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Characterization of a 5GHz Modular Radio Frontend for WLAN Based on IEEE 802.11p

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Abstract

The number of vehicles has increased significantly in recent years, which causes high density in traffic and further problems like accidents and road congestions. A solution regarding to this problem is vehicle-to-vehicle communication, where vehicles are able to communicate with their neighboring vehicles even in the absence of a central base station, to provide safer and more efficient roads and to increase passenger safety.

The goal of this thesis is to investigate basic physical layer parameters of a inter-vehicle communication system, like emission power, spectral emission, error vector magnitude, guard interval, ramp-up/down time, and third order intercept point. I also studied the intelligent transportation system's channel layout in Europe, how the interference of other systems are working in co-channel and adjacent channels, and some proposals to use the allocated frequency bands. On the other hand, the fundamentals of OFDM transmission and definitions of OFDM key parameters in IEEE 802.11p are investigated.

The focus of this work is on the measurement of transmitter frontend parameters of a new testbed designed and fabricated in order to be used at inter-vehicle communication based on IEEE 802.11p.

Dedicated to :

My Parents

And to my lovely wife Samaneh

Acknowledgement

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I would Like to particularly grateful to Professor Christoph F. Mecklenbräuker and Professor Arpad L. Scholtz for introducing me to the subject and providing continuous guidance and support, and giving me the opportunity to develop and work at this institute. Thanks are extended to Alexander Paier for his kind assistance with patience.

I am deeply appreciative of my family for their endless love, care and support.

List of Abbreviations

ACP	Adjacent Channel Power
CCH	Control Channel
CDF	Cumulative Distribution Function
CP	Channel Power
DFS	Dynamic Frequency Selection
DSO	Digital Storage Oscilloscope
DUT	Device Under Test
ECC	Electronic Communications Committee
EVM	Error Vector Magnitude
FCC	Federal Communications Commission
FS	Fixed Service
FSS	Fixed Satellite Service
FWA	Fixed Wireless Access
GI	Guard Interval
GPS	Global Positioning System
IFFT	Inverse Fast Fourier Transform
IP3	Third Order Intercept Point
ISI	Inter-Symbol Interference
ISM	Industrial, Scientific and Medical band
ITS	Intelligent Transportation System
IVC	Inter-Vehicle Communication
LCR	Level Crossing Rate
LOS	Line of Sight
NLOS	Non Line of Sight
OBU	On Board Unit
OFDM	Orthogonal Frequency Division Multiplexing
OoB	Out of Band
PDF	Probability Density Function
PHY	Physical layer
PSD	Power Spectral Density
R2V	Roadside-to-Vehicle Communication
RBW	Resolution Bandwidth
RL	Radiolocation
RMS	Root Mean Square
SRD	Short-Range Devices
RSU	Road Side Unit
RTTT	Road Transport and Traffic Telematics

SCH	Service Channels
TDMA	Time Division Multiple Access
V2I	Vehicle-to-Infrastructure Communication
V2V	Vehicle-to-Vehicle Communication
VSA	Vector Signal Analyzer
VSG	Vector Signal Generator
WAVE	Wireless Access in Vehicular Environments
WLAN	Wireless Local Area Network

Contents

Chapter 1

Background

Road accidents take the life of many people in the world each year, and much more people have been injuring and maiming. Statistical studies show that accidents could be shunned by 60 % if drivers be informed only half a second before the accident, [1]. The main reason of these accidents is a limitation in view of roadway emergency events that can be due to the distances, darkness, and existence of an inhibiter in the road (a vehicle, building, rock, etc). Also a delay of the vehicle's driver to react against the events on the roadway could make irreparable results, [2].

Communication between vehicles, Vehicle-to-Vehicle (V2V), and between a vehicle and an immobile access point, Vehicle-to-Infrastructure (V2I), have the potential to contribute considerably to the elimination of traffic accidents. V2V and V2I communications (called V2X) could be profitable in traffic congestion decreasing. The concept of this communication is to send safety messages by a vehicle to many other vehicles via wireless connection. In this technology, vehicles can communicate and collaborate with each other, exchanging both safety and non-safety information. Therefore commercial benefits can be mentioned in this communication too.

A very promising specification for vehicular communications is the draft standard IEEE 802.11p, [3], also known as Wireless Access in Vehicular Environments (WAVE). This specification is an advancement of the well-known Wireless Local Area Network (WLAN) standard IEEE 802.11, [4], which operates in the 5.9 GHz frequency band and is conceived for data communication in traffic scenarios with speeds up to 72 m/s.

In the IEEE 802.11p standard, communication signals are generated with the Orthogonal Frequency Division Multiplexing (OFDM) technique principle. This work describes fundamentals of OFDM transmission as well as front-end characterization such as emission power, spectral emission, Error Vector Magnitude (EVM), Guard Intervals (GI), ramp up/down time and 3rd order Intercept Point (IP3) in chapter 2. All these subjects are under investigation to use in V2X communications.

In this thesis I investigate a transceiver, which has implemented the draft standard IEEE 802.11p. OFDM parameters and Physical layer (PHY) signals of the transceiver must meet the specifications defined in the standard. This device named "RouterBOARD 532A" is developed by Siemens AG Austria and has two antennas for transmitting and receiving the signals.

Finally the measurements on the transceiver, for the desired parameters will be explained in chapter 4. Measuring the Front-end characterization of transmitter like emission part, specrum mask, error vector magnitude, and ramp-up/down time are categorized in the practical part of the thesis. All these specifications will be compared with the IEEE 802.11p standard.

Chapter 2

Introduction

In this chapter, fundamentals of an OFDM transmission are introduced and some important parts creating an OFDM signal, such as Inverse Fast Fourier Transform (IFFT), cyclic prefix and the effect of subcarrier amount on the spectrum of an OFDM signal, are explained in detail. Afterward the fundamental parameters of frontend characterization are discussed. In section 2.3 the importance of dynamics of vehicular wireless channels are clarified and explained in detail.

2.1 Fundamentals of OFDM Transmission

The draft standard IEEE 802.11p is based on OFDM transmission technology. Therefore a higher spectral efficiency, lower sensitivity in synchronization errors and less Inter-Symbol Interference (ISI) could be expected, compared to the other techniques like Time Division Multiple Access (TDMA). In an OFDM signal, a higher data bit rate channel is divided into multiple orthogonal sub-channels in the frequency domain with lower bit rates. By this multiplexing technique, there exist several narrow-band subcarriers instead of a wide band carrier. This conversion is shown clearly in Figure 2.1. In the first part of the figure, three symbols A, B, and C are included in a signal with a specific frequency and separated in time. In the second part of the Figure 2.1 these symbols are extended in time, but separated in carrier's frequency, so the probability of wasting a symbol due to multipath propagation of the signal is reduced, because in the new situation, the symbols have less overlap on the adjacent symbols. A more complete description of an OFDM signal can be seen in Figure 2.2. As Figure 2.2 shows, an OFDM signal is divided in both time and frequency domain and so increases the capacity of the system in addition to the less interference of the adjacent symbols. The guard interval between the symbols in time domain is shown also in the Figure 2.2. More detail explanation about guard interval in OFDM signal is explained in Section 2.1.2.

2.1.1 IFFT

To create the OFDM symbol in practice, a serial to parallel chip is used in order to convert a signal with N serial symbols to a signal with N parallel symbols.

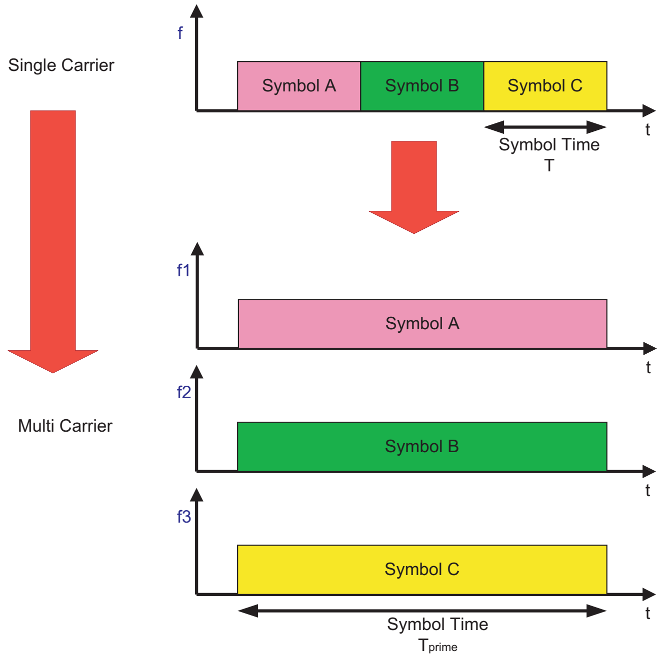

Figure 2.1: Single carrier comparison with multi carrier.

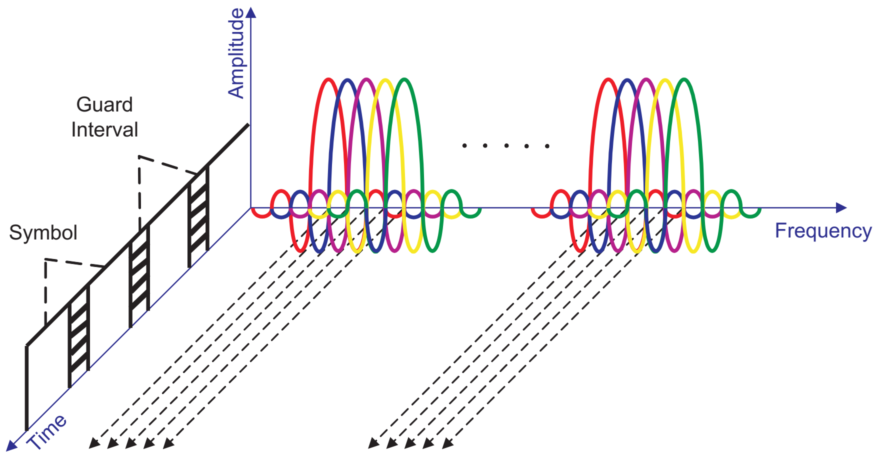

Figure 2.2: OFDM time/frequency representation.

Each parallel data symbol (orthogonal sub-carrier) is modulated and then the modulated subcarriers are added together. because of practical reasons, this procedure is implemented by an IFFT block. Figure 2.3 shows a simple block diagram of an IFFT system.

2.1.2 Cyclic Prefix Insertion

Wireless communications systems are predisposed to multi-path propagation on the radio channel. Adding a cyclic prefix to the signal reduces the ISI. The

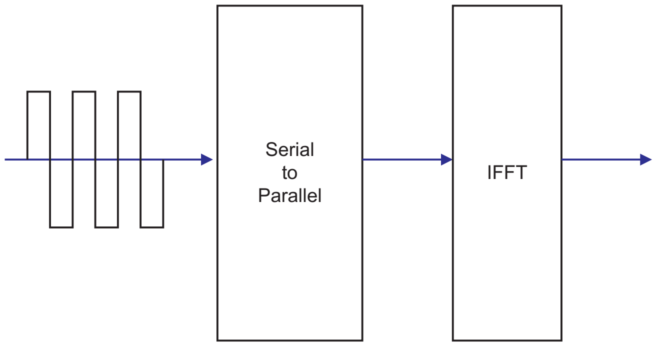

Figure 2.3: IFFT.

cyclic prefix is repetition of the last part of a symbol at the beginning of the same symbol that is illustrated in Figure 2.4. Multi-path propagation causes the original signal to fade, so a guard interval in the symbol will improve the transmission. The cyclic prefix technique is being used as a guard interval in the OFDM signals. In the presence of a cyclic prefix, interference signals do not interfere with the main part of the symbol, [5].

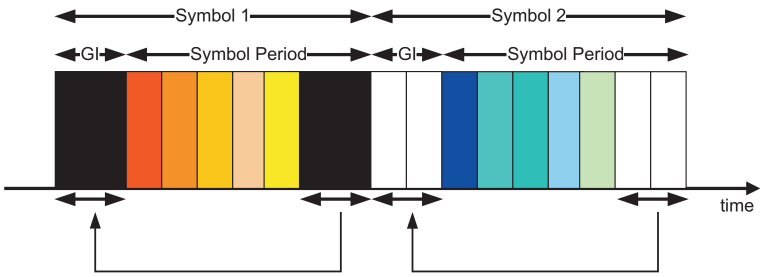

Figure 2.4: Cyclic Prefix Insertion.

2.1.3 OFDM Spectrum

A number of sub-carriers, k, of an OFDM signal with the same bandwidth is affecting the power level of the side-lobes in the power density spectrum. A faster side-lobe decay is due to a larger amount of the K. Spectrum mask of IEEE 802.11p is described in detail in Section 2.2.1. The spectrum mask in IEEE 802.11p is divided into 64 sub-carriers.

2.2 Fundamentals of Frontend Characterization

2.2.1 Emission Power and Spectral Emission

The transmit spectrum mask specifies the power limitation in a specific frequency bandwidth and a certain offsets relative to the maximum carrier power, therefore

Table 2.1: Emission power limitation for each class [3]

Power class	Max. output power (dBm)
Class A	0
Class B	10
Class C	20
Class D	28.8

the unit is in dBr which stands for dB relative. Spectrum masks ensures that multiple WLAN devices do not interfere with each other and adjacent channels also have no interference with each other. The spectrum mask test can be a good indicator of fading presentation in a channel. By transmit power spectrum mask measurements, the in-band (working channel) and out-of-band (adjacent and non-adjacent channels) spurious signals could be specified and measured.

For WLAN, the peak Power Spectral Density (PSD) is used as the reference power in the signal. All offset results are measured according to the peak PSD. In the IEEE 802.11p standard the bandwidth of a channel is 10 MHz and the spectrum mask is defined up to 15 MHz offset from center frequency of each channel.

Transceivers according to the IEEE 802.11p standard, transmit signals in different classes (A, B, C, D). A maximum power defined for each class of transceiver and 800 mW (28.8 dBm) is the highest transmit power in class D, [3]. More details about limitations of each class are discussed in section 4.3. In class A, the transmitter has the lowest transmit power, up to 1 mW (0 dBm). For operation in the $5.850 - 5.925$ GHz band, according to the IEEE 802.11p standard, the emission power and transmitted spectrum should correspond to Table 2.1 and Table 2.2.

The spectrum masks for all classes are defined for a 10 MHz channel bandwidth. The exact values can be seen in Table 2.2, but in general the higher transmit power the faster spectrum edge decay. So design and fabrication of transceivers in higher values of transmit power could be more difficult because of the nonlinearity of components in transceivers.

In class A through class D the ramp of the main edge in the defined spectrum mask (between 4.5 and 5.5 MHz offset) increases, because of the higher maximum output power in class D. The relative power level of the unwanted signals at an offset of ± 15 MHz from the centre frequency reduces from -40 dBr in class A to -65 dBr in class D. Table 2.2 specifies the spectral mask for class A to class D operations.

2.2.2 Error Vector Magnitude (EVM)

The EVM is a parameter used to specify the quality of a transceiver. A signal received by a receiver or sent by a transmitter shall have all constellation points

Table 2.2: Spectrum mask of different classes [3]

Different classes	±4.5 MHz offset	±5 MHz offset (dBr)	±5.5 MHz offset (dBr)	±10 MHz offset (dBr)	±15 MHz offset (dBr)
Class A	0	−10	−20	−28	−40
Class B	0	−16	−20	−28	−40
Class C	0	−26	−32	−40	−50
Class D	0	−35	−45	−55	−65

in the I-Q plane like the main signal. Various problems in the implementation of a device (such as carrier leakage, low image rejection ratio, phase noise, etc.) cause deviations of the actual constellation points. Therefore the average distance between ideal constellation points and received points by receiver is called EVM. Figure 2.5 shows the definition of EVM. This parameter could be expressed in dB or percent (%) and is related to the ratio of the power of the error vector to the Root Mean Square (RMS) power of ideal signal.

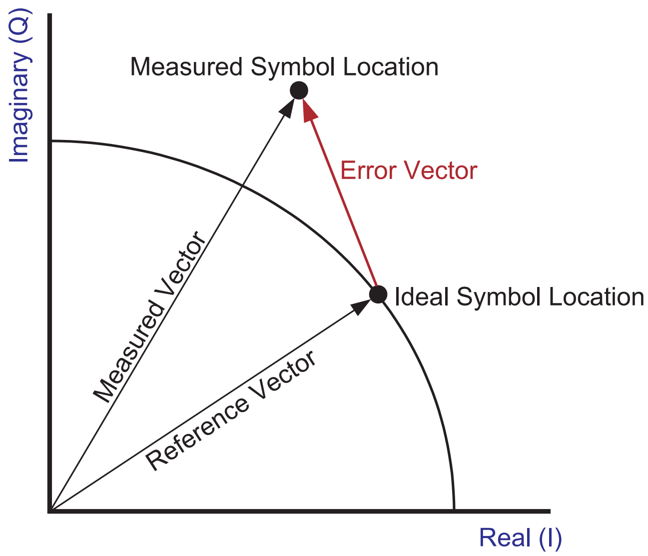

Figure 2.5: Constellation error [4].

Possible data rates in IEEE 802.11p and related constellation errors are illustrated in Table 2.3. Also the related modulation type for each data rate is shown in this table (the data rate changes according to modulation type and code rate). In order to measure the EVM of a signal, the data rate and modulation type has to be specified.

2.2.3 Guard Interval

The guard interval is the separation between two neighbor symbols of telecommunication signals, in order to prevent the transmission symbols interfere with

Table 2.3: Allowed EVM versus data rate and modulation type in IEEE 802.11p

Modulation type	Code rate	Data rate (Mb/s)	Relative constellation error(dB)
BPSK	1/2	3	−5
BPSK	3/4	4.5	−8
QPSK	1/2	6	−10
QPSK	3/4	9	−13
16 QAM	1/2	12	−16
16 QAM	3/4	18	−19
64 QAM	2/3	24	−22
64 QAM	3/4	27	−25

each other. Therefore signals have more immunity against delay in propagation, when using guard interval. Different delays in multipath propagation are coming from different reflections, diffraction, and transmission of the individual paths. In OFDM, a cyclic prefix technique is implemented as guard interval. At the beginning of each symbol, a copy of the last part of the symbol is included, which is called cyclic prefix or guard interval. This is explained in Section 2.1.2. In Figure 2.6 a symbol of an OFDM signal is shown with the definition of the guard interval.

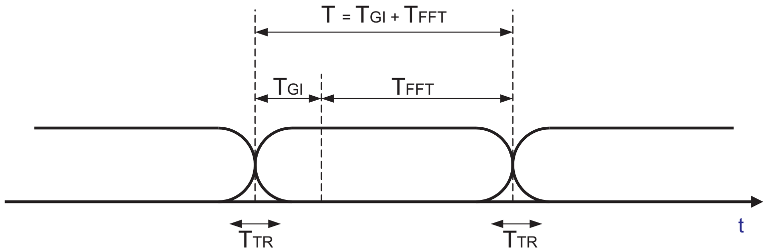

Figure 2.6: Guard interval in an OFDM signal.

The guard interval duration and symbol duration in the IEEE 802.11p standard are defined as following:

$T_{SYM} = T_{GI} + T_{FFT} = 8\mu s$

$T_{GI} = 1.6\mu s$

T_{sym}, T_{GI}, and T_{FFT} is defined in Figure 2.6.

2.2.4 Ramp-up and Ramp-down Time

The ramp-up time is the necessary time for a signal amplitude to rise from 10 % to 90 % of the maximum level of the signal power, and vice versa for the ramp-down time. This factor shows the system delay in order to reach a stable level. It is important to be sure that this delay is not larger than the delay of sending data since the device starts sending data. More details are discussed in Section 4.7. Figure 2.7 shows the definition of ramp-up and ramp-down time.

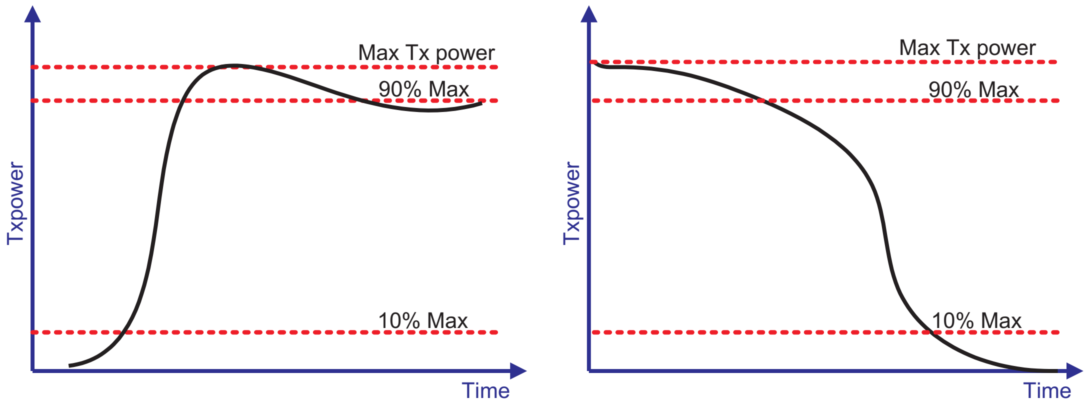

Figure 2.7: Transmit power on/down ramp.

2.2.5 Third Order Intercept Point (IP3)

The Third Order Intercept Point (IP3) is a factor to measure the nonlinearity of systems and devices. The intercept point is a mathematical concept, and does not correspond to a practically occurring physical power level. The n_{th} order intermodulation products appear at n times the frequency spacing of the input tones. Figure 2.8 shows the intermodulation products of a two tone signal. Third order intermodulation products are more important than other intermodulation products due to the high relative power level and less distance to main tones.

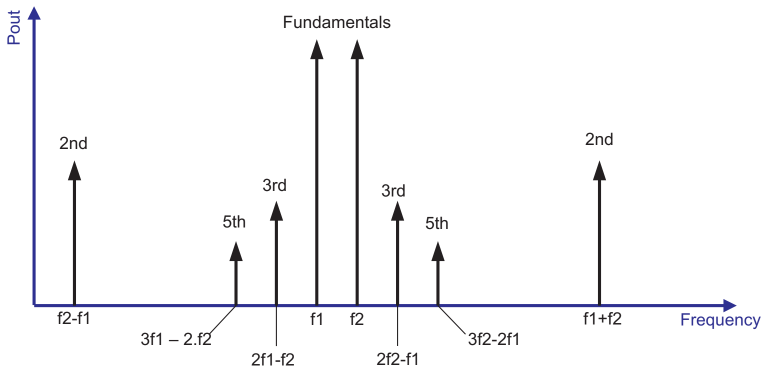

Figure 2.8: Intermodulation products.

The output power versus the input power, both in logarithmic scale, are shown in Figure 2.9. One curve belongs to the fundamental response of an input signal and is linearly amplified, and the other curve shows the third order intermodulation product's response, which is nonlinearly amplified (with slope 3).

The nonlinearity of amplifiers, implemented in transceivers, leads to a 3 dB increase in third order products when the input power is increased only by 1 dB. Therefore a limitation for amplifier's input power is required in order to prevent disappearing of the main signal. The third order intercept point is defined at

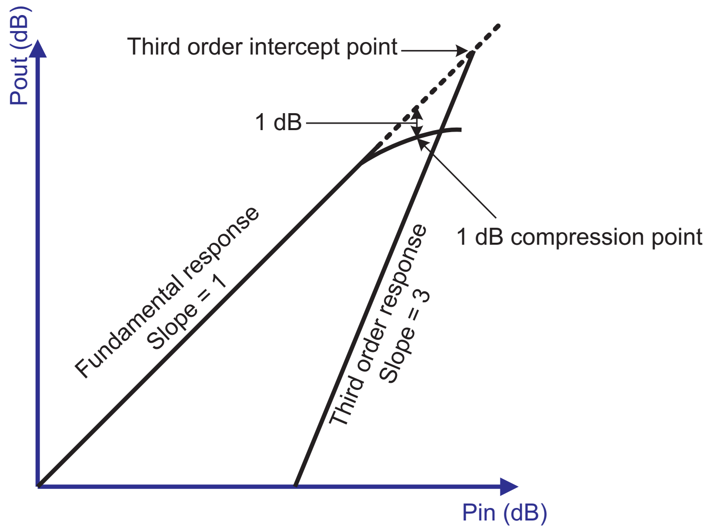

Figure 2.9: Third order definition.

the intersection of the linear fundamental response curve with the third order response curve. The third order intercept point is higher than the 1 dB gain compression point, which is defined at the input power, where the saturated fundamental curve is 1 dB below the linear fundamental curve. Both , the third order interception point and the 1 dB compression point are shown in Figure 2.9

2.3 Dynamics of the Vehicular Wireless Channel

Fading can be defined generally as the distortion of a modulated telecommunication signal occurred during the signal propagation in the channel. In WLAN communication, fading is caused by multipath propagation. Finding the rate of fading's changes can help us to program the amplifiers in transmitter and receiver in order to have a clearer signal in receiver. Level Crossing Rate (LCR) is a factor to measure the rapidity of the fading. LCR shows how often the fading crosses a certain threshold in positive direction, [6]. Figure 2.10 shows the concept of LCR.

The dynamic of a wireless channel can be separated in pathloss and fading that is described in the next sections.

2.3.1 Path Loss

Path loss is the attenuation in power of an electromagnetic wave between a transmitter and a receiver. Path loss depends on many factors like free space loss, refraction, diffraction, reflection, absorption, ground forms, environment, and

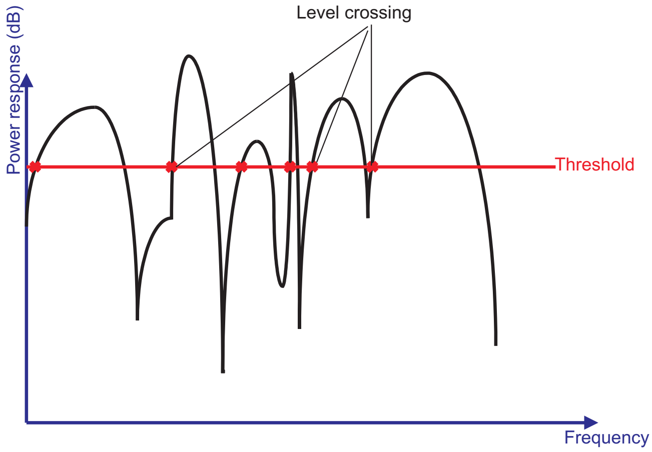

Figure 2.10: Level Crossing Rate (LCR).

propagation medium. In V2V communication, a Line of Sight (LOS) path exists if no blockage is between the transmitter vehicle and receiver vehicle. According to the existence of LOS, different characteristic are defined for path loss. The path loss can be investigated in different scenarios like highway, urban and rural roads, where some factors are different in each scenario, like speed and traffic congestion.

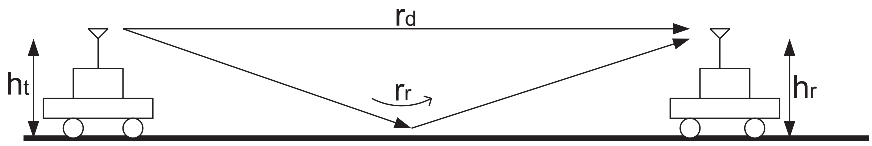

Figure 2.11: Two ray path loss model.

For the LOS case one approach is the two ray path loss model for determining the received signal power level, described in [7].

$$P_r = \frac{P_t G_t G_r}{L(r_d)} \left[D_d \left(\frac{\lambda}{4\pi r_d} \right) + D_r \left(\frac{\lambda}{4\pi r_r} \right) \eta e^{-j\{k(r_d - r_r) + \phi\}} \right]^2 \quad (2.1)$$

P_t is the Txpower, G_t and G_r are the gains of the antennas at transmitter and receiver, alternatively, λ is the propagating signal's wavelength, r_d and r_r are the path lengths of the direct and reflected signals, see Figure 2.11. ϕ is the phase rotation due to ground reflection, η is the reflection coefficient, D_d and D_r are the antenna directivity's coefficients, $L(r_\mathrm{d})$ is the the factor regarding to the absorption.

Two scenario can be defined in path loss study, LOS propagation and Non Line of Side (NLOS) propagation. The NLOS case happens when obstacle appear in between the transmitter antenna and receiver antenna. This scenario happens when there is heavy traffic or the communication distance is large. In this case a LOS path may exist only among the adjacent vehicles. One possibility to model the path loss in NLOS scenario is the log-distance model with an exponent between $2.8 - 5.9\,\text{GHz}$, [7].

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi}\right)^2 \qquad d \leq 1m \tag{2.2}$$

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi}\right)^2 \frac{1}{d^\gamma} \qquad d > 1m \tag{2.3}$$

Where d is the distance between the transmitter and the receiver, and γ takes value from 2.8 to 5.9, [7].

2.3.2 Fading

The variation of the amplitude and/or relative phase in a received signal can be defined as fading. Therefore fading can be described as the variation of the characteristics of the propagation path over time or location. Small scale fading describes the oscillation of the received signal strength over very short time duration or a short distance. Rician and Rayleigh fading are often used for small scale fading. Large scale fading is caused by shadowing. The mobile station has to move over a large distance to remove the effects of shadowing. For shadowing the log normal distribution is often used, [8].

Rician Fading

Rician fading is a stochastic model used for radio propagation. When a signal received by receiver from different paths, a part of signal could be canceled by itself due to different path distances. In the case that one of the signals received by receiver be much stronger and be dominant, Rician fading can be considerable. In Rician fading the amplitude of the field strength of the received signal can be described by a Rician distribution.

$$P(r) = \frac{r}{\sigma^2} e^{-\frac{r^2+A^2}{2\sigma^2}} I_0\left(\frac{Ar}{\sigma^2}\right) \qquad \text{for}(A \geq 0, r \geq 0) \tag{2.4}$$

The A is the amplitude of the dominant component and I_0 is the modified Bessel function of the first kind and zero-order. The σ^2 is the time-average power of the received signal. A very important parameter is the Rice-factor, or K-factor which is defined by the ration between the power of the LOS component and the diffuse component.

$$K(dB) = 10\log\frac{A^2}{2\sigma^2} \tag{2.5}$$

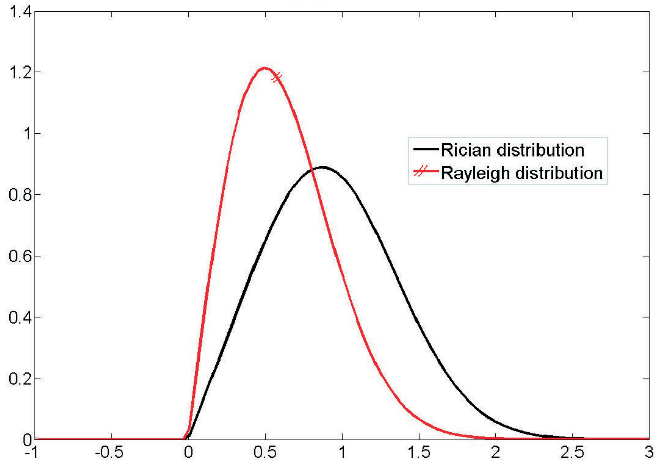

Figure 2.12: Rician and Rayleigh Probability Density Function (pdf).

For $K >> 1$ the Rician distribution can be approximated by a Gaussian distribution. One example of a Rician distribution is shown in Figure 2.12.

Rayleigh Fading

Rayleigh fading is a kind of Rician fading when $K \rightarrow 0$ which means that there exists no dominant path. Rayleigh fading happens if a signal goes through a channel and the amplitude of the field strength of the signal varies or fades according to the Rayleigh distribution model. The Rayleigh distribution is defined as

$$p(r) = \begin{cases} \frac{r}{\sigma^2} exp\left(-\frac{r^2}{2\sigma^2}\right) & (0 \leq r \leq \infty) \\ 0 & (r < 0) \end{cases} \tag{2.6}$$

where σ^2 is the time-average power of the received signal.

The Cumulative Distribution Function (CDF) is defined in order to specify the probability that the received signal does not exceed a specific level R.

Log-Normal Fading

In log-normal fading, the amplitude gain is characterized by a log-normal distribution with probability density function

$$f(x; \mu, \sigma) = \frac{e^{-(\ln x - \mu)^2/2\sigma^2}}{x\sigma\sqrt{2\pi}} \tag{2.7}$$

For $x > 0$, where μ and σ are the mean and standard deviation of the variable's logarithm.

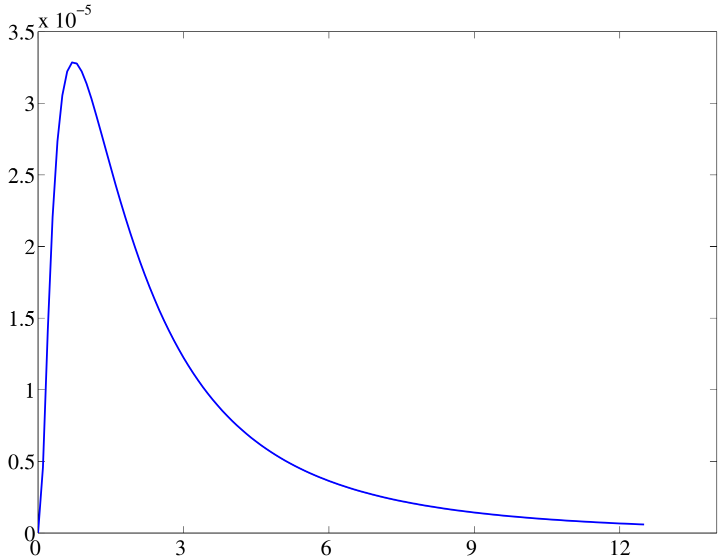

Figure 2.13: Log-normal distribution.

Chapter 3

Wireless LAN According to IEEE 802.11p

3.1 Definition of Key OFDM Parameters

The OFDM technique divides a signal with high data rate into several parallel signals with lower data rates which are transmitted over orthogonal frequency subcarriers.

The PHY of the standard IEEE 802.11a is using the OFDM technique with 64 subcarriers, [9], (the IEEE 802.11p standard is based on IEEE 802.11a). 52 subcarriers out of 64 are used for actual transmission, where 48 are data subcarriers and 4 are pilot subcarriers. The pilot subcarriers are used for tracing the frequency offset and phase noise. The PHY data packet structure is illustrated in Figure 3.1. This structure is the same for IEEE 802.11a and IEEE 802.11p. The short training symbols, which are located at the beginning of every PHY data packet, are used for signal detection, coarse frequency offset estimation and time synchronization. The long training symbols, which are located after the short training symbols, are used for channel estimation and synchronization reasons. A guard interval time GI, i.e. cyclic prefix, is located in the OFDM data packet, in order to remove the ISI caused by the multipath propagation. GI decreases the system capacity and so the received effective signal to interference and noise ratio.

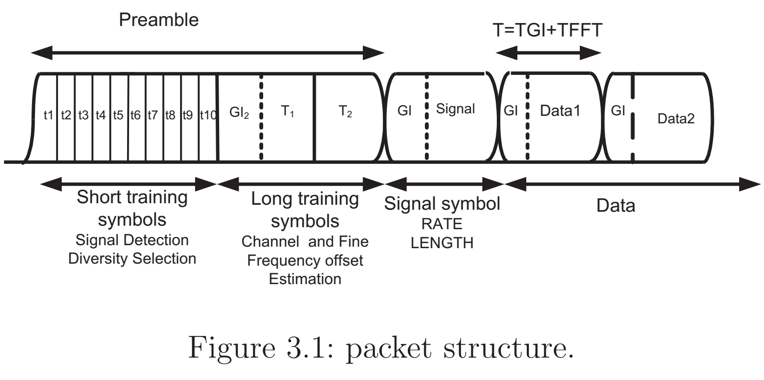

Figure 3.1: packet structure.

Table 3.1: Key parameters of IEEE 802.11p PHY and IEEE 802.11a PHY (source [7])

Different parameters	IEEE 802.11a	IEEE 802.11p	Changes
Bitrate Mb/s	6, 9, 12, 18, 24, 36, 48, 54	3, 4.5, 6, 9, 12, 18, 24, 27	Half
Modulation type	BPSK, QPSK, 16 QAM, 64 QAM	BPSK, QPSK, 16 QAM, 64 QAM	No change
Code rate	1/2, 1/3, 1/4	1/2, 1/3, 1/4	No change
Number of subcarriers	52	52	No change
Symbol duration	4 μs	8 μs	Two times
Guard time	0.8 μs	1.6 μs	Two times
FFT Period	3.2 μs	6.4 μs	Two times
Preamble Duration	16 μs	32 μs	Two times
Subcarrier frequency spacing	0.3125 MHz	0.15625 MHz	Half

To prepare the data packet of IEEE 802.11p for high mobility vehicular communications, the bandwidth of the IEEE 802.11p PHY signal is decreased from 20 MHz to 10 MHz, which means that all parameters in the time domain are doubled. Table 3.1 illustrates the difference between the 802.11p PHY and the original IEEE, [7].

3.2 Definition of European 5.8 GHz Channel Layout

The Federal Communications Commission (FCC) of the US has allocated 75 MHz bandwidth at 5.855 − 5.925 GHz for the Intelligent Transportation System (ITS). This bandwidth is divided into seven 10 MHz channels, as shown in Figure 3.2, and consists of one Control Channel (CCH) and six Service Channels (SCH). IEEE 802.11p, in the US also called DSRC, has been adopted as a technique to offer ITS services on this frequency band. The IEEE 802.11p PHY is a variation of the OFDM based IEEE 802.11a standard, [9].

After investigations in Europe, a 30 MHz channel is recommended for road safety applications (5875−5905 MHz), and further 20 MHz (5905−5925 MHz) are suggested to be considered for future ITS expansion, [10]. The 30 MHz channel is divided into the SCH and CCH as follows:

1. SCH1: (5.875 − 5.885 GHz) will be used for safety messages with lower priority (in comparison with CCH) and traffic efficiency applications.
2. SCH2: (5.895 − 5.905 GHz) will be used for short distance transmissions which results in lower interference for SCH1 and CCH, because of the lower transmit power.

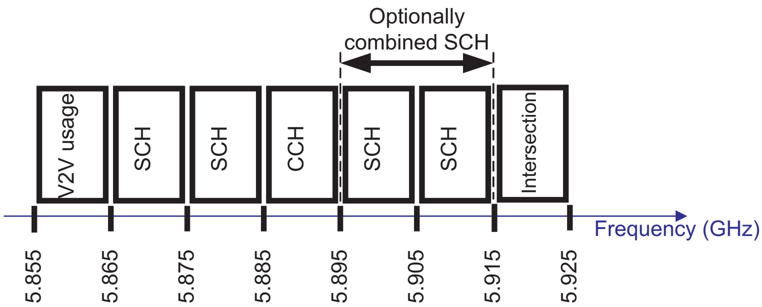

Figure 3.2: Frequency allocation of DSRC/IEEE 802.11p in the US.

3. CCH: (5.885 – 5.895 GHz) will be used for high priority safety messages and beacons.

The further 20 MHz (5.905 – 5.925 GHz) could be used in a different way. One possibility is that the lower part is used as a SCH with low transmit power similar to SCH2, and the higher part is used as a SCH with high transmit power similar to SCH1. This possibility increases the channel usage efficiency. The proposed European frequency allocation for ITS applications is illustrated in Figure 3.3.

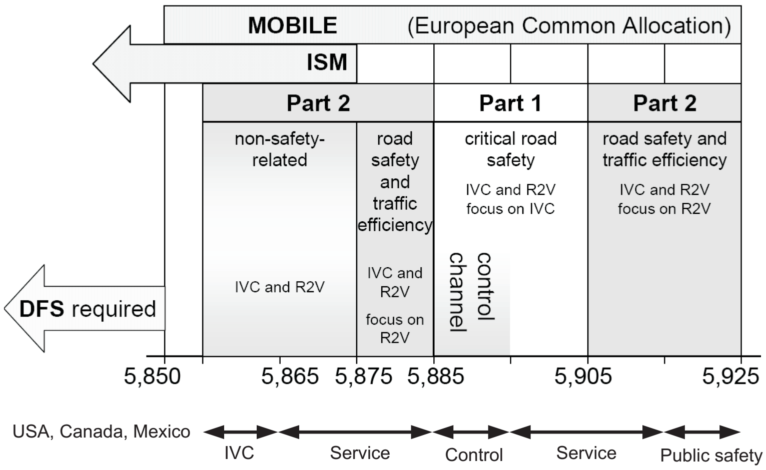

Figure 3.3: Proposed ITS spectrum allocation in Europe [11].

There are interferences between different channels of ITS. Moreover, there are some other systems that work in this frequency band and adjacent bands that can suffer ITS or located as a victim from ITS side. These systems are introduced in following:

1. Fixed Satellite (Earth-Satellite) Service (FSS)
2. Radiolocation Service (RL)
3. Non-Specific Short-Range Devices (SRD)
4. Fixed Wireless Access (FWA) devices
5. Fixed Service (FS) (above 5925 MHz)

Table 3.2: Interferences in 5.875 GHz to 5.925 GHz (source [12])

Services and **applications**	**ITS as interferer**	**ITS as victim**
1. FSS	Compatible	Compatible due to limit number of stations
2. RL	Compatible due to low transmit power below 5.85 GHz	Interference exist in 5.85 – 5.875 GHz
3. SRD	Mitigation technique required in channels 172 – 174 (5.855 – 5.875 GHz)	Mitigation technique required required in channels 172 – 174
4. FWA Section 3.2.2	Mitigation technique in 172 – 174, compatible in other ITS channels	Mitigation technique is needed in 172 – 174
5. FS	frequency separation or filtering required, no study due to limit number of devices	Interference exist in co-channel band (channels 172 – 174)
6. Radio amateur	Compatible	Compatible
7. RTTT Section 3.2.1	Compatible due to low transmit power in RTTT frequency range	Interference depends on antenna beam and limited to RTTT zone

6. Radio amateur (below 5850 MHz)
7. Road Transport and Traffic Telematics (RTTT) below 5815 MHz

The summary of Electronic Communications Committee (ECC) report, [12], about adjacent channels is:

- 5875 – 5905 MHz: ITS will not suffer from excessive interference resulting from other systems/services.
- 5855 – 5925 MHz: ITS are compatible with all services providing
  - unwanted emission power below 5850 MHz is less than −55 dBm/MHz.
  - unwanted emission power below 5815 MHz is less than −65 dBm/MHz or alternatively, a mitigation technique would be to switch off ITS while within the RTTT communications zone.
  - the unwanted emission power above 5925 MHz is less than −65 dBm/MHz.
- Mitigation techniques are implemented by ITS in the frequency range 5855–5875 MHz to ensure compatibility with FWA and SRD equipments.

The report of ECC is summarized in Table 3.2. The most important interference between other systems and ITS, is due to RTTT and FWA. This investigation is done according to the technical requirements of ITS devices that are explained in detail in [12].

3.2.1 Interference Between ITS and RTTT

Road Transport and Traffic Telematics (RTTT) works in 5795 – 5805 MHz by possible extension to 5815 MHz, for use by initial road to vehicle systems. Road toll systems works in 5805−5815 MHz and so there is 40 MHz guard band between ITS and RTTT systems. RTTT DSRC devices are divided into two categories.

- Road Side Unit (RSU) is an active device with a high level of emission power and the sensitivity value can be compared to the value of ITS devices.
- On Board Unit (OBU) is a passive device with low level of emission power and poor level of sensitivity.

The main problems between ITS and RTTT that may happen can be categorized into three subjects:

- Interference from the RTTT RSU on the ITS (OBU) when the car is below the RTTT RSU in the main lobe to main lobe configuration. Such a situation may happen in a short time and very low probability.
- Interference from the ITS on the RTTT RSU. If the unwanted level of ITS devices is lower than −65 dBm/MHz within the RTTT frequency band (5795 − 5815 MHz) then ITS OBU will not create interference on RTTT RSU. Anyway a mitigation technique that switch off ITS within the RTTT communications zone could be a good method to prevent interference.
- Interference from the ITS on the RTTT OBU. The OBU requires a −60 dBm signal to wake up and understand commands. The unwanted emission level of ITS devices is unlikely to reach such low sensitivity. However if the RTTT OBU receiver is not filtered and is too sensitive outside its identified band, such situation may occur within the ITS band.

3.2.2 Interference Between ITS and FWA

Fixed wireless access (FWA) are wireless systems, those provide local connectivity for a variety of applications and using a variety of architectures and works in 5.725 − 5.875 GHz.

To protect interference with FWA, some parameters should be investigated as follows:

- Required propagation loss (attenuation) should be calculated (link budget).
- Separation distance should be calculated.
- Out of Band (OoB) attenuation factor (if the victim and interferer do not share the same active band).
- Side lobe attenuation factor (if the transmission scheme does not imply the main beam).

In this section two scenarios are defined, co-channel interference and adjacent-channel interference. In a co-channel analysis (5855 − 5875 MHz), protection ranges must be greater than a few kilometers. But in adjacent channel scenario (5875 − 5925 MHz), a few hundred meters protection range can be enough to avoid the interference. So the protection ranges explained in [12] reduce if ITS and FWA do not share the same frequency range. Anyhow some mitigation techniques are required when FWA and ITS devices use a part of the spectrum together (in the co-channel band 5855 − 5875 MHz). The protection ranges are very small in order to protect ITS from FWA.

In general, ITS will not receive too much interference from FWA devices if they do not share the same frequency band, but in the frequency range 5855 − 5875 MHz ITS may suffer from interference. The protection ranges regarding to the different channels are achieved by using the required propagation loss (L_{FS}) that is given by, [12],

$$L_{FS} = C + 10\log\left(\frac{B_i}{B_v}\right) - G_v - e.i.r.p. - S. \qquad (3.1)$$

- $S = C/I$ is the protection criterion (S=6 dB)
- C is the sensitivity of the victim at the antenna input in dBm
- B_i is the receiver bandwidth of the interferer in MHz
- B_v is the bandwidth of the victim in MHz
- G_v is the victim antenna gain in dBi
- $e.i.r.p.$ is the equivalent isotropically radiated power of the interferer in dBm.

3.2.3 Basic Channel Usage Scenarios

The main frequency band allocated for ITS applications in Europe is 5.875 − 5.905 GHz. Three scenarios can be defined to divide the allocated bandwidth, as explained in [10]:

- Single 30 MHz channel MHz, that will need new technologies beside WAVE.
- Three 10 MHz channels, which needs two transceiver (SCH1 + SCH2 + CCH) → Scheme A.
- One 20 MHz and one 10 MHz, channel-interference problems exist and needs WAVE channel switching (CCH + 2 × SCH) → Scheme B.

In order to describe the property of these channels, some parameters, as explained in [10], are considered like latency, channel interference, bandwidth usage efficiency etc and finally a suggestion is prepared.

Latency

Low latency is an important factor for safety messages. Latency in scheme A corresponds to the priority of channels. CCH and SCH1 have the higher priority in comparison with SCH2. So the delay for messages in the CCH and SCH1 is less than in SCH2.

CCH and SCH in Scheme B have the same switching cycle, so the probability that a message finds CCH to be active or inactive will be the same as for SCH (each SCH is active after the service notice in CCH). The definitions of CCH, SCH1 and SCH2 are explained in Section 3.2.

Channel Interference

There is very limited interference in scheme A between CCH and SCH1, because these channels are non-adjacent. SCH2 has more interference with the other channels, but if SCH2 has lower power than CCH and SCH1 (for example 15 dB lower), then there will be no considerable interference from SCH2 on the other two channels. Finally a problem remains, SCH2 always suffers by interference from the CCH and SCH1 (SCH2 has less priority in comparison with CCH and SCH1).

In scheme B if CCH be located between two SCHs, there will be no adjacent channel interference, because each channel, CCH or SCH, works only on it's own time interval. But there exists still a small non-adjacent channel interference. In this situation, scheme B is slightly preferred.

Hardware

There are two channels in Scheme A that work at the same time, two wireless network interfaces are needed that may cause extra costs. In this case software drivers are available for the hardware and so there will be no need to additional drivers. But Scheme B has one active channel at a time, so it needs only one wireless network interface, but requires an implementation of WAVE synchronized channel switching. Overall the Scheme B is slightly preferred over Scheme A, but it still depends on the hardware prices.

Bandwidth Usage Efficiency

In this section the efficiency of channel allocation is investigated according to the duration of bandwidth usage. Bandwidth usage efficiency can be defined by $E = \sum Bandwidth \times Percentage\ of\ active\ time$. In scheme A, CCH and SCH1 can be active at the same time, so efficiency can be calculated easily by: $E_{schemeA} = 2 \times 10\,\text{MHz} \times 100\% = 10\,\text{MHz} \times 200\%$.

In scheme B, every channel can be active only half of the time, so the bandwidth usage efficiency is $E_{schemeB} = (1 \times 20\,\text{MHz} + 1 \times 10\,\text{MHz}) \times (50\% - x\%)$ and x is the switching time. By comparing $E_{schemeA}$ and $E_{schemeB}$, we can see that Scheme A is preferred over scheme B in this case.

Additional Frequency Band (5.905 - 5.925 GHz)

In scheme A the first lower 10 MHz channel of the additional bandwidth (5.905 – 5.925 GHz) can be like SCH2 with lower transmit power in compare with SCH1 and CCH. The last channel can work similar to the SCH1. By this usage, the channel usage efficiency will raise by $10\,MHz \times 100\%$.

In Scheme B two 10 MHz channel can be added to the SCH. So the whole SCH bandwidth will be 40 MHz. But still the adjacent channel interference problem exists with the new added channels, so both added channels can not work at the same time. In this situation to reduce the adjacent channel interference, two new channels can not work at the same time and so the active time should be reduced. Total channel usage efficiency increases by 10 MHz $\times$ 50% in scheme B, which is less than the increased efficiency in scheme A. Finally scheme A is preferred in this case over scheme B.

Reliability

Reliability is also a critical factor for safety messages and therefore it is essential for the final suggestion. All devices must be synchronized in Scheme B, with a unit reference. Unsynchronized devices or any kind of inaccuracy can make the WAVE channel switching not possible. Scheme A has no need for synchronization. So scheme A is preferred over scheme B in the reliability evaluation.

Node Density and Prioritization

When the amount of nodes, that want to have communication together, increases, controlling the amount of data traffic will be important and it can be done by controlling the packet size, changing the packet generation rate and transmitting power. Available congestion control mechanisms can be implemented on both schemes, so there is no preference for these parameters. Also both schemes can carry prioritization of different message types, so no preference will exist due to this factor.

Briefly, the 30 MHz channel scenario requires new hardware (transceiver), which is a drawback. Concurrent usage of two adjacent channels causes considerable packet loss and also 20 MHz channels are more susceptible to BER than 10 MHz channels. On the other hand interference happening between nonadjacent channels is much lower than interference between the adjacent channels. Totally the advantages of scheme A are greater than of scheme B. But Interference on neighboring systems and infects from other devices those investigated in sections 3.2.1 and 3.2.2 can change this priority. These factors can be a good guide to decide on the extra bandwidth ($5.905 - 5.925$ GHz) usage. Using the extra band is an open question and is still under investigation, [10].

Chapter 4

Measurements of Transmitter Frontend

In this chapter, measurements of different parameters are explained in detail and the final results are compared with the specified values from IEEE 802.11p standard. At the beginning, some test signals similar to the IEEE 802.11p signals are generated by a Vector Signal Generator (VSG) from *Rohde&Schwarz* named *SMU*-200*A*. There is a software related to this generator named *WinIQSIM* that can generate IEEE 802.11a signals. The IEEE 802.11p test signals also could be generated after some changes. This software is connected to the *SMU*-200*A* through LAN and finally the desired test signal could be achieved in signal generator's output. After this measurements were done with a real IEEE 802.11p WLAN transceiver developed by Siemens AG Austria, introduced in Section 4.1 in detail. Measurements were done at the transmitter like emission power, spectral emission, guard interval and ramp-up / ramp-down time. The measurement of some other parameters could not be implemented due to limited in access to the physical layer parameters of the Device Under Test (DUT).

4.1 Siemens WLAN Transceiver (DUT)

The whole desired measurements were implemented on a new WLAN transceiver made by Siemens AG Austria, fabricated for V2V communications based on IEEE 802.11p standard. Beside the IEEE 802.11p function also Global Positioning System (GPS) is included (over an external antenna). The DUT is shown in Figure 4.1:

- A: Transceiver's antenna
- B: Attenuator used in class C measurements (10 dB, 2 Watt, 6 GHz)
- C: 50 cm cable
- D: Serial port
- E: LAN cable
- F: Power cable

A 10 dB attenuator is used in class C measurements, in order to reduce the input power of the analyzer, because there is a limitation of 30 dBm in the *FSQ*-

Figure 4.1: IEEE 802.11p Transceiver (Siemens).

26 spectrum analyzer (this analyzer is introduced in Section 4.2). In order to work in a linear area, it is suggested to work with an input power of 10 dBm at maximum.

To work with the Siemens transceiver, we need to be connected to it by computer using a general client. Several parameters in this device can be controlled, like txpower, bitrate (which defines the modulation type and coding ratio), and working channel. There are several software tools for connection to the transceiver through LAN. In this case *PuTTY* is used. *PuTTY* is a terminal emulator application that can behave as a client. Figure 4.2 shows the *PuTTY* configuration window and Figure 4.3 shows the window of this client to enter commands.

An IP address has been defined for each transceiver by Siemens AG Austria. Therefore this IP address must be entered into the IP address block of the *PuTTY*. The changeable parameters can be changed after connecting to the device by using some predefined commands. The most usable commands are "iwlist" (to list the changeable parameters) and "iwconfig" (to see the current values of parameters). The command format is "iwlist" to list the whole parameters, or "iwlist bitrate" to show the options for each parameter, and to set a parameter like transmit power, the command is: "iwconfig ath0 txpower 10". The Siemens device has two antenna ports, named *ath*0 and *ath*1 that has to be chosen for each parameter setting. The digit 10 in the command specifies the txpower level in dBm.

4.2 Measurement devices

A spectrum analyzer *FSQ*-26 from *Rohde&Schwarz* company is employed to measure the spectrum mask and emission power of the transmitter. The frequency range of *FSQ*-26 is 20 Hz − 26.6 GHz and it also can work in time domain. But to measure time domain parameters of the transmitter, like guard

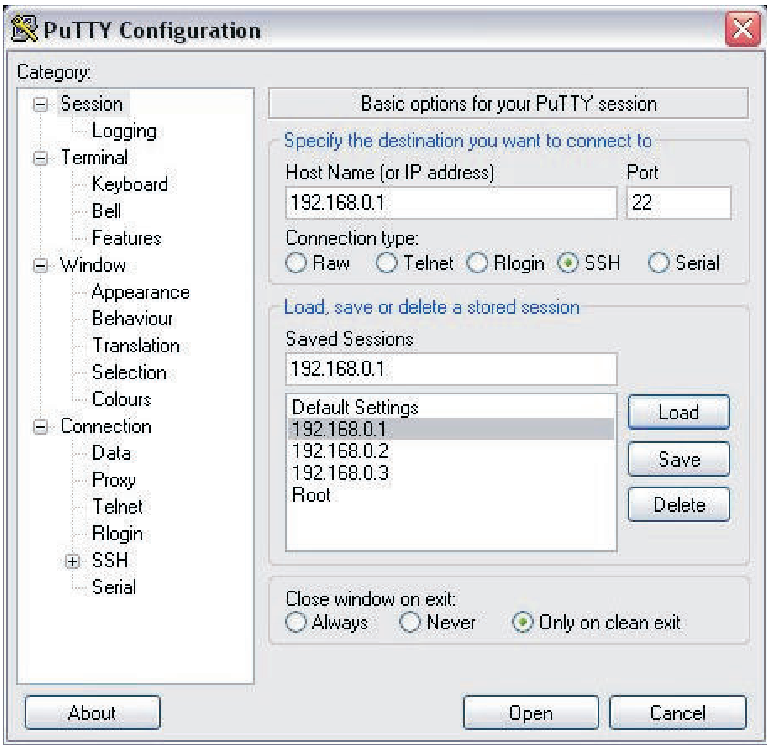

Figure 4.2: Configuration window of *PuTTY* client.

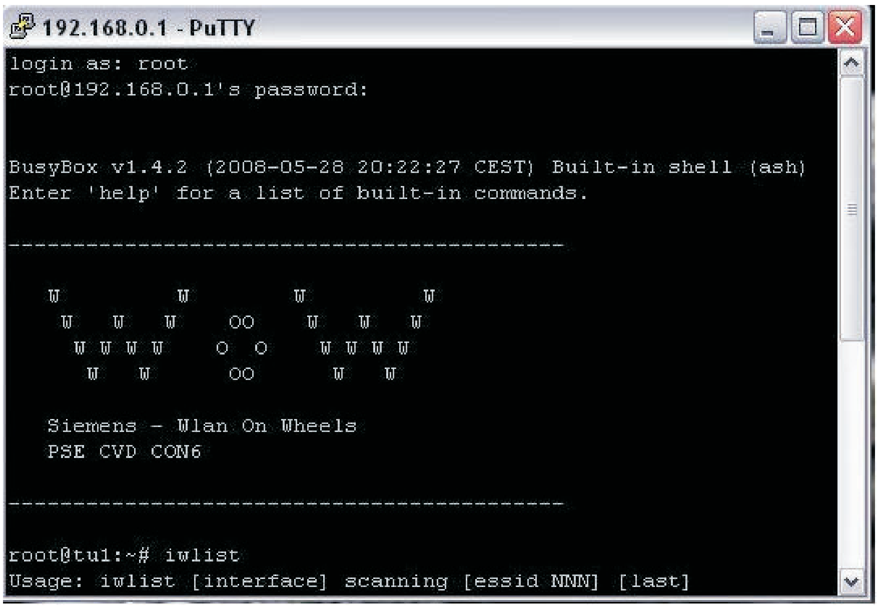

Figure 4.3: Command window of *PuTTY* client.

interval (cyclic prefix in this case) and ramp-up/ramp-down time, an oscilloscope with 12 GHz frequency range and 40 Gsa/s sampling rate is used. This oscilloscope is a digital storage oscilloscope (DSO91204A) from the company

Agilent Technologies. Figure 4.4 shows the employed oscilloscope connected to the transceiver with a 50 cm coaxial cable.

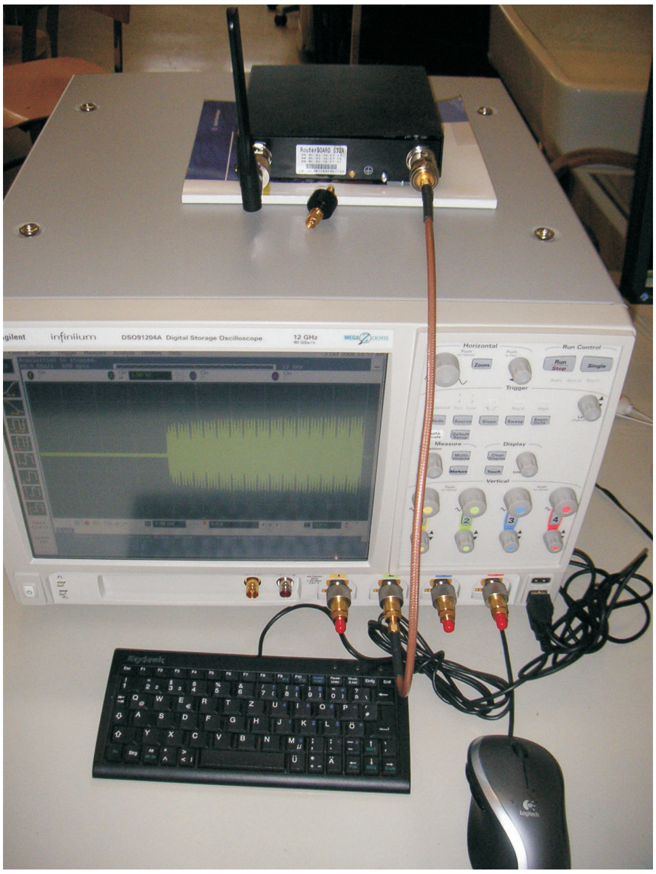

Figure 4.4: Agilent Oscilloscope connected to the Siemens transceiver.

4.3 Emission Power

In this section, the setting of the transceiver and spectrum analyzer for emission power measuring is explained. Further the measurement results are compared with the specifications from IEEE 802.11p standard.

4.3.1 Measurement Set-Up

This test ensures that the maximum output power does not exceed the specified value. Excessive output power may result in blocking other WLAN devices from transmission or non-conformance with national regulations for the assigned frequency bands.

Present device (RouterBOARD 532A, Siemens) does not support class D, so measurements were done on class A, B and C (more details about transmission classes are explained in Section 2.2.1). To set the device to transmit in each class, we need to map the set value by software to the real output power. This means that Txpower of the DUT should be set on 6 dBm to be in the desired range of class A. According to the IEEE 802.11p standard it should be 0 dBm.

Emission power was measured with the signal analyzer (FSQ-26 *Rohde&Schwarz*). First of all, the centre frequency of the analyzer is set to the centre frequency of working channel. In this case channel number 184 ($5.915 - 5.925$ GHz) is used, so the frequency is set to 5.92 GHz. To see the whole signal of the channel and also the shoulders of the signal (effect of the channel on the adjacent channels), a 40 MHz span is defined. The signal reaches to the noise floor and has no effect on the adjacent and non adjacent channels. The reference level of analyzer changes depending on the transmission class. In this work, the reference level is set to 20 dBm to cover the measurements in all classes.

The Resolution Bandwidth (RBW) specifies the FFT bin size and determines the smallest frequency that can be diagnosed and also determines the measurement precision. The higher RBW value the lower frequency resolution and vice versa. The smaller value of RBW is more efficient for narrow band signals due to higher frequency resolution requirement. But in our case, the bandwidth of the channel is 10 MHz, therefore 100 kHz RBW value can cover the required resolution.

To see a more reliable signal, the RMS detector is selected to display the RMS value of measured power. Therefore the root mean square of all sampled level values is formed during the sweep of a pixel. The sweep time determines the number of averaged values and with increasing sweep time a better averaging result can be obtained. The video bandwidth must be at least 10 times of the selected RBW (in our case: $10 \times 100\,\text{kHz} = 1\,\text{MHz}$) to ensure that video filtering does not cancel the RMS values of the signal. The display for small signals is, however, the sum of signal power and noise power. For short sweep times, the RMS detector is equivalent to the sample detector. If the sweep time is longer, more and more uncorrelated RMS values supply the RMS value measurement and therefore the trace becomes more smooth. At a RBW of 100 kHz the maximum frequency display range is 62.5 MHz (suitable for our case) and higher sweep time causes smoother and more stable signal. The best choice for sweep time is the smallest possible value for a given span and resolution bandwidth. Overall the sweep time is selected to 200 ms according to the 40 MHz span and 100 kHz RBW, [13].

After choosing the setting, the channel power measurement configuration is enabled and then 10 MHz is defined for the channel bandwidth. The signal analyzer's setting is as following:

- Frequency: 5.92 GHz, Centre frequency of working channel (channel 184)
- Span: 40 MHz to see the complete signal
- Reference level: Maximum expected output power, depends on working class, (I set this parameter on 20 dBm to cover all classes)
- RBW: 100 kHz
- VBW: 1 MHz
- Sweep time: 200 ms
- Detector: RMS detector sweep
- Channel power ACP → CP / ACP Config → Channel bandwidth: 10 MHz (ACP is pointing to adjacent channel power and CP is pointing to channel power)

4.3.2 Measurement Results

For Class A, maximum specified Txpower is equal to 0 dBm. Figure 4.5 shows the analyzer screen shot for this measurement. The measured value for class A is 1.8 dBm that is slightly higher than standard definition. In this class, transmitter is set by software to 6 dBm, which means that there is an offset between the software set power and the read output power.

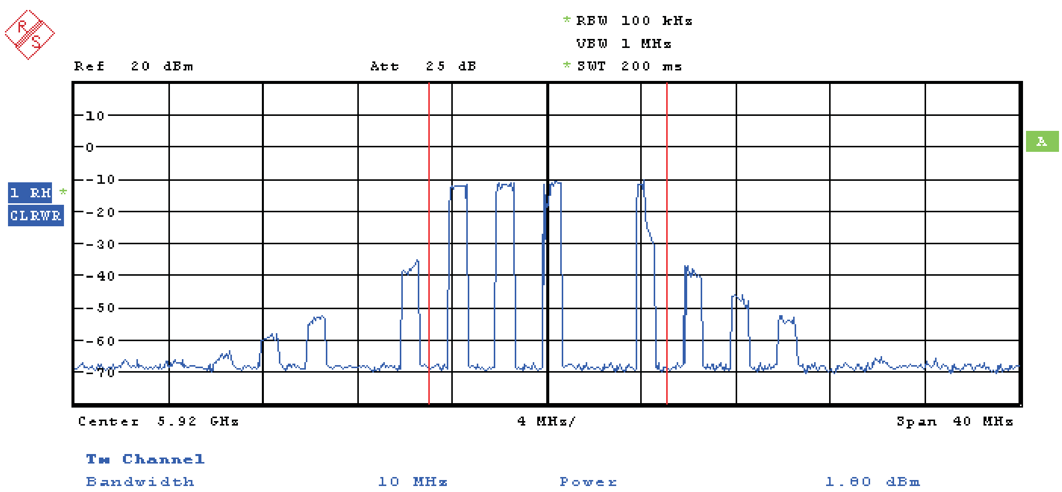

Figure 4.5: Measurement result for emission power in class A.

For Class B, maximum specified Txpower is equal to 10 dBm. Figure 4.6 shows that the emission power in class B is 9.24 dBm and therefore this value is located in the predefined range from the standard.

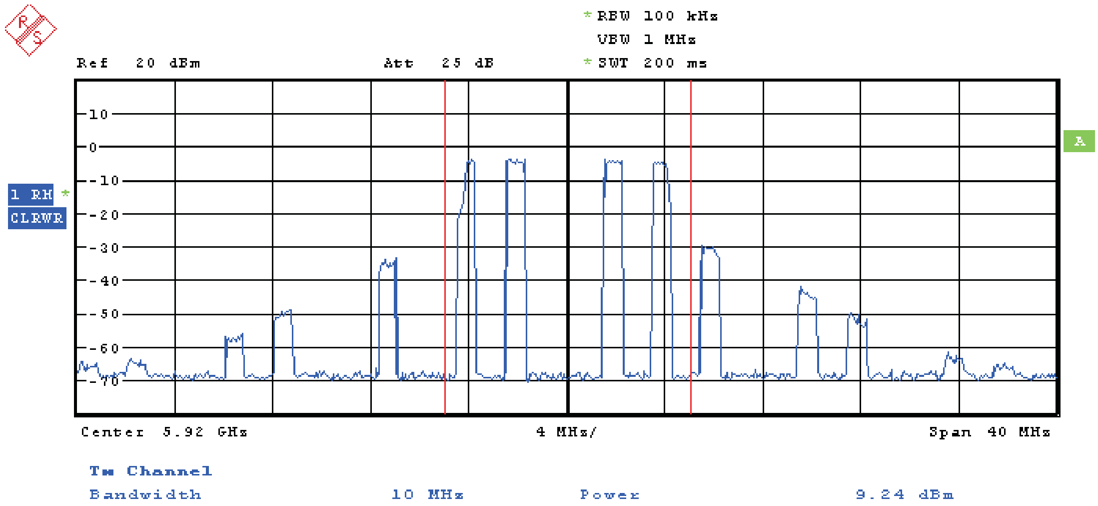

Figure 4.6: Measurement result for emission power in class B.

For Class C, maximum specified Txpower is equal to 18 dBm. As illustrated in Figure 4.7, emission power is equal to 17.66 dBm, therefore transmitter works properly in this class.

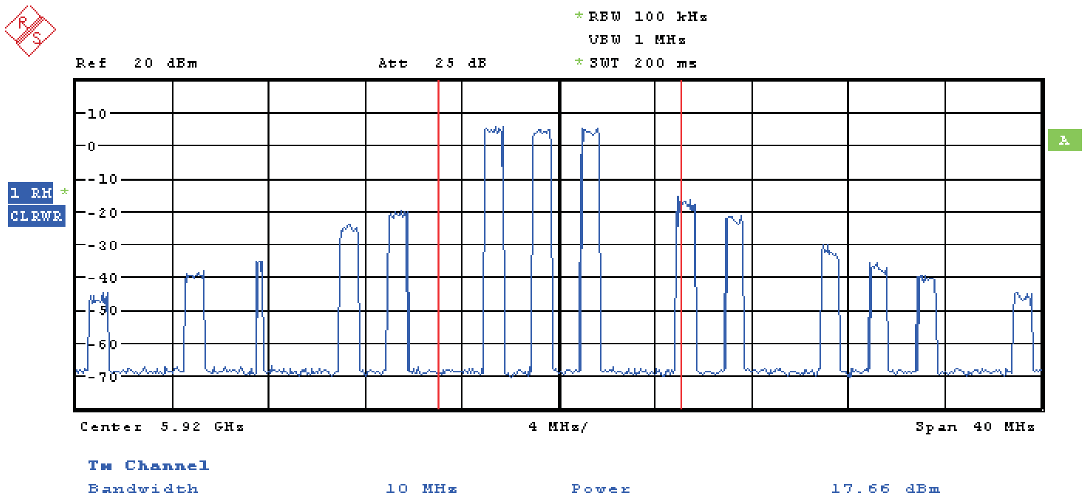

Figure 4.7: Measurement result for emission power in class C.

These measurement were done in channel 184 (5.915 – 5.925 GHz). Investigation of the measurement in other channels of IEEE 802.11p shows the same results for the DUT (RouterBOARD 532A, Siemens).

Consideration of total emission power shows that the device can be used in class B and C without any problem, in class A the output power is slightly higher than the maximum allowed output power.

4.4 Spectral Emission

Emission power spectrum mask measurement are done to ensure that the DUT does not manipulate WLAN devices working in adjacent channels. Transmitter filter is not defined in IEEE 802.11p standard, but transmitter spectrum mask is defined and must be passed. Therefore, design of the transmitter shall fulfill the specification of spectrum mask defined by IEEE 802.11p standard, [14].

To see the spectrum mask of the transmitter working with OFDM signals, there is an option that can be installed on the signal analyzer $FSQ - 26$. This option is named WLAN and designed for working under IEEE 802.11a, b, g, j standards. The other way is a manual setting of the analyzer for such a signal. In this case, I set the analyzer manually step by step.

There are 4 classes of transmitters defined in IEEE 802.11p and each case has its own mask. The mask regarding to the class A, B, C, D are shown in Figure 4.8.

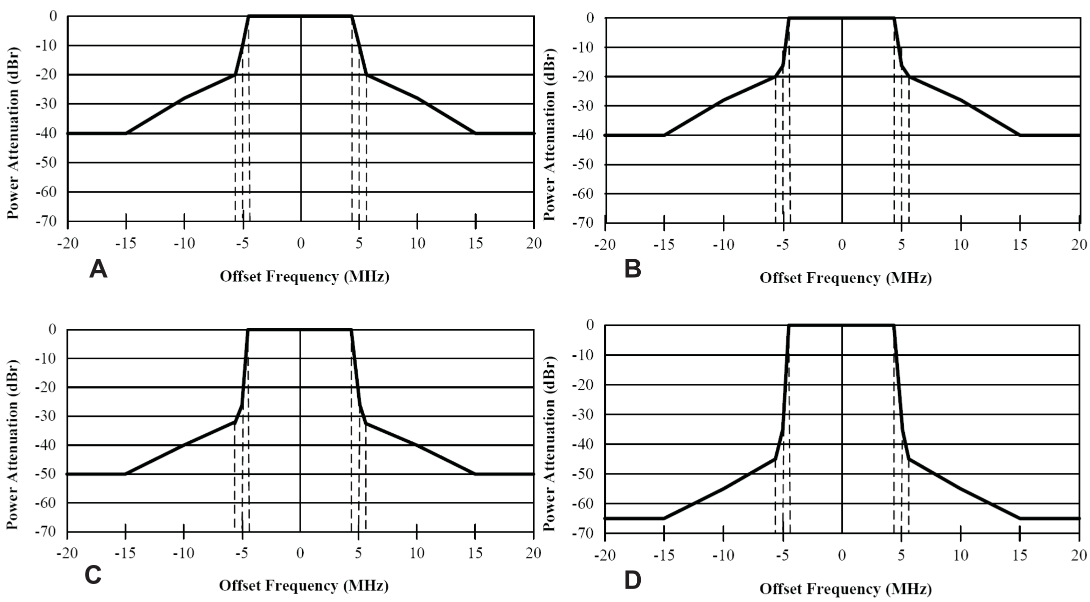

Figure 4.8: Class A, B, C, and D spectrum masks defined in IEEE 802.11p standard.

4.4.1 Measurement Set-Up

First of all, each mask is defined manually for the analyzer. For this purpose, the "Lines" menu is used. Limit lines are defined for the analyzer to determine spectral distribution boundaries. These lines point to the upper limits for radiation to prevent interfering to other systems and also to protect the human from high power radiations.

For each limit line regarding to each transmission class, the following characteristics are defined in frequency domain:

1. The name of the limit line.
2. The reference of the interpolation points to the X axis.
3. The reference of the interpolation points to the Y axis.
4. The limit line units to be used. The units of the limit line must be compatible with the level axis in the measurement window.

As shown in Figure 4.8, the spectrum mask is defined for 40 MHz bandwidth (20 MHz offset from the centre frequency of working channel). Therefore 40 MHz span is a good choice. The reference level is set on a value to ensure that the peak of the signal can be observed. On the other hand, the defined mask unit is dBr. Therefore each signal has an offset depend on the working class to set the highest level of the signal on 0 dBm. A reference level between 5 dBm to 15 dBm is suitable in this case to see the spectrum of the signal.

A 100 kHz RBW is selected due to the same reason discussed in Section 4.3.1. The detector is set on maximum peak detector and the VBW of 300 kHz is selected in this case. To see the unstable signal as we have in this case, maximum hold option is enabled in "Trace" menu. Moreover to have a stable shape of the signal, a few seconds delay are required between enabling the maximum hold option and registering the result.

Overall, the analyzer settings are defined as following:

- Frequency: 5.92 GHz, Centre frequency of working channel (channel 184)
- Span: 40 MHz
- Reference level: 12.5 dBm for class A (between 5 dBm and 15 dBm is suitable)
- RBW: 100 kHz
- VBW: 300 kHz
- Detector: Maximum peak detector
- Trace: Maximum hold

4.4.2 Measurement Results

The transmitted signals regarding to the spectral mask measurement are in dBr and shown below. The red lines in the figures below show the mask defined by IEEE 802.11p standard that I entered manually in the analyzer. The spectrum of the transmitted signal in different classes is plotted with blue color.

Figure 4.9 shows the comparison between the signal in class A and the defined mask of the standard. An offset of −2.5 dB is added to the signal in class A to be matched with the predefined mask in the standard in dBr unit. As illustrated in Figure 4.9, the signal has 2 dB to 10 dB margin to the predefined mask in the adjacent channel. But the margin for nonadjacent channel is approximately 10 dB and constant. The mask for class A is not so sharp compared with other classes and so the signal is below the mask and does not exceed the limitation. Therefore the transmitter meets the specification of IEEE 802.11p standard in class A.

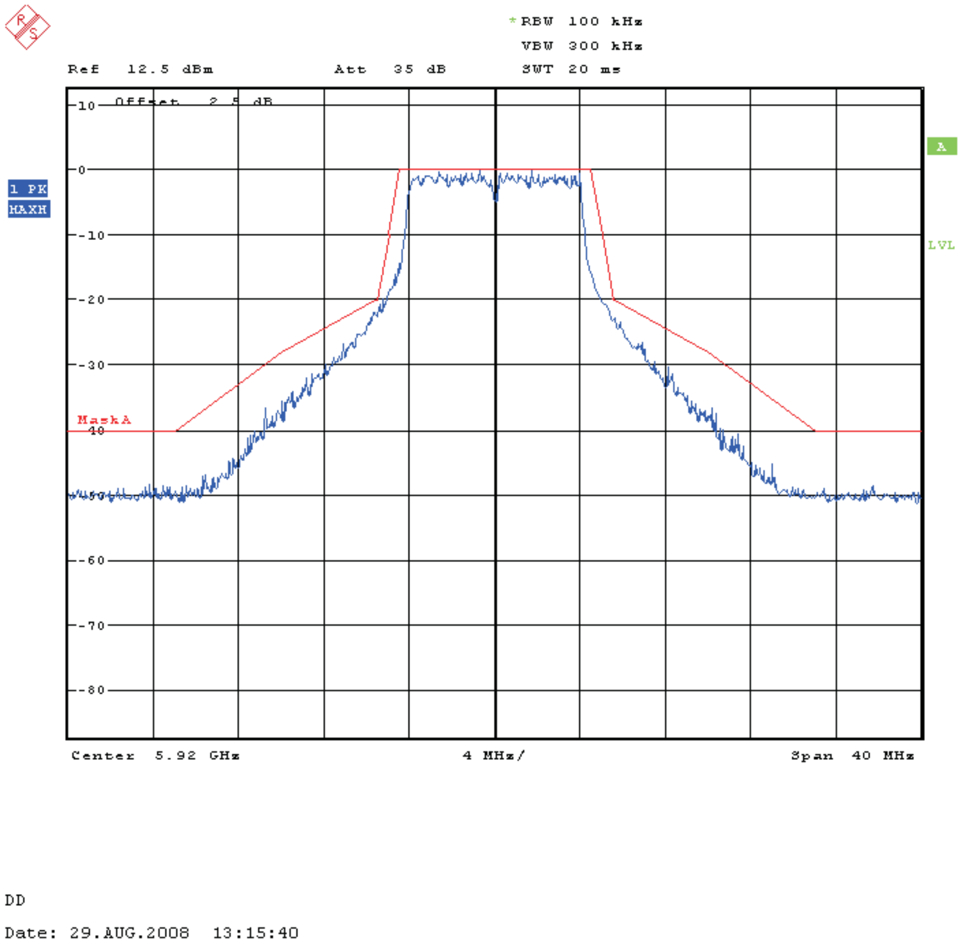

Figure 4.9: Class A spectrum mask compared with IEEE 802.11p.

In class B, −3.5 dB offset match the highest level of the signal on 0 dBm and therefore the signal level converts to dBr unit. By comparison of the signal with the defined mask, the margin can be observed. As in Figure 4.10 illustrated, the margin in adjacent channels is between 0 to 10 dB and is larger than 10 dB for nonadjacent channels. Overall, the spectrum is acceptable for class B and passes the necessary specifications.

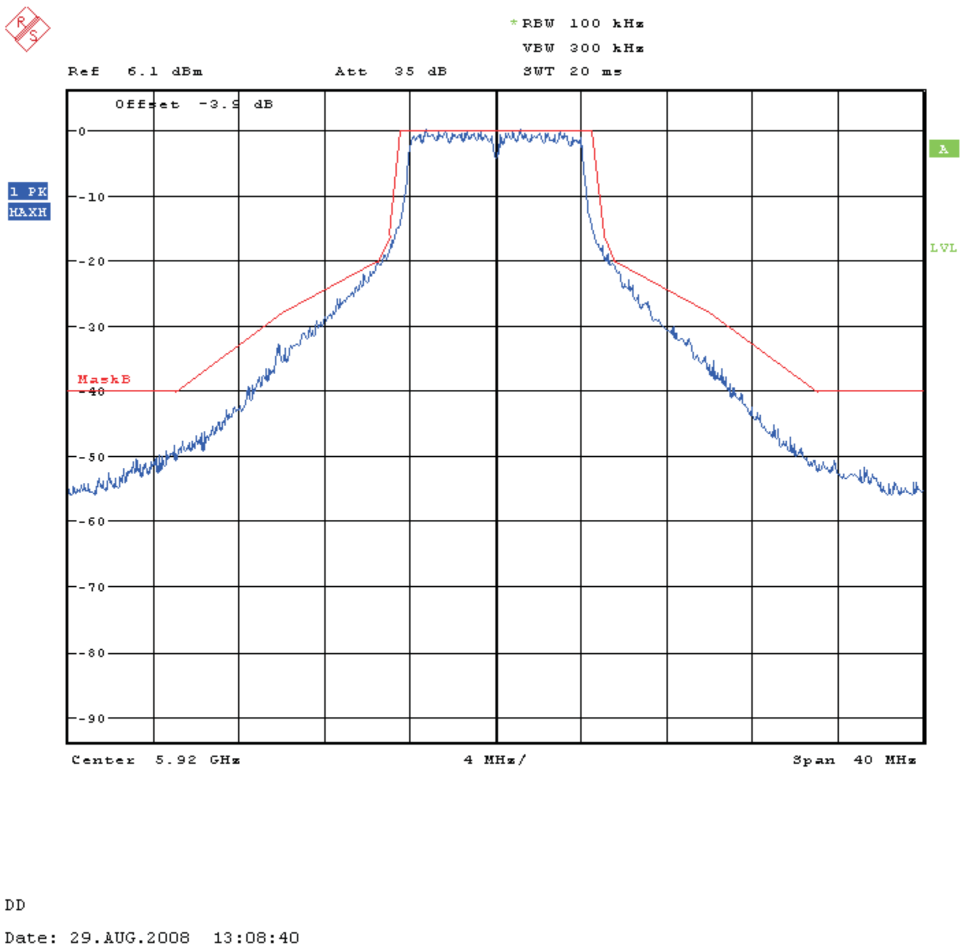

Figure 4.10: Class B spectrum mask compared with IEEE 802.11p.

Comparison of class C with related mask shows that the spectrum of transmitted signal can not follow the defined mask and exceeds in both, adjacent channels and nonadjacent channels. One point should be mentioned that the edges of the spectrum mask defined by IEEE 802.11p standard are sharper in this class compared with class A and B. Figure 4.11 illustrates the predefined mask and transmitted spectrum from the DUT (RouterBOARD 532A, Siemens).

4.5 Error Vector Magnitude

To measure the Error Vector Magnitude (EVM), a Vector Signal Analyzer (VSA) (for example *FSQ-K70 Rohde&Schwarz*) can be used. There are several possibilities to measure the EVM from an OFDM signal:

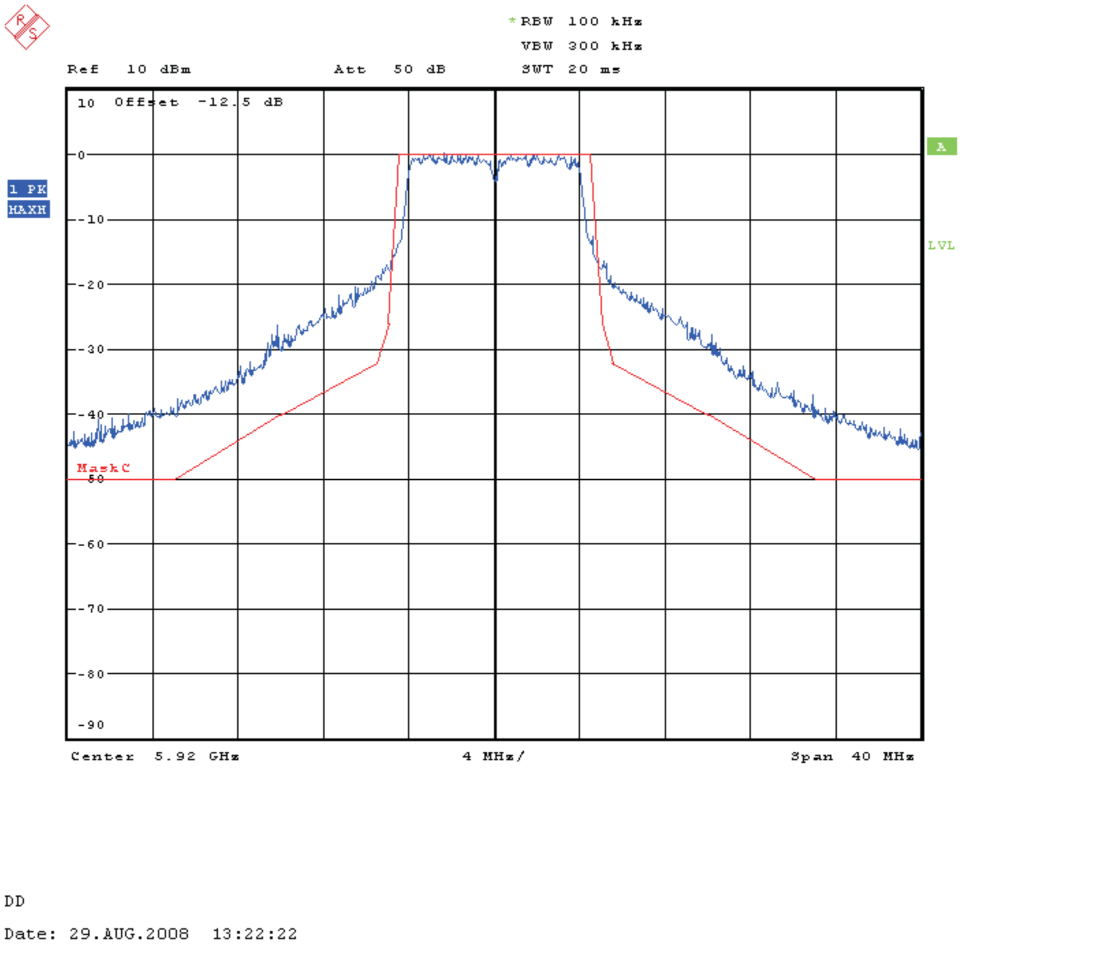

Figure 4.11: Class C spectrum mask compared with IEEE 802.11p.

- MATLAB: Importing the signal to MATLAB, demodulation and calculating the EVM by signal processing. It takes a lot of work and time.
- Carrier: In this case the EVM could be measured individually for each carrier. One subcarrier can be selected and be sent to the VSA as a single carrier signal to measure the EVM. For this purpose, the transmitted signal's specifications must be known and also we must have access to the subcarriers for edition (at present DUT, "RouterBOARD 532A" transceiver, there is no access to the subcarriers). Following parameters must be defined at the VSA before EVM measurement.
  - Modulation type
  - Bitrates
  - Modulation filter type

  Possible choices for these parameters can be found in Table 3.1.
- Using an OFDM demodulator software based on IEEE 802.11p in the VSA: The software option $K96$ is a general OFDM demodulator and not specified

for IEEE 802.11p signals. There are some other options specialized for IEEE 802.11a,b,g but still nothing designed for IEEE 802.11p.

Due to limitation in time and available equipment during the thesis working period, it was not possible to measure the EVM.

4.6 Guard Intervals

Guard interval's concept is explained in detail in sections 2.1.2 and 2.2.3. Overall, 1.6 μs of symbol time is allocated as guard interval and the cyclic prefix technique is used for the OFDM signal. The symbol period is 6.4 μs and therefore the whole symbol takes 8 μs (6.4 μs + 1.6 μs), illustrated in Figure 2.4. In this section, the measurement setup, regarding to the guard interval measurement is defined followed by results of these measurements.

In this work, I did a visual measurement on the transmitted signal in time domain. A more exact measurement can be implemented by correlating the transmitted signal, $x(t)$, with the signal itself by a delay equal to the symbol period (6.4 μs), $x(t + \tau)$. Since cyclic prefix is used as guard interval in OFDM signal, the result of correlation is a peak in guard interval duration. Figure 4.12 shows this process. The delayed signal can be generated by a channel emulator. In the following, the measurement setup and the results for the case of visual measurements is described.

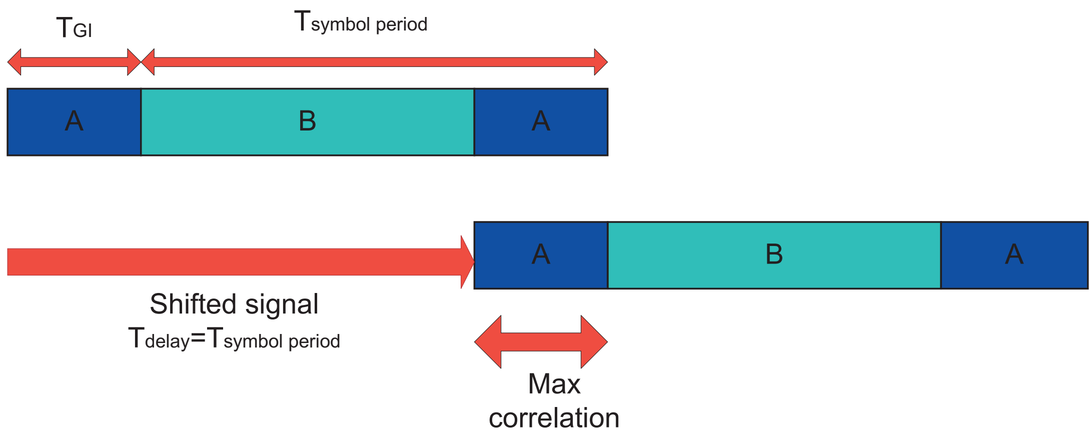

Figure 4.12: A measurement process to find cyclic prefix duration.

4.6.1 Measurement Set-Up

As mentioned before, a visual measurement of the guard interval (cyclic prefix) is provided for an OFDM signal transmitted by the DUT. The measurement is done in time domain, implemented with the oscilloscope introduced in section 4.2. The transmitter is set to transmit signal in class B (10 dBm emission power), with 9 Mb/s data rate and centre frequency of 5.92 GHz (channel number 184). At the oscilloscope the vertical scale is set to 1 V and horizontal scale is set to 1 μs, therefore 10 μs of the signal can be observed on the screen (the length of a symbol is 8 μs).

4.6.2 Measurement Results

The transmitted data is a periodic random signal. We know that the cyclic prefix technique is used in the transmitted signal. This means if we find two parts in the signal with 1.6 μs length, similar to each other, we can say that one of them is cyclic prefix and the other one is the last part of the symbol that is repeated at the beginning. Figure 4.13 shows 10 μs of the transmitted signal. T is the whole symbol duration plus the cyclic prefix, equal to 8 μs and the T_{symb} is the symbol duration, equal to 6.4 μs (8 μs − 1.6 μs). The left red arrow shows the cyclic prefix of the signal with duration of approximately 1.6 μs, that meets the specifications of the IEEE 802.11p standard.

Figure 4.13: Cyclic prefix visualizing.

4.7 Ramp-Up/Ramp-Down Time

Ramp-up and ramp-down duration show the rapidity of the device reaching to a stable carrier level depending on transmitter's working class. Different transmitter classes are explained in section 2.2.1 in detail. Data transferring in an OFDM signal shall be started with a delay larger than the ramp-up duration. IEEE 802.11 standard defines a maximum 2 μs for ramp-up/down duration for Direct Sequence Spread Spectrum (DSSS) signal, [4], and there is no specified definition for ramp-up/down time for OFDM signals in IEEE 802.11p standard. Therefor I assumed this limitation value be the same for IEEE 802.11p, too. Results of measurements can be optimized by finding the stable level of the carriers with higher accuracy (*Max Hold* detection in oscilloscope). But I do not expect considerable differences. In the case of using the *Max Hold*, it is necessary to set the trigger to see a stable signal on the screen.

4.7.1 Measurement Set-Up

To measure the ramp-up / ramp-down duration for class B and C, the vertical and horizontal scale of the oscilloscope is set on 1 V and 5 μs, respectively. By this setting the first part of the signal can be observed, which shows the transmission start time and data sending time. In class A, the vertical scale is set to 500 mV due to lower emission power. Then the horizontal scale is reduced to find the stable level of the carrier before data transmission. After calculation of 10 % and 90 % of the stable level, and locating the horizontal markers on these levels, the vertical markers location can be find to measure the ramp-up duration. The left marker is placed on the junction of lower horizontal marker with the signal, and the right marker shows the first point where the signal reaches the upper horizontal level. The transceiver is transmitting 9 Mbit/s data rate and is working in channel 184. The next section shows to the results of ramp-up measurements. First of all, the transceiver is set to class C and a 10 dB attenuator is used to protect the oscilloscope (4 V is the limitation of input voltage in the oscilloscope).

4.7.2 Measurement Result

Figure 4.14 shows the start point of transmission of a packet of data (each packet takes 4 ms). Carriers are reaching to the stable level after approximately 10 μs, and then data transmission is started by 16 μs delay from start transmission point.

The next task is to find the stable level of the carriers, illustrated in Figure 4.15. The maximum stable level is approximately at 2 V and a marker Ay is located on this point. Now 10 % and 90 % of this level are calculated according to the ramp-up definition:
$2\,V \times 90\% = 1.8\,V$

Figure 4.14: Signal envelope in class C by 10 dB attenuation.

$2\,V \times 10\% = 0.2\,V$

Horizontal markers, Ay and By, are located on calculated levels as illustrated in Figure 4.16, and vertical markers, Ax and Bx, are located on the junctions as described in section 4.7.1. Finally the ramp-up time can be observed in the bottom of the figure (white arrow is pointed to the ramp-up time). The assumed limitation is $2\,\mu$s, but ramp-up time is equal to $2.18\,\mu$s for $RouterBOARD532A$ which slightly larger than the specified value.

Measurements are implemented for class A and B too. In order to measure class A and B, attenuator is removed due to lower level of the transmitted signal, which is less than the oscilloscope's limitation. The largest value for ramp-up time belongs to the transmission in class B, $3.60\,\mu$s, which is more than $1.6\,\mu$s larger than the limitation. In class A, the ramp-up time is equal to $2.41\,\mu$s, therefore the transmitter needs to be optimized in this class too.

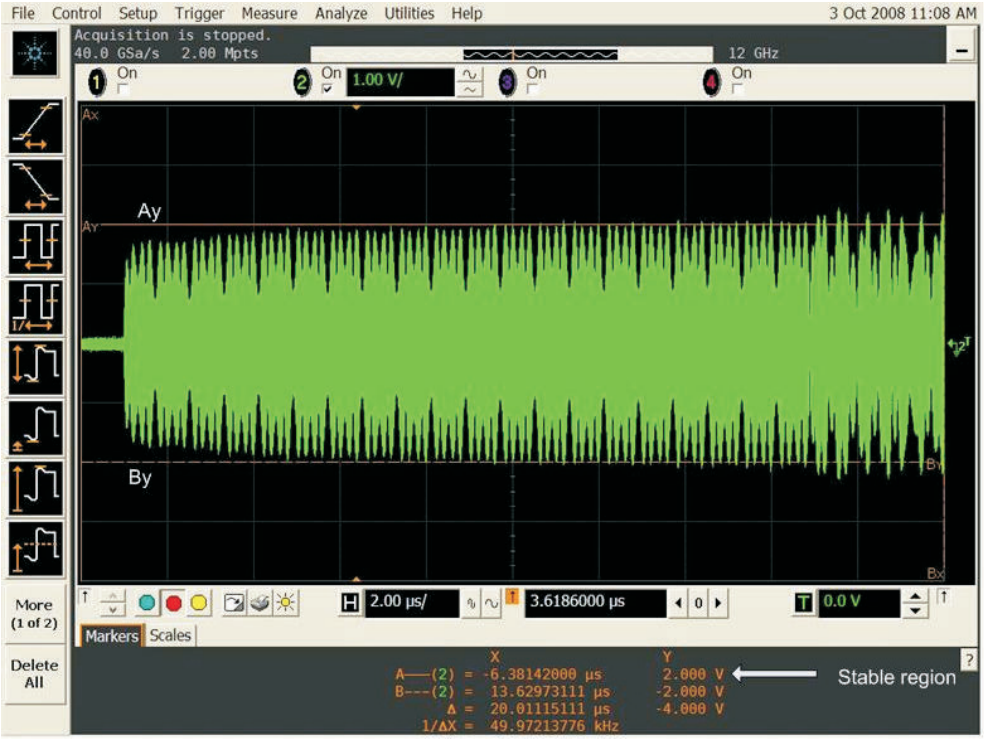

Figure 4.15: Stable level of carriers in class C by 10 dB attenuation.

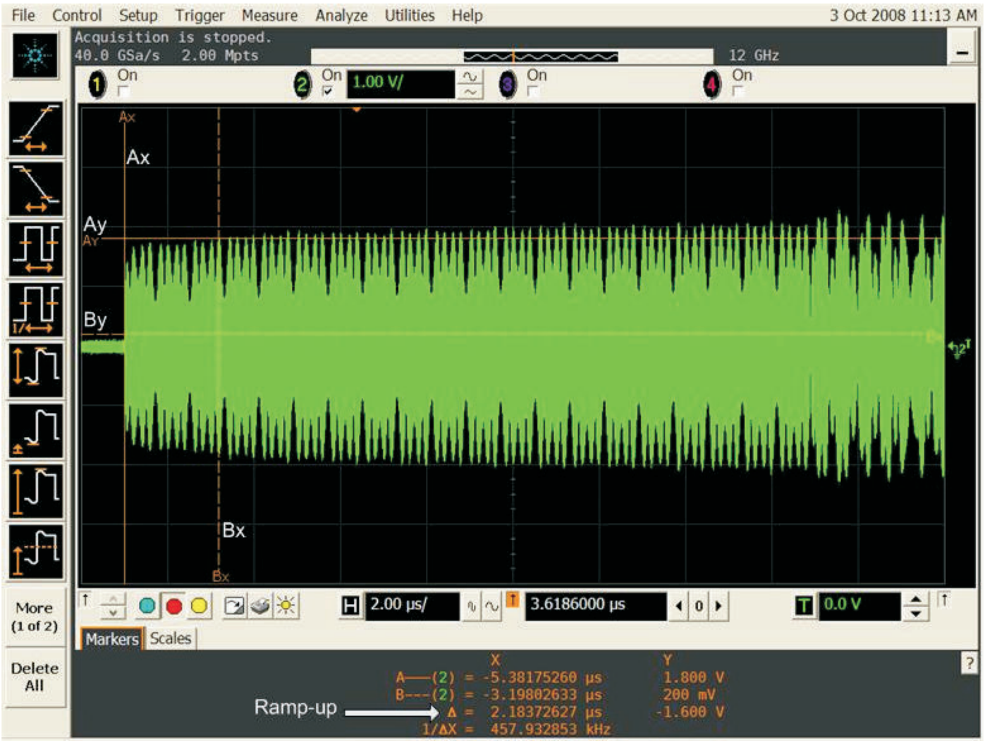

Figure 4.16: Ramp-up observation in class C by 10 dB attenuation.

Chapter 5

Summary

In this thesis, I first described fundamentals of OFDM transmission and frontend characterization parameters in general. I further extended these investigation to the specifications of IEEE 802.11p standard regarding to each parameter. This defines the expected requirements of an inter-vehicle communication transceiver.

Then specifications of a WLAN transmission based on IEEE 802.11p are studied and different possibilities of the bandwidth usage are evaluated.

The RF frontend consists of transmitter, receiver and local oscillators. The main work of this thesis was performing different measurements to evaluate the performance of the transmitter. After research on expected values for each parameter, the measurement setup was implemented and the results were compared with IEEE 802.11p standard specifications. The measurement setup and results have been given in Chapter 4. The results describe the behavior of the transmitter in the frequency domain as well as in the time domain and at different power levels. Furthermore they show how much the transmitter fulfills its specifications.

In the case of measuring the emission power, the results for transmission classes B and C are fulfilled, but the transmitter needs some optimization in class A. The spectrum of the emission signal meets the specifications in classes A and B, but the spectrum in class C exceeds the limitations. The guard interval of the transmitted signal meets the specifications of the standard. Also ramp-down time fulfilled the requirements. In the case of ramp-up measurement the measured times are slightly more than the expected values in all classes.

Overall, the work on other parts of RF frontend like receiver and the local oscillator, measuring of the other frontend parameters like EVM and IP3, and the ability of receiver to mitigate the effect of fading in data transmission are necessary to have a reliable evaluation on the DUT.

Bibliography

[1] C. D. Wang and J. P. Thompson, "Apparatus and method for motion detection and tracking of objects in a region for collision avoidance utilizing a real-time adaptive probabilistic neural network," in *US. Patent No. 5,613,039*, 1997.

[2] X. Yang, J. Liu, F. Zhao, and N. H. Vaidya, "A vehicle-to-vehicle communication protocol for cooperative collision warning," in *1st International Conference on Mobile and Ubiquitous Systems: Networking and Services (Mobiquitous 2004)*, Boston, MA, 22-26 August 2004.

[3] "Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications amendment 8: Wireless access in vehicular environments," IEEE P802.11p^{tm} /D4.0, March 2008.

[4] "Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," ANSI/IEEE Std. 802.11, 1999 (R2003).

[5] http://zone.ni.com/devzone/cda/tut/p/id/3740, national Instruments.

[6] T. S. Rappaport, *Wireless Communications: Principles and Practice, 2nd edition*. Prentice-Hall, Inc., 2001.

[7] Y. Zang, L. Stibor, G. Orfanos, S. Guo, and H. J. Reuerman, "An error model for inter-vehicle communications in highway scenarios at 5.9GHz," in *International Workshop on Modeling Analysis and Simulation of Wireless and Mobile Systems*, 2005.

[8] http://www.its.bldrdoc.gov, institute for Telecommunication Sciences.

[9] "Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications, high-speed physical layer in the 5 GHz band," IEEE Std. 802.11a, 1999 (R2003).

[10] L. Le, W. Zhang, A. Festag, and R. Baldessari, "Analysis of approaches for channel allocation in car-to-car communication," in *First international conference on the internet of things (IOT 2008) Workshop*, 2008.

[11] "Electromagnetic compatibility and radio spectrum matters (ERM); intelligent transport systems (ITS), technical report, draft ETSI TR 102 492-2, V1.1.1_0.0.16," ETSI Technical Committee Electromagnetic compatibility and Radio spectrum Matters (ERM), Tech. Rep., 2006.

[12] "Compatibility studies in the band 5855 5925 MHz between intelligent transport system (ITS) and other systems," Electronic Communications Committee, ECC report 101, Tech. Rep., 2007.

[13] http://www2.rohde-schwarz.com/file/FSQ_OpMa_en.pdf, Rhode&Schwarz.

[14] Rohde&Schwarz, "WLAN tests according to standard 802.11a/b/g."

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