Universität der Bundeswehr München

Fakultät für Elektrotechnik und Technische Informatik

Institut für Hochfrequenztechnik und Nachrichtenübertragungstechnik
– ETTI5

Musterbeispiele von Online Lehrinhalten für labAlive

Paradigm Examples of Online Experiments for a Virtual Communications Lab

Dominic Nolde

Betreuer: Prof. Dr.-Ing. Erwin Riederer

Masterarbeit

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Erklärung

gemäß Beschluss des Prüfungsausschusses für die Fachhochschulstudiengänge der UniBwM vom 25.03.2010

Hiermit versichere ich, dass ich die vorliegende Arbeit selbständig verfasst, noch nicht anderweitig für Prüfungszwecke vorgelegt und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe, insbesondere keine anderen als die angegebenen Informationen.

Neubiberg, den

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Dominic Nolde

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Abstract

The present master thesis gives an overview of multimedia learning using the example of the online platform labAlive. labAlive deals with topics of telecommunications engineering. This goes hand in hand with the fact that multimedia learning is now the most commonly used way of learning content and then applying it. Restricting yourself to individual media such as books or lectures is a thing of the past and has long been overtaken in many areas. The newly developed structure of labAlives site arrangement and content will be considered as a guide to further development. In addition, it should help the user to learn and provide subsequent transfer.

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1. Introduction

1.1 Motivation

The ways of learning nowadays are no longer limited to books, but many use the numerous possibilities of multimedia learning. This means that learning contents are presented with different, meaningful combined media formats that are useful for learning new content.

Therefore, I would like to pick up on my own problems during my studies at the "Universität der Bundeswehr" and give beginners a helping hand to learn course contents more effectively and sustainably. In addition, I would like to achieve the goal of generating more traffic on the pages of the virtual communications lab "labAlive", which was founded and realized by Prof. Dr.-Ing. Erwin Riederer.

1.2 Task and Objectives

The aim of this master thesis is to create paradigm examples of online tutorials and experiments for a virtual communications lab called "labAlive". labAlive is a graphical and interactive simulator tool for communications systems. The virtual experiment environment emulates a real-world laboratory and encourages students to experiment actively and learn experimentally. labAlive also serves students as a link between the lectures and the practical laboratory courses. Furthermore, the experiments built within the labAlive simulation frame work might constitute a valuable contribution within online learning initiatives, e.g. massive open online courses (MOOC).

Its incentive is it to provide meaningfully chosen content and focus on the essentials of each addressed topic. The student and future user needs to have the chance of using the common online learning advantages such as availability, reproducibility and scalability in order to be effective in making progress by learning new content.

Regarding topics, the main emphasis will lie on Orthogonal Frequency Division Multiplexing (OFDM) from its fundamentals to its calculation of parameters and the Radio channel. This new content will act as a guideline for future addressed topics regarding how it is going to be displayed on the pages of labAlive and how the users are interacting with it.

1.3 Thesis Overview

Following the introductory chapter, the remainder of this thesis is divided into four chapters. Chapter 2 characterizes the methodical and didactic concept for the paradigm examples of the online experiments for labAlive. In addition, the new structure of the platform and its content will be presented. Chapter 3 outlines the essentials on wireless communication systems, radio channel and covering the fundamentals of multi-carrier transmission. Chapter 4 main concern will be OFDM and its calculation of parameters. A concluding chapter will sum up and reflect on the preceding points of this thesis.

1.4 Realization

During the work on this master thesis, the following software and tools were used.

Table 1: used hard- and software

Software / Tools / Hardware	Version
Microsoft Office (Excel, Visio & Word)	2016
labAlive online platform	
HP Notebook	

2. Methodical and Didactic Concept

2.1 General Overview

Depending on the level of knowledge, a person's memory absorbs information at different speeds. Learners who are dealing with a new technical task for the first time, such as measuring a spectrum, will first have to develop the individual skills in dealing with complex technical experimental setups, because usually the entire technical context is unclear.

Students with a solid basic technical knowledge will be able to grasp problems quickly, since the rough technical interaction is already known and thus the learning progress is faster.

It therefore requires a differentiation of the target group, since the level of knowledge brought in by each student and user may vary.

"Media-based learning offers require always systematic planning and conception". [13]

For this reason, the conception of the multimedia instruction must be adapted to the prior knowledge of the user. Furthermore, it is necessary to consider the working memory and its receptivity, since there is a limitation of capacity of human information processing. The paradigm examples, which will be displayed on labAlive, are based on the following model. [1]

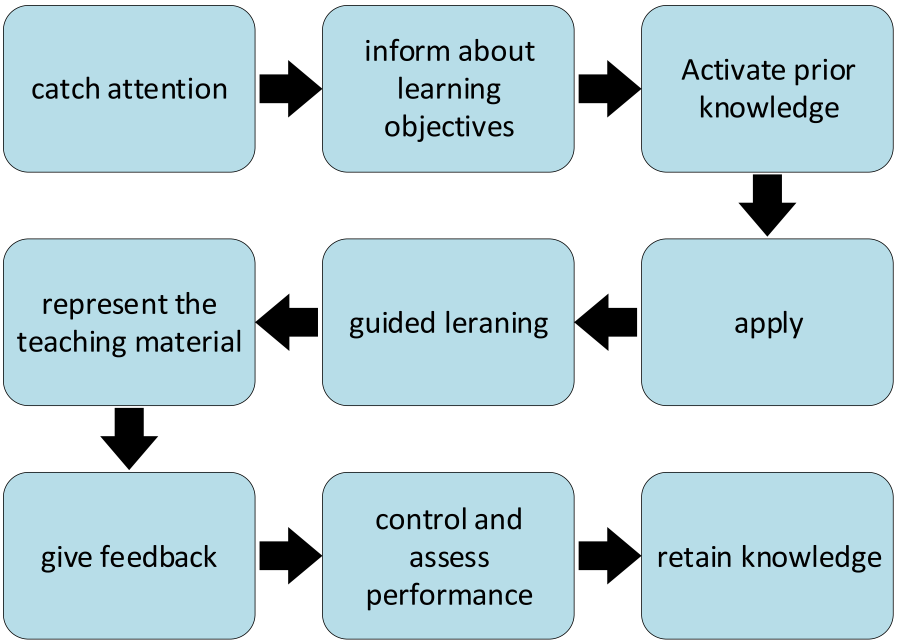


Figure 1: The nine teaching steps [13]

2.2 Typical Problems

The ability to learn the handling of complex technical tasks or programming often turns out to be a difficult project and leads to high dropout rates in technical studies. There are various reasons, such as insufficient teaching materials, lack of basic knowledge, as well as a lack of one-to-one lessons. [14][9][18]

2.3 Structure of labAlive Content

The following figure 2 illustrates the schematic structure of the new labAlive website and content alignment. The cursor shows how the get from one level to the next.

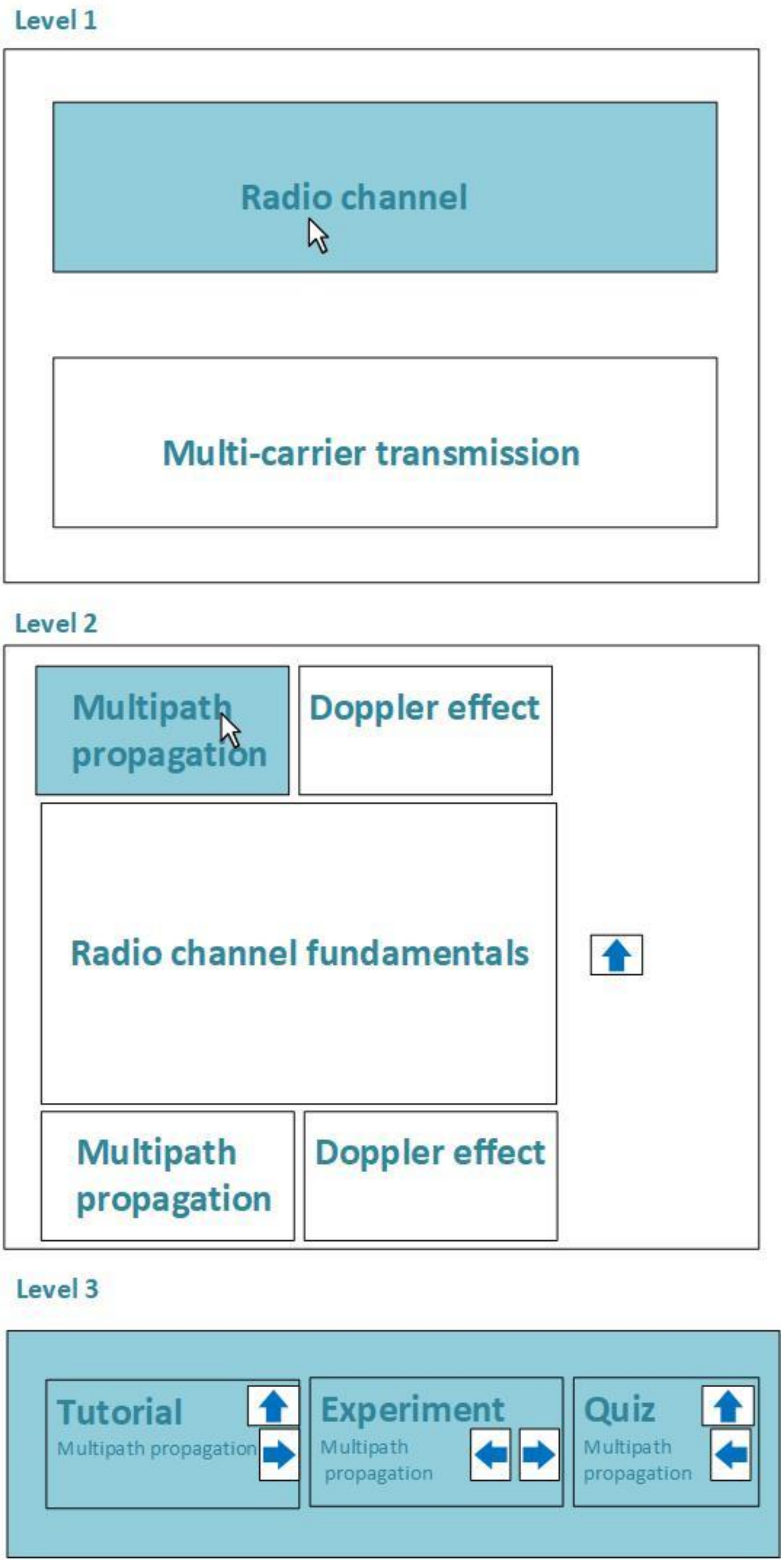


Figure 2: labAlive schematic

Users should find a presentation of several topics of telecommunications engineering as a teaser on the labAlive homepage (figure 3). This is automatically the first level, where the user can decide to click on a topic of his personal interest. The small teaser displays a little image which is related to the chosen topic to evoke attention at first. In addition, there is a short description about the topic. In terms of editorial effort, the description and graphic should always have the same size to ensure uniformity.

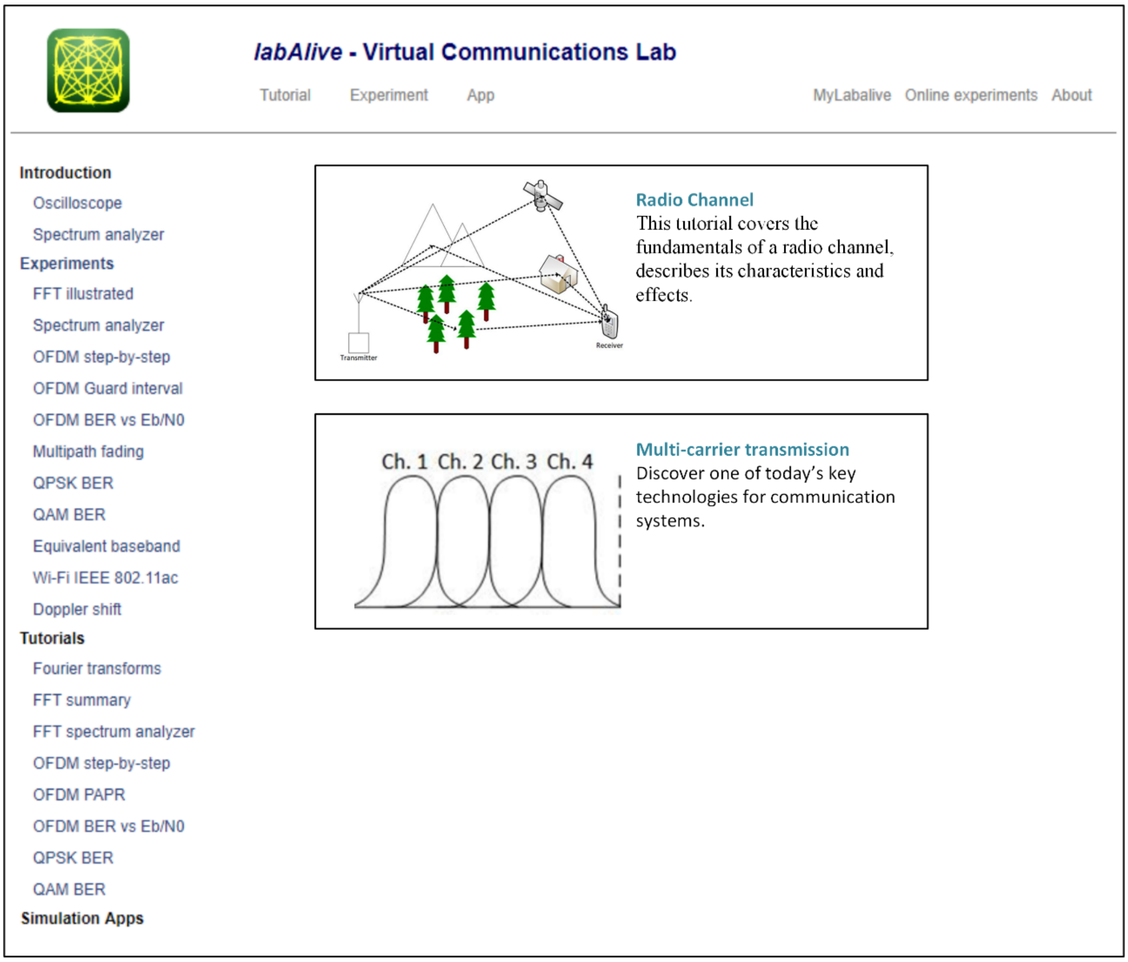


Figure 3: Level 1 -Homepage with teasers

After clicking, for instance, on the teaser “Radio channel”, the user is directed to the main page of the topic “Radio channel” depicted in figure 4, which is level 2 in the labAlive content hierarchy. All-important fundamentals are displayed between more teasers, which will direct the user to subtopics by clicking on them. This page is for picking up or refreshing general knowledge with regards to further, more profound topics, where the basics are indispensable.

In addition, it is possible not only to navigate with the browsers buttons, but with an implemented navigation control illustrated by the blue arrow. The navigation is only possible in certain restricted directions, depending on where you are within labAlive.

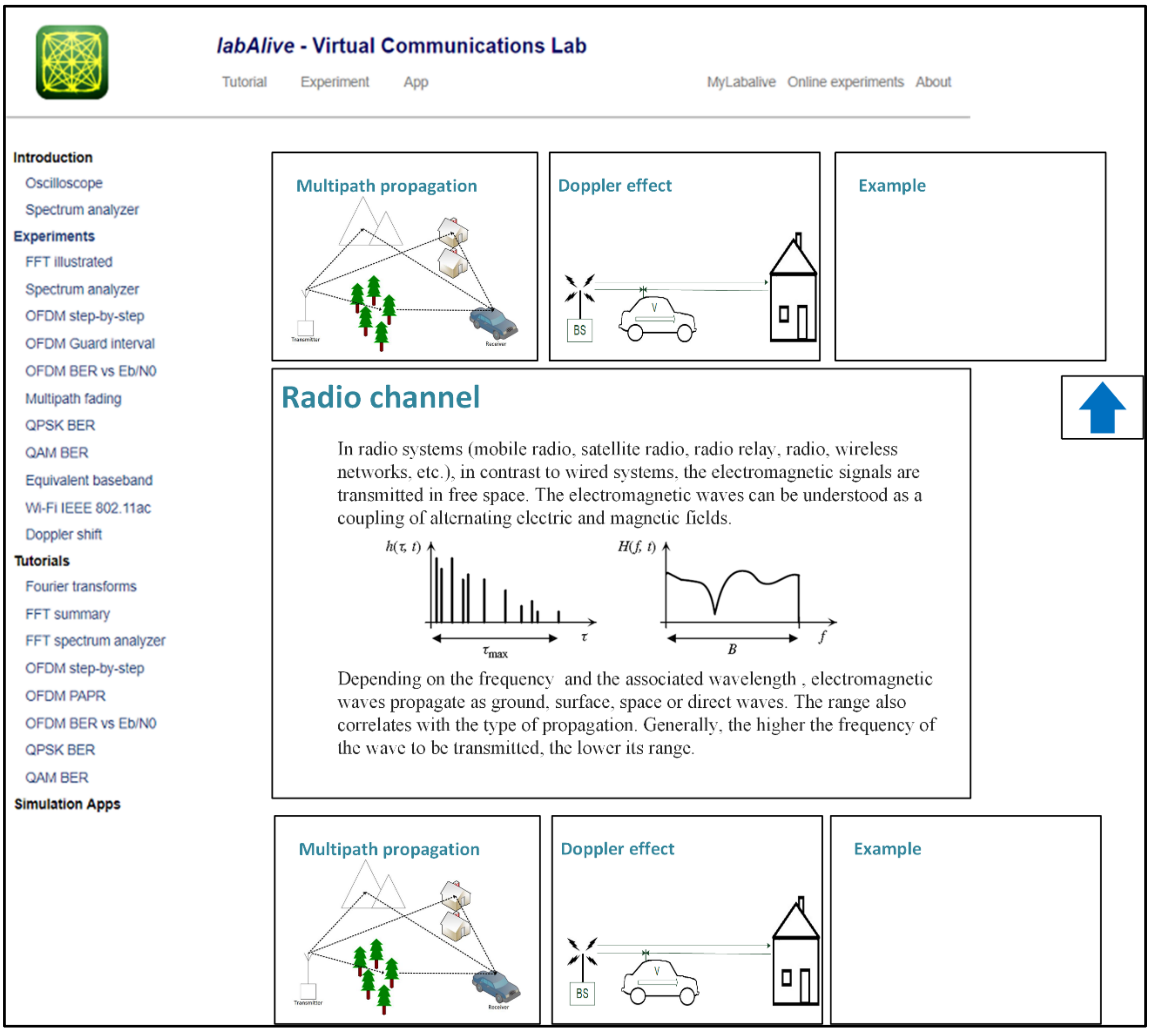


Figure 4: Level 2 - Main page "Radio channel"

By clicking the teaser multipath propagation on level 2, the user will be able to see a specific subtopic and advance to level 3, which is the last level within the new labAlive content structure. Level 3 is horizontally structured and contains the three brackets “Tutorial”, “Experiment” and “Quiz”.

Once a user decides to click in a subtopic, he’ll be first displayed the “Tutorial” (Figure 5), which contains fundamental knowledge. The user has now the chance to either go up to level 2, or advance to the next bracket “Experiment”.

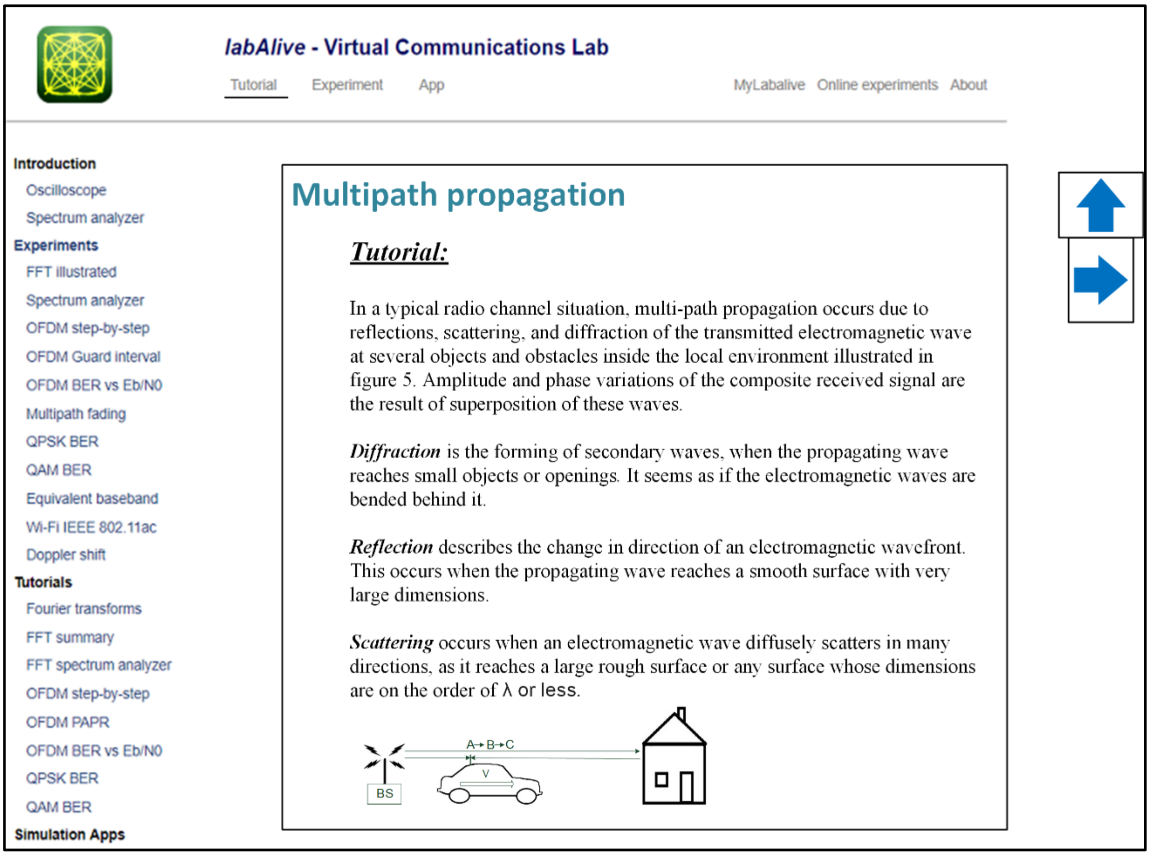


Figure 5: Level 3 - Tutorial multipath propagation

Within the “Experiment” (Figure 6), the user can apply the acquired knowledge, to deepen and, moreover, gain practical skills. Its aim is to provide meaningfully chosen content and focus on the essentials of each topic. The student and future user needs to have the chance of using the common online learning advantages such as availability, reproducibility and scalability to be effective in making progress by learning new content. Furthermore, the user has the choice to navigate back to the “Tutorial”, up to level 2 or going on with the “Quiz”.

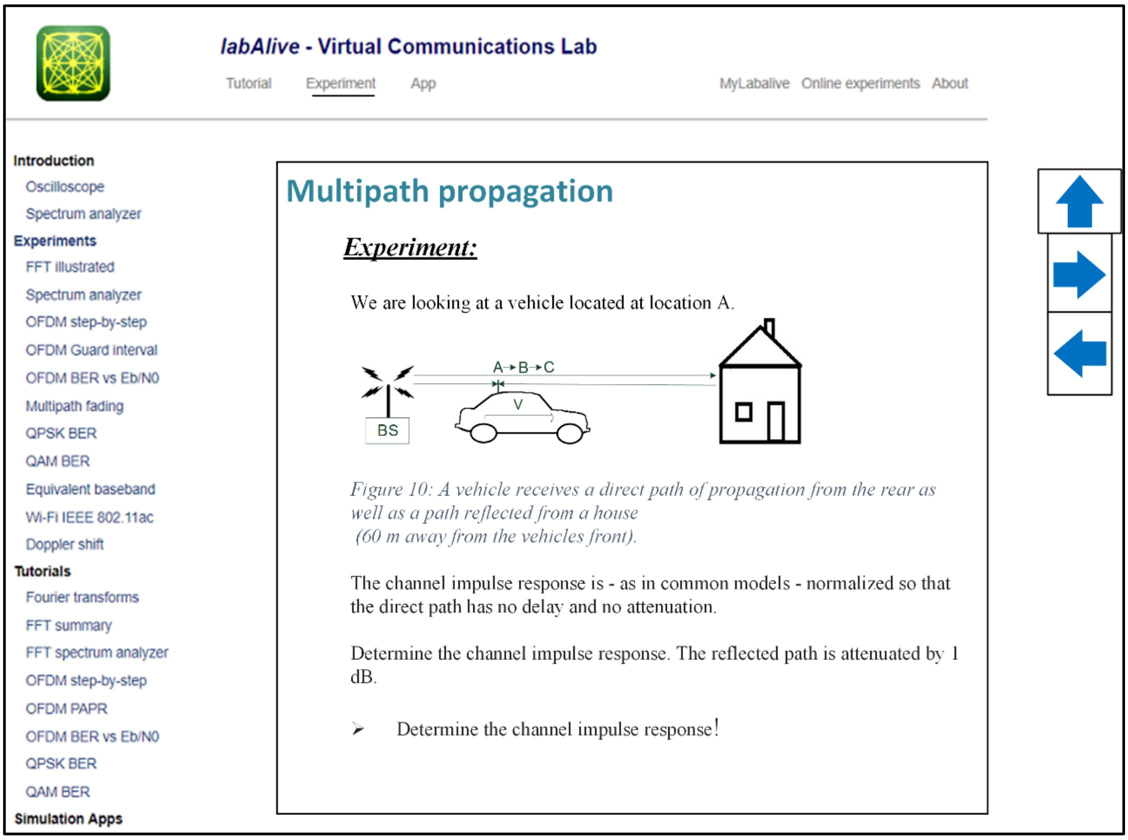


Figure 6: Level 3 - Experiment multipath propagation

After conveying the fundamentals and completing the experiment, the user can still perform a "Quiz" (Figure 7). It contains topic-related questions and the user can again check the consolidation of important content. It is possible to navigate back to "Experiment", or up to level 2.

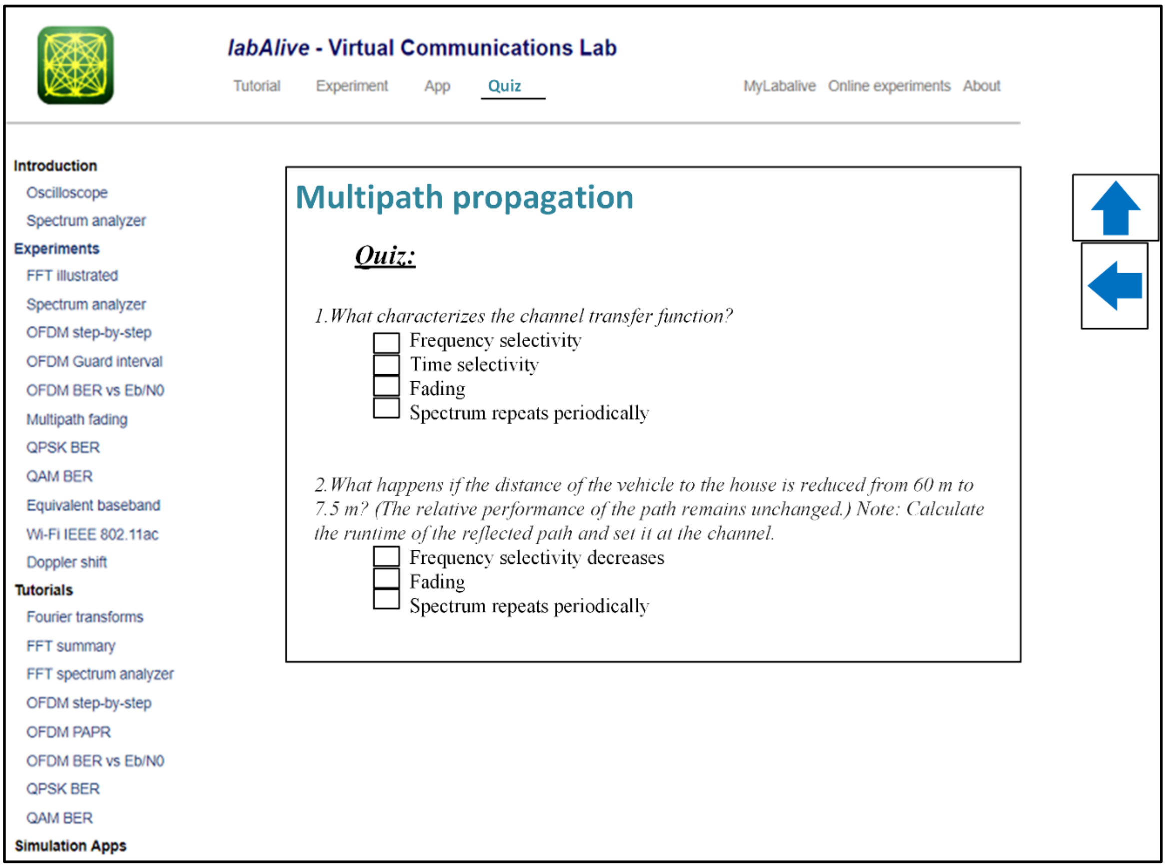


Figure 7: Level 3 - Quiz multipath propagation

3. Fundamentals and OFDM

This chapter gives an overview and starts by describing the basics of wireless communication nowadays. Furthermore, the description of the radio channel and its characteristics will be covered and illustrated. In addition, we are going to have a look at the basics of Multicarrier modulation, which is a key technology in nowadays communication systems. This is followed by the introduction of OFDM's functionality.

3.1 Wireless Communication Systems

The mere thought to go on in life without a smartphone or any other wireless device is a nightmare scenario for many within our society. Wireless technologies are an integral part of our everyday lives and are indispensable for humanity.

Communication services should be available whenever possible, and people should be as mobile as possible in conjunction with this technology.

Thanks to a major advance in wireless transmission in recent years, users can, for example, use high definition programs and videos without sacrificing quality. The devices are thin, light and inexpensive to buy. Their efficiency and performance in all technological areas is far from reaching its borders.

3.1.1 Digital Broadcasting Systems

Today many people feel the need to acquire information through audio and video transmission. The introduction of amplitude modulation (AM) radio dates back to the 1920s. Immediately before the Second World War, TV programs were broadcasted for the first time. In the mid-twentieth century, short-wave broadcasting (also frequency modulation FM) became available and was actively used by society. All those technologies are based on analogue communication and brought news, music, movies and much more to society.

Over the years, digital transmission methods began to displace the analogue. Reasons for this include more and improved quality transmission techniques, such as digital audio broadcasting (DAB) and digital video broadcasting (DVB).

Digital Audio Broadcasting (DAB)

is a digital transmission standard for terrestrial digital radio reception. It is suitable for the frequency range from 30 MHz to 3 GHz and therefore includes the distribution of radio programs via cable and satellite. DAB is among the first standards that use the OFDM technique. When DAB is based on OFDM, there is one distinct benefit: a single frequency network (SFN). Within a SFN, one carrier frequency can be used for all transmitters to broadcast the same program on radio, within for example a country. Moreover, it doesn't suffer from co-channel interference. Compared to the FM system, where only approximately 15 possible frequencies can be used, it results in a very inefficient frequency re-use factor of 15. A SFN compared to a multi-frequency network are shown in Figure 8.

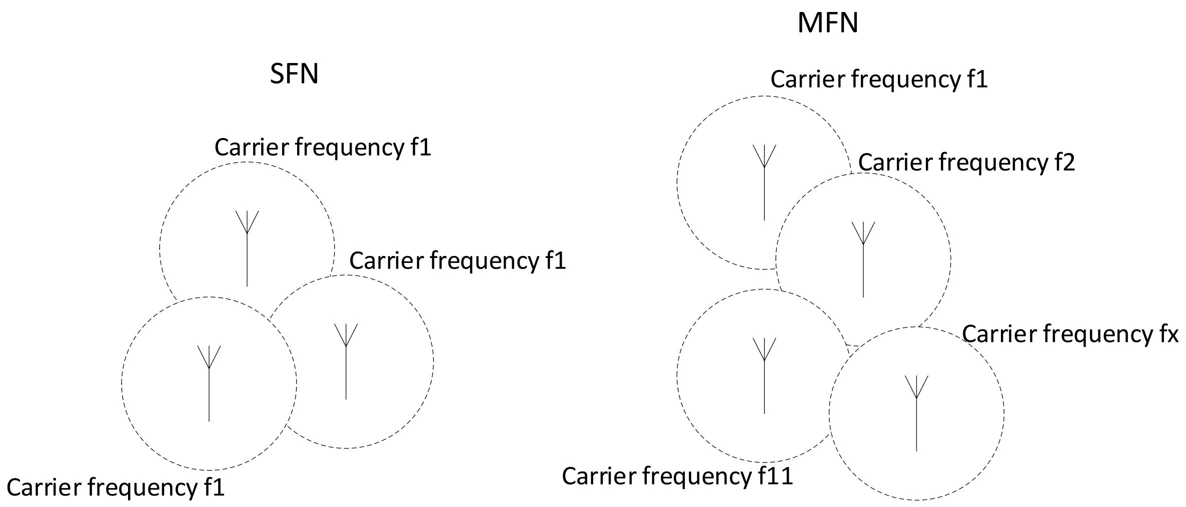


Figure 8: Single-frequency vs. multi-frequency network

There is another difference compared to AM/FM radios, because within the DAB system it is not necessary to search for radio stations. So-called multiplexes integrate the programs of all radio stations. In addition, it is possible, that variable bandwidths can be assigned to each program, fulfilling their respective demands for the sound quality. At last, the DAB system features improved mobile reception quality thanks to OFDM.

Digital Video Broadcasting (DVB)

refers to the standardized processes for the transmission of digital content (television, radio, multi-channel sound, surround sound, interactive services such as MHP, EPG and teletext and other ancillary services) through digital technology. DVB-T receivers started to be sold in the late 1990s and nowadays digital DVB-T programs are available in many countries around the world. Some of the DVB-standards utilize OFDM as the modulation scheme (for example DVB-T & DVB-H). [7]

3.1.2 Mobile Cellular Systems

Smart- and mobile phones are indispensable for our modern society. Those systems offer a broad spectrum of functionalities from voice service to picture, video, and broadband data services. In order to be online at all times, certain technologies are necessary. There are now many mobile standards that allow data transmission.

Due to the rapid spread of mobile devices in the last 15 years, there is an almost nationwide infrastructure of mobile stations, with a variety of different mobile systems.

The mobile radio channel is a radio channel in the frequency range of about 400 MHz - 2 GHz, in which moves at least one of the two communication partners. [11]

Table 2: Evolution of major cellular communications systems [8]

Generation	Standard	Max. Bandwidth	Widely in use
2G	GSM	9,6 Kbit/s	1992
2.5G	GPRS	54 Kbit/s	2001
2.75G	EDGE	220 Kbit/s	2006
3G	UMTS	384 Kbit/s	2007
3.5G	HSPA ; HSPA+	7,2 Mbit/s 42 Mbit/s	2010/2011
3.9G	LTE	150 Mbit/s	2010
4G	LTE Advanced	300 Mbit/s	2014
4.5G	LTE Advanced Pro	600 Mbit/s	2017

A precursor to LTE was introduced by Nortel Networks under the name High Speed OFDM Packet Access (HSOPA). LTE uses orthogonal frequency division multiplexing techniques (OFDM) as well as multiple-input / multiple-output antenna technology (MIMO). The radio interface is defined in standard E-UTRA, the architecture of LTE is purely packet-oriented and described in the Evolved Packet System (EPS).

OFDM is considered as the modulation scheme within LTE. This scheme has the distinct advantage of combatting frequency-selective fading channels, which is quite a challenge for receivers of wideband systems. In Addition, OFDM can achieve efficient spectrum utilization, flexible subcarrier allocation and adaptable subcarrier modulation. [16]

3.1.3 Wireless Network Systems

A wireless network is a network in which at least two terminals (for example, a laptop, PDA, etc.) can communicate without a cable connection. Bluetooth and IEEE 802.11 wireless local area network are two famous wireless networks.

Wireless networks are based on the connection of radio waves (radio and infrared) instead of physical cables. There are several technologies that differ in terms of radiation frequency, data rates and range.

They also allow easy connection of devices that can be several meters to kilometers away. In addition, the installation of such networks does not require much work on existing infrastructures, as is the case with cable networks (digging for the installation of cables, building cabling, cable ducts, plugs). This has led to a rapid development of this technology.

There is also the question of regulation of radio wave transmissions because they are used in a variety of ways (military, science, private), but are susceptible to interference. Therefore, each country needs its own regulation setting frequency blocks and transmission power for the different use categories.

In addition, it is difficult to confine electromagnetic waves to a particular geographic area. Therefore, the network is easy to listen to if the information circulates unencrypted (default setting). Therefore, precautions must be taken to ensure the confidentiality of the data in the wireless network.

The Institute of Electrical and Electronics Engineers (IEEE) has already defined several wireless data network standards as depicted in Figure 9. The smallest wireless network is the personal area network (PAN). This network covers only a few meters around the user. Operating within a bigger environment, the wireless local area network (LAN) IEEE 802.11 is by far the most successful and popular wireless computer network standard. Within a LAN, short-distance communications in a range of several meters up to about 100 meters are provided.

A Metropolitan Area Network (MAN) is a broadband telecommunications network. Normally, a MAN connects numerous local area networks using a backbone technology, which is usually implemented in fiber optic technology. An MAN can have an extension of up to 100 km.

A Wide Area Network (WAN) is a computer network that, unlike a LAN or MAN, covers a very large geographic area. The number of connected computers corresponds to the maximum of IPv4 or IPv6. WANs span across countries or even continents. WANs are used to network different LANs as well as individual computers. Some WANs are owned and used by specific organizations. Other WANs are being built or expanded by Internet service providers to provide access to the Internet. [29]

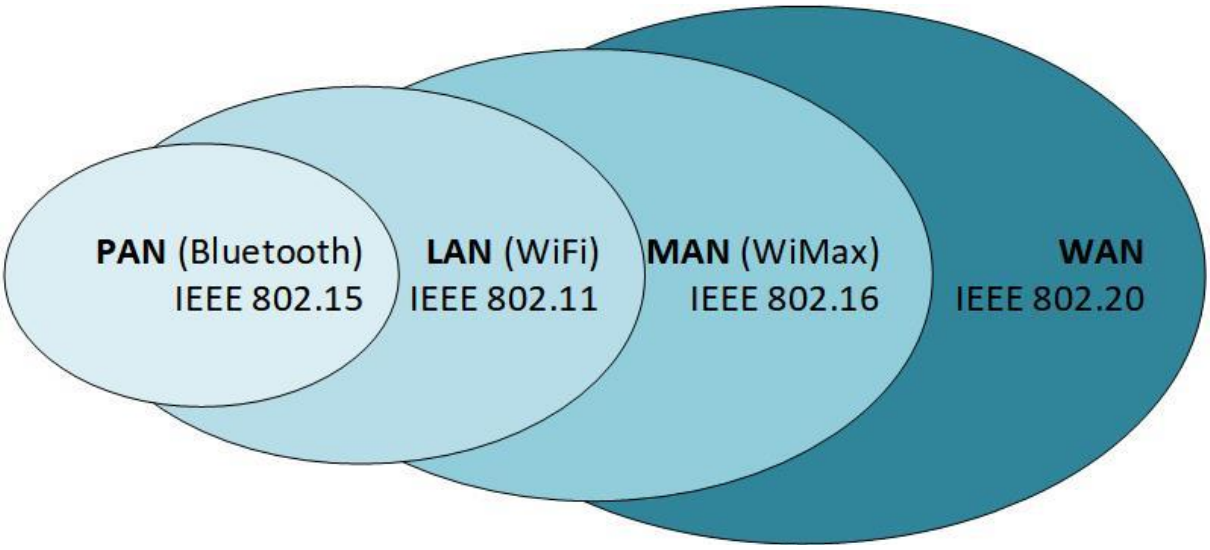


Figure 9: Wireless network standards

3.2 Radio Channel

title	Radio channel example: Radio Channel Fundamentals
descrip-tion	This tutorial covers the fundamentals of a radio channel and describes its characteristics
keywords	examples demo images illustration demonstration radio channel delay spread doppler spread multipath propagation shadowing slow fast fading pathloss deflection reflection scattering coherence bandwidth fading frequencies

Fundamentals:

A radio channel is in terms of radio technology, a frequency or a frequency range on which a radio signal, like analog voice or digital data, is transmitted.

The radio transmission is used within the military, wireless LAN, broadcast, emergency services, wireless phones and many more areas.

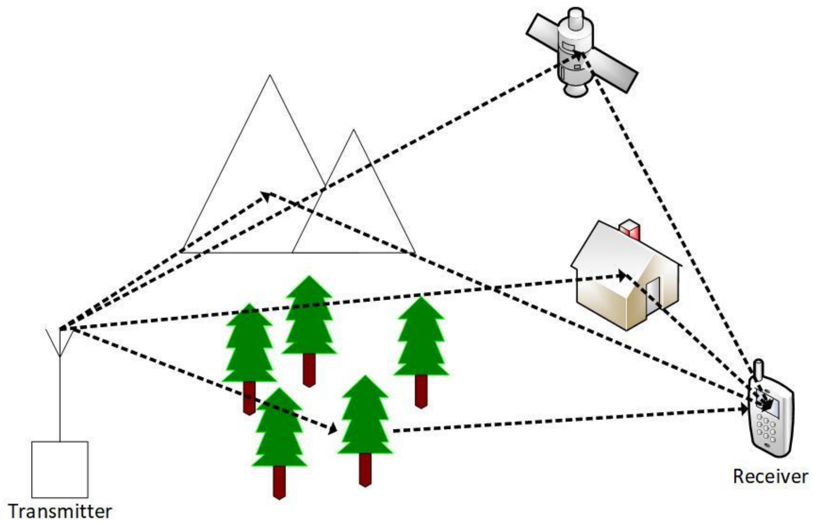


Figure 10: Radio Channel

In radio systems (mobile radio, satellite radio, radio relay, radio, wireless networks, etc.), in contrast to wired systems, the electromagnetic signals are transmitted in free space. The electromagnetic waves can be understood as a coupling of alternating electric and magnetic fields.

Depending on the frequency f and the associated wavelength λ, electromagnetic waves propagate as ground, surface, space or direct waves. The range also correlates with the type of propagation. Generally, the higher the frequency of the wave has to be transmitted, the lower its range.

It is crucial to understand the characteristics of the communications medium for the appropriate selection of transmission architecture, optimizing system parameters and the dimensioning of its components. The bandwidth of the channel determines the amount of information that can be sent per unit of time. The larger the bandwidth selected, the more data can be transmitted, but the fewer channels will fit (without overlapping) into a particular

frequency band. In addition, the bandwidth is crucial for spatial signal fluctuations. With digital transmission one speaks of the data rate of a channel.
Furthermore, radio channels are considered as being the most difficult channels. Multi-path fading, interference, Doppler shift and shadowing are imperfections, that must be handled, and the engineer needs to be aware of.

The transfer function $H(f,t)$ and the impulse response $h(\tau,t)$ are equivalent parameters of linear systems, which can be converted into each other via the Fourier transformation. This means that with known transfer function and the impulse response of the system is known and vice versa. With these two parameters, the radio channel can be characterized. [10][11]

$$h(\tau,t) = \sum_{v=0}^{n-1} a_v e^{j(2\pi f_{D,v} t + \varphi_v)} \delta(\tau - \tau_v),$$

where

$$\delta(\tau - \tau_v) = \begin{cases} 1 & if\ \tau = \tau_v \\ 0 & otherwise \end{cases}$$

a_v	Amplitude of the v Path
$f_{D,v}$	Doppler Frequency
φ_v	Phase of the v Path
τ_v	Delay of the v Path

The channel impulse response represents the response of the channel at time t due to an impulse applied at time $t - \tau$. [10]

This form of impulse response is complex and requires an analytical signal or an equivalent baseband signal at the input. [24]

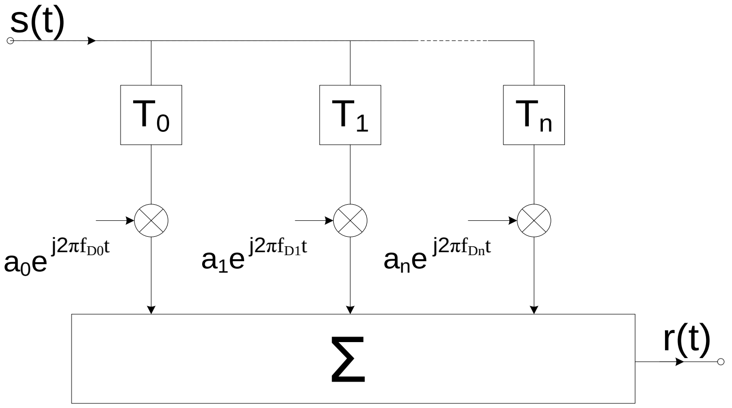


Figure 11: Radio channel model [24]

The channel transfer function $H(f,t)$ results in:

$$H(f,t) = \sum_{v=0}^{n-1} a_v e^{j\left(2\pi(f_{D,v}t + f\tau_v) + \varphi_v\right)}.$$

a_v	Amplitude of the v Path
$f_{D,v}$	Doppler Frequency
φ_v	Phase of the v Path
τ_v	Delay of the v Path

3.2.1 Multipath Propagation

title	Multipath Propagation Tutorial, Experiment and Quiz
description	This tutorial covers the characteristics and fundamentals of a multipath channel.
keywords	examples demo images illustration demonstration radio channel delay spread doppler spread multipath propagation shadowing slow fast fading pathloss deflection reflection scattering coherence bandwidth time-variant multipath channel transfer function model

Tutorial:

In a typical radio channel situation, multi-path propagation occurs due to reflections, scattering, and diffraction of the transmitted electromagnetic wave at several objects and obstacles inside the local environment illustrated in Figure 12. Amplitude and phase variations of the composite received signal are the result of superposition of these waves.

Diffraction is the forming of secondary waves, when the propagating wave reaches small objects or openings. It seems as if the electromagnetic waves are bended behind it.

Reflection describes the change in direction of an electromagnetic wave front. This occurs when the propagating wave reaches a smooth surface with very large dimensions.

Scattering occurs when an electromagnetic wave diffusely scatters in many directions, as it reaches a large rough surface or any surface whose dimensions are on the order of λ or less.

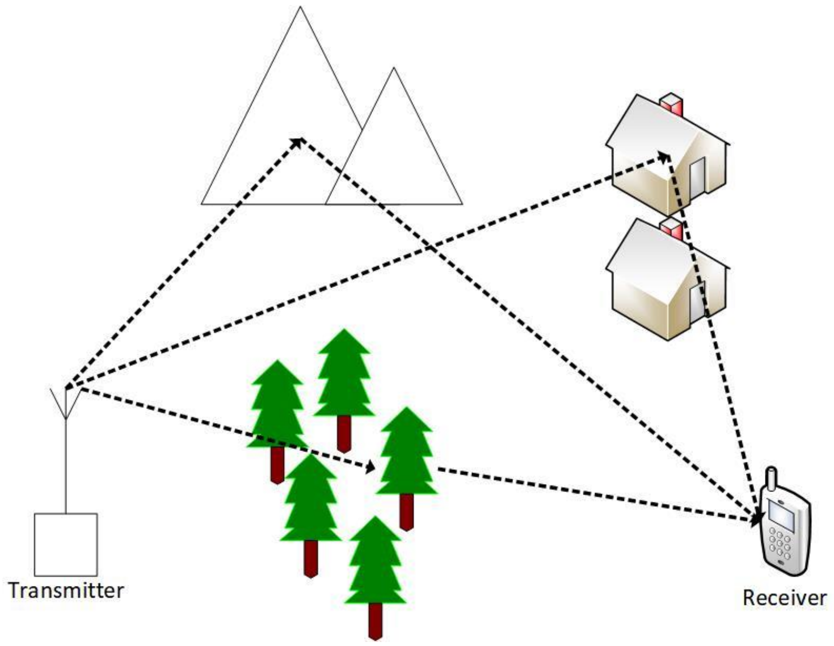


Figure 12: Multipath propagation scenario

The ***delay spread*** can be interpreted as the difference between the time of arrival of the earliest significant multipath component, usually the LOS (Line of sight) component, and of the last one depicted in Figure 13. This is also called the Total Delay Spread. The power delay profile (PDP) needs to be found at first, in order to make a characterization of the extent of channel delay spread possible. The PDP describes the time distribution of the received signal power, when an impulse waveform is transmitted through the radio channel (Figure 13).

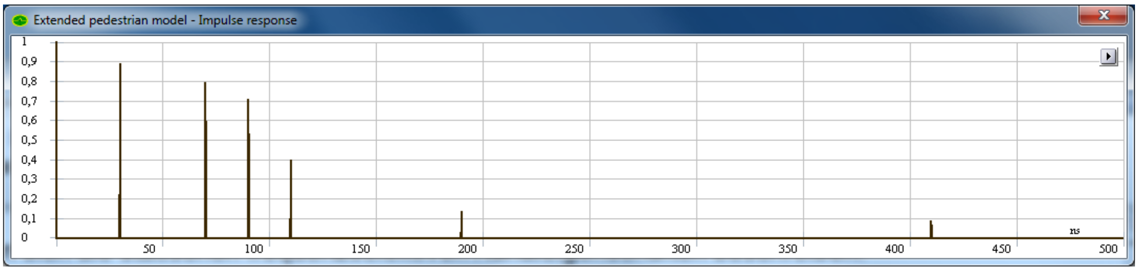


Figure 13: Impulse response of the Extended Pedestrian A model (LTE channel model) [24]

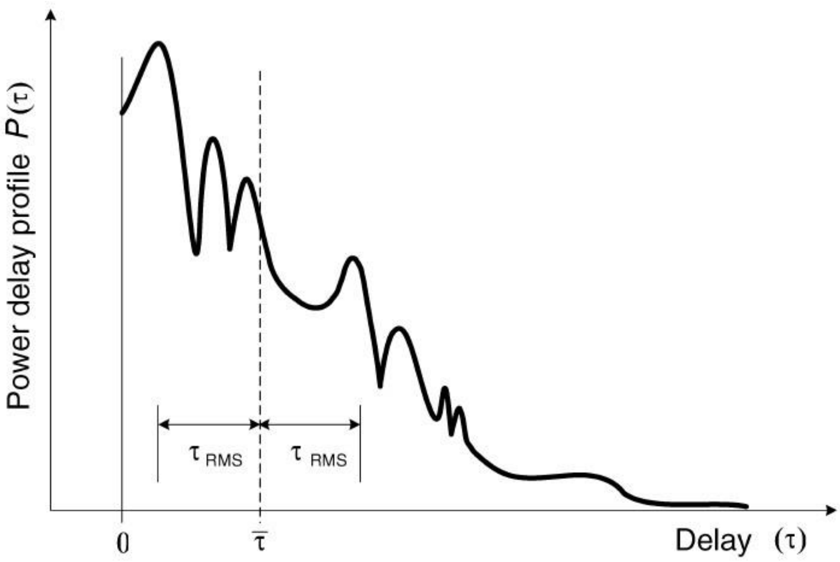


Figure 14: Typical multipath channel power delay profile[7]

As seen in Figure 14, the root mean square (RMS) delay spread is the standard deviation of the delays, weighted with the respective path energy and an important indicator for the radio channel.

A large delay spread characterizes a highly dispersive channel with high frequency selectivity.

The ***Coherence Bandwidth*** is the inverse of the Total Delay Spread (τ).

$$f_{Coherence} = \frac{1}{\tau_{\max}}$$

The Coherence Bandwidth is the frequency range in which electromagnetic waves from a given source remain coherent. Waves with a wide coherence bandwidth remain coherent only over short distances, those with a small coherence over longer ones. [24]

Experiment:

We are looking at a vehicle located at location A.

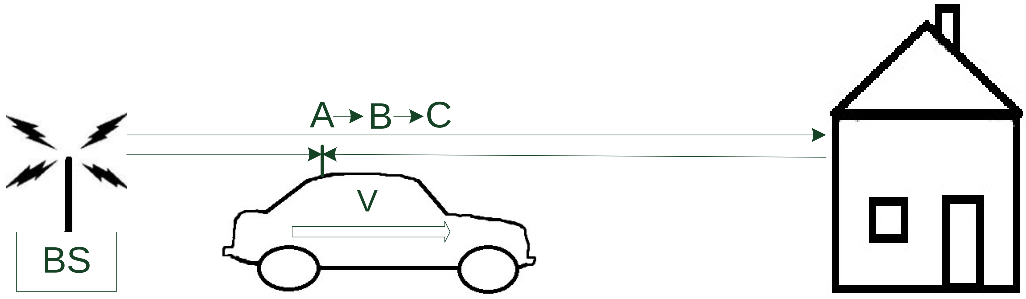


Figure 15: A vehicle receives a direct path of propagation from the rear as well as a path reflected from a house (60 m away from the vehicles front.[24]

The channel impulse response is - as in common models - normalized so that the direct path has no delay and no attenuation.

Determine the channel impulse response. The reflected path is attenuated by 1 dB.

Table 1: Channel impulse response - location A [24]

Excess tap delay [ns]	Relative power [dB]
0	0.0
	-1.0

- Determine the channel impulse response!
- Where is the channel impulse response located?

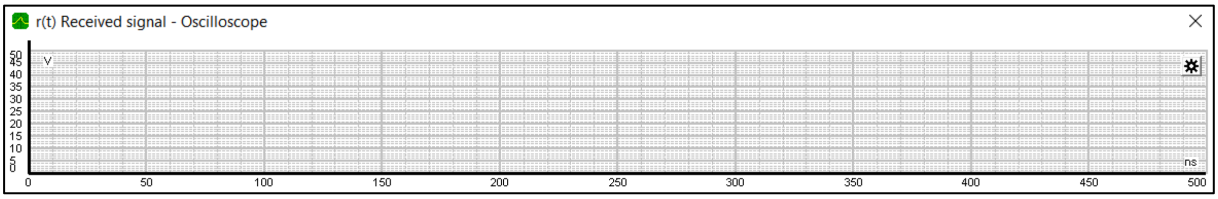


Figure 16: template for impulse response

- Determine the channel transfer function

$$H(f) =$$

- Determine the frequency and the corresponding amount of the channel transfer function in the following places:

f [MHZ]	$\|H(f)\|$
0	
*	
**	
995	
1005	

Table 2: Amount of channel transfer function [24]

**Smallest frequency with min $|H(f)|$*

***Next largest frequency with max $|H(f)|$*

- Start the simulation app [Multipath propagation]().
- You can set the channel properties - Click on "Multipath Channel" to open the properties window. Check the settings for location A.

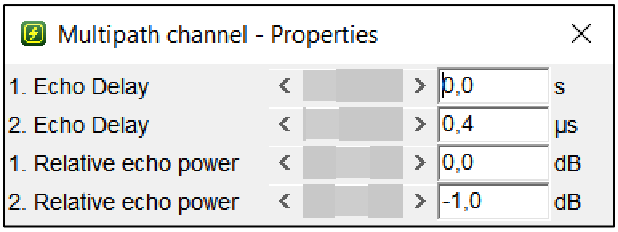


Figure 17: multipath channel properties

- Check your preparation for the channel impulse response and channel transfer function! These can be opened by a right-click on the channel system:

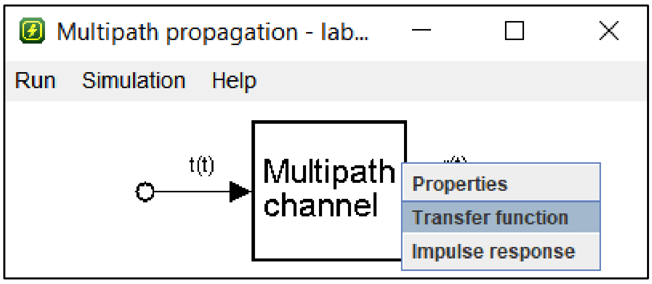


Figure 18: multipath channel

Quiz:

1. *What characterizes the channel transfer function?*

- ☐ Frequency selectivity
- ☐ Time selectivity
- ☐ Fading
- ☐ Spectrum repeats periodically

2. *What happens if the distance of the vehicle to the house is reduced from 60 m to 7.5 m? (The relative performance of the path remains unchanged.) Note: Calculate the runtime of the reflected path and set it at the channel.*

- ☐ Frequency selectivity decreases
- ☐ Fading
- ☐ Spectrum repeats periodically

3. *What happens if the relative power of the reflected path is reduced to -3 dB?*

- ☐ Frequency selectivity decreases
- ☐ Fading
- ☐ Spectrum repeats periodically

4. *What is meant by the term diffraction?*

- ☐ The forming of secondary waves, when a propagating wave reaches small objects or openings. It seems as if the electromagnetic waves are bended behind it.
- ☐ The change in direction of an electromagnetic wave front. This occurs when the propagating wave reaches a smooth surface with very large dimensions.
- ☐ When an electromagnetic wave diffusely scatters in many directions, as it reaches a large rough surface or any surface whose dimensions are on the order of λ or less.

5. *What is meant by the term reflection?*

- ☐ The forming of secondary waves, when a propagating wave reaches small objects or openings. It seems as if the electromagnetic waves are bended behind it.
- ☐ The change in direction of an electromagnetic wave front. This occurs when the propagating wave reaches a smooth surface with very large dimensions.
- ☐ When an electromagnetic wave diffusely scatters in many directions, as it reaches a large rough surface or any surface whose dimensions are on the order of λ or less.

title	Time-variant Multipath Propagation Tutorial, Experiment and Quiz
descrip-tion	This tutorial covers the characteristics and fundamentals of a time-variant multipath channel. It is shown that even small movements - i.e. minor changes in the path delays - have major impact on the channel characteristics.
keywords	examples demo images illustration demonstration radio channel delay spread doppler spread time-variant multipath propagation shadowing slow fast fading pathloss deflection reflection scattering coherence bandwidth time-variant multipath channel transfer function model

3.2.2 Time-variant Multipath Propagation

Tutorial:

Looking at figure 19, local changes lead to relative runtime changes of the propagation paths. Even a small change in location in the range of half a wavelength leads to a completely different wave superposition and transfer function. Such a channel is time-dependent.

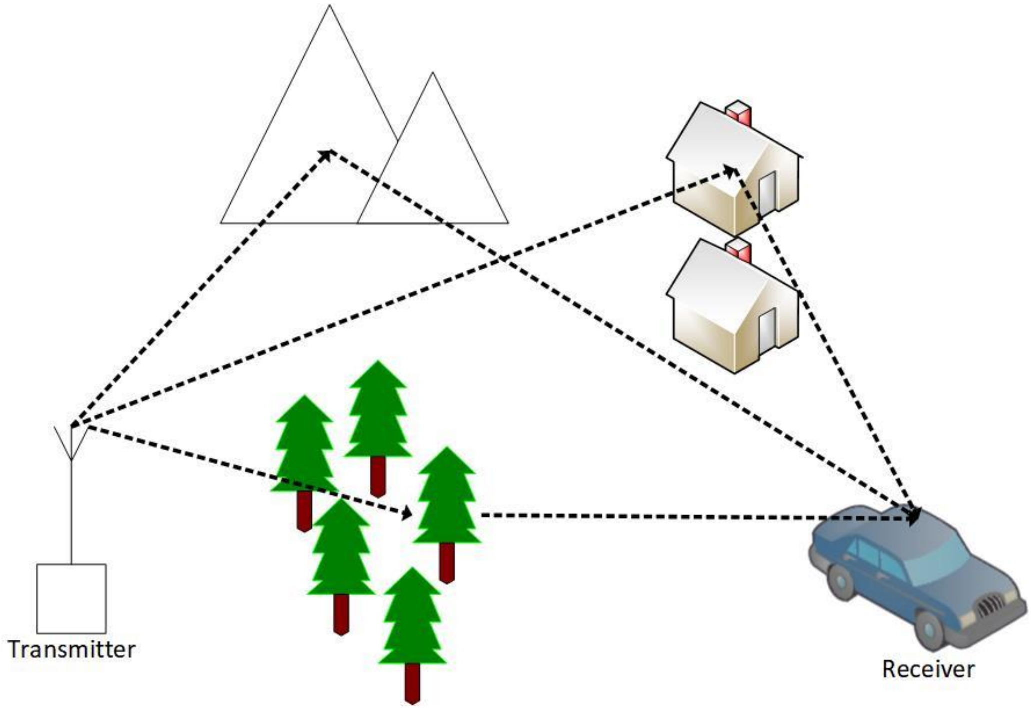


Figure 19: Time-variant multipath propagation

Shadowing describes a slow change in reception conditions due to the changing environment, for example when passing a building or when leaving a wooded area. This results in more or less strong attenuation of the signal strength. The results of shadowing are called slow fading and can be described through a log-normal distribution.

Fading refers to the temporal fluctuation of the amplitude of the received signal by the mean distance-dependent reception level due to changing shadowing ratios and multipath reception.

Path loss detects the attenuation of the electromagnetic wave, which depends strongly on the distance between transmitter and receiver.

So, Radio signals propagating through the free space attenuate at a rate which is inversely proportional to the squared distance between the transmitter and the receiver:

$$P_r(d) \propto \left(\frac{\lambda}{4\,\pi\,d}\right)^2$$

$Pr\ (d)$ is the received power at distance d from the transmitter. The wavelength of the carrier signal is λ. The scenario above presumes that there isn't any obstacle between the transmitter and receiver. This is also called the line of sight (LOS).

Like most measurement experiments of wireless communication systems, the LOS is not the norm. Non-LOS (NLOS) situations will mostly be the case and they bring a more severe attenuation with them.

The degree of signal power attenuation represents the path loss, as the distance between the transmitter and receiver increases. The following formula will describe a simplified log-distance path loss model:

$$L = 10n\ log\left(\frac{d}{d_{dref}}\right) + L_{ref}$$

The letter n stands for the path loss exponent. d is the distance between the transmitter and the receiver. L_{ref} expresses the path loss value in free space for the reference distance d_{ref}. The path loss exponent n can vary from 2(free space) to 6 (severe obstruction).

Due to obstacle positions and surrounding environment, the previous formula of path loss fails, because e.g. two locations with an equal distance from the transmitter may experience a different signal attenuation. Measurement analysis show, that the actual signal loss at a consistent distance d is random with a log-normal distribution.
The above-named shadowing describes such a random effect and it is superposed on the path loss model introduced before. Shadowing varies faster with distance than path loss and, in a range of hundreds of meters, the signal strength variation can be 20 dB. Including the log-normal distributed shadowing effect, the total loss then is given by

$$L = 10n\ log\left(\frac{d}{d_{dref}}\right) + L_{ref} + X$$

The variable X represents the shadowing effect after converting to dB and is also normal-distributed (Gaussian-distributed). The standard variation can be higher than 10 dB in some cellular and indoor environments. [6][7]

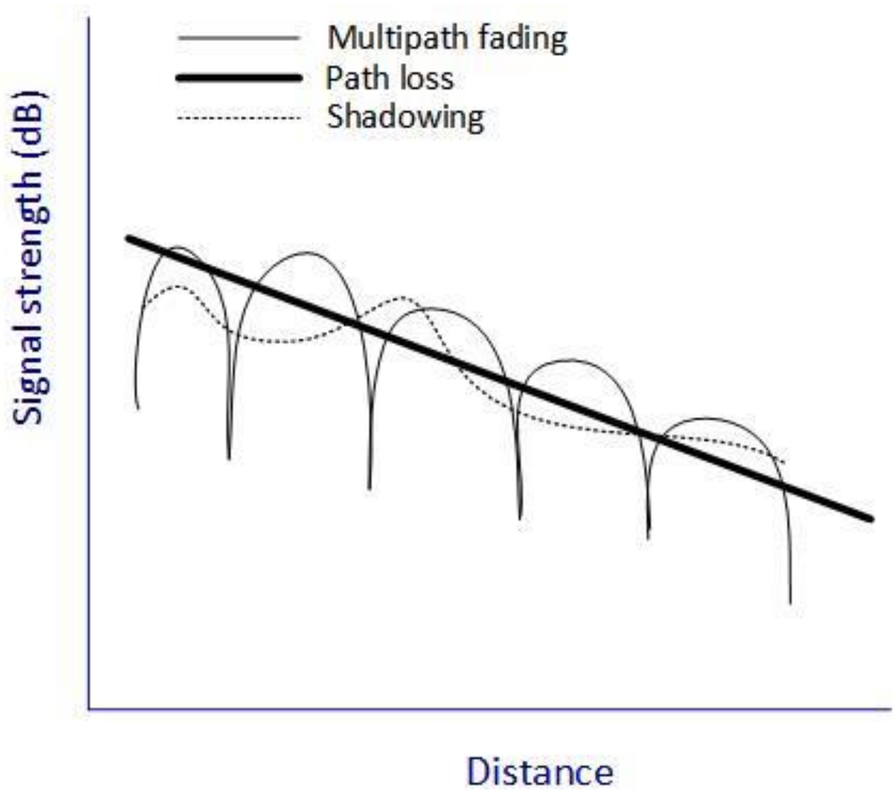


Figure 20: Illustration of path loss, shadowing and multipath fading

Path loss and shadowing are not the only large-scale channel attenuation effects, there are also existing tremendous channel fluctuations within a small area. The signal strength can vary up to 40 dB in one half-wavelength (3 cm in a 5 GHz carrier system). This type of fading (multipath fading) is caused by the combined effect of different versions of the transmitted signal, that arrives at the receiver, along different paths. At the receiver's side, the waves are constructively or destructively combined in amplitude and phase. Figure 20 displays an illustration of the above-named effects, that cause fluctuation in signal strength that have traversed the channel.

A wireless communication system can be categorized as flat fading or under frequency-selective fading. This is due to the relation between the coherence and signal bandwidth. If the coherence bandwidth of the channel is larger than the signals bandwidth, we talk about flat fading. This results in the same magnitude of fading of all frequency components. When the coherence bandwidth is smaller than the bandwidth of the signal, frequency-selective fading occurs. That means, that different frequency components of the signal experience uncorrelated fading. Figure 21 illustrates the scenarios of flat fading and frequency-selective fading. [7]

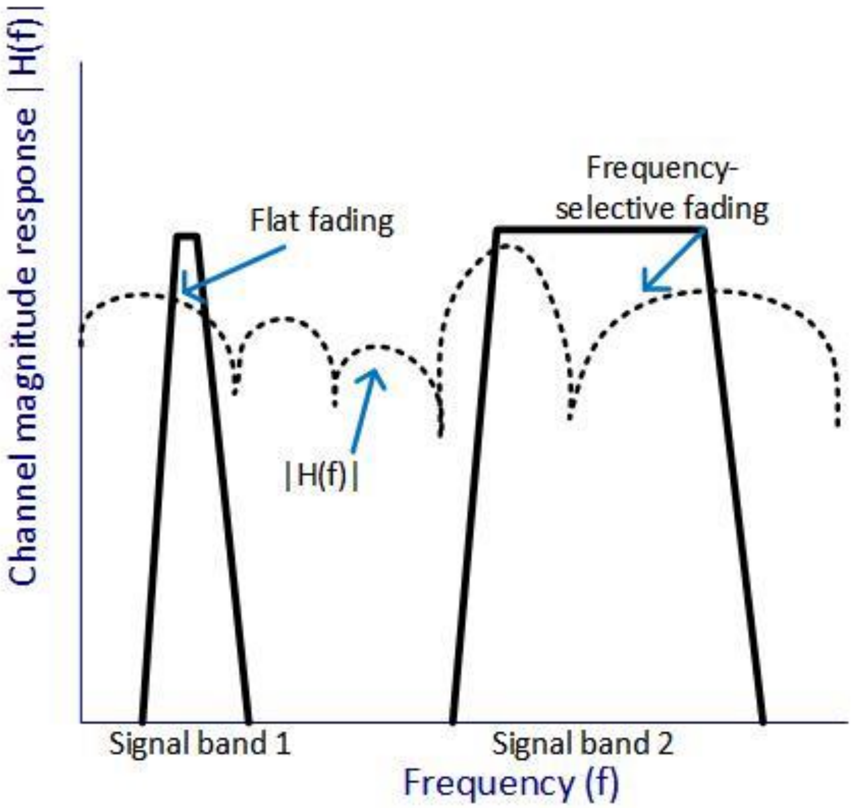


Figure 21: Channel frequency response and signal bands for flat and frequency-selective fading

Experiment:

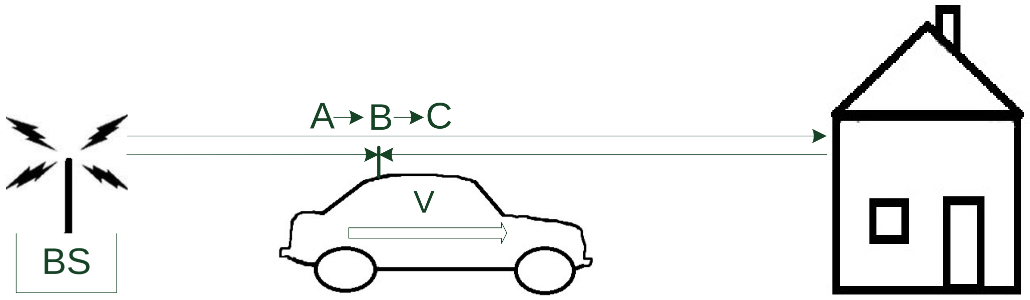


Figure 22: The vehicle now drives 7.5 cm further to B [24]

The running times of the paths change, the relative performances of the paths remain unchanged. Determine the channel impulse responses.

- Location B: Determine the delays of the paths.

Table 3: Channel impulse response - location B [24]

Excess tap delay [ns]	Relative power [dB]
	0.0
	-1.0

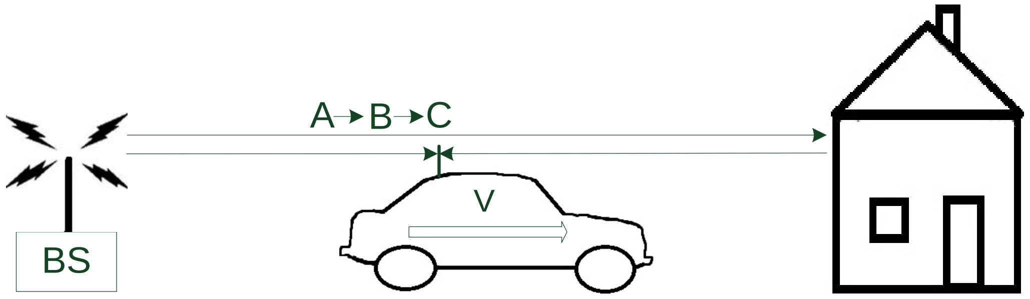


Figure 23: The vehicle now drives again 7.5 cm further to C [24]

Table 4: Channel impulse response - location C [24]

Excess tap delay [ns]	Relative power [dB]
	0.0
	-1.0

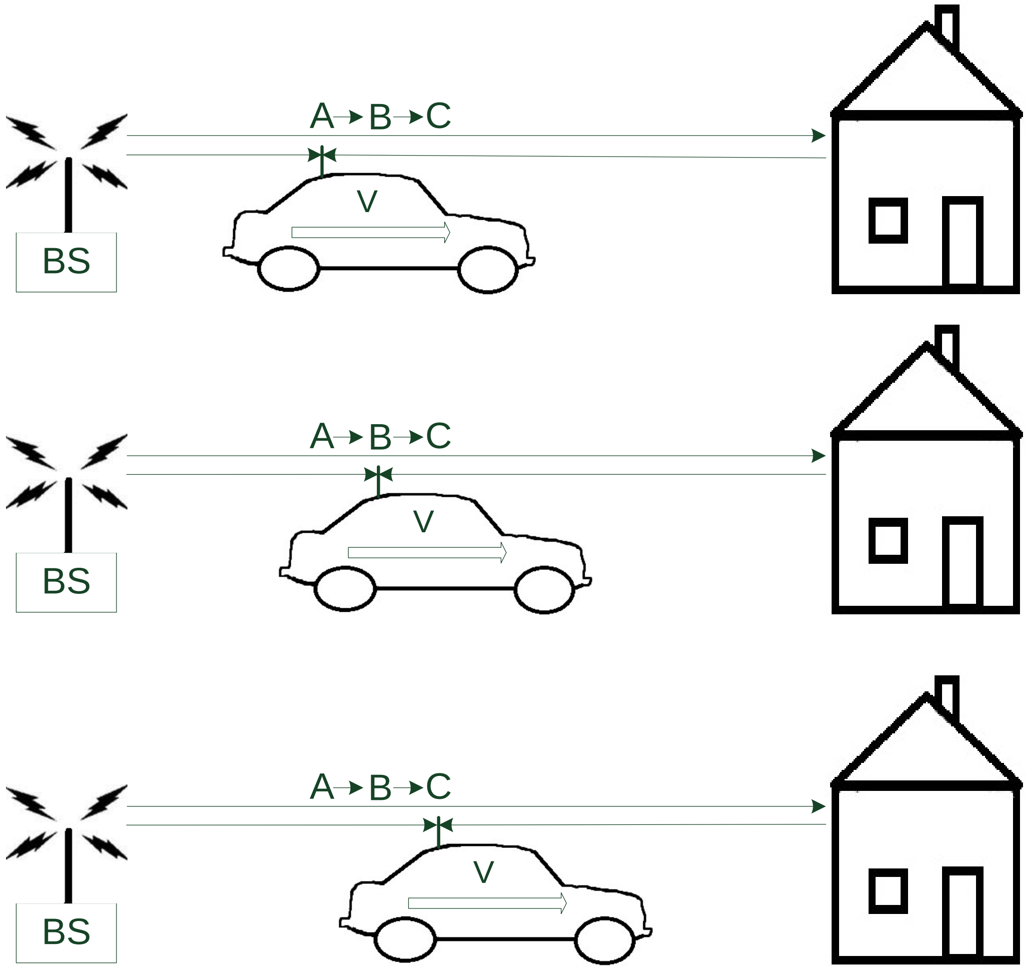


Figure 24: The vehicle drives from A via B to C [24]

Static analysis:

- Start the simulation app *Multipath propagation* again.
- You can set the channel properties - Clicking on "Multipath Channel" opens the properties window.
- Use the simulation to represent the channel transfer function at location B! Make the setting as determined in the preparation.
- Use the simulation to represent the channel transfer function at location C! Make the setting as determined in the preparation.

Dynamic analysis:

The movement of the vehicle is now taken into account in the simulation.

- Start the simulation app *Time-variant multipath propagation*.

- Consider the channel transfer function several times, i.e. at different times. (Several times right-click on channel and transfer function select or CTRL + click on channel.)

Multipath fading propagation – Extended Pedestrian A model:

- Start the simulation app Multipath fading propagation – Extended Pedestrian A model

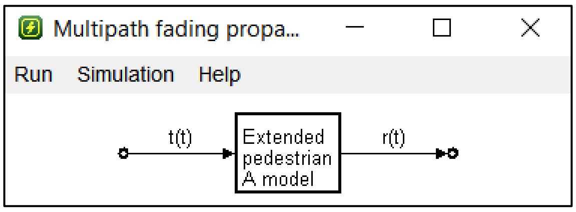


Figure 25: Multipath fading propagation channel

- Left click on the Extended Pedestrian A model to open the properties and have a look at the channel transfer function.

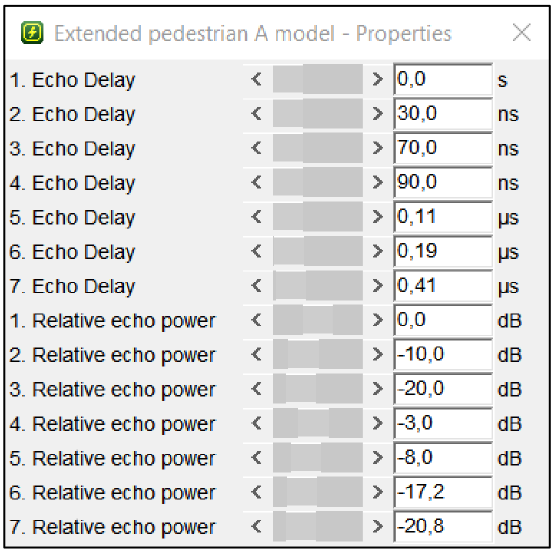


Figure 26: Multipath fading propagation properties

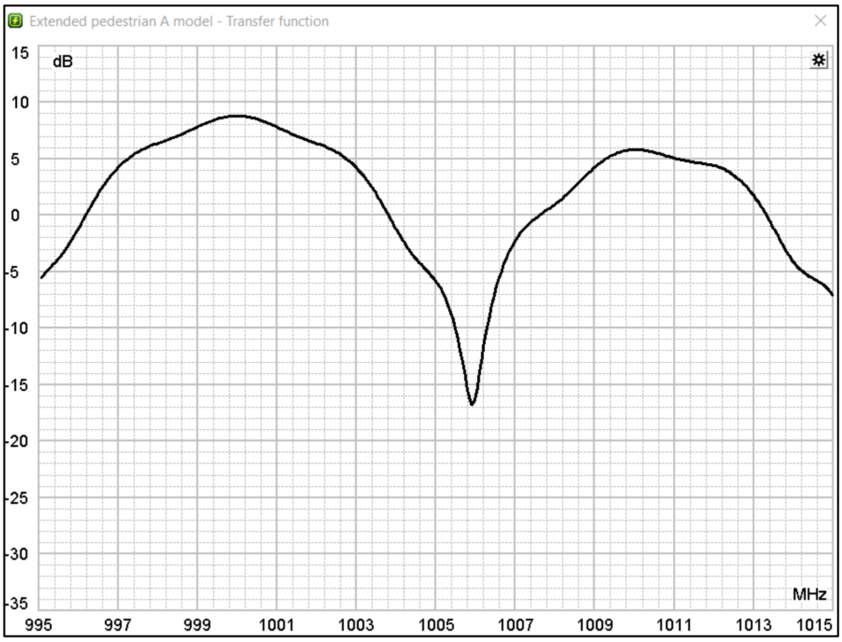


Figure 27: Multipath fading propagation transfer function with preset properties

- ➢ Change some settings e.g. 2. Echo delay and some power values and check how the channel transfer function is changing.

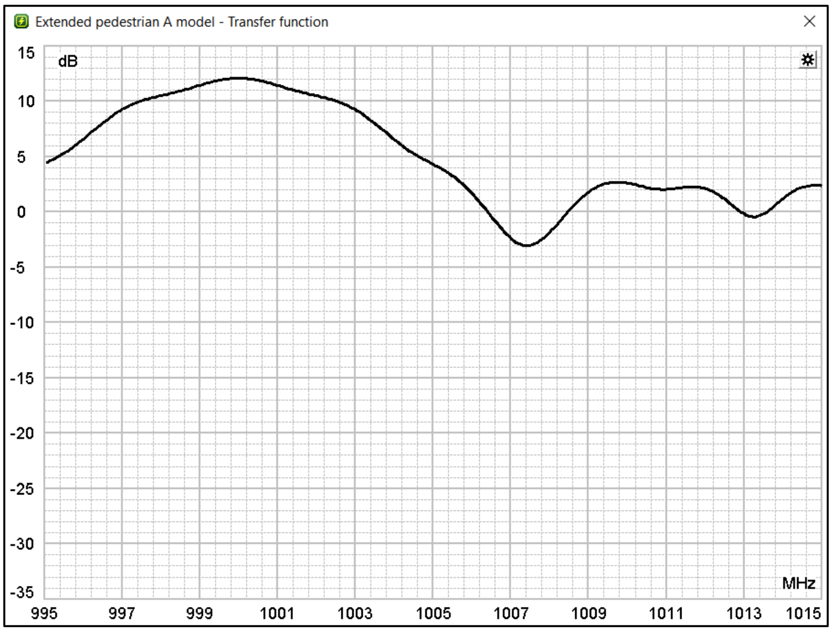


Figure 28: Multipath fading propagation transfer function with 1. Echo delay 30 ns

- ➢ Also have a look on the channel impulse response by right clicking on the model and selecting channel impulse response.

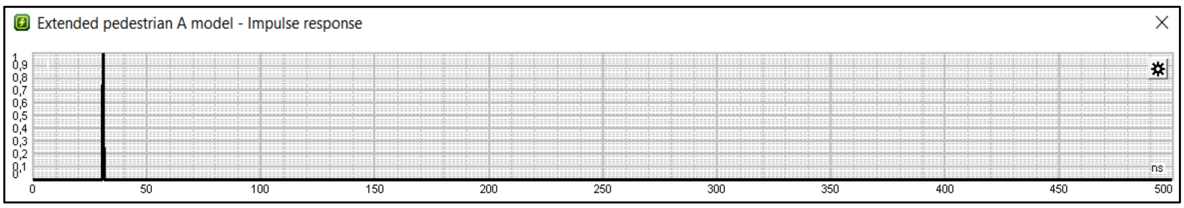


Figure 29: Multipath fading propagation impulse response with 1. Echo delay 30 ns

Quiz:

1. *What is meant by shadowing?*

☐ Describes a slow change in reception conditions due to the changing environment, for example when passing a building or when leaving a wooded area. This results in more or less strong attenuation of the signal strength.
☐ The temporal fluctuation of the amplitude of the received signal by the mean distance-dependent reception level due to changing shadowing ratios and multipath reception.
☐ The detection of the attenuation of the electromagnetic wave, which depends strongly on the distance between transmitter and receiver.

2. *Path loss and shadowing are large-scale channel attenuation effects?*

☐ True
☐ False

3. *What characterizes fading?*

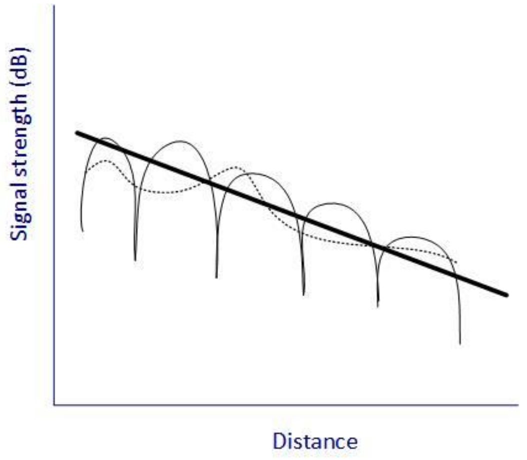
☐ Describes a slow change in reception conditions due to the changing environment, for example when passing a building or when leaving a wooded area. This results in more or less strong attenuation of the signal strength.
☐ The temporal fluctuation of the amplitude of the received signal by the mean distance-dependent reception level due to changing shadowing ratios and multipath reception.
☐ The detection of the attenuation of the electromagnetic wave, which depends strongly on the distance between transmitter and receiver.

4. *Due to the relation between the coherence and signal bandwidth, a wireless communication system can be categorized as flat fading or frequency selective fading.*

☐ True
☐ False

5. *Match each effect to the graph.*

Shadowing
Multipath fading
Path loss



3.2.3 Doppler Effect

title	Doppler example: Doppler Effect - labAlive Tutorial
descrip-tion	In this tutorial and experiment the Doppler shift of a high frequency transmission signal will be analyzed.
keywords	examples demo images illustration demonstration doppler shift spread multipath propagation echoes channel superposition shadowing slow fast fading pathloss

Tutorial:

Thanks to wireless communication, the user is no longer dependent on a wired device. The user of a wireless communication device thus almost always has the opportunity to move around freely. When either the transmitter, the receiver or the scatterers is in motion, the received signal will be dispersed in frequency as a result of the Doppler effect (figure 18).

"The Doppler effect is the change in the perceived frequency of waves of any kind, which then results when the source (transmitter) and observer (receiver) are relative move each other."

Figure 30: Definition of Doppler effect [26]

The Doppler effect is the temporal compression or expansion of a signal with changes in the distance between transmitter and receiver during the duration of the signal. The cause is the change in the running time. This purely kinematic effect occurs in all signals that propagate at a certain speed, usually the speed of light or the speed of sound.

Generally, the direction of movement and the signal propagation direction can deviate from one another and the Doppler frequency results:

$$f_D = \frac{v\, f_C \cos(\alpha)}{c}$$

f_D	Doppler-frequency
v	Velocity
f_C	Carrier-frequency
α	Angle of Incidence
c	Speed of Light

Figure 31: Doppler-frequency [24]

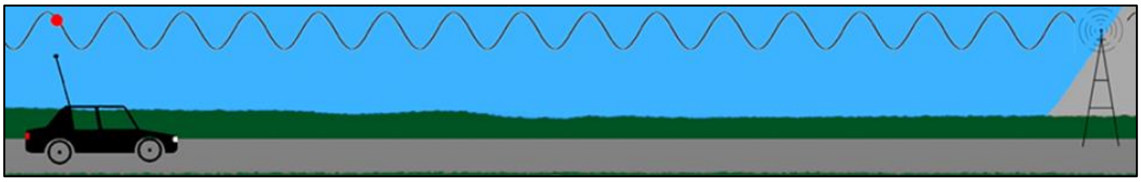


Figure 32: Doppler shift 1[26]

The base station sends a carrier signal $s(t) = \cos(2\pi fct)$. Where f_C is the carrier frequency.

The wave takes some time to reach the car.

- The distance between car and base station is x_0
- c is the speed of light.
- T_0 is the delay of the wave. $T_0 = \frac{x_c}{c}$

Therefore, the car receives a phase shifted signal $r(t) = \hat{r}\cos(2\pi f_c t - \varphi_0)$.

Where φ_0 is the phase shift. $\varphi_0 = 2\pi f_c T_0$.

$$T = \frac{vt}{c}$$

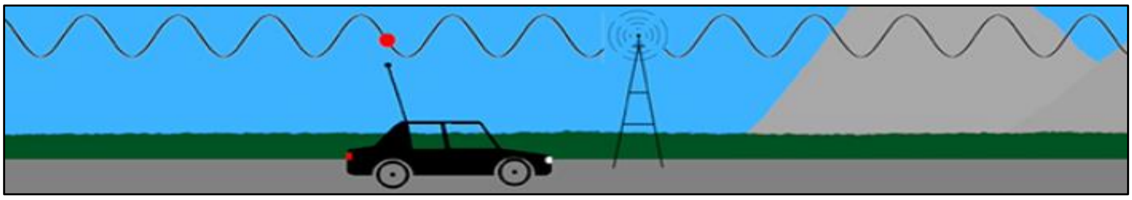


Figure 33: Doppler shift 2 [26]

When the car moves away an additional signal propagation delay occurs.

The received signal yields to:

$$r(t) = r\hat{}cos(2\pi f_c(t - \frac{vt}{c}) - \varphi_0) = r\hat{}cos(2\pi(f_c - \frac{v}{c}f_c)t - \varphi_0)$$

Where the frequency shift - known as Doppler shift is given by:

$$f_D = \frac{v\, f_c}{c}$$

An angle between wave propagation and velocity needs to be considered:

$$f_D = \frac{v\, f_c \cos(\alpha)}{c}$$

Experiment:

Video Doppler shift: Calculate the speed of the car!

All details you need for doing that are given in the video:

- $f_c = 1$ GHz
- $f_D = 40$ Hz
- $c = 3 \times 10^8 \frac{m}{s}$

Figure 34: Doppler shift video [26]

The cars speed yields to:

$$v = \frac{f_D \times c}{f_c} = \frac{40\ Hz\ \times\ 3 \times 10^8 \frac{m}{s}}{1\ GHz} = 12 \frac{m}{s}$$

Direct and reflected path

We look at the moving car and examine the frequency shifts caused by the driving speed.

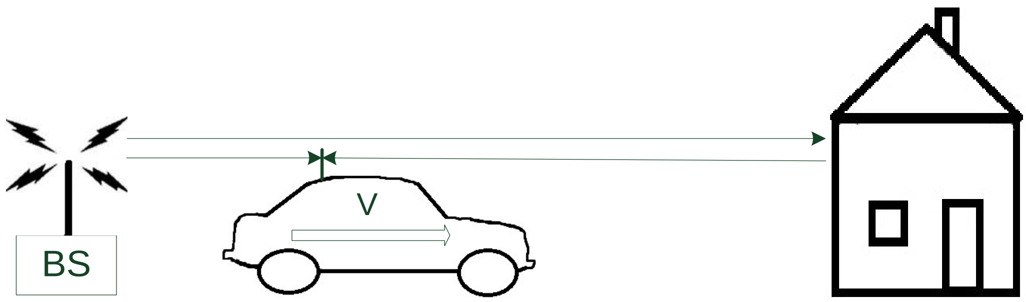


Figure 35: A vehicle receives a direct path of propagation from the rear as well as a path reflected from a house [24]

A carrier frequency is sent and the received spectrum is analyzed.

Table 5: Parameters [24]

Carrier frequency	1000 MHz
Velocity *v*	12 m/s
Driving time A – B and B – C	6,25 ms (75 mm / 12m/s)

- Calculate the occurring Doppler frequencies
- How big are the Doppler spread and the coherence time?
- Sketch the reception spectrum! The reflected path is attenuated by 1 dB.

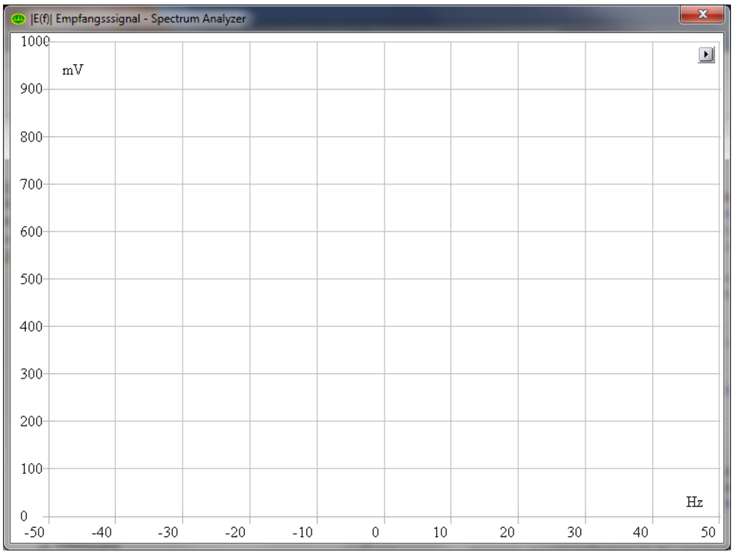


Figure 36: Reception spectrum template

- Start the simulation app [Doppler shift in wireless communications](#).

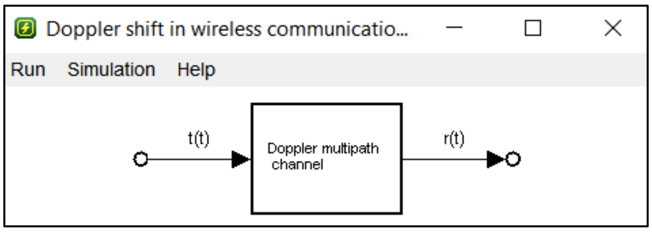


Figure 37: Doppler multipath channel

- Check the settings of the channel modeling the scenario of the moving car.

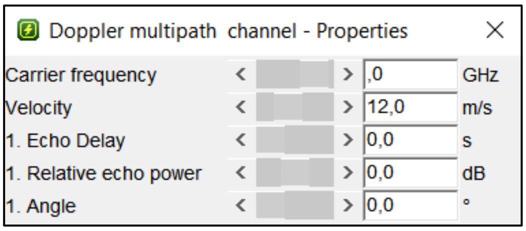


Figure 38: Doppler multipath channel properties

- Check the reception spectrum determined in the preparation (a direct propagation path from the rear and one from the front).

Quiz:

1. *The Doppler effect is the change in the perceived frequency of waves of any kind, which then results when the source (transmitter) and observer (receiver) are relative move to each other.*

☐ True
☐ False

2. On which parameters does the Doppler effect depend on?

☐ v Velocity
☐ f_c Carrier-frequency
☐ α Angle of incidence
☐ c Speed of light

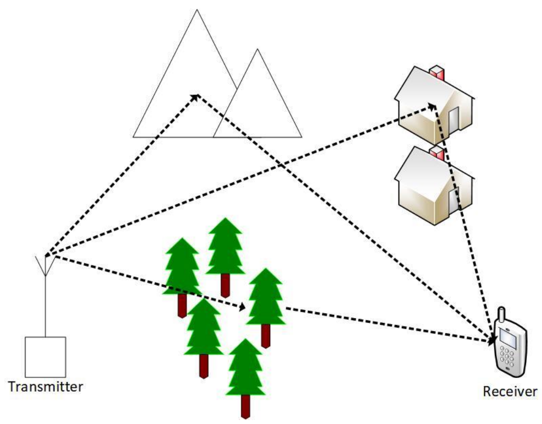
3. *The bandwidth of the received signal is the Doppler spread!*

☐ True
☐ False

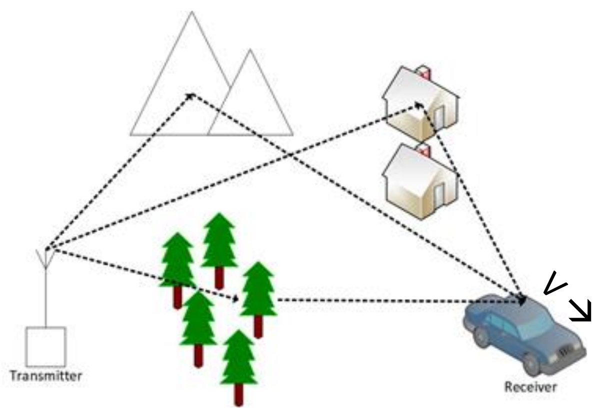
4. *Which effects influence the radio channel?*

☐ Doppler effect
☐ Multipath fading
☐ Shadowing

5. *Which image is more fitting to the Doppler effect?*
☐ a) ☐ b) ☐ Both



a)



b)

3.3 Multi-Carrier Transmission

title	Multi-Carrier Transmission: Fundamentals
descrip-tion	Fundamentals of multi-carrier transmission are covered within this tutorial.
keywords	examples demo images illustration tutorial multi-carrier transmission serial to parallel converter subcarrier Inter-carrier interference inter-symbol interference peak to power ratio multi-carrier modulation system scheme techniques

Fundamentals:

Multi-carrier transmission is one of today's key technologies for communication systems. They use several sinusoidal waves, which are transmitted simultaneously. The basic idea of multicarrier technology is to fragment a frequency-selective channel into narrowband subchannels such that each of these subchannels becomes approximately non-selective. Furthermore, another principle of multi-carrier transmission is to convert a serial high rate data stream on to multiple parallel low rate sub-streams depicted in Figure 39.

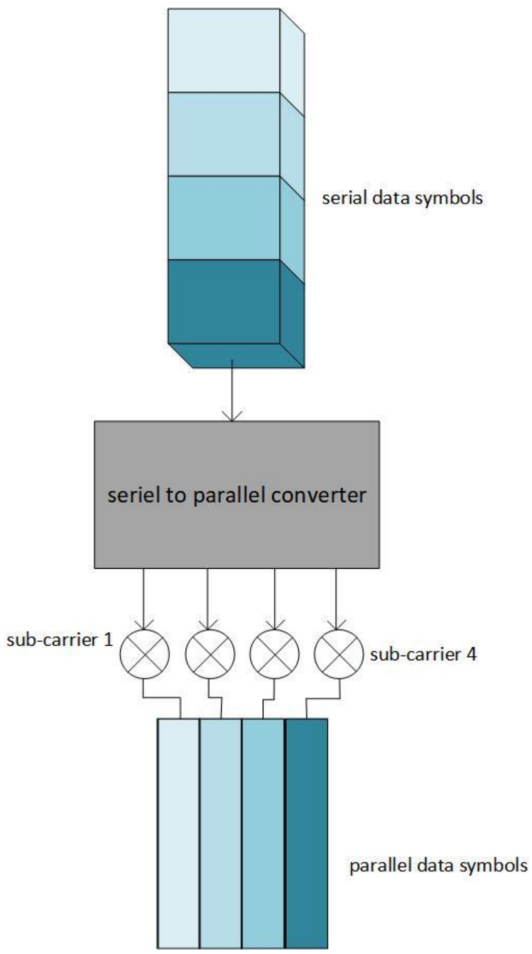


Figure 39: Multi-carrier modulation

Every single sub-stream is modulated on another sub-carrier. The result is that the effects of delay spread. i.e. intersymbol interference (ISI), significantly decrease. The equalization effort can thereby considerably be reduced.

Inter-carrier interference (ICI) and ISI represent a serious issue while using a multicarrier system. This is mainly due to an effort, to save spectral space by placing the subcarriers as close as possible to one another. Since the subcarriers are affected by the Doppler shift and multipath propagation, the subcarriers may overlap. This effect is called ICI. [5]

Intersymbol interference (ISI) arises when a large delay spread occurs. It occurs when for example a symbol is being carried by the LOS path and interfered by a forgoing symbol that is carried by reflected paths. [5]

Peak to power ratio (PAPR) denotes and expresses the ratio of peak power to the average power of a signal. It is expressed in the units of dB. OFDM uses many orthogonal subcarriers and the OFDM signal is formed from a sum of individual subcarriers which are produced by the IFFT operation of a rectangle pulse. This results in a signal which has a shape of a sinc function with one huge peak in the time domain. We will inevitably receive huge PAPR, when these signals of represented subcarriers are summed up.

Peak to Power Ratio (PAPR) can be computed as is written here: [12]

$$PAPR\ (x_\tau, \tau) = \frac{max_{\tau \in \tau} |x_\tau|^2}{E\{|x_\tau|^2\}}$$

τ is the time index used to represent the successive time variable t and also the discreet time index n. The $max_{\tau \in \tau} |x_\tau|^2$ indicates the maximal value of power of the signal x and finally $E\{|x_\tau|^2\}$ denotes the mean value of the signal. This equation is the general expression of PAPR, but Tellado [27] shows an alternative equation used for computing PAPR in the frequency domain. Where N is the number of subcarriers.

$$PAPR\{x^m(t)\} \ \leq N\ \frac{max|x_K|^2}{E\{|x_K|^2\}}$$

All in all, PAPR occurs when within a multicarrier system the different subcarriers are out of phase with each other.

At the beginning of using parallel transmission systems, a couple non-overlapping sub-channels shared the whole frequency band. This was done to eliminate the possible interference ICI among contiguous sub-channels.

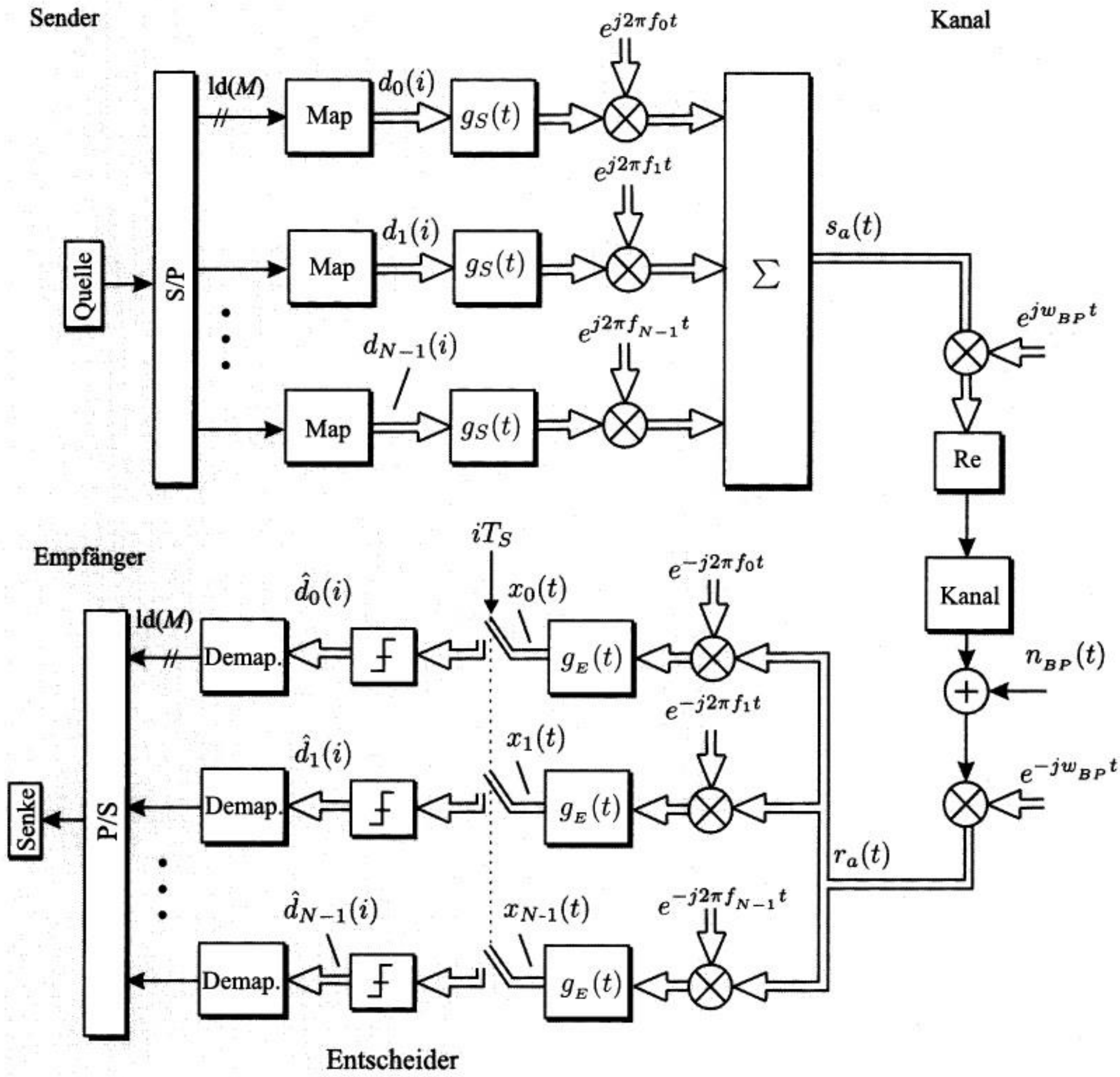


Figure 40: Multicarrier-System [15]

The figure 40 above is showing the equivalent baseband model of a multicarrier transmission system.

At the transmitter, parallel streams are being formed out of the source bits into $ld(M)$ bits each. After the conversion into symbols from an M-level alphabet (mapping), the limitation of the bandwidth through low-passes with their real impulse responses $g_S(t)$ is being executed. Subsequently the parallel data signals are modulated on the subcarriers $f_0,\ldots,f_{N-1}$ and being summed up. The channel is characterized by its initially time-variant scheduled impulse response $h_a(t)$ and described by a white Gaussian distributed noise source. The received signal must be split into the subchannels again. This is done by the analyses filter database at the receivers input, consisting of multiplications with the subcarriers and with the receivers low-passes with their impulse responses. This results in the decided data bits, after the de-mapping and parallel/serial conversion is fulfilled. [15]

Later developments implemented an overlapping of the sub-channels. The result of over-lapping those was a saving up to 50 % of the used spectrum (Figure 41).

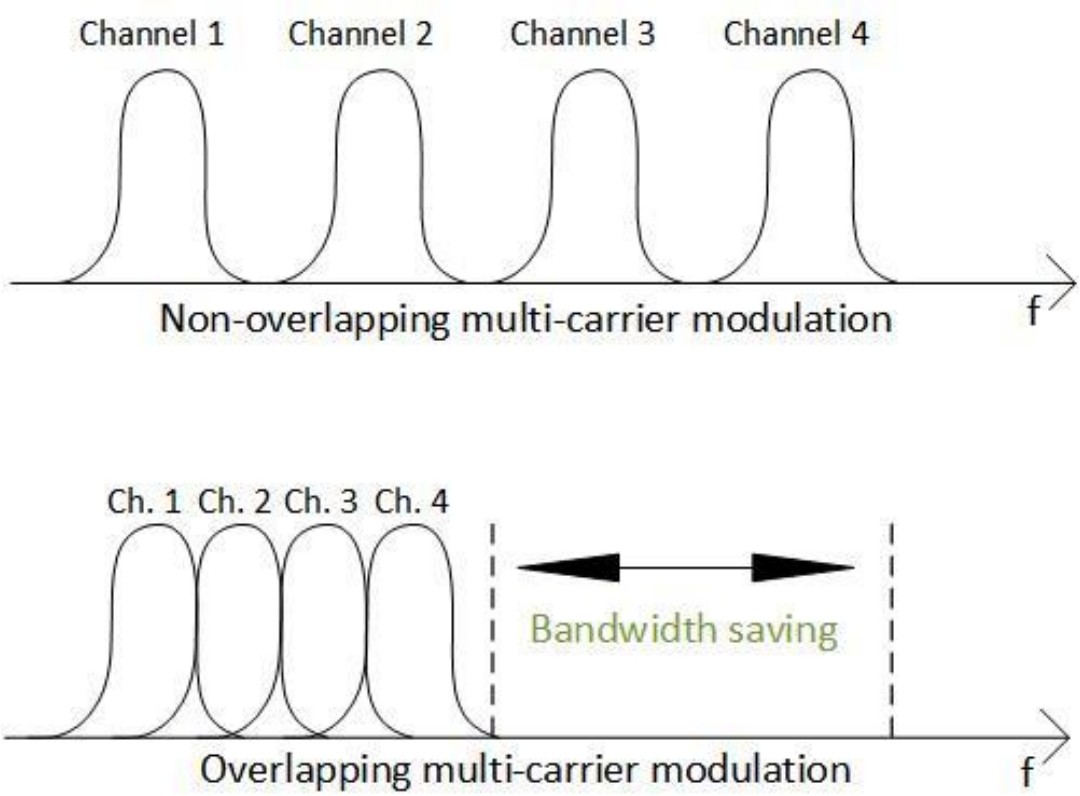


Figure 41: Overlapping and non-overlapping multi-carrier modulation

At the beginning of using parallel transmission systems, a couple non-overlapping sub-channels shared the whole frequency band. This was done to eliminate the possible inter-ference among contiguous sub-channels, also known as inter-carrier interference (ICI).
After further research and demonstration of the many benefits of this technique, OFDM has been developed in 1966. [19]

3.3.1 Orthogonal Frequency Division Multiplexing (OFDM)

title	Orthogonal Frequency Division Multiplexing: OFDM - labAlive Tutorial
descrip-tion	The basics of OFDM are explained and illustrated.
keywords	basics examples explained demo images illustration tutorial demonstration orthogonal frequency division multiplexing ofdm advantages disadvantages drawbacks ofdm system ofdm basic structure frequency- and time occupancy

<u>Tutorial:</u>

OFDM and OFDM-based transmission schemes are dominating current wireless communication standards (WLAN, LTE, DAB and DVB). This is due to the following capabilities and benefits of OFDM:

- Robustness against frequency selective fading with the division of information symbols in parallel narrowband channels
- Efficient use of spectrum due to overlapping transmission of orthogonal parallel narrowband channels
- Low-complexity implementation with the use of Fast Fourier Transforms (FFT)
- Low-complexity channel equalization compared with single-carrier solutions
- Robustness against intersymbol interference (ISI) with the use of cyclic prefix
- Robustness against impulsive noise
- Simple integration of multiple-input multiple-output (MIMO) systems in the OFDM transmitter/receiver chain
- Ability to easily integrate adaptive modulation and coding techniques to efficiently exploit the radio channel
- Provision of direct extension to a multiplexing scheme with orthogonal division multiple access (OFDMA) for resource sharing

Figure 42: OFDM advantages [16]

All in all, compared to single-carrier modulation, OFDM main advantages include high spectral efficiency, robustness against multipath ISI, the simplicity to equalize in frequency domain and the efficiency of applying FFT. Of course, there are also disadvantages like the large Peak to Average Power Ratio, out auf band leakage and the sensitivity to imperfect time and frequency synchronization, but this will be evaluated later in this chapter. [6]

The OFDM method is also used for wired transmission and also known as Discrete Multi-Tone (DMT). [24]

3.3.2 OFDM's Basic Structure

We assume an equivalent baseband transmission with on sample per symbol. Complex data symbols, each representing two bits in Quadrature phase-shift keying (QPSK), are transmitted.

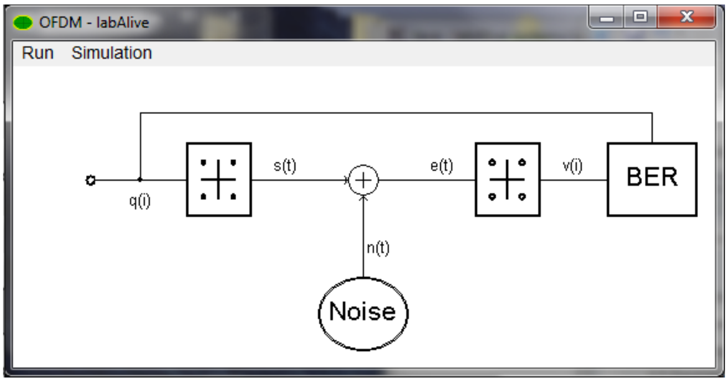


Figure 43: equivalent baseband transmission with one sample per symbol [24]

The complex symbols and data is spread on N_c subcarriers, so the data rate per subcarrier is reduced by N_c. The spreading is done through a serial-to-parallel (S/P) conversion. In addition, the mapping is being performed.

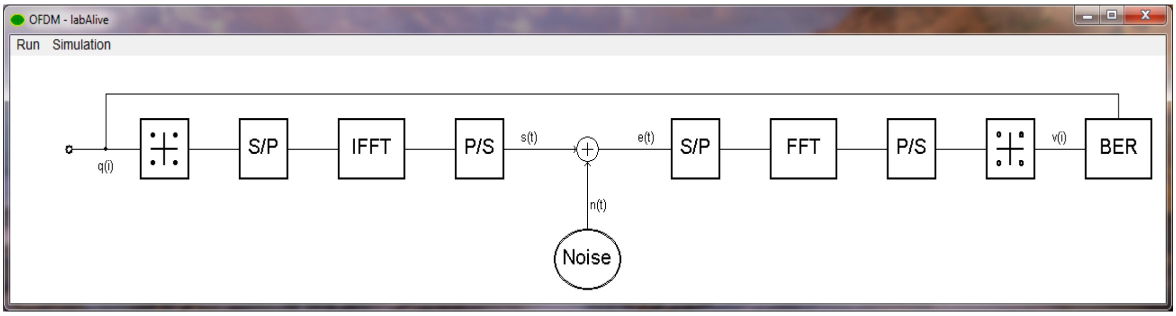


Figure 44:Simplified block diagram of an OFDM System [24]

The parallel arrangement of modulators here is reduced to the Inverse Discrete Fourier Transform, which is characterized and realized by the IFFT. This means, that a block of N symbols is transformed from spectral to time domain. Next, a parallel-to-serial converter is converting a block of symbols and transmitting them sequentially.
At the receiver, the sub-channels are separated by the Discrete Fourier Transform, realized by the FFT. Therefore parallelization, inverse transformation and serialization is done the same way. So, after demodulation, de-mapping and serial conversion you receive the decided bits.

3.3.3 Frequency- and Time Occupancy

Figure 45 shows a single carrier occupying the entire frequency band with its symbol duration T_{SC}. The shown impulse response below is extended over several symbol intervals. This results in strong ISI.

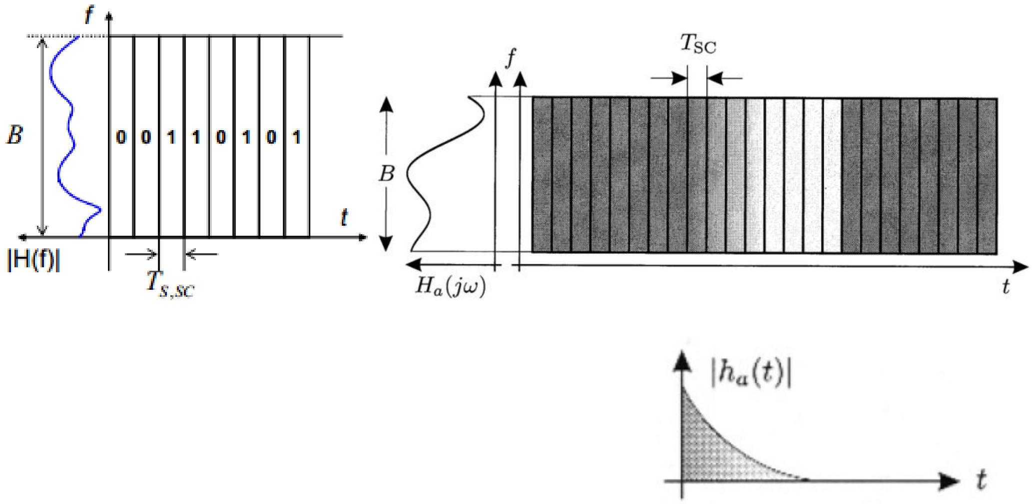


Figure 45: Single Carrier [15][24]

A Multi-Carrier with eight subcarriers is displayed in Figure 46. Due to the parallelization of the data streams, the symbol duration increases eightfold. Since the channel impulse response covers now only a part of the symbol, the ISI is reduced significantly. A corresponding illustration can also be found within the frequency domain. Using a SC, the laterally indicated channel response takes effect on the entire bandwidth and leads to strong distortions on every symbol. Looking at the multicarrier method, there are almost constant gradients and thus non-selective conditions are present.

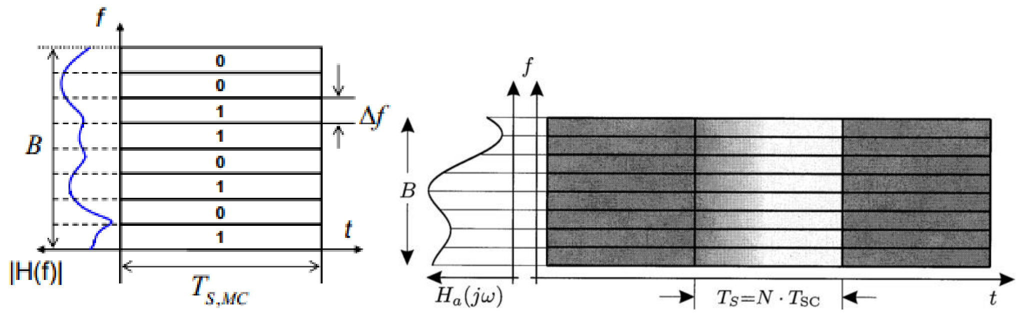


Figure 46: Multi Carrier [15][24]

In OFDM, the symbol duration is N times as large as the corresponding SC symbol duration. This applies only to the simple OFDM structure here without a guard interval and null subcarrier.

$$T_S = N \times T_D$$

T_S / $T_{S,MC}$	Basic OFDM Symbol Duration
T_D / $T_{S,SC}$ / T_{SC}	Source Symbol Duration
N	FFT / DFT length

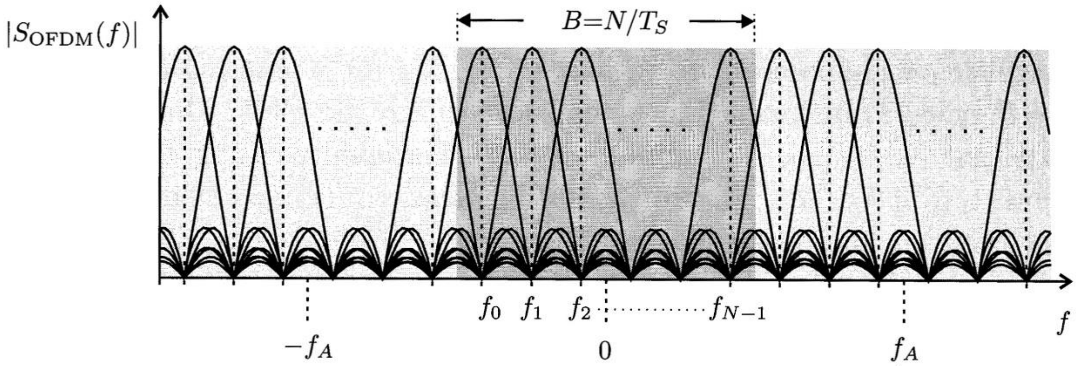


Figure 47: OFDM spectrum [15]

Figure 47 shows the magnitude spectrum of the entire multicarrier signal. The individual spectra of the subcarriers are arranged that, in their maxima, only zero points falls of the adjacent spectra. If the spectrum is sampled exactly at these frequencies, there will be no ICI. Thus, the multicarrier signal meets the first Nyquist condition in the frequency domain.

A multicarrier signal with rectangular pulse shaping, which is by far the most common one for OFDM, satisfies the first Nyquist condition in the time and frequency domain if the subcarrier spacing is equal to 1 / T_S. The name OFDM was derived from the orthogonal characteristic within the frequency domain. [6]

3.3.4 OFDM Drawbacks

Since requirements become more demanding, OFDM disadvantages become a limiting factor towards 5G.

- Due to the use of rectangular pulses in the time domain, OFDM presents powerful sidelobes, that is, high out-of-band emissions. This fact imposes the use of null guard subcarriers at the edges of the transmitted signal spectrum. As a result, spectrum efficiency is reduced and the use of OFDM in fragmented spectrum is not recommended.

- The use of cyclic prefix is beneficial in many aspects; however, it reduces spectral efficiency significantly.

- OFDM requires synchronization accuracy in time and frequency. Despite the fact, that the cyclic prefix can provide protection against timing synchronization errors, high accuracy in frequency alignment is difficult to achieve in a multiuser environment with distributed coordination. Errors in frequency synchronization can be extremely harmful in OFDM, since they lead to ICI

- OFDM exhibits large peak-to-average power ratio (PAPR) and thus is not recommended for use in low-cost user equipment hardware, where poor amplifier performance and low Digital-to-Analog converter resolution may lead to unrecoverable signal distortion.

- Phase noise caused by the imperfections of the transmitter and receiver oscillators influences the system performance.

Figure 48: OFDM disadvantages [16]

4. OFDM – Calculation of Parameters

title	Orthogonal Frequency Division Multiplexing: OFDM – Calculation of Parameters - labAlive Tutorial, Experiment & Quiz
description	Introduction of OFDM parameters and its calculation
keywords	basics examples explained demo images illustration tutorial demonstration orthogonal frequency division multiplexing ofdm system ofdm parameters estimation design

The following chapter introduces the individual OFDM parameters. Furthermore, calculate the OFDM parameters of the wireless LAN IEEE 802.11g.

Tutorial:

4.1 Subcarrier (DFT/FFT length)

The total number of subcarriers- or channels N, consists of the number of data-, pilot- and null subcarriers.

$$N = N_c + N_P + N_V$$

N_c	Data Subcarriers
N_P	Pilot Subcarriers
N_V	Null Subcarriers
N	Total Number of Subcarriers or FFT / DFT Length

The number of subcarriers N always occurs in a power of two and expresses also the length of the DFT / FFT.

4.2 Data Subcarrier

The data subcarriers N_C represent the number of subchannels used for data transmission. In a simple OFDM structure without virtual subcarriers, the number of subchannels is equal to the FFT length N.

4.3 Pilot Subcarrier

OFDM allows the insertion of so-called pilot tones. Pilot tones are generated by modulating individual subcarriers with specified complex symbols in a fixed time sequence. The complex values of the pilot tones are known in advance to the receiver so that an estimate of the channel inflows or a fine synchronization of the symbol clock can be carried out in the receiver. [3]

Pilot subcarriers N_P however cannot be used for channel estimation as they are too far apart for interpolation. These Pilot subcarriers only serve the tracking of the carrier synchronization. [15]

4.4 Null Subcarrier

Null subcarriers N_V are mandated in most OFDM wireless standards. These subcarriers are not occupied but serve to reduce the PAPR of multi-carrier transmission. This is achieved by reordering the null-subcarriers and data-subcarriers. In addition, they are used to prevent leakage to adjacent bands since OFDM Systems usually do not transmit any data on the subcarriers near the two edges of the assigned band. The unused subcarriers are also known as guard subcarriers or virtual subcarriers. Altogether they are called guard band. [4][7]

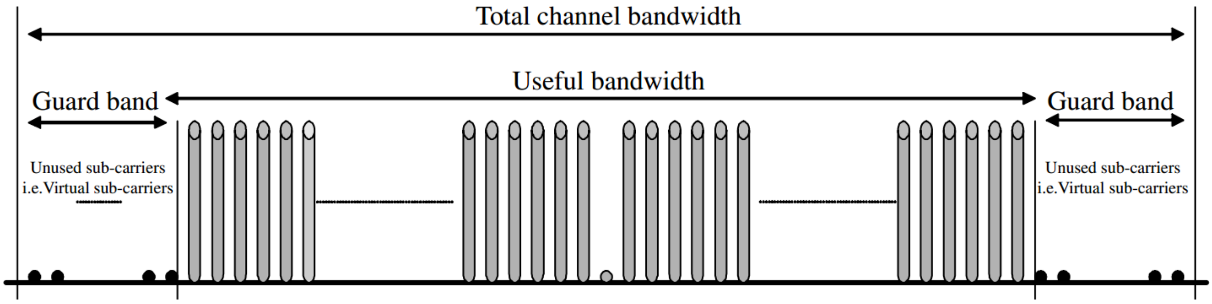


Figure 49: Total Channel Bandwidth and Guard Band [24]

4.5 Discrete Length of the Guard Interval

A guard interval, also known as cyclic prefix, is used to prevent certain transmissions from mixing. They increase the immunity to propagation delays, echoes, and reflections, against which digital data tends to be very vulnerable. The length of the guard interval (GI) determines how susceptible a transmission is. The longer such an interval is, the better it protects against interference, but the data rate is reduced. [28]

To eliminate ISI, a guard interval is usually inserted at the beginning of each OFDM symbol depicted in figure 50. In addition, it corresponds to a copy of the last seconds of the basic OFDM symbol. The main idea behind this method is to dimension the GI so large, that the signal components delayed by the channel, only disturb the signal component during the GI duration and not the basic OFDM symbol. [21]

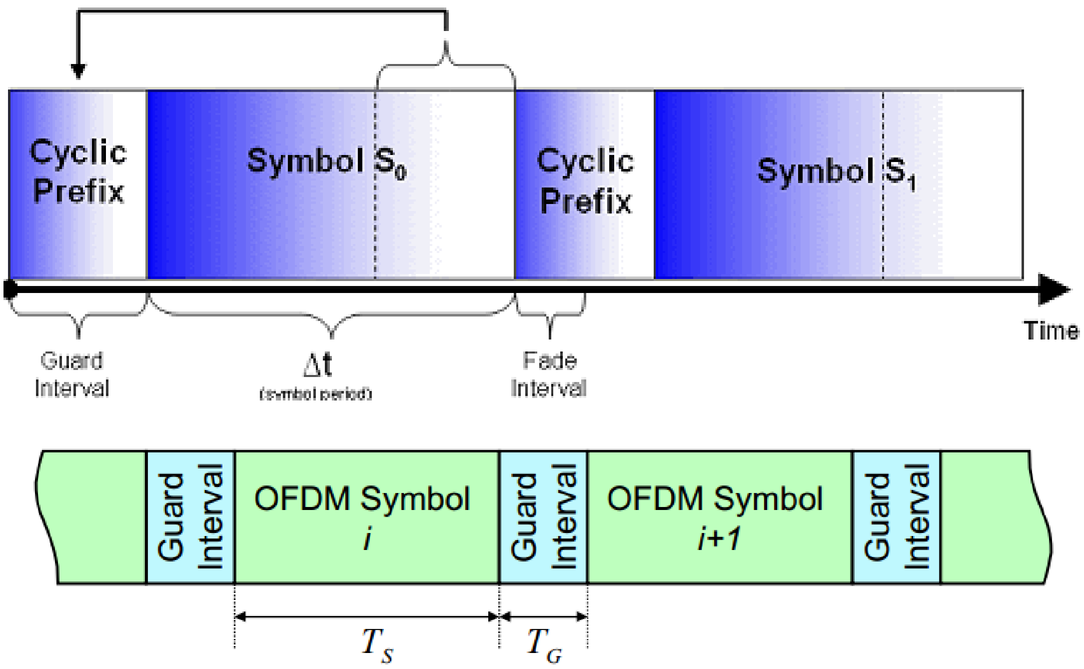


Figure 50: Cyclic Prefix [24][25]

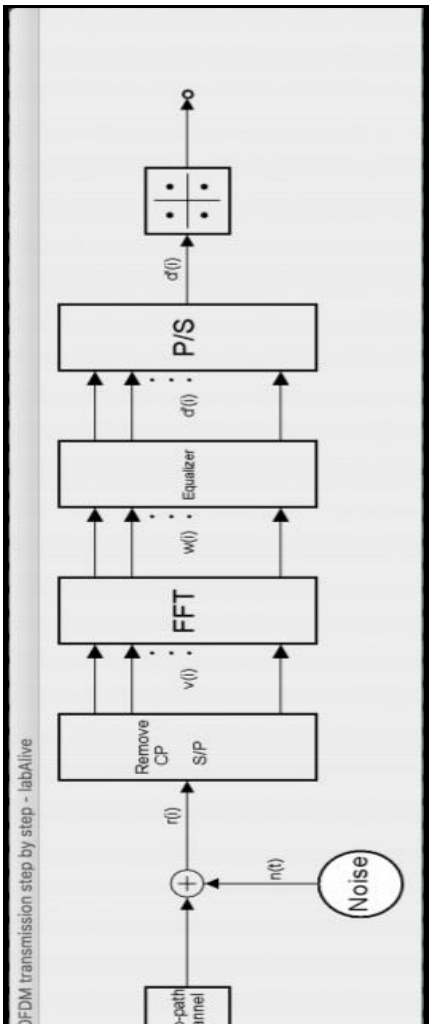


Figure 51: OFDM transmission with Cyclic Prefix [24]

For highly frequency selective channels, the cyclic prefix should increase accordingly. In existing standards like LTE with extended prefix or IEEE 802.11, the cyclic prefix is ¼ of the OFDM symbol duration. [16]

The discrete length of the GI results too:

$$N_G = \frac{T_G \times N}{T_S}$$

N_G	Discrete Length of GI
T_G	GI Duration
T_S	Basic OFDM Symbol Duration
N	Total Number of Subcarriers or FFT / DFT Length

ISI can be removed at the receiver by removing the GI and using only the undisturbed signal portion for the subsequent FFT.

4.6 Guard Interval Duration

The exact duration of the guard interval results in:

$$T_G = N_G \times t_S$$

or

$$T_G = \frac{N_G \times T_S}{N}$$

N_G	Discrete Length of GI
T_G	GI Duration
T_S	Basic OFDM Symbol Duration
t_S	Symbol Duration
N	Total Number of Subcarriers or FFT / DFT Length [24]

4.7 Source Symbol Duration

The source symbol duration T_D is referred to as the duration of the symbols to be transmitted between source, channel coder and interleaver. T_D of the serial data symbols results after serial-to-parallel conversion in the "Total OFDM Symbol Duration".[10]

$$T'_S = N_C \times T_D$$

$$T_D = \frac{T'_S}{N_C}$$

N_C	Data Subcarriers
T_D	Source Symbol Duration
T'_S	Total OFDM Symbol Duration

4.8 Symbol Duration

For the determination of the OFDM time raster, it is very helpful to use the symbol duration of the transmit signal, also called sampling period, before the RF modulator, as a reference. The symbol duration is as follows [24]:

$$t_S = \frac{T'_S}{N + N_G} = \frac{T_S}{N} = \frac{T_G}{N_G} \quad \text{RF-symbol duration}$$

$$t_S = \frac{N_C T_D}{N + N_G} = \frac{T'_S}{N + N_G} \quad \text{Realtime condition}$$

$$t_S = \frac{T_S}{N}$$

$$t_S = T_D \quad \text{without GI}$$

N	Total Number of Subcarriers or FFT / DFT Length
N_C	Data Subcarriers
N_G	Discrete Length of GI
t_S	Symbol Duration
T_D	Source Symbol Duration
T_G	GI Duration
T_S	Basic OFDM Symbol Duration
T'_S	Total OFDM Symbol Duration

4.9 Basic OFDM Symbol Duration

The long OFDM symbol duration in OFDM systems opens a particularly elegant way to avoid ISI. As already mentioned under 4.5, it can be reached by prefixing a GI. However, the "Basic OFDM symbol duration T_S" is without a GI and the number of data subcarriers is equal to the total number of subcarriers.

$$T_S = N \times t_S$$

N	Total Number of Subcarriers or FFT / DFT Length
t_S	Symbol Duration
T_S	Basic OFDM Symbol Duration

4.10 Total OFDM Symbol Duration

The total OFDM symbol duration T'_S is the basic OFDM symbol duration extended by the GI.

$$T'_S = T_S + T_G$$

$$T'_S = (N + N_G) \times t_S$$

N	Total Number of Subcarriers or FFT / DFT Length
N_G	Discrete Length of GI
t_S	Symbol Duration
T_G	GI Duration
T_S	Basic OFDM Symbol Duration
T'_S	Total OFDM Symbol Duration

The parameters of a basic OFDM symbol extended by the GI are depicted in Figure 52.

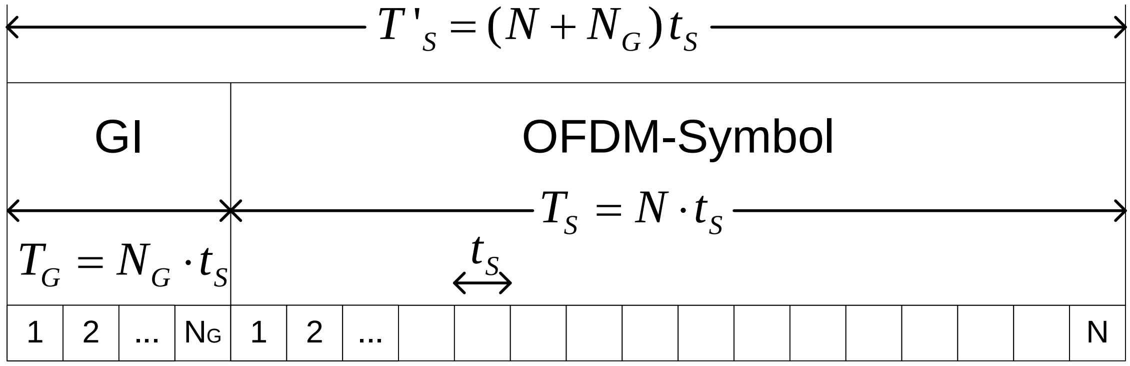


Figure 52: Parameters of a basic OFDM symbol extended by the GI [24]

4.11 Bit Rate

The bit rate $R_{B,brutto}$ of the OFDM system measures the amount of transmissible messages within a time interval. If the message set is being quantified with the unit bit, the term bit rate is used. If the same modulation alphabet is used for all subcarriers and a transmission with a GI is assumed, then the bit rate is calculated as follows:

$$R_{B,brutto} = \sum_{i=1}^{N} \frac{n_i}{T'_S}$$

$$R_{B,brutto} = \frac{N_C \times n}{T'_S}$$

$$R_{B,netto} = R_C \times R_{B,brutto}$$

N_C	Data Subcarriers
n_i	Bit per Symbol
T'_S	Total OFDM Symbol Duration

Assuming a transmission without a guard interval, so by the reduction of T'_S, an increase in the transmission rate is possible. [21]

4.12 Bit per Symbol

In a multi-level transmission, a group of n bits are combined into one character (symbol) and transmitted within a signal step of the duration T_S.

Indeed, there is a correspondance between the number n of bits transmitted per signal step and the required number of steps M of a digital signal. [11]

$$M = 2^n \quad / \quad n = ld(M)$$

M	Number of Different Modulation Symbols
n	Bit per Symbol

4.13 Code Rate

The code rate R_C of an optimal, theoretically possible code of infinite length, also referred to as the channel capacity of the binary symmetric channel, can be calculated as follows [24]:

$$R_C = R_{opt} = C_{bin} = 1 + \text{p} \times log_2 \times p + (1-p) \times log_2 \times (1-p)$$

C_{bin}	Channel Capacity Binary
p	Bit Error Rate
R_C	Code Rate
R_{opt}	Optimal Code Rate

4.14 Symbol Rate

The Symbol rate f_S is also known as baud rate within terms of digital communications. It is the number of symbol changes, waveform changes, or signaling events, across the transmission medium per time unit using a digitally modulated signal or a line code. [30]

$$f_S = \frac{1}{t_S}$$

f_S	Symbol Rate
t_S	Symbol Duration

4.15 Subcarrier Spacing

Subcarriers should only suffer of flat fading. Therefore, subcarrier spacing within OFDM system must be designed carefully.

The spacing F_S is such that the subcarriers are orthogonal, so they won't interfere with one another despite the lack of guard bands between them. This comes about by having the subcarrier spacing equal to the reciprocal of basic OFDM symbol duration, which means, that the spacing is directly related to the basic OFDM symbol duration. [23]

$$F_S = \frac{1}{T_S}$$

F_S	Subcarrier Spacing
T_S	Basic OFDM Symbol Duration

4.16 Bandwidth Efficiency

Bandwidth efficiency β, also known as Spectral Efficiency, is an important piece of communications technology that specifies how many units of information per hertz are transmitted within the available bandwidth. It is thus the ratio of the data transfer rate to the occupied bandwidth, which is given in bit / s / Hz.

The spectral efficiency depends on the used modulation method and the coding. Since the available bandwidths cannot be arbitrarily increased, the frequency economy and the modulation method used are decisive for spectral efficiency.

The spectral efficiency is limited by the signal-to-noise ratio (SNR). The relationship between bandwidth and signal-to-noise ratio is determined by the Shannon-Hartley law. Thereafter, the channel capacitance increases linearly with the bandwidth and is affected logarithmically by the signal-to-noise ratio. With modern modulation techniques, such as OFDM and complex antenna constellations, such as multiple input multiple output (MIMO), the S / N ratio, the bandwidth efficiency can be improved.

The bandwidth efficiency is adversely affected by the GI and reduced proportionately because the channel is occupied during the GI without data being transmitted. On the receiver side, the GI is not used in terms of detection, but the proportion of signal energy is lost. [24][31]

$$\beta = \frac{T_S}{T_S + T_G}$$

$$\beta = \frac{N}{N + N_G}$$

β	Bandwidth Efficiency
N	Total Number of Subcarriers or FFT / DFT Length
N_G	Discrete Length of GI
T_G	GI Duration
T_S	Basic OFDM Symbol Duration

4.17 Nyquist Bandwidth

The Nyquist bandwidth B_N is the bandwidth required for optimal pulse shaping. Although the symbols of the GI do not transmit payload, they proportionately consume transmission bandwidth.

The required Nyquist bandwidth thus results from the number of subcarriers and the respective subcarrier spacing. [24]

$$B_N = (N_C + N_P) \times F_S$$

$$B_N = (N_C + N_P + N_{DC}) \times F_S$$

$$B_N = \frac{1}{\beta \times T_D}$$

β	Bandwidth Efficiency and also S/N Loss
B_N	Nyquist Bandwidth
F_S	Subcarrier Spacing
N_C	Data Subcarriers
N_P	Pilot Subcarriers
T_D	Source Symbol Duration
N_{DC}	Not Occupied DC Subcarriers

4.18 Calculation of WLAN IEEE 802.11g OFDM Parameters

Experiment:

IEEE 802.11g is a standard for a wireless LAN with a maximum transmission rate of 54 Mbps from 2003. IEEE 802.11g is the successor of IEEE 802.11b with an improved modulation method. The standard uses the 2.4 GHz frequency band.

- Determine the missing parameters.

Table 8: IEEE 802.11g parameters [24]

Parameters:	IEEE 802.11g
Subcarrier N	64
Data Subcarrier N_C	52
Pilot Subcarrier N_P	4
Null Subcarrier N_V	
Discrete Length of GI N_G	16
GI Duration T_G	
Source Symbol Duration T_D	
Symbol Duration t_S	
Basic OFDM Symbol Duration T_S	
Total OFDM Symbol Duration T'_S	4 µs
Bit Rate $RB, brutto$	
Bit per Symbol n	6
Code Rate R_C	0,75
Symbol Rate f_S	
Subcarrier Spacing F_S	
Bandwidth Efficiency β	
Nyquist Bandwidth B_N	
Nyquist Bandwidth with DC Subcarrier B_N	

Table 9: IEEE 802.11g parameters calculation

Parameters:	Calculation method:
Subcarrier N	$N = N_c + N_P + N_V$ $N = 52 + 4 + 8 = 64$
Data Subcarrier N_C	$N_c = N - N_P - N_V$ $N_c = 64 - 4 - 8 = 52$
Pilot Subcarrier N_P	$N_P = N - N_C - N_V$ $N_P = 64 - 52 - 8 = 4$
Null Subcarrier N_V	$N_V = N - N_P - N_C$ $N_V = 64 - 4 - 52 = 8$
Discrete Length of GI N_G	$N_G = \frac{T_G \times N}{T_S} = \frac{0{,}8\ \mu s \times 64}{3{,}2\ \mu s} = 16$
GI Duration T_G	$T_G = N_G \times t_S = 16 \times 0{,}05\ \mu s = 0{,}8\ \mu s$ $T_G = \frac{N_G \times T_S}{N} = \frac{16 \times 3{,}2\ \mu s}{64} = 0{,}8\ \mu s$
Source Symbol Duration T_D	$T_D = \frac{T'_S}{N_C} = \frac{4\ \mu s}{52} = 0{,}077\ \mu s$
Symbol Duration t_S	$t_S = \frac{T'_S}{N + N_G} = \frac{4\ \mu s}{80} = 0{,}05\ \mu s$
Basic OFDM Symbol Duration T_S	$T_S = N \times t_S = 64 \times 0{,}05\ \mu s = 3{,}2\ \mu s$
Total OFDM Symbol Duration T'_S	$T'_S = T_S + T_G = 3{,}2\ \mu s + 0{,}8\ \mu s = 4\ \mu s$

Bit Rate $RB, brutto$	$$R_{B,brutto} = \frac{N_C \times n}{T'_S} = \frac{52 \times 6}{4\ \mu s} = 78\ MHz$$
Bit Rate $RB, netto$	$$R_{B,netto} = R_C \times R_{B,brutto}$$ $$= 0{,}75 \times 78\ MHz = 58{,}8\ MHz$$
Bit per Symbol n	$$M = 2^n \quad / \quad n = ld(M)$$ $$64 = 2^6 \quad / \quad 6 = ld(16)$$
Code Rate R_C	$$R_C = 1 + \mathrm{p} \times log_2 \times p + (1-p) \times log_2 \times (1-p)$$
Symbol Rate f_S	$$f_S = \frac{1}{t_S} = \frac{1}{0{,}05\ \mu s} = 20\ MHz$$
Subcarrier Spacing F_S	$$F_S = \frac{1}{T_S} = \frac{1}{3{,}2\ \mu s} = 312{,}5\ KHz$$
Bandwidth Efficiency β	$$\beta = \frac{T_S}{T_S + T_G} = \frac{3{,}2\ \mu s}{3{,}2\ \mu s + 0{,}8\ \mu s} = 4/5$$
Nyquist Bandwidth B_N	$$B_N = (N_C + N_P) \times F_S$$ $$= (52 + 4) \times 312{,}5\ KHz = 17{,}5\ MHz$$
Nyquist Bandwidth B_N with DC Subcarrier	$$B_N = (N_C + N_P + N_{DC}) \times F_S$$ $$= (52 + 4 + 1) \times 312{,}5\ KHz = 17{,}8\ MHz$$

Quiz:

1. *Determine which of the following are OFDM advantages.*

☐ Efficient use of spectrum due to overlapping transmission of orthogonal parallel narrowband channels

☐ Phase noise caused by the imperfections of the transmitter and receiver oscillators influences the system performance.

☐ Robustness against frequency selective fading with the division of information symbols in parallel narrowband channels

2. Which description represents Inter-carrier-interference?

☐ ___ represents a serious issue while using a multicarrier system. This is mainly due to an effort, to save spectral space by placing the subcarriers as close as possible to one another. Since the subcarriers are affected by the Doppler shift and multipath propagation, the subcarriers may overlap.

☐ ___arises when a large delay spread occurs. It occurs when for example a symbol is being carried by the LOS path and interfered by a forgoing symbol that is carried by reflected paths.

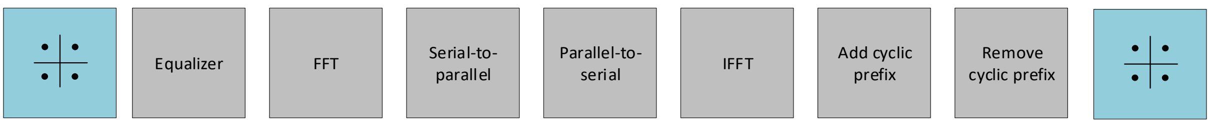
3. *The basic idea of multicarrier technology is to fragment a frequency-selective channel into narrowband sub-channels such that each of these subchannels becomes approximately non-selective.*

☐ True
☐ False

4. *A guard interval, also known as cyclic prefix, is used to prevent certain transmissions from mixing. They increase the immunity to propagation delays, echoes, and reflections, against which digital data tends to be very vulnerable.*

☐ True
☐ False

5. *Put the block into the correct order of the OFDM system arrangement.*
1.___ 2.___ 3.___ 4.___ 5.___ 6.___ 7.___



a) b) c) d) e) f) g)

5. Conclusion and Outlook

This last chapter summarizes essential ideas of the thesis. Further on, a suggestion of further possible improvements of labAlive is given.

5.1 General Conclusion

The goal of the master thesis was to create paradigm examples of online tutorials and experiments, with its aim to provide meaningfully chosen content and focusing on the essentials of each treated topic.

To achieve this, the structure of the online platform lab Alive was changed first in order to ensure a consistent and, above all, learning-friendly presentation of the content. The horizontal arrangement of the structure with the content of a tutorial, experiment and quiz should also ensure maximum learning success. Thus, the beginning of a reorganization of existing topics was started and sub-topics usually assigned to a parent.

This was followed by the research and evaluation of several topics of telecommunications engineering, such as the fundamentals of the radio channels and more profound sub-topics as time-variant multipath propagation. In addition, the functionality of multicarrier transmission and its basics were examined and presented. Furthermore, the basics of OFDM as well as its calculation of parameters were illustrated by an example including a “Quiz”.

Finally, the developed content was transferred and integrated with the cooperation of the Dept. of Electrical and Computer Engineering (ETTI) – Institute 5, onto the pages of labAlive and the aim of this thesis fully achieved.

5.2 Outlook

labAlive will serve the students as a link between the lectures and the practical laboratory courses even more, since there is more content on its pages. Another side-effect might be that more traffic should automatically be generated on the platform, since each site was improved for being crawled and indexed by a website crawler.

Furthermore, the experiments built within the labAlive simulation frame work might constitute a valuable contribution within online learning initiatives, e.g. massive open online courses (MOOC).

Now it is time to put more content of telecommunications engineering topics on labAlive, so that the platform can be used as a powerful source of information and learning for the future.

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Annex

The electronic annex contains:

- Graphics
- Updated Formulary
- Quiz & Answers
- Master Thesis