MIMO-Enabling PHY Layer Enhancement for Vehicular Ad-Hoc Networks

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***Abstract*—Depending on traffic density and environmental influences, the radio channel in Vehicular Ad-Hoc Networks (VANETs) can be a limited resource. The Shannon-Hartley theorem gives a theoretical maximum amount of data which can be transmitted per time unit under given channel conditions. This limitation can be exceeded by using multi-antenna approaches commonly known as multiple-input, multiple-output (MIMO) communication systems. While these systems are already common in both infrastructural Wireless LAN (i.e. IEEE 802.11n or IEEE 802.11ac) and in modern cellular mobile networks (i.e. Long Term Evolution), the IEEE 802.11p standard for vehicle-to-vehicle communication still comes without any multi-antenna approaches. In this paper we show in a simulation study that compared to plain IEEE 802.11p a MIMO-extended PHY layer based on IEEE 802.11p offers a considerably higher robustness against short-term fading caused by the vehicles' mobility and other channel-caused adverseness. Therefore we implemented a MIMO-extended PHY model using Orthogonal Space-Time Block Codes (OSTBC) and linked the PHY model to a realistic MIMO radio channel model that is based on a large measurement campaign.**

Keywords*—VANET; Vehicle-to-Vehicle; PHY Model; Realistic Simulation; SISO; MIMO; IEEE 802.11p; Radio; Channel; Multi-Path; Propagation; Delay Spread; Doppler Spread

I. INTRODUCTION

The radio channel in Vehicular Ad-Hoc Networks (VANETs) is a challenging resource. Depending on the street traffic condition, it is not only shared by a highly fluctuating number of vehicles, but it is also highly varying due to the vehicles mobility. The vehicles' mobility introduces short-term fading effects due to changing multi-path propagation. Especially in urban scenarios the short-term influence caused by obstacles can be remarkable ([1], [2], [3]). A simple increase of the transmit power will not help to overcome the situation in any way because the radio channel is a shared medium. Increasing the transmit power used by a vehicle will result in a higher noise level to other vehicles which are communicating simultaneously. This can lead to a increase of packet collisions or cause ready-to-transmit stations to wait for a longer time to access the radio channel. Also the bandwidth, which is available for usage in vehicle-to-vehicle communication, is usually restricted by regulating authorities. The spatial topology in VANETs is defined by the positions and densities of the vehicles and cannot be influenced by the network designer. The mentioned limitations regarding power/noise, frequency band and spatial distribution and their impact on the maximum data rate which can be achieved is described in general by the Shannon-Hartley theorem ([4], [5]).

While the Shannon-Hartley theorem gives a theoretical limit of the amount of information which can be transmitted in a frequency-bounded channel, in its original form it is only valid for classical single-input, single-output systems (SISO), see also Figure 1.

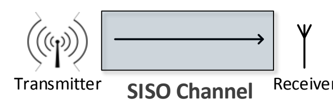

Figure 1. SISO system

Communication systems based on this concept are usually, but not necessarily, implemented as systems having one antenna for each transceiver. One possibility to increase the data rate beyond the Shannon-Hartley limit is using multi-antenna transceivers. For VANETs this means that each vehicle would be equipped with more than one antenna. All antennas are working simultaneously, are connected to the same radio device and use the same frequency channel. The corresponding system-theoretic model would be a multiple-input, multiple-output system (MIMO), see also Figure 2.

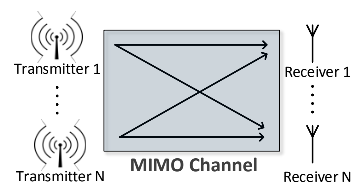

Figure 2. MIMO system

Communication systems based on the MIMO concept exploit multi-path propagation that takes place in almost all non-ideal radio channels. Electromagnetic waves propagating on various paths interact differently with obstacles which causes different attenuations and delay spreads for each signal. While the simultaneously sent signals will result in a superposition at the receiver's side without any doubt, the characteristics of the superposition are dependent on the receivers' antennas positions in space – caused by the above mentioned multi-path propagation. A MIMO-capable receiver is able to decode the differing signal superpositions by decomposing them into the original signals.

While multi-antenna systems can be also used for beam forming or, in general, for a smart antenna concept, where a phase-driven antenna array is used to transmit the sender's power into a specific spatial direction, in this paper we focus on MIMO systems to enhance the radio channel capacity.

Communication systems using MIMO are not new, anymore. Wireless LAN according to IEEE 802.11n and the most recent-version IEEE 802.11ac make use of the MIMO approach and are already available on the market. The cellular mobile standard Long Term Evolution (LTE) makes also use of MIMO. Nevertheless, the research and industry standard for VANETs, IEEE 802.11p, does not come with a specification for a MIMO-enabled version. As the radio channel in VANETs is very challenging due to the above mentioned reasons, we think that MIMO systems can be quite promising also for vehicular networks.

For this reason we implemented a MIMO-enabled version of IEEE 802.11p and compared it to the classical 802.11p protocol.

The paper is structured as follows: The next section will be used to introduce necessary background information about the radio channel and PHY layer concepts typically used in VANETs and their simulations. In the third section the related work focusing MIMO in VANETs is discussed. In the fourth section we present our MIMO approach and the parameterization of our simulation study. The fifth chapter is used to publish the simulation studies' results while the last chapter closes the paper with a roundup and a little outlook on possible further research.

II. MIMO Communication in VANETs

This section introduces the basics of MIMO communication in VANETs.

A. VANET Radio Channel

The characteristics of the radio channel play a fundamental role in the design and performance of VANET systems. Therefore we will explain the most important properties of the radio channel in VANETs. The most important channel effect is the multi-path propagation. This is caused by the interaction of the transmitted electromagnetic signal with obstacles (buildings, other vehicles, street surface, trees and small objects like street poles or traffic signs). The most important physical effects are specular and diffuse reflection (scattering) at objects' surfaces, refraction when waves propagate through materials and diffraction at edges. In the frequency range of 5.9 GHz buildings regularly have considerable shadowing effects to electromagnetic waves. This leads to the effect that in inner-city scenarios with a high density of buildings vehicle-to-vehicle communication often takes place without a direct line of sight. Due to the interactions with obstacles the signal will typically reach a receiver via different paths. Each path influences phase, signal power and propagation time individually depending on obstacle interactions and the lengths of the paths. Therefore, the receiver detects a superposition of the signal parts that arrive via different paths. This effect is also called delay spread and shown in Figure 3.

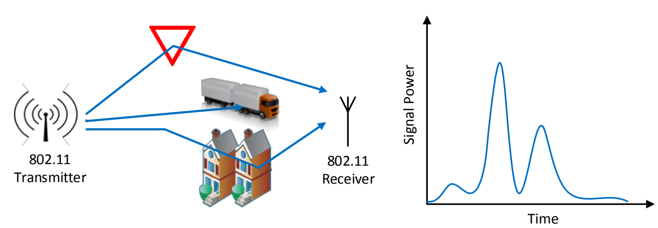

Figure 3. Multi-Path Propagation results in a delay spread of the signal at the receiver's side

Additionally, as a result of the vehicles' mobility, a Doppler shift occurs. IEEE 802.11p uses Orthogonal Frequency Division Mutiplexing (OFDM) as a multi-carrier modulation system. In OFDM systems Doppler shifts can cause the displacement of transmit power from one OFDM sub-carrier into another. This leads to a lower Signal to Noise Ratio (SNR) in all affected sub-carriers as signal-power from sub-carrier n poses noise for sub-carrier $n+1$ and sub-carrier $n-1$. The Doppler effect has been considered explicitly in our study.

B. VANET Radio Channel Simulations

As our approach is studied in a simulation, a short overview about modeling radio channels in VANET simulations will be given here.

1) *Measurement-based Channel Models.* This is accomplished by setting up impulse responses based on measured frequency sweeps in the real-world vehicle-to-vehicle scenarios which are studied. For many studies this approach is too expensive, because vehicles have to be equipped with prototypes and channel sounding equipment. Also a lot of measurement data have to be collected to average out side effects.
2) *Purely Statistical Channel Models.* These models are originally also based on measured channel characteristics. Contrarily to the above mentioned approach, they completely abstract from the scenario's environment. The measured data lead to a statistical distribution of the SNR and thus the packet error rate. Typically, the distance between transmitting and receiving node is used as an input value. The purely statistical models are quite inaccurate as they do not consider specific obstacles.
3) *Deterministic Channel Models.* The idea behind deterministic channel models is to reproduce the physical effects which occur to a signal on its spread from transmitter to receiver in a computer simulation. Therefore, a realistic model of the whole scenario is part of the simulator. The signal propagation is typically simulated by geometrical optics, but enhanced by models for wavelength specific effects like edge-diffraction. While these models simulate the channel's characteristics quite accurately, the computation time needed for their execution is tremendous.
4) *Combined Approaches.* To overcome the drawback of each approach, combinations can be used. It is, for example, possible to use a very simplified geometrical optics simulation just to calculate the existence of a direct line of sight between transmitter and receiver. Based on the result, an according statistical channel model can be chosen. Of course, this method can be performed also in more fine-granular ways.
   To evaluate our approach, we needed an explicit MIMO channel model, therefore we deciced for the first of the mentioned methods. The impulse responses we used to verify our MIMO PHY layer are based on a large field study done by Schneider et al. at Ilmenau University ot Technology ([6], [7]), see also Figure 4. We combined their channel models with Doppler spreads (see Figure 5) which typically occur in VANETs due to the vehicles' mobility.
   To the best of our knowledge no other MIMO study of that thoroughness is available for research purpose.

C. PHY Layer in VANETs

IEEE 802.11p constitutes the industry standard for VANET. Therefore we use this as a reference. From a PHY layer perspective, the most important fact is that IEEE 802.11p uses OFDM like many other IEEE 802.11 standards do.

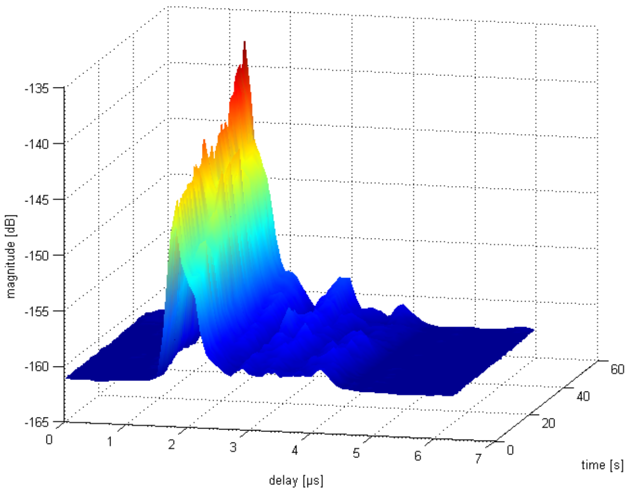

Figure 4. Channel Measurement data from Ilmenau University ot Technology ([6], [7])

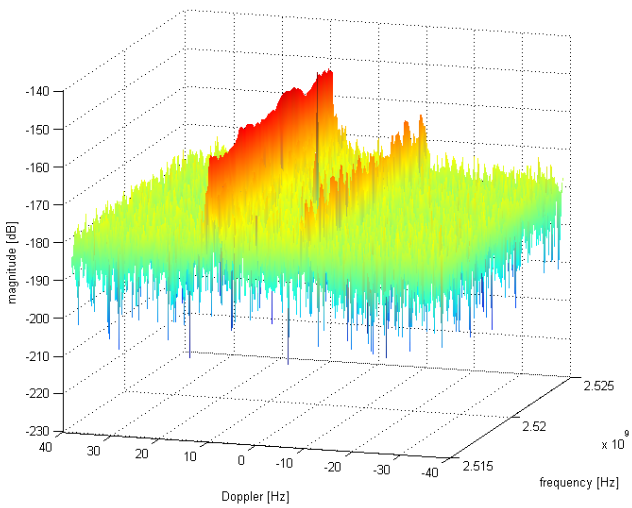

Figure 5. Doppler Spectrum

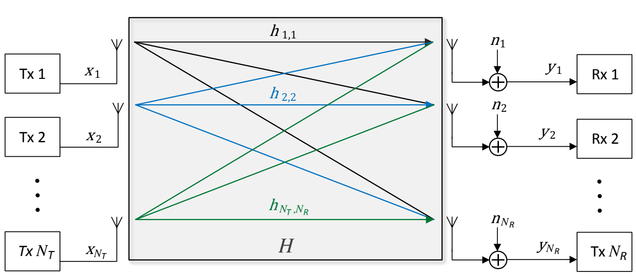

Figure 6. MIMO communication system exploiting the MIMO properties of the radio channel. For each pair of transmitter output and receiver input the radio channel behaves differently. The according impulse response is $h_{i,j}$. The channel response matrix H contains the impulse response for all transmitter and receiver pairs.

D. PHY Layer in VANET Simulations

The majority of VANET simulations, especially when the focus of research is on the routing layer or above, gets along without explicit PHY simulations. This means that in many simulation studies it is regularly abstracted from the quite complex and computationally intensive PHY layer calculations. The abstraction can be accomplished by a kind of table which describes a relation between SNR on the one hand and both, bit rate and bit error rate on the other hand. This allows to work completely within the bit or even packet perspective. While this leads to quite an efficient simulation, it typically abstracts from fluctuating short-term fading effects that occur to the signals. It also requires that a deep understanding of the influence of the SNR on a specific PHY layer is already present.

In our study, we focus especially on the PHY layer, which is the core of our work. For this reason we have to simulate it explicitly. Besides that, we do not have a direct link between SNR and bit error rate, yet.

E. MIMO Communication

In general, the term MIMO stems from system theory and classifies system according to their number of inputs and outputs. It the field of wireless communication, MIMO systems are communication systems which exploit the MIMO characteristics of the radio channel. They can be seen as a subset of multi-antenna communication systems.

The MIMO concept can be used for three fundamental purposes:

1) *Diversity Gain.* By transmitting a bit stream via more than one antennas (transmit diversity) and by receiving it via more than one antenna (receive diversity), the error rate can be reduced for a given bit rate. This means, a diversity gain system does not offer higher data rates for one link, but higher robustness. Due to the reduction of bit errors, the number of possibly expensive re-transmissions of packets will decline.
2) *Multiplexing Gain.* In this case, more than one bit stream is transmitted via a multi-antenna system simultaneously. In theory, the data rate can be multiplied by the number of the parallel bit streams. Therefore, the spectral efficiency of the system can be increased, but it does not behave more fault-tolerantly.
3) *Smart Antennas.* From a system-theoretic point of view, a communication system driving an phased-array of antennas can be also seen as a MIMO system. This approach is usually not counted to the typical variants of MIMO. Nevertheless, it is possible to combine this approach with the above mentioned.

In this paper, we focus on diversity gain MIMO systems. This decision is based on the fact that a lot of applications, especially the safety-related ones, in VANETs rather benefit from a more robust system than from a higher data throughput. Of course, in the area of infotainment, also applications demanding a high data rate can be assumed. It makes sense to explore that in a separate work.

III. Related Work

As mentioned in the introduction, MIMO communication systems are not new at all. They are commercially available, for example in WLAN devices based on IEEE 802.11n or IEEE 802.11ac and in LTE devices. In this section we focus on the research done by other groups that refer to the usage of MIMO in VANETs or ad-hoc networks.

Sundaresan et al. ([8]) discuss alternative MAC approaches for ad-hoc networks. By showing that a stream-controlled medium access protocol (SCMA) can reach a higher performance and fairness compared to CSMA/CA they propose also MIMO communication systems for ad-hoc networks.

Abdullah et al. ([9]) used Space-Time Block Codes in an IEEE 802.11p VANET environment combined with modifications of the MAC layer to show that STBC codes in general can be used to enhance the range of receipt in a high-way scenario by up to 80%.

Fernández-Caramés et al. ([10]) implemented a prototype of a communication system consisting of multi-antenna IEEE 802.11p transceiver. An FPGA-based channel emulator is used to reproduce a configurable MIMO radio channel behavior. Based on this setup they evaluated various multi-antenna configurations and compared them to the classical SISO approach with very interesting results: The MIMO variants proposed in ([10]) showed significant improvements compared to the SISO communication according to IEEE 802.11p. We extended their comparisons by doing further configurations. While the FPGA-based channel emulation offers a high performance, we focus on a pure simulation-based approach that is more flexible in early studies because FPGA programming and the connection to the FPGA can be omitted.

IV. MIMO-Enabling PHY Layer Enhancement for IEEE 802.11p

In the context of MIMO systems, a lot of varying versions are possible. One of the main distinguishing properties is the question, on which side (transmitter or receiver) multiple inputs or outputs exist. Therefore, the following types of MIMO systems can be described:

- *Single input, single output (SISO).* This is the classical, non-MIMO-capable base system like proposed in the industry standard IEEE 802.11p.
- *Single input, multiple outputs (SIMO).* This is also called *receive diversity*. Please note the possibly confusing terms as the input and outputs are seen from the radio channel's perspective and not from the communcation device's.
- *Multiple inputs, single output (MISO).* This is also called *transmit diversity*.
- *Multiple inputs, multiple outputs (MIMO).* This means full *transmit* and *receive diversity*.

These types can be further sub-categorized according to the number of inputs or outputs they have, for example SIMO system can be in the variant 1x2 and 1x4 which means that it has a two-times (resp. four-times) receive diversity, i.e. two or four antennas.

For our study, we set up the following systems:

- *SISO* SISO system 1x1 (= plain 802.11p)
- *MRC 1x2* SIMO system 1x2 (receive diversity, with maximum-ratio combining in the receiver)
- *MRC 1x4* SIMO system 1x4 (receive diversity, with maximum-ratio combining in the receiver)
- *OSTBC 2x1* MISO system 2x1 (transmit diversity via Orthogonal Space-Time Block Codes (OSTBC))
- *OSTBC 2x2* MIMO system 2x2 (combination of transmit diversity via OSTBC and receive diversity)
- *OSTBC 2x4* MIMO system 2x4 (combination of transmit diversity via OSTBC and receive diversity)

We started our simulation study with a PHY model of IEEE 802.11a. This is available in the examples of the Simulink Communications Toolbox from The Mathworks ([11]). The main differences between IEEE 802.11a and 802.11p are the frequency band and the channel width. As our PHY layer model works in the baseband anyway, the different frequencies could be neglected. We adjusted the channel bandwidth from 20 MHz in IEEE 802.11a to 10 MHz in 802.11p which implied changing the parameters of our model as given in Table I.

Table I. Parameters changed in IEEE 802.11a PHY model to adjust to the smaller channel with in IEEE 802.11p

Parameter	802.11a	802.11p
Δ_{F}: Frequency band per OFDM subcarrier	$0.3125\mathrm{MHz}$ $(= 20\mathrm{MHz}/64)$	$0.15625\mathrm{MHz}$ $(= 10\mathrm{MHz}/64)$
T_{FFT}: FFT and IFFT Period	$3.2\mu s(1/\Delta_{\mathrm{F}})$	$6.4\mu s(1/\Delta_{\mathrm{F}})$
T_{PREAMBLE}: Duration of the PLCP Preamble	$16\mu s$ $(= T_{\mathrm{SHORT}} + T_{\mathrm{LONG}})$	$32\mu s$ $(= T_{\mathrm{SHORT}} + T_{\mathrm{LONG}})$
T_{SIGNAL}: Duration of the SIGNAL BPSK-OFDM Symbol	$4\mu s$ $(= T_{\mathrm{GI}} + T_{\mathrm{FFT}})$	$8\mu s$ $(= T_{\mathrm{GI}} + T_{\mathrm{FFT}})$
T_{GI}: Duration of the Guard Interval	$0.8\mu s$ $(= T_{\mathrm{FFT}}/4)$	$1.6\mu s$ $(= T_{\mathrm{FFT}}/4)$
T_{GI2}: Duration of the Training Symbol	$1,6\mu s$ $(= T_{\mathrm{FFT}}/2)$	$3.2\mu s$ $(= T_{\mathrm{FFT}}/2)$
T_{SYM}: OFDM Symbol Interval	$4\mu s$ $(= T_{\mathrm{GI}} + T_{\mathrm{FFT}})$	$8\mu s$ $(= T_{\mathrm{GI}} + T_{\mathrm{FFT}})$
T_{SHORT}: Duration of the short training sequences	$8\mu s$ $(= 10 \cdot T_{\mathrm{FFT}}/4)$	$16\mu s$ $(= 10 \cdot T_{\mathrm{FFT}}/4)$
T_{LONG}: Duration of the long training sequences	$8\mu s$ $(= T_{\mathrm{GI2}} + 2 \cdot T_{\mathrm{FFT}})$	$16\mu s$ $(= T_{\mathrm{GI2}} + 2 \cdot T_{\mathrm{FFT}})$

The resulting SISO PHY model for IEEE 802.11p has been used as a base for the MIMO enhancements we developed and as a reference in our analysis chapter. The model of the 2x2-MIMO system is shown in Figure 2.

V. Simulation Results and Analysis

For the simulation, we tested the implemented PHY models und varying signal to noise ratios by applying AWGN noise to the presented channel. This is equal to reducing the transmit power. We used the following simulation parameters:

- *SNR:* From 0 to 20 dB in intervals of 4 dB.
- *Duration of Simulation:* We stop after 10^5 bit errors or after 10^8 transmitted bits.
- *OFDM Parameters:* 20 OFDM data symbols and 4 training symbols.
- *Channel model:* Ilmenau Models as described in Section 2.

The environment used for simulation was Matlab/Simlink 2013a with the Communication Toolbox.

Figure 8 shows comparisons of bit error rates for given signal to noise ratios. All simulations have been run under the same channel setup, a Doppler enhanced version of the MIMO channel measurement data from Ilmenau University of Technology. The figure shows that the 802.11p SISO model performs quite bad compared to the more advanced models. It also shows that pure transmit diversity (OSTBC 2x1) does not improve the situation much. Pure receive diversity (e.g. MRC 1x2 and MRC 1x4) perform much better. As expected, the full MIMO system combining transmit and receive diversity performs best (OSTBC 2x4). The bit error rate for OSTBC 2x4 drops to 0 even at an SNR of 4 dB.

In Figure 9 and Figure 10 the direct link between varying SNR values and occurring bit errors for a simulation period of 1 s is given. It shows how the fluctuation of the SNR causes bit errors. It can be clearly seen that the SIMO approaches

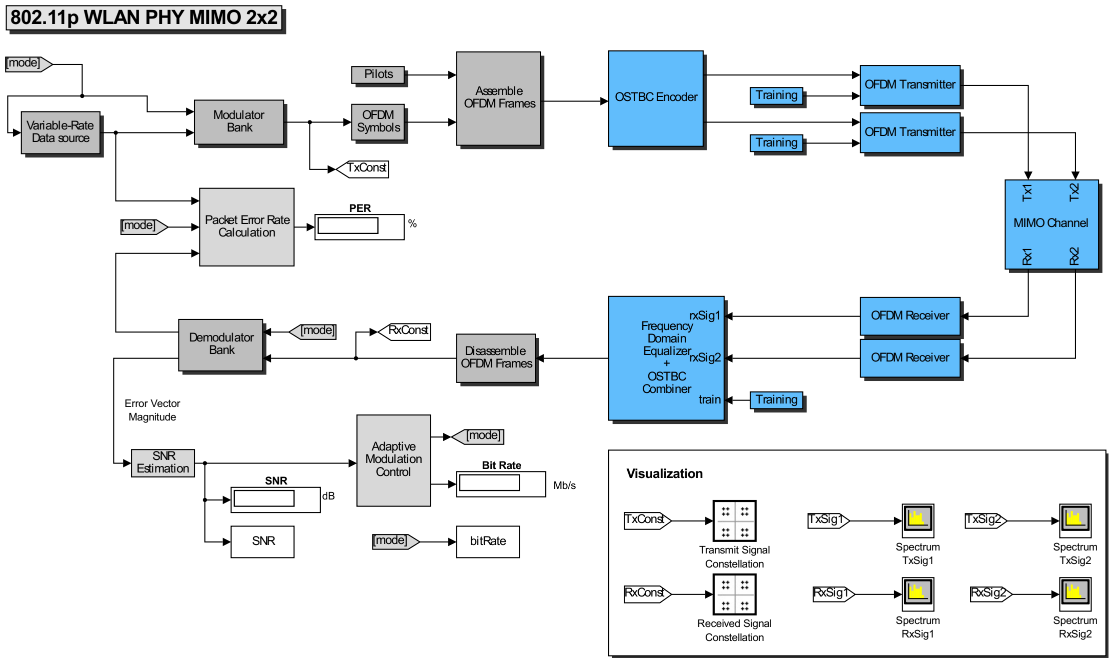

Figure 7. OSTBC-based MIMO Enhancement of the 802.11p PHY Layer in Matlab/Simulink

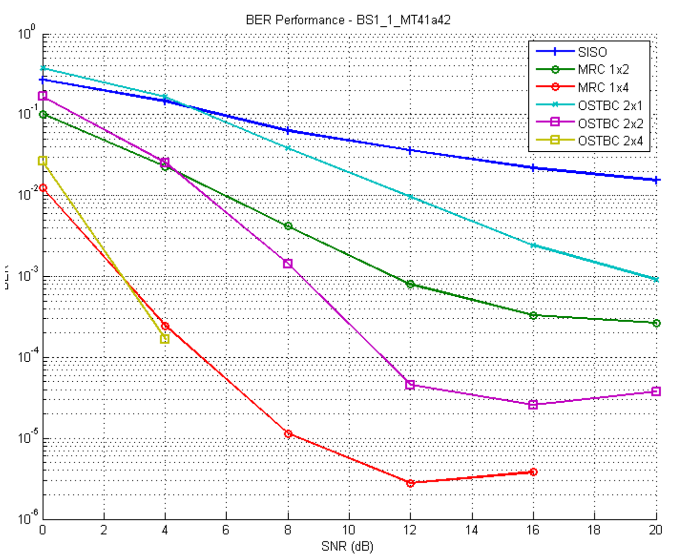

Figure 8. Bit Error Rate (BER) Comparison for Different Multi-Antenna Enhancements of IEEE 802.11p.)

perform much better than the MISO variant. As expected, also here OSTBC 2x4 performs best.

VI. Conclusion and Outlook

In this paper we have shown that the industry standard IEEE 802.11p for VANETs can be extended to a full MIMO system which can be used for advanced network simulations. We have further shown that some variants of MIMO can make the communication in a typical VANET environment remarkably more robust compared to classical SISO systems. The drawback of MIMO systems is the higher complexity of the transmitter and the receiver resulting in a higher power usage. During the last years MIMO systems have found their way into infrastructure-based communication systems which has led to cheap and energy-efficient chip-sets. It can be assumed that this trend will go on in future.

For this reason their potential for VANETs have to be explored more thoroughly. Research is needed which goes beyond the scope of this paper.

Especially, the following questions must be answered:

- MIMO communication systems exploit the radio channel's multi-path propagation behavior. It has to be clarified if there are any channel constellations, especially in a highly-shared medium, which can impact the MIMO system in a way that it performs worse than the corresponding SISO system. Therefore the MIMO PHY layer must be included in a holistic simulation model as proposed in [12] or [3] to run simulations at large.
- In this work, we have focused on the diversity gain purpose of MIMO communication systems as we think that a robust communication platform for VANETs is especially interesting for safety-relevant applications. In a highly-shared medium the multiplexing approach can be also interesting, especially when it is linked with medium access control mechanisms to reduce network access latency in crowded situations.
- How much does MIMO actually improve the performance of the whole VANET? Noticeable improvements for the performance of a VANET can be assumed especially when retransmissions or multi-hop communication can be avoided because messages can be transmitted over a longer distance or in a noisier channel. Probably the strategy for packet forwarding decisions ins VANETs have to be adjusted.
- Which antenna configurations are the optimum and how do MIMO approaches interact with beam forming approaches in a realistic environment?

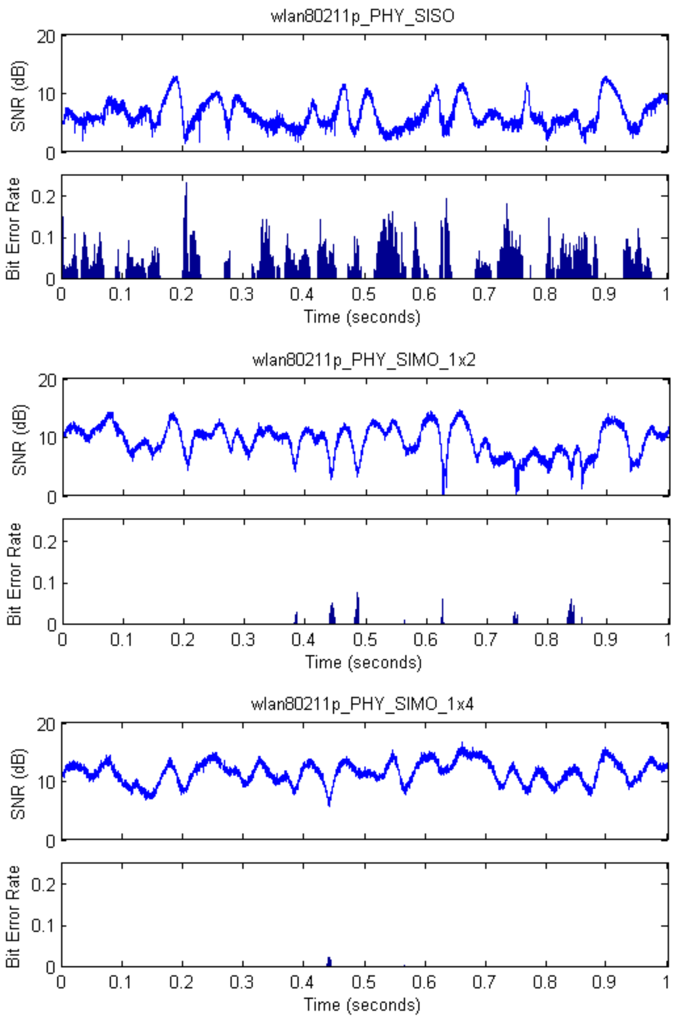

Figure 9. Relation between SNR values and occurring bit errors for SISO, SIMO 1x2 and SIMO 1x4

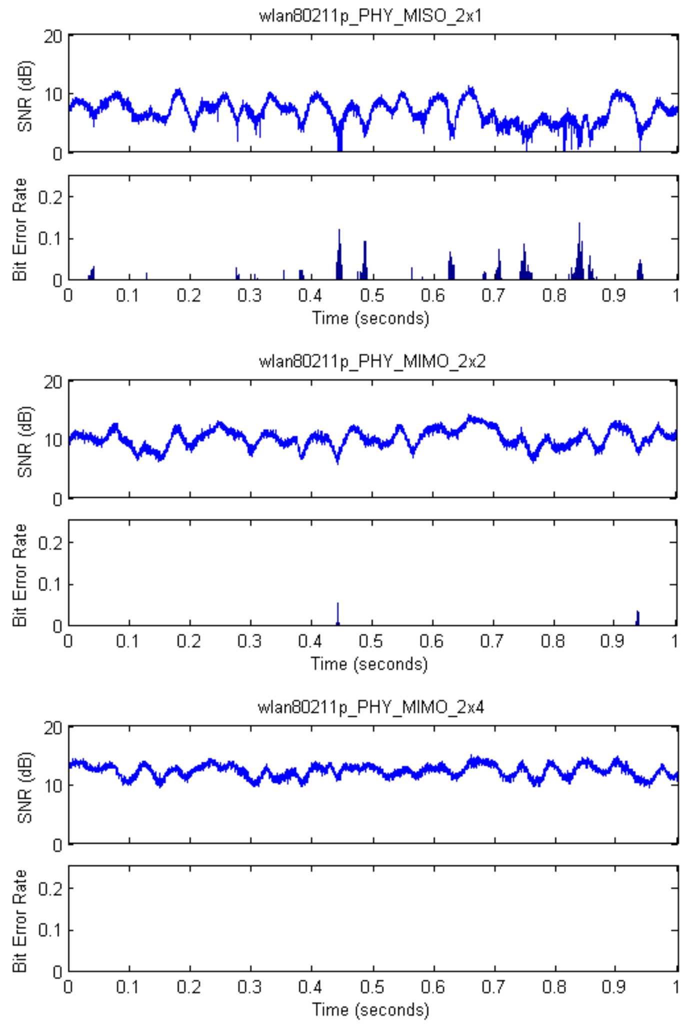

Figure 10. Relation between SNR values and occurring bit errors for MISO 1x2, MIMO 2x2 and MIMO 2x4

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