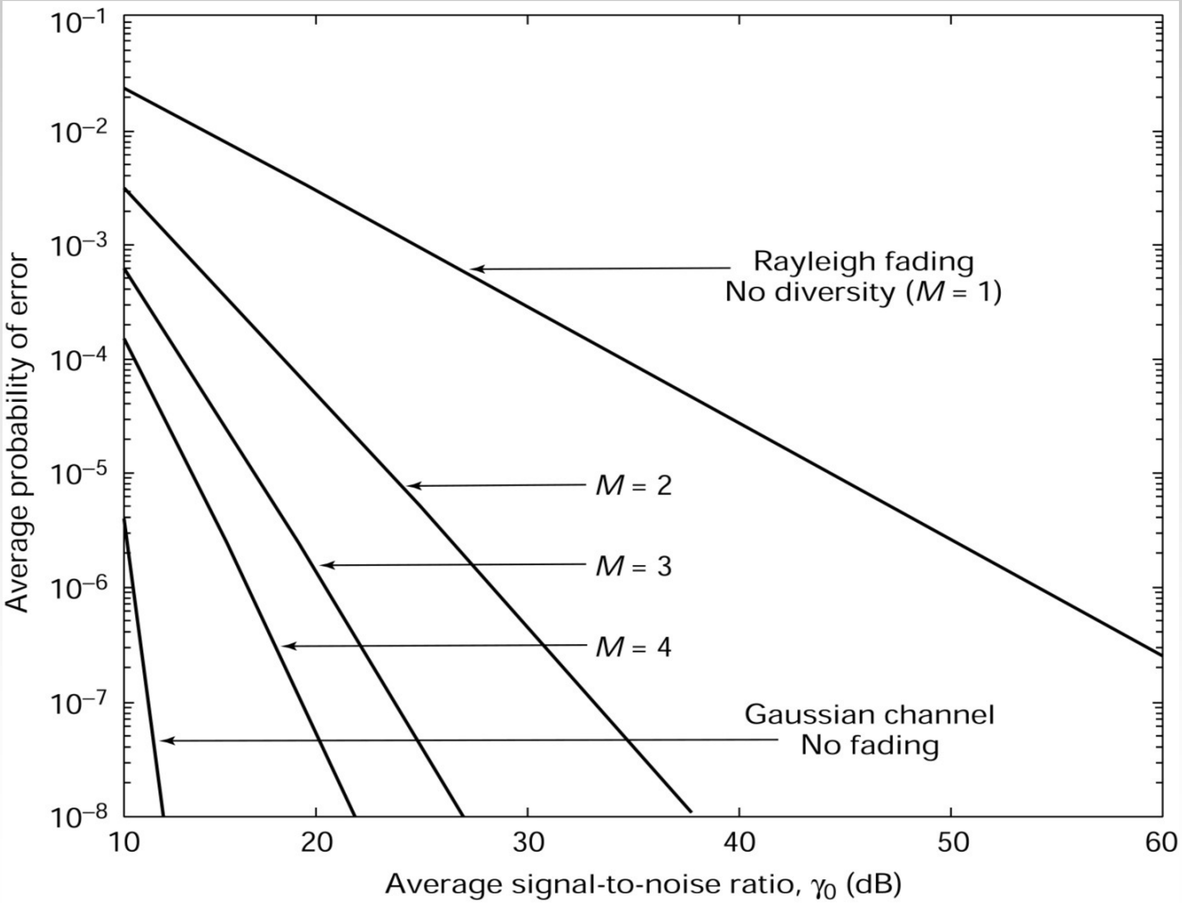
$$p_{av}(e) = \int_0^\infty p(e) f(\gamma) d\gamma$$

Where p(e) is the bit error probability as a function of SNR, γ, and $f(\gamma)$ is the probability density distribution of the SNR.

This gives the BER as a function of average SNR, γ_0.

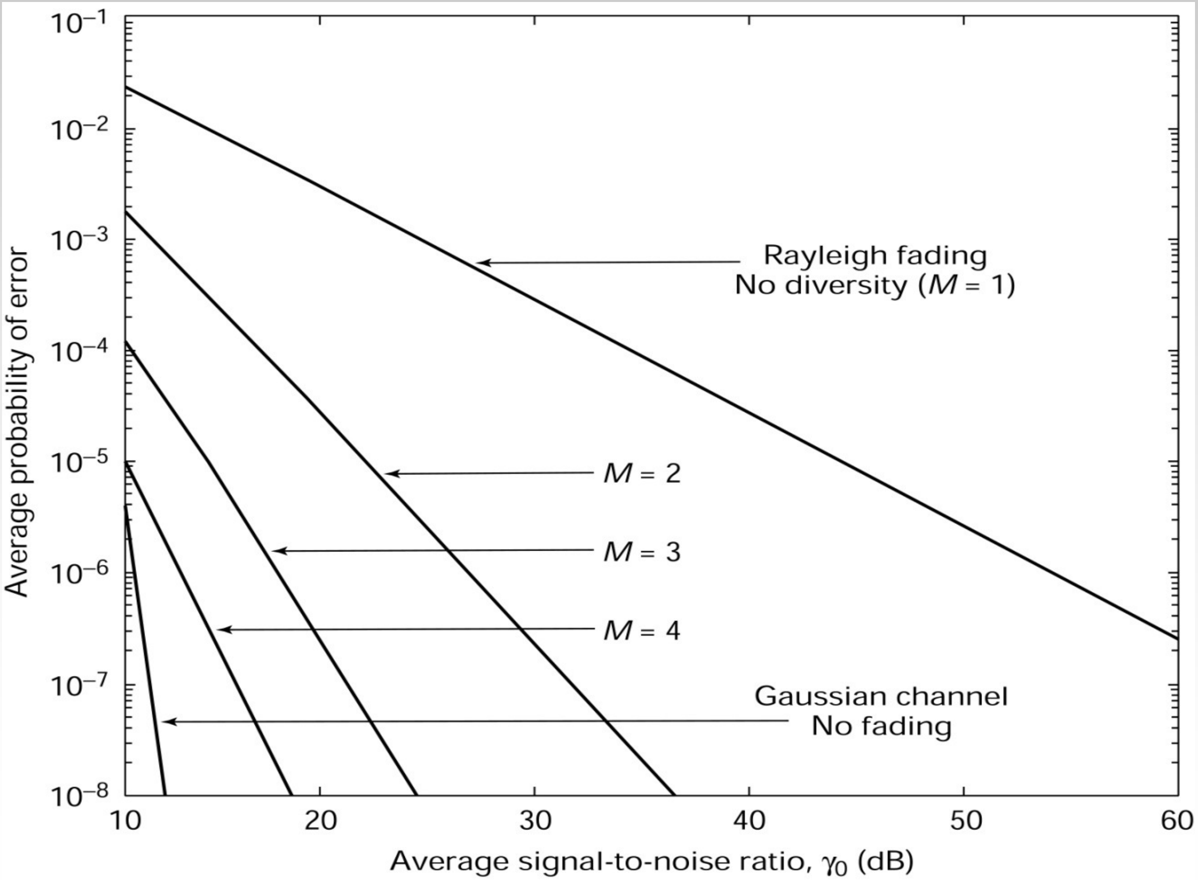
Performance improvement - SC

Average BER for different number of diversity channels (BPSK modulation):



Performance improvement – MRC (1)

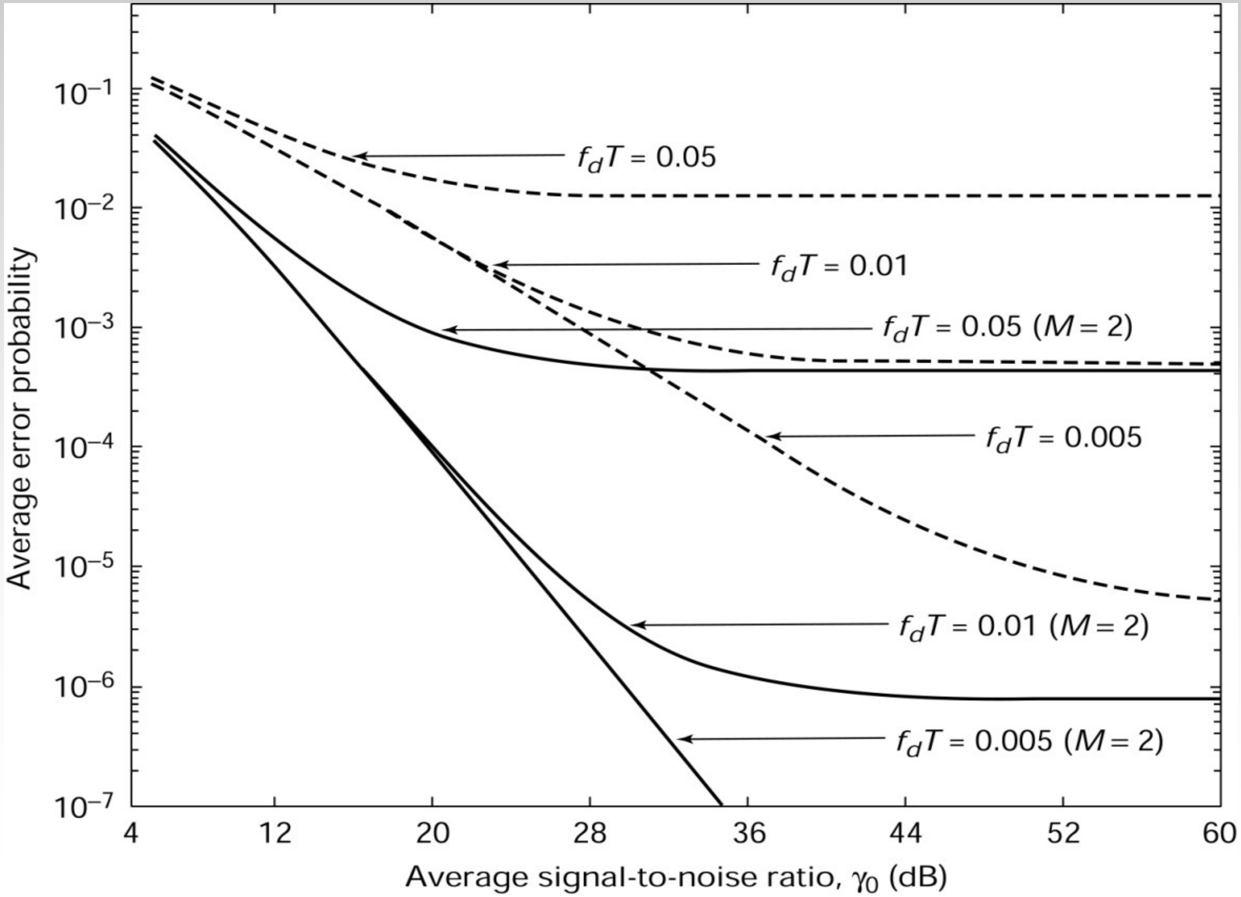
Average BER for maximum-ratio combining for different number of diversity channels (BPSK modulation):



Performance improvement – MRC (2)

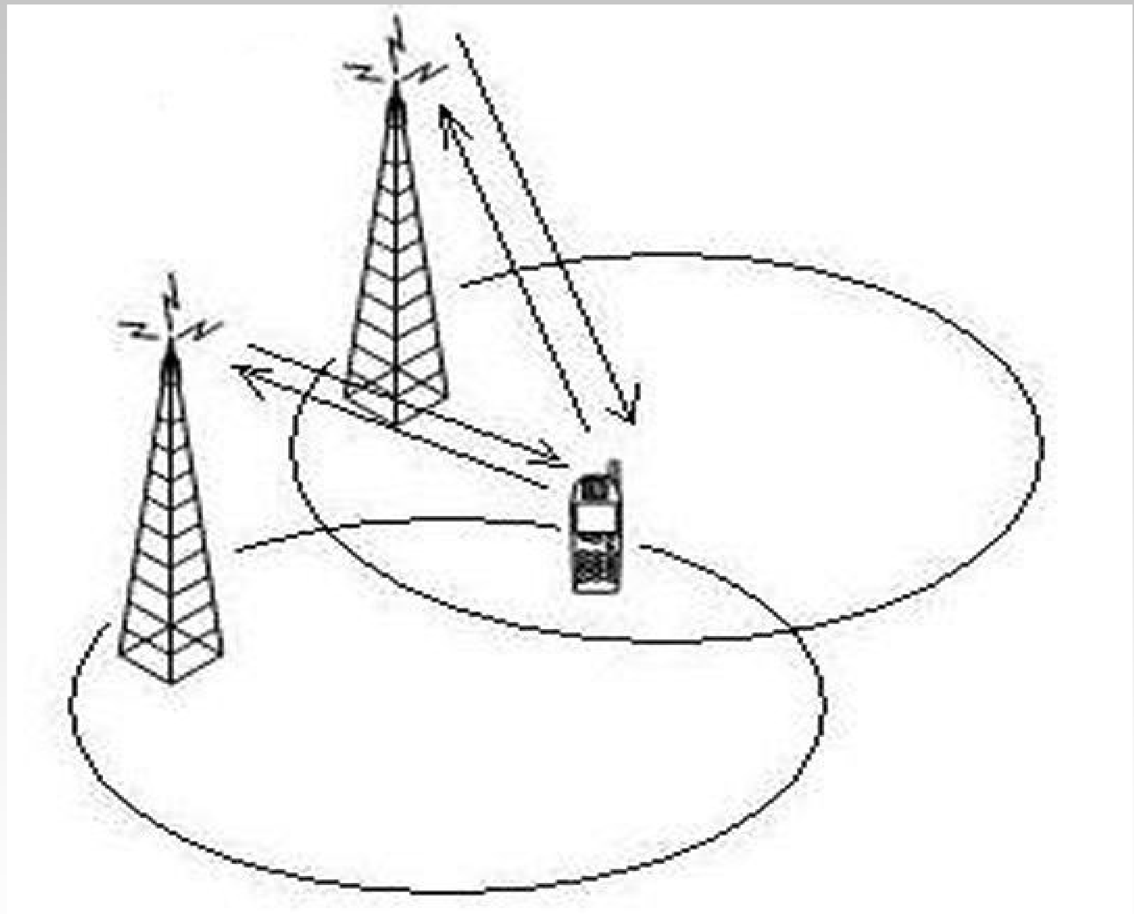
Average BER without diversity and with two-branch maximum ratio-combining

Diversity lowers the "floor" for the bit error rate -



Macro diversity

- The techniques discussed so far fights fast (short term) fading
- To combat slow (long term) fading required separation between recipients who are high in relation to terrain and building formations affects the signal distribution
- This is called macro-diversity, or the base station diversity and is usually based on communication with two or more base stations
- Hand-over of the mobile systems can be seen as a form of macro diversity



Agenda

- Introduction of fading
  - Effect of fading
- Diversity and types of diversity
- Combining techniques of diversity
- Equalizers

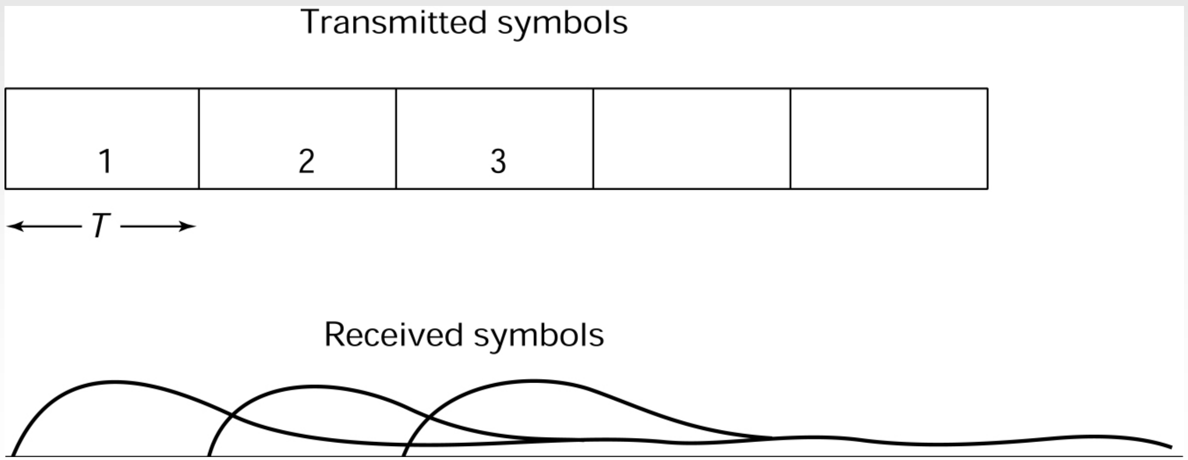
Channel equalization

When the time dispersion is significant compared to the symbol length it leads to Inter-Symbol Interference (ISI)

In the frequency domain, this corresponds to the coherence bandwidth being smaller than the information bandwidth, which leads to frequency selective fading

ISI is a particular problem at high rates, when the symbol times are short

ISI can be mitigated by using *channel equalization*, which means to filter the signal so that it counteracts the frequency-selective fading and ISI



Equalizer requirements (I)

The *transfer function* of the channel is: $$H_c(f) = A(f)\exp\left[\theta(f)\right]$$

- Where $A(f)$ is the amplitude and $\theta(f)$ is the phase response

The *envelope delay* is: $$\tau(f) = -\frac{1}{2\pi}\frac{d\theta(f)}{df}$$

The criterion for a distortion free channel is: $$A(f) = A_0, \quad \tau(f) = \tau_0$$

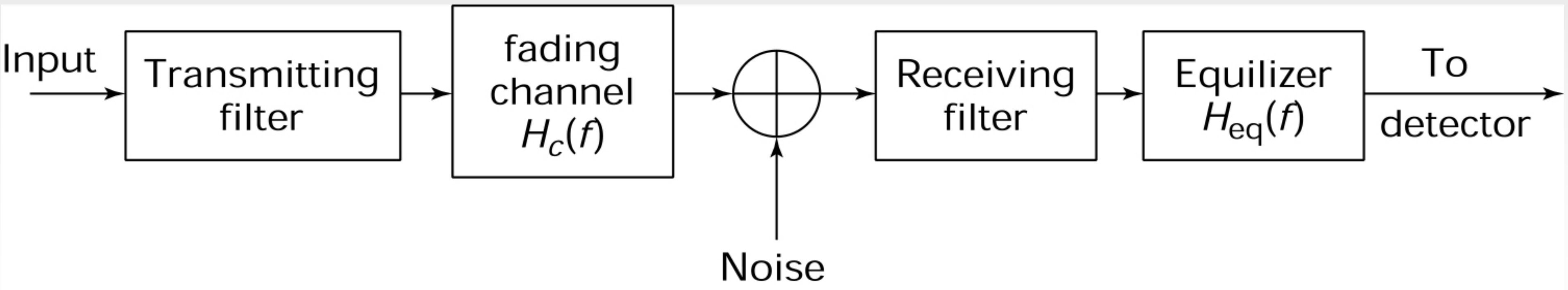
- Constant amplitude and linear phase (within the information bandwidth)
- *If this is not fulfilled, the signal will be distorted and experience ISI*

Equalizer requirements (II)

The equalizer is a filter with a response $H_{eq}(f)$ such that the resulting response of the channel and equalizer fulfils the requirement of a distortion free channel

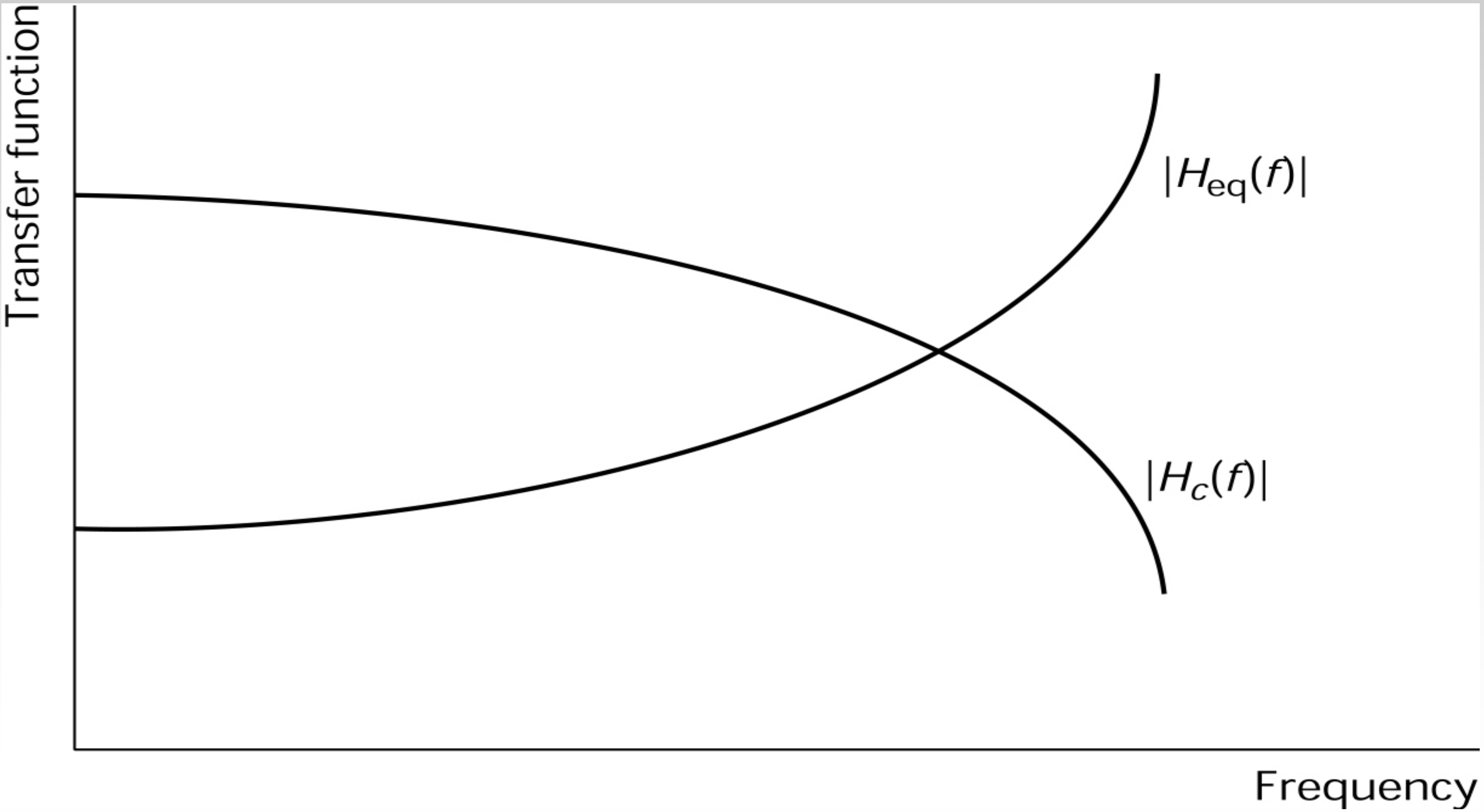
$$H_{eq}(f)H_c^*(-f) = 1$$

The channel is time-variant and the filter must be adaptive



Channel response and equalizer response

The equalizer response has to compensate for the channel response to make the sum equal, i.e. the channel response is «equalized»



Summary chapter 5

Signal variations caused by fading increase the BER

Random FM caused by Doppler and co-channel interference results in a BER «floor»

- The BER cannot be improved further by increasing SNR

Diversity means that multiple copies of the signal, which experience independent fading, are combined.

- This reduces the need for fading margins

Spatial, frequency, angular, polarization, time and multipath diversity are different types of diversity

Selection combining, maximum ratio combining and equal gain combining are different methods for combining the diversity signal.

- MRC is optimum, but also most complex

Macro-diversity means that the receivers are spaced with large distances, usually different base stations.

- Macro-diversity fights long-term fading

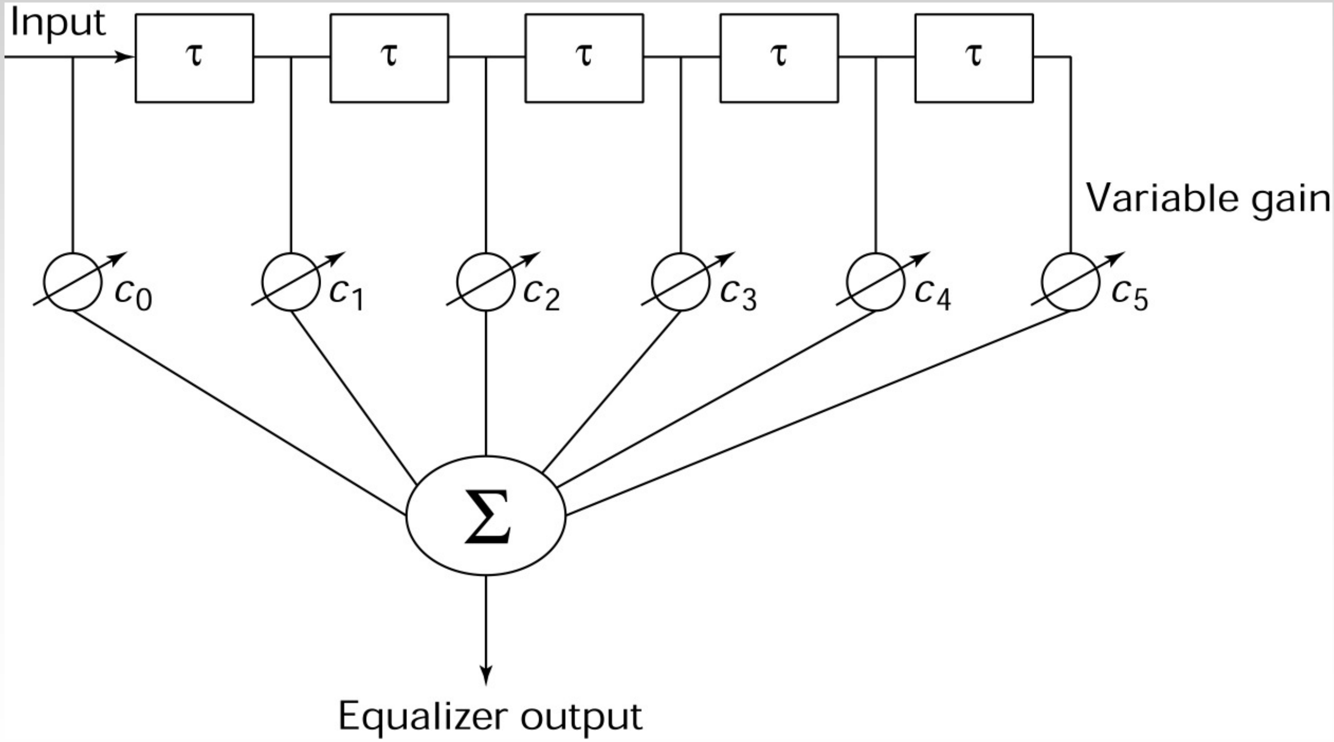
Inter-symbol interference (ISI) cased by frequency-selective fading can be mitigated with channel equalizers

Spare slides

Linear Transversal Equalizer (LTE)

An LTE structure is shown below

The required length of the filter depends on the variation in channel delay (the length of the channel's impulse response)



Properties of the Linear Transversal Equalizer

Different optimizing criteria exists to estimate the values of the filter coefficients c_i.

Zero-forcing (ZF) tries to force the ISI to zero.

- This is not always optimum
- Can give noise amplification in parts of the bandwidth

Symbol-spaced equalizer:

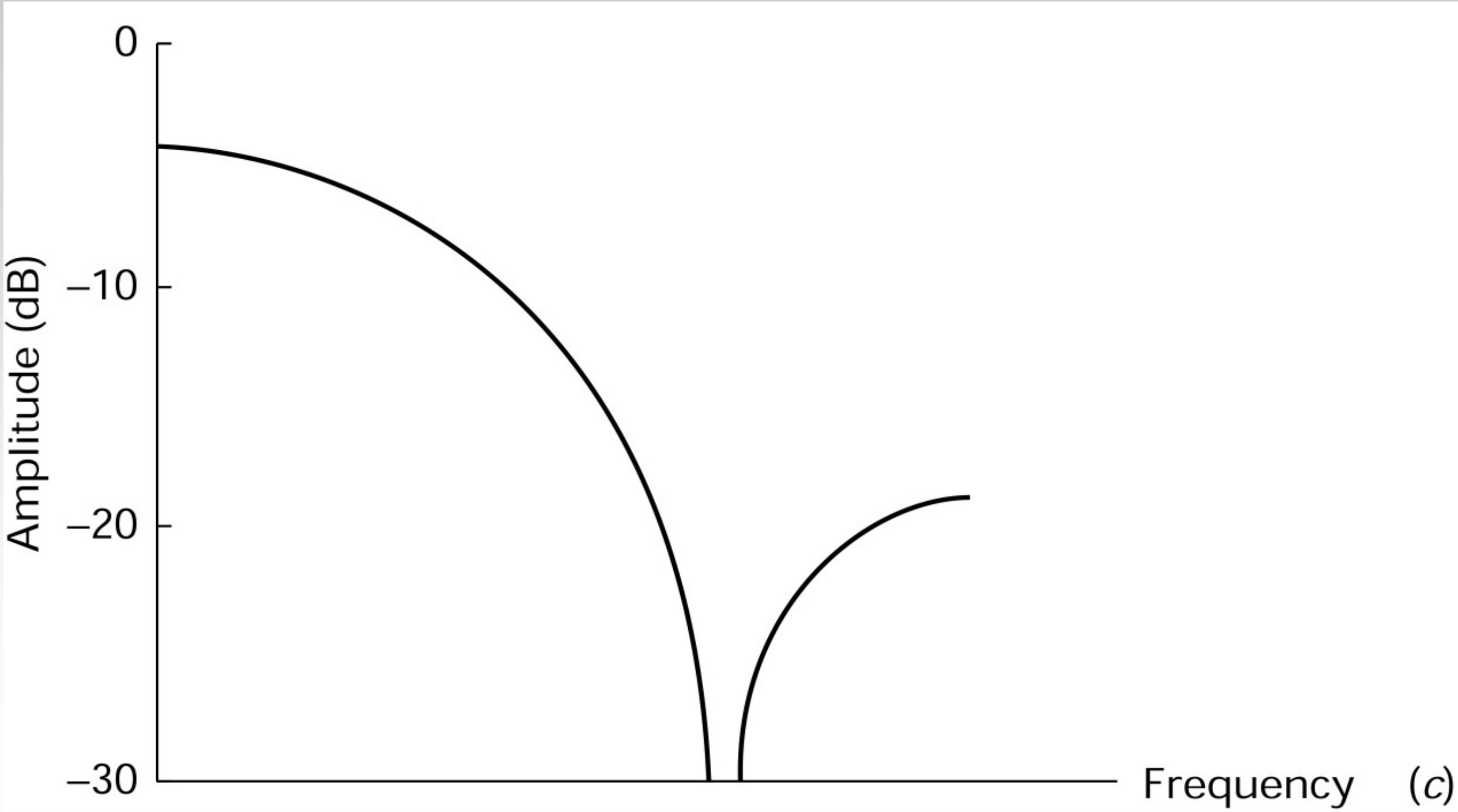
- the unit delay between two coefficients is equal to the symbol length T

Fractionally spaced equalizer:

- The unit delay between two coefficients is less than the symbol length T

Non linear equalizers

In some cases, non-linear equalizers are suitable, especially when the channel experiences deep nulls

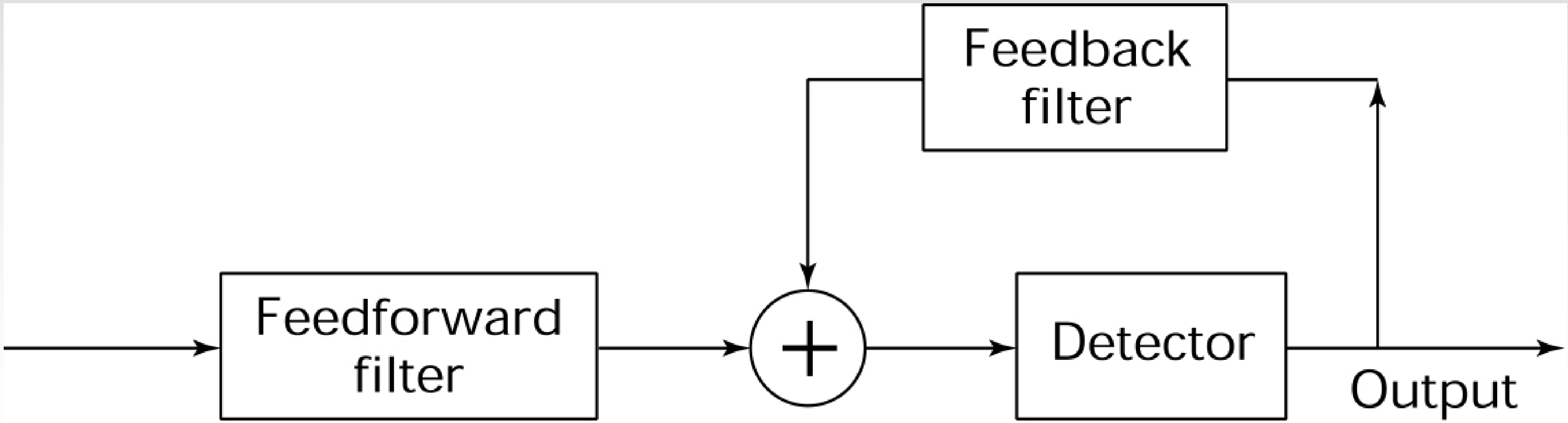


Decision feedback equalizer (DFE)

The feedforward filter is usually a fractionally spaced equalizer

The feedback filter is usually a symbol spaced equalizer

The input of the feedback filter consists of previously detected symbols and the feedback filter subtracts the amount ISI introduced by these symbols



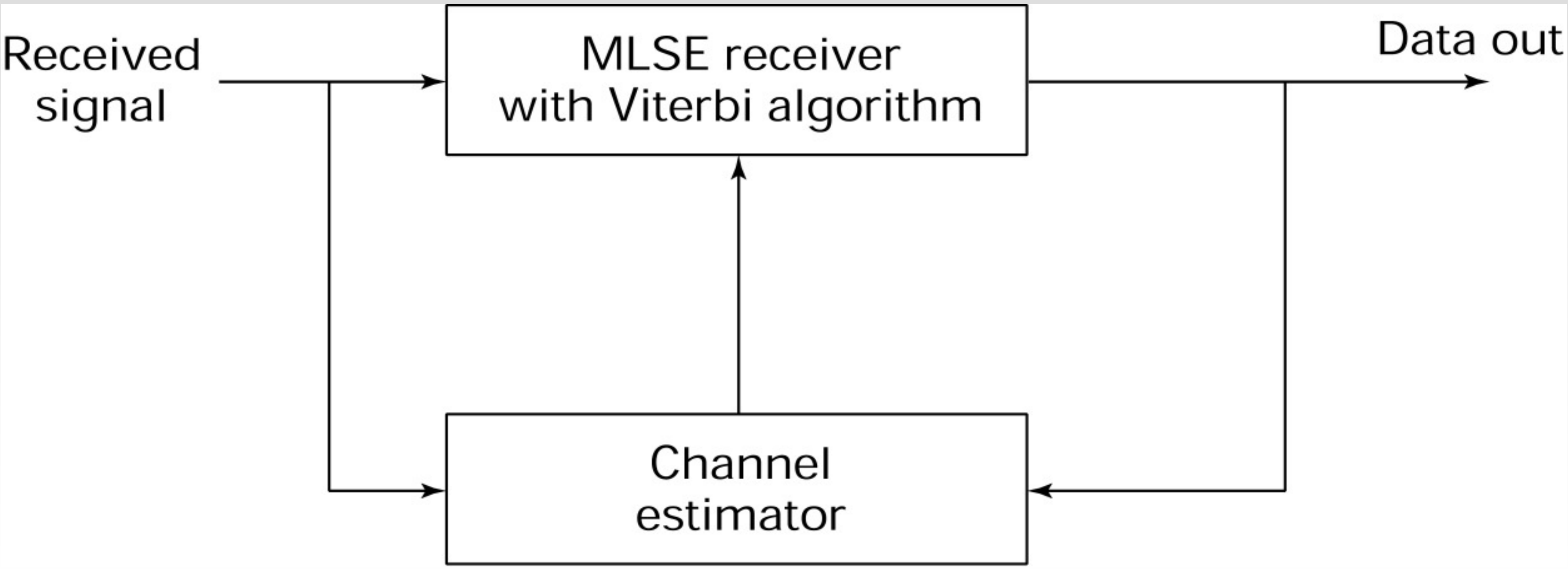
Maximum Likelihood Sequence Estimator (MLSE)

The channel impulse response is calculated

A Viterbi algorithm is used to estimate the most likely symbol sequence

MLSE is an optimum method for removing ISI

- But the complexity increase exponentially with the length of the channel response

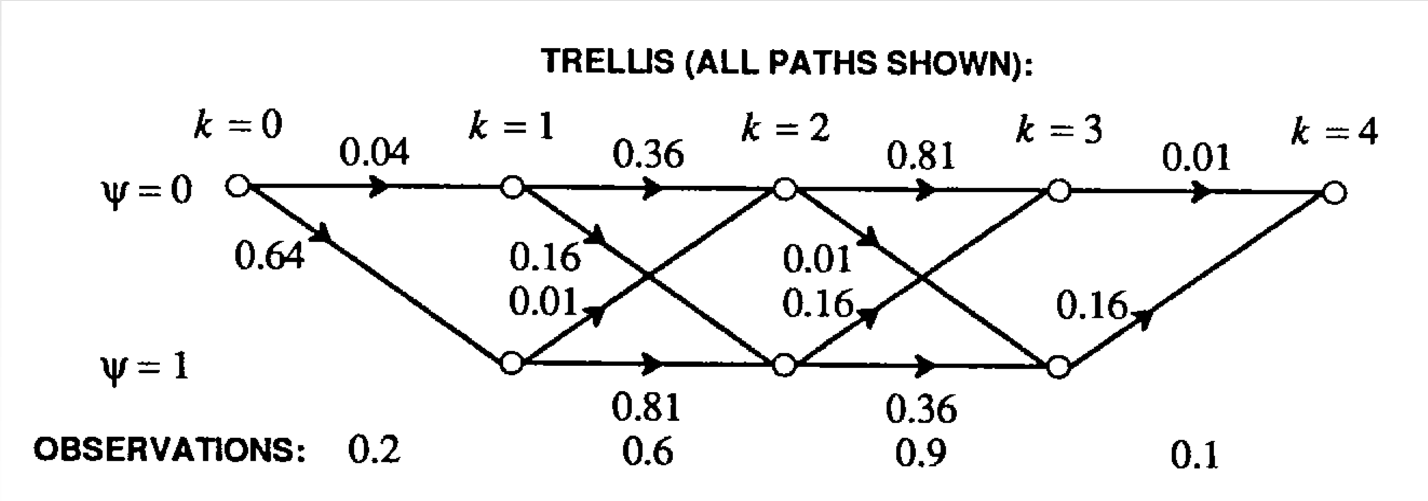


How MLSE works

The Viterbi algorithm finds the sequence s_k through a trellis which minimizes the Euclidean distance between the sequence and an observation:

$$\sum_{k=1}^{K} \left| r_k - s_k \right|^2$$

Example: $h = 1 + 0.5z^{-1}$ (fig: [Lee, 1994]) :



Orthogonal Frequency Division Multiplex (OFDM) (1)

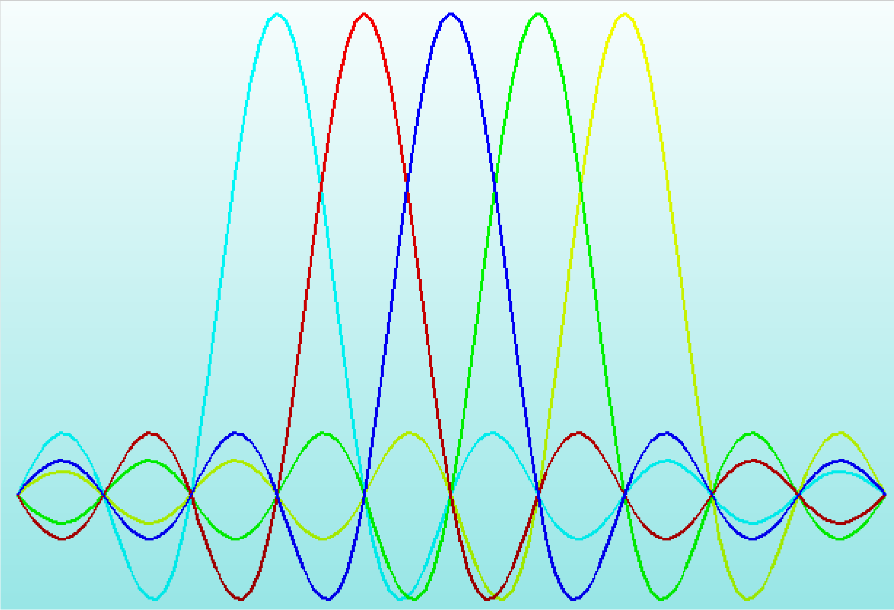
A fundamental problem in mobile communication is the ISI which occurs when the data rate is high

- Channel equalizers counteract this, but becomes too complex when they must span many symbol periods

Another solution is to construct the data stream by using many wave carriers each one having a low data rate

- This is robust against multipath propagation because each of the carriers have relatively narrow bandwidth, and thereby flat fading

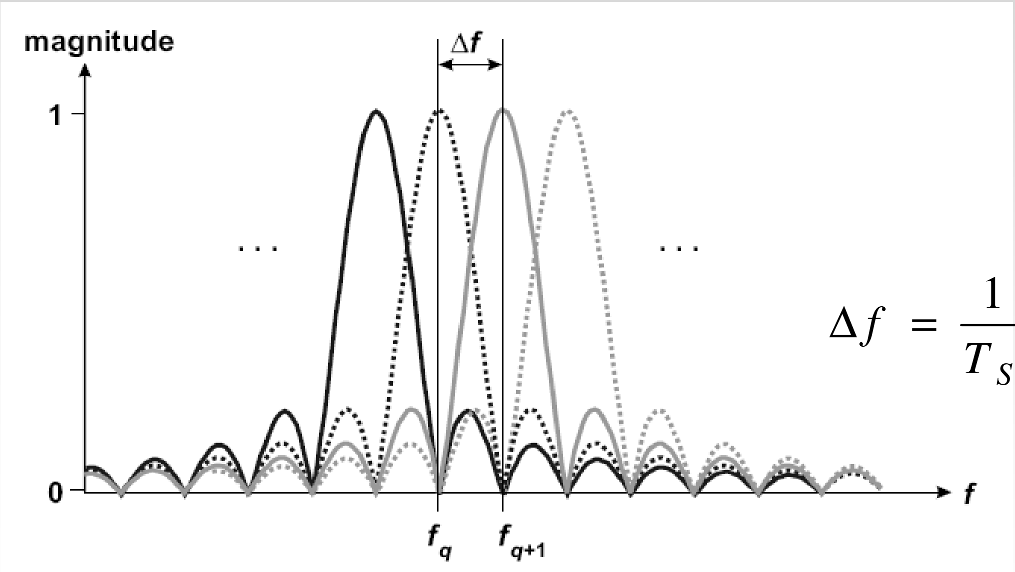
The highest bandwidth efficiency (bit/s/Hz) is achieved by using overlapping orthogonal carriers



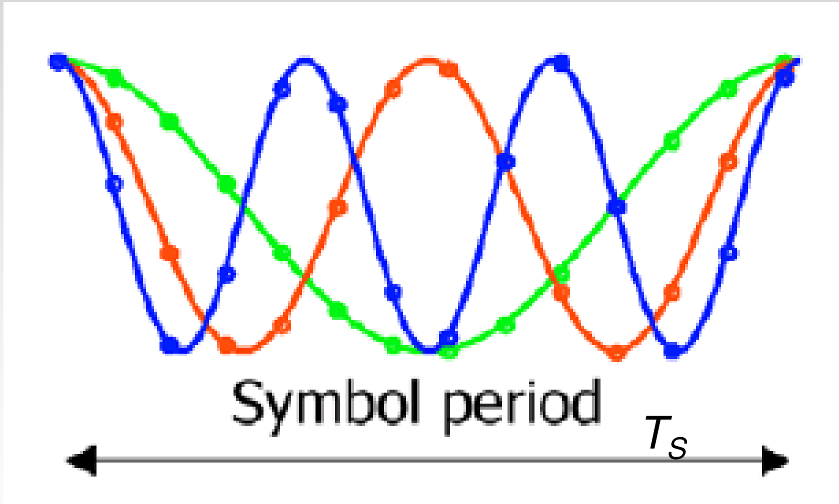
Orthogonal Frequency Division Multiplex (OFDM) (2)

The individual subcarriers in OFDM can overlap without disturbing each other if the frequencies are chosen to be orthogonal

This means that during a symbol period, the signal goes through an integer number of cycles.



$$\Delta f = \frac{1}{T_S}$$



Orthogonal Frequency Division Multiplex (OFDM) (3)

Because of its good performance in fading channels, OFDM has gained increased popularity

It is now chosen for most new mobile and wireless systems with high data rates in fading channels

Examples:

- Digital terrestrial broadcast (DVB, DAB)
- New standards for WLAN
  - IEEE 802.11a, g, n (Wi-Fi)
  - IEEE 802.16 (WiMAX)
- LTE – Long Term Evolution – «4G»