1 Introduction

The fascinating story of public mobile communications began in 1947 when the concept of cellular radiotelephony was developed inside the Bell Laboratories. It required several decades before the technology matured into a perfect digital telephony system commercialized via the Global System for Mobile Communications (GSM) standard in the early 1990s. The main focus at that time was made on pure voice communication and short message service.

This situation started to change with the General Packet Radio Service (GPRS) extension introduced to cover the emerging needs for exchanging computer data. However at the beginning of the data era the demand for broadband wireless communication was not very high. The luck of key applications as well as absence of consumer-oriented multimedia mobile devices together with cost reasons were slowing down the acceptance of novel technologies. At that time the researches and engineers dealing with broadband transmission were very much ahead of the market trying to target the prospective use cases of the future.

The introduction of several very successful smartphones and netbooks dedicated for mobile use of Internet and broadband data services dramatically changed the landscape in the second half of 2000s. The networks of mobile operators became overloaded with data traffic, which soon surpassed the conventional voice traffic. At the same time ever growing number of active mobile users started to ask for even higher data rate and increased Quality of Service (QoS). The market push intensified the development and roll out of new mobile standards such as High Speed Downlink Packet Access (HSDPA) and later Long Term Evolution (LTE) [3GPP].

At the same time already achieved very high transmission rate allows wireless systems such as WiMAX [WIMAX] to compete with the classical Digital Subscriber Line (DSL) technology for household Internet access. The advantages of relatively low installation cost and additionally offered user mobility makes it a perfect solution especially for developing countries with poor wireline infrastructure.

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At present the progress in wireless transmission technology continues into the direction of even higher data rates and enhanced QoS. According to IMT-Advanced initiative of ITU UN agency [ITU] the requirement for future 4G communication standards are set on the level of 1Gbits/s peak data rate. These ambitious goals impose great technological challenges on the development of wireless systems. A lot of research is carried out in order to satisfy ever growing expectations on data rate and increasing number of users, under the natural constraints of limited available frequency resources and transmit power.

Two most promising techniques, identified in the last years as basis for current and future development, are Orthogonal Frequency Division Multiplexing (OFDM) and Multiple-Input Multiple-Output (MIMO). OFDM allows building scalable broadband transmission systems with moderate equalization complexity, while MIMO can be used to increase bandwidth efficiency beyond the limits of single antenna systems. The powerful combination of MIMO and OFDM appears to be ideally suited for systems with very high data rate. It represents the key technology applied in many present and upcoming wireless standards.

MIMO technology established itself as very broad separate area inside the telecommunication science with a large number of research papers published in the past 15 years. However it still remains an issue to develop efficient broadband MIMO-OFDM communication systems operating in a variety of propagation scenarios with different requirements on user and base station equipment. The frequency selective time variant MIMO radio channel represents the major design challenge due to complexity of the underlying physical effects with very large number of involved parameters. Several questions, which are important for MIMO-OFDM system design, are listed here:

- Which MIMO algorithms are to be selected in every particular scenario?
- What are the potential performance advantages vs. the associated system overhead?
- How much performance gain could be expected under realistic channel conditions taking into account all kinds of impairments?

These open issues motivated the research work on MIMO-OFDM physical layer algorithms for broadband communication system, which underlies this thesis.

In the meantime the area of MIMO became so broad that it is impossible to cover all of the reported algorithms in the framework of a thesis. Therefore in this work a subset of available MIMO techniques representing diversity and multiplexing approaches is picked up for detailed examination. The focus is made on receiver diversity, orthogonal space-time block codes, spatial multiplexing as well as MIMO systems with linear precoding. Unfortunately a lot of interesting space-

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time processing alternatives such as linear dispersion code [HH02], space-time trellis codes [TSC98], quasi-orthogonal space-time block codes [Jaf01] and many others fall out of the scope of the thesis.

Two fundamentally different design opportunities are analyzed in this work: coherent systems with channel equalization, when the receiver has full knowledge of the Channel State Information (CSI) obtained via some estimation procedure and differential systems, designed to avoid channel estimation by using non-coherent detection algorithms. At first the coherent MIMO-OFDM transmission systems are considered. The selected MIMO techniques are extensively analyzed both analytically and using numerical simulations with the emphasis on the performance under various radio propagation conditions. The effort is made to investigate the robustness of MIMO algorithms where some interesting observations are made and the improvements proposed. It is clear that future MIMO-OFDM transmission systems will be designed in a very flexible and adaptive way in order to deliver the best possible performance in all environmental multipath conditions. The presented research should give a background for intelligent selection of MIMO techniques according to the current channel situation.

Coherent systems spend a lot of resources in order to estimate the current radio channel with sufficient precision. User mobility results into quickly changing radio conditions, increasing the required overhead for channel estimation and reducing the overall system efficiency. Differential transmission techniques, operating without any need for channel estimation, represent another interesting alternative, which is extensively analyzed in the thesis. The recent research [Tön08] shows that under realistic conditions the differential single antenna systems may be superior to their coherent counterparts in terms of performance and complexity. In the MIMO era the channel estimation is associated with more overhead than it used to be for single antenna systems making differential scheme even more advantageous. In this thesis several novel algorithms for differential transmission using single as well as multiple antennas are designed and compared with existing approaches.

The thesis is organized as follows:

In Chapter 2 the general introduction into the topic of digital communication over multipath radio channel using MIMO-OFDM is given.

Chapter 3 is devoted to the analysis and comparison of spatial multiplexing (SM) and diversity based systems. The available decoding alternatives for SM are evaluated taking into account performance and complexity of the algorithms. The special attention is made on analyzing the conditions when even the simplest technique delivers optimal decoding result.

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In Chapter 4 the general framework of linear and non-linear MIMO precoding is developed. Several linear precoding techniques are considered in detail and the improvements of SVD based transmission scheme are highlighted. The developed framework of non-linear MIMO precoding is used to analyze STBCs and design the universal decoding algorithms.

Chapter 5 is devoted to the topic of realistic MIMO channel modelling. In this chapter simple general broadband MIMO WSSUS channel model is developed and evaluated.

In Chapter 6 the performance of coded MIMO-OFDM systems with different MIMO processing algorithms is studied for various propagation scenarios using the channel model developed in Chapter 5. Based on the conducted research the adaptive selection of MIMO techniques is identified as a key technology for reliable high throughput data transmission.

Chapter 7 is devoted to the differential transmission techniques. Two novel differential schemes are presented: block differential modulation scheme with boosted midamble symbol and APSK modulation scheme for differential space-time block codes.

In Chapter 8 the main results of the thesis are summarized and the conclusions are drawn.

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2 Mobile communication over multipath radio channel

One of the most important factors to be considered when designing any transmission system is the communication channel. In order to reach the desired performance standard and achieve planned QoS requirements it is often necessary to adopt carefully the system parameters to the properties of the used communication channel. For this adaptation detailed knowledge of the channel is essential, therefore the channel is always a starting point for any system considerations on the physical layer.

The broadband frequency selective nature of mobile radio channel requires sophisticated signal processing to perform high rate data transmission. OFDM is a widely used digital transmission technique designed to operate in terrestrial mobile environment. It is relatively simple, but frequency efficient and scalable. Further more OFDM performs very well even in the presence of fading or narrowband interference and it allows straightforward implementation of adaptive FDMA/TDMA multiple access schemes.

Another advantage of OFDM comes out of the combination with MIMO. Multiple antenna technology, introduced in the recent years to enhance the spectrum efficiency, appears to be extremely well suited for OFDM. The majority of MIMO processing algorithms developed so far rely on a frequency flat channel, which means either low rate narrowband transmission or OFDM.

Joint MIMO-OFDM system design represents now the ultimate choice for majority of the current and future broadband communication systems. That is why the MIMO-OFDM transmission concept is considered throughout the thesis as the basis for broadband wireless communications. This chapter is focused primarily on the description of the mobile radio channel, the basics of OFDM and how it can be combined with MIMO.

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2.1 Radio channel for mobile communication systems

A wireless mobile communication system uses the radio waves as the prime media dedicated for data transmission. In comparison to fixed wireline communications the wireless channel is more complex and less predictable, especially when the system is operating in modern urban environment, inside the buildings or from fast moving vehicle.

The physical phenomena such as reflection, scattering, diffraction, attenuation, penetration into objects and absorption as well as noise and interference play an important role in the description of the electromagnetic waves propagation. Sufficient understanding of the properties of the radio channel is an essential prerequisite to start the design of mobile wireless communication systems. In this section the properties of the terrestrial radio channel, which are important for mobile applications, are highlighted for classical systems with single transmit and receive antennas.

2.1.1 Radio wave propagation

The terrestrial radio wave propagation for typical mobile applications is a very complex process, which depends on many physical parameters of the environment. There are several fundamental effects, which help to describe and visualize the propagation of the electro-magnetic waves. Some of these phenomena are highlighted here.

Line of sight propagation: In the open space the electromagnetic waves travel from transmitter to receiver with the speed of light using the shortest way, which is a direct Line of Sight (LOS) path.

Attenuation (Path loss): The signal strength decays with the travelled path length so that the received power decreases with the increase of the distance from the transmitter. In a free space situation the received signal power is inversely proportional to the squared distance between the transmitter and receiver.

Shadowing: In realistic propagation conditions the radio signal is often partially blocked by buildings, trees or hills so that the LOS path may not exist. These shadowing effects cause additional attenuation, which depends on the relative positions of transmitter, receiver and surrounding objects.

Reflection: An electromagnetic wave may reflect fully or partially if it meets the surface of the size much larger than the wavelength. The reflection typically alters the propagation direction of radio signal.

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Penetration and Absorption: The reflection is almost never ideal, so that certain part of the total energy is penetrating the object and will either be absorbed in the material or come trough the object contributing to the received signal.

Diffraction: When the electromagnetic wave impinges objects which are comparable to the wavelength it undergoes diffraction, i.e., changes the direction of propagation and amplitude. Diffraction allows the electromagnetic waves to bend the obstacles and propagate around the corners.

Scattering: The scattering occurs on irregular structures like trees or wall roughness forcing the electromagnetic wave to diverge in space.

The superposition of the above-mentioned effects defines the propagation environment, while all of them contribute to the characteristics of the radio channel.

Suppose the base station is sending a signal to the mobile terminal located somewhere in the urban area (Figure 2.1). The radio waves travel using many independent paths before reaching the receiver. Along the way different versions of the transmitted signal undertake reflections, scattering, diffractions and other phenomena. At the mobile terminal all these replicas are superimposed and form the useful received signal. If the mobile user moves, the propagation conditions changes, altering the received signal in a way which is very hard to predict.

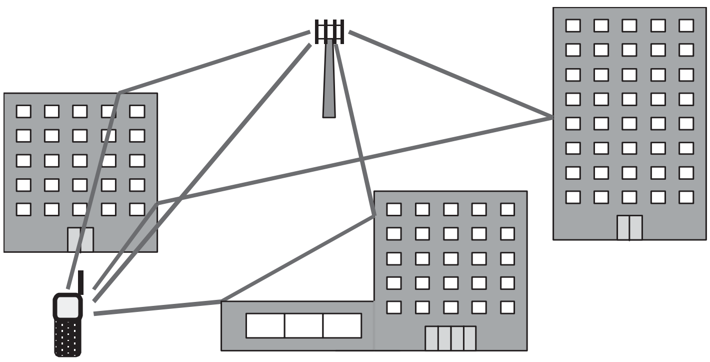

Figure 2.1: Radio wave propagation in urban environment

High complexity of the radio wave propagation process makes it almost impossible to calculate the channel characteristics analytically. Even if such calculations are made the result will be very specific to the considered scenario, location of the objects and their properties. The large number of involved parameters makes it difficult to use this result for practical system design, which is not location specific. Instead of the exact calculation it is more useful to grasp general properties of the terrestrial radio channel and make a system, which is able to operate efficiently in all practical scenarios.

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2.1.2 Radio communication as linear time variant system

Electromagnetic wave propagation in typical cellular environment is linear with very high precision. Due to mobility the propagation conditions become variable over time.

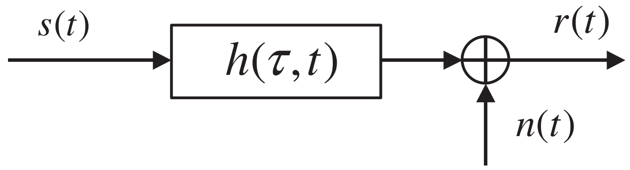

Figure 2.2: Model of the linear time variant system with additive noise

Therefore radio communication can be described as a general linear and time variant system (Figure 2.2). Here $s(t)$ and $r(t)$ denote the baseband transmit and received signal in time domain. The linear transformation from $s(t)$ to $r(t)$ is characterized using the time variant impulse response function $h(\tau,t)$ as follows:

$$r(t) = \int_{-\infty}^{\infty} h(\tau,t) \cdot s(t-\tau) d\tau + n(t) \tag{2.1}$$

In addition to the useful signal the receiver is exposed to different kinds of noise like for example thermal noise, and interferences from other stations in the same frequency band. These effects are described by an additive noise component $n(t)$ that has no relation to the transmitted signal.

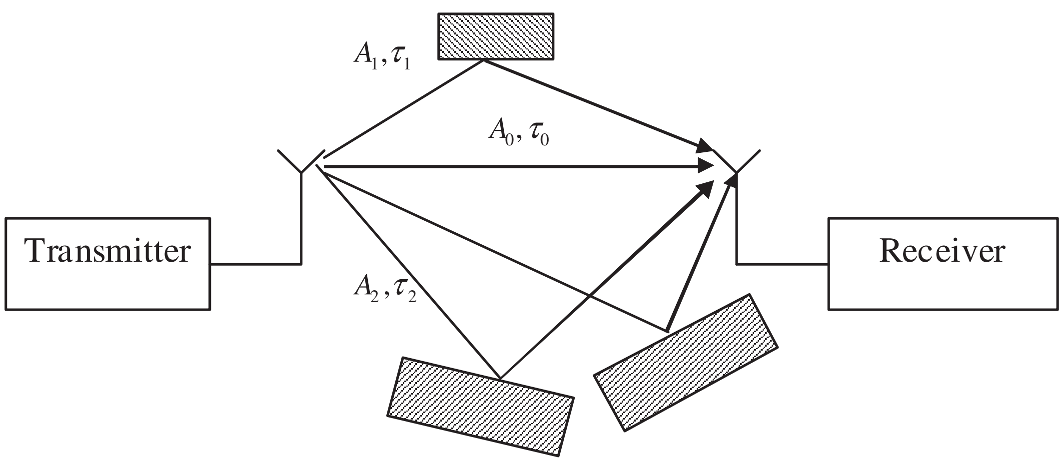

Figure 2.3: Multipath propagation model for a wireless channel

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Due to the multipath propagation effect the received signal can be represented as a superposition of several instances of the transmit signal arrived via different paths and therefore, having different amplitudes, phases and delays (Figure 2.3).

Let the number of individual paths be $L_p(t)+1$, which consists of $L_p(t)$ non LOS (NLOS) components and a single LOS component. The time variant impulse response of the multipath channel can be represented as:

$$h(\tau,t) = A_0(t)\cdot\delta(\tau-\tau_0) + \sum_{l=1}^{L_p(t)} A_l(t)\cdot\delta(\tau-\tau_l(t)) \tag{2.2}$$

Here the complex coefficients $A_l(t)$ $l=0,1,...,L_p(t)$ correspond to amplitude and phase of each individual path, while $\tau_l(t)$ correspond to delays. A typical channel impulse response according to (2.2) is visualized in Figure 2.4, where $\tau_{\max}$ denotes the maximal path delay.

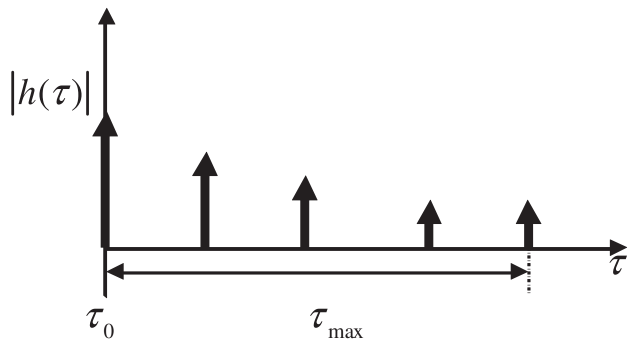

Figure 2.4: Example of the channel impulse response

Relative motion of transmitter and receiver as well as motion of the scatterers and reflectors causes time variance of the channel impulse response. When the mobile user is moving in the area covered by a base station the propagation conditions vary, so that the number of active scatterers as well as their signal amplitudes, phases and delays change along the travelled path. Some of these changes occur rapidly as for example phases, while the other parameters change slowly and alter the long-term channel characteristics.

In order to model the radio channel variation over a short period of time the number of active paths as well as their amplitudes and delays can be assumed quasi-stationary. During this time frame any movement of transmitter and receiver can be approximated as linear motion with constant velocity. The channel variations are calculated by considering only the fast phase drift, which is caused by the Doppler effect. In this quasi-static channel model the impulse response can be represented as:

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$$h(\tau,t)=A_0\cdot e^{j2\pi f_0^D\cdot t}\cdot\delta(\tau-\tau_0)+\sum_{l=1}^{L_p}A_l\cdot e^{j2\pi f_l^D\cdot t}\cdot\delta(\tau-\tau_l) \tag{2.3}$$

In (2.3) A_l represents the initial complex amplitude and f_l^D is the Doppler frequency shift. The signal amplitude $|A_l|$ is assumed to be constant during the short time period of observation so the changes affect only the phase components of each signal instance. The Doppler frequency shift f_l^D depends on the speed of the mobile terminal v, carrier frequency f_0 and the angle between the signal path and moving direction:

$$f_l^D=\frac{f_0 v}{c}\cos(\varsigma_l) \tag{2.4}$$

Since each path has a unique angle ς_l the Doppler frequency shift varies between $-f_{\max}^D$ and $f_{\max}^D$ for signal instances arrived through different paths:

$$-f_{\max}^D\le f^D\le f_{\max}^D,\text{where } f_{\max}^D=\frac{f_0 v}{c} \tag{2.5}$$

For a single path radio channel it is relatively easy to compensate Doppler shift using frequency and phase tracking methods. The estimated carrier offset can then be corrected at the receiver, which allows eliminating fast channel variations and simplifying the channel estimation procedure. However in the multipath channel condition this operation could not be performed due to the variety of Doppler shifts associated with the received signal. Therefore the multipath radio channel experiences uncompensated fast channel variations, which have to be considered in system design. In order to describe the time variant behaviour of the radio channel it is useful to introduce a one-value measure that can characterize the speed of the channel variations. This variable, called coherence time is usually calculated based on the statistical properties of the considered radio channel. For the purpose of this work the coherence time can be approximated as follows:

$$T_{coh}=\frac{1}{f_{\max}^D} \tag{2.6}$$

During a time interval Δt, which is significantly less than the coherence time ($\Delta t\ll T_{coh}$) the radio channel can be assumed to be approximately constant. In order for digital communication system to work properly the radio channel has to be constant during a single modulation symbol and therefore $T_s\ll T_{coh}$.

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2.1.3 Narrowband and broadband communication systems

As shown in Section 2.1.2 a linear transmission system can be characterised in the time domain using the channel impulse response. Alternatively any linear time invariant system can be described in the frequency domain with the help of the channel transfer function as follows:

$$R(f) = H(f) \cdot S(f) + N(f) \tag{2.7}$$

Equation (2.7) can be obtained as the Fourier transform of (2.1) if the channel transfer factor is assumed to be constant over the time of observation. The frequency domain description gives a useful insight into the functioning of the mobile communication system.

2.1.3.1 Frequency selective fading

The time variant channel transfer function $H(f,t)$ can be obtained by the Fourier transform of the channel impulse response:

$$H(f,t) = \int_{-\infty}^{\infty} h(\tau,t) \cdot e^{-j2\pi f \cdot \tau} d\tau \tag{2.8}$$

If the impulse response is represented by (2.3), the corresponding transfer function can be calculated by substituting (2.3) into (2.8):

$$H(f,t) = \sum_{l=0}^{L_p} A_l \cdot e^{j2\pi f_l^D \cdot t} \cdot e^{-j2\pi f \tau_l} \tag{2.9}$$

When the norm $\left|H(f,t_0)\right|^2 = \left|H(f)\right|^2$ taken at a certain time instance t_0, is plotted vs. frequency f for sufficiently large bandwidth the picture will look similar to Figure 2.5.

The norm $\left|H(f)\right|^2$ varies over frequency due to the interference of several multipath components arriving at the receiver with different phases and amplitudes. The relations between the phases change with f according to (2.9) resulting into a frequency selective behaviour of the channel. The received power on frequency f is proportional to $\left|H(f)\right|^2$, therefore when some of the frequencies

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are attenuated much more than the average level $\left|H(f_{fad})\right|^2 \ll E\left(\left|H(f)\right|^2\right)$, the corresponding signal components experience a deep fade.

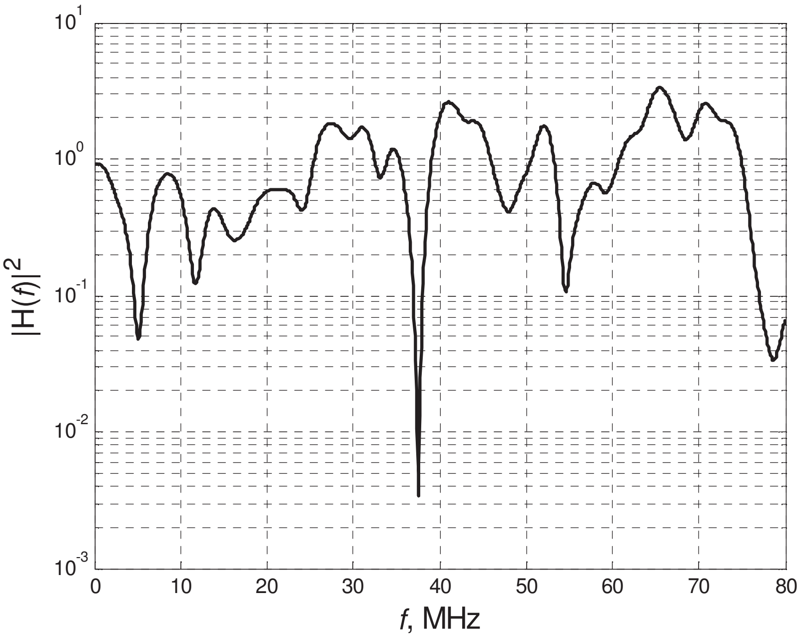

Figure 2.5: Sample transfer function for frequency selective NLOS radio channel

From the radio channel point of view the deep fading situation can be explained by the destructive interference of the signal instances arriving via different paths. The exact shape of the frequency selective channel transfer function depends on the phases and amplitudes of the signal instances arriving via different paths. If these parameters change, e.g. due to the motion of the mobile terminal, the fading characteristics also change, leading to time variant fading.

In order to describe the frequency selectivity it is useful to introduce a parameter that will characterise the frequency variation of the radio channel. As follows from (2.9) the amplitude of the channel transfer function is defined by the relative phase shift between the signal components. The maximal variation of the relative phase shift, which occurs when the target frequency is changed by Δf , is given as:

$$\Delta\varphi_{\max} = 2\pi\Delta f \tau_{\max} \tag{2.10}$$

Clearly $\left|H(f)\right|^2$ can be considered nearly constant over the frequency interval Δf if $\Delta\varphi_{\max} \ll 2\pi$, which is equivalent to:

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$$\Delta f \ll B_{coh} = \frac{1}{\tau_{\max}} \tag{2.11}$$

Where B_{coh} is called the coherence bandwidth of the radio channel. If the operating bandwidth of the radio transmission system is significantly less than the coherence bandwidth of the channel ($W \ll B_{coh}$), then the system is called narrowband, frequency nonselective. Such system experiences frequency flat channel transfer function. On the other hand if $W > B_{coh}$ the system is called broadband. It operates over the bandwidth which is large enough to observe frequency selectivity.

2.1.3.2 Broadband systems with frequency selective channel

The system which operates over a frequency selective channel ($W \gg B_{coh}$) is exposed to the effect of intersymbol interference in the receive signal. In this section the transmission of digital modulation symbols over such a channel is considered. The transmitted symbol in time domain $s(t)$ can be represented as:

$$s(t) = \sum_i s_i \cdot m(t - i \cdot T_s) \tag{2.12}$$

where s_i denotes the sequence of the modulation symbols, while *m(t)* is the modulation impulse. The length of the modulation impulse can be estimated as $T_s \approx \frac{1}{W}$ and therefore $T_s \ll \tau_{\max}$. Let the number of signal instances received due to the multipath propagation be equal to three (Figure 2.6). Each independent path in the multipath channel has different delay τ_l, thus the signal instances at the receiver side are shifted from the others in time. Since $T_s \ll \tau_{\max}$ the time shifts lead to overlapping of several sequentially transmitted signals and therefore to inter symbol interference.

In order to restore the original signal the equalization procedure is necessary, which is typically performed using linear filtering of the received signal. Clearly in order to fulfill the function correctly the equalization filter has to adapt to the time variant channel conditions. The complexity of the equalizer (the length of the digital filter) grows with the ratio $\tau_{\max} / T_s$, and can become a limiting factor for systems with very low relative symbol duration.

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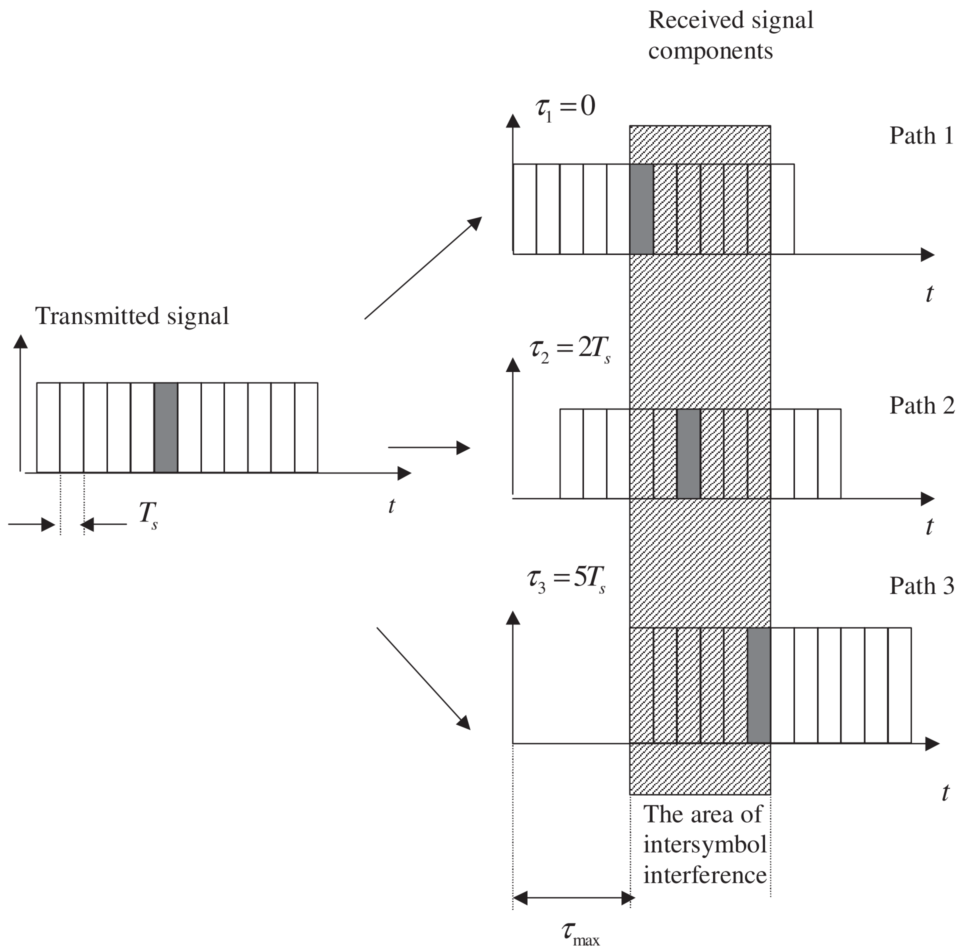

Figure 2.6: The mechanism of the intersymbol interference

2.1.3.3 Narrowband systems with flat fading channels

If the radio transmission system is operating in a narrow frequency band $W \ll B_{coh}$ and consequently $T_s \gg \tau_{\max}$, then the channel conditions can be considered constant inside the system bandwidth. In this case (2.7) will look like:

$$R(f) = H \cdot S(f) + N \tag{2.13}$$

The transmitted signal is scaled uniformly over the used bandwidth by the channel transfer factor. In time domain the transformation is reduced to scaling and delaying of the transmitted signal.

For narrowband transmission the intersymbol interference is transformed into the intrasymbol interference, which causes the fading effect (Figure 2.7). The signal components arrive to the receiver via different paths with the delays difference, very small compared to symbol duration. Therefore the signals overlap region

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spreads mainly over single modulation symbol. Depending on the phases the interference may be constructive when the resulting amplitude increases or destructive, which leads to very weak received faded signal.

The complex valued channel transfer factor H defines the current fading factor of the radio channel. As the radio channel varies in time the interference conditions change causing the variation in the received signal power, this effect is called time variant fast fading. The rate of the fading depends on the coherence time of the channel.

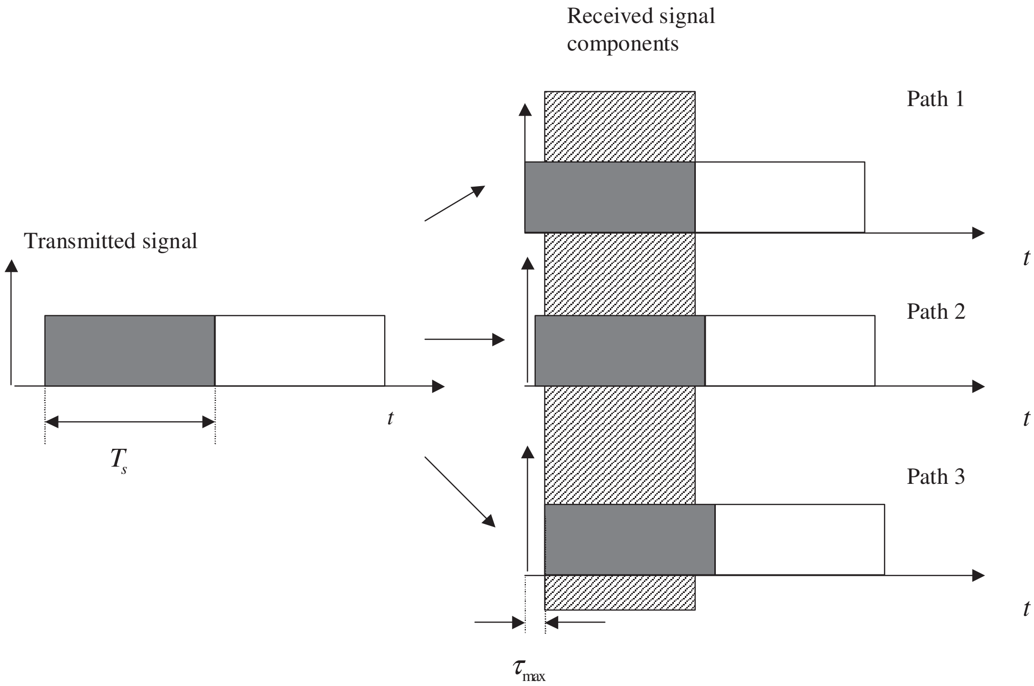

Figure 2.7: Fading mechanism

Fading plays fundamentally negative role for system performance. When deep fade situations occur the received power may be not sufficient for unambiguous detection, and the equalization is not able to improve the signal quality. Narrowband digital radio communication systems require special measures to combat time variant fast fading. Otherwise the bit error probability decreases very slowly with increase of average SNR, so that for practical values of SNR the error rate often remains far above the QoS requirements. Such behaviour can be easily explained using the time variant fading model, where weak received signal unavoidably occurs from time to time even if the power of each path component is high.

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Besides fading narrowband systems also experience the intersymbol interference, which is limited to $\tau_{\max}$ and localized in a small portion of two adjacent symbols. There is a way to eliminate fully the influence of the intersymbol interference by inserting the guard interval of the length $\tau_{\max}$ in front of each symbol. Since $T_s \gg \tau_{\max}$ the overhead associated with this operation is relatively small.

2.2 Multicarrier broadband transmission

Modern and future mobile communication systems require very large bandwidth of tenths or even hundredths of MHz to accommodate high data rate. The used bandwidth is much larger than the coherence bandwidth in typical propagation conditions, which means that the prospective mobile systems are essentially broadband and have to operate over a frequency selective channel. High data rate transmission using a single carrier system leads to small symbol durations T_s so that $\frac{\tau_{\max}}{T_s} > 100$. The resulting intersmbol interference affects hundreds of adjacent symbols making equalization a very challenging and computationally expensive task. To simplify the equalization it is possible to use multicarrier transmission and split the total bandwidth into a number of subchannels with low data rate and increased symbol duration. The independent data streams are transmitted over separate carriers with relatively low $\frac{\tau_{\max}}{T_s}$ ratios and require only a simple equalizer. The transmission occurs in parallel over all the subchannels and therefore the total data rate can be calculated as a sum of the data rates for all the subchannels.

Straightforward realization of the multicarrier transmission will require high quality expensive filter banks to separate the subchannels at the transmitter and receiver side. Another disadvantage of the filter-based technology is the unavoidable frequency guard space around each subchannel to eliminate the interchannel interference, which sacrifices the spectral efficiency. In contrast OFDM presents an elegant solution to the problem of efficient multicarrier transmission [RMBG99]. It divides the system bandwidth into a set of narrowband orthogonal subchannels using computationally efficient IFFT/FFT processing. Proper guard interval selection completely avoids the inter symbol interference (ISI), which simplifies the equalization to complex division. These advantages make OFDM an ultimate candidate for next generation mobile communication systems.

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