SDR Demonstration System for the Investigation of Cooperative Communication and the Scaling Behaviour of MANETs

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Abstract. Efficient broadcasting is very important for currently poorly scaling mobile ad-hoc networks (MANETs). Cooperative transmission protocols can significantly improve the scaling behaviour. This paper focuses on the implementation of a scalable MANET demonstration system with multiple software-defined radios (SDRs) which allows to thoroughly investigate different cooperative transmission and broadcast techniques and the improvements which can be achieved in practical systems. Measurement results show the advantages of cooperative broadcasting, distributed transmit diversity, and signal-to-noise ratio (SNR) aggregation.

Keywords: Demonstration-System · Cooperative Communication · Distributed Transmit Diversity · Space-Time Block Codes · Alamouti · Software Defined Radio (SDR) · Signal-To-Noise-Ratio (SNR) Aggregation · Cooperative Broadcast · Mobile Ad-hoc Network (MANET) Scalability · Quadrature Amplitude Modulation (QAM), Orthogonal Frequency Division Multiplexing (OFDM), Filter Bank Multi-Carrier (FBMC)

1 Introduction

Mobile ad-hoc networks (MANETs) play a vital role in mission critical communication systems that should deliver reliable communication means in all situations, e.g. if conventional networks (LTE, Wi-Fi, wired broadband systems, etc.) are not available or collapse. As such systems cannot rely on fixed infrastructure such as wired routers or managed access points, they have to be designed in a decentralized manner, should be self-organizing, and avoid single points of failure. Advantages of MANETs over managed networks include flexibility (they can be built everywhere), low administration costs (no need to build infrastructure), self-healing ability (new paths can be established if links break or nodes disappear), and scalability (networks can easily be extended by more nodes) [1]. Due to their dynamic and flexible nature, MANETs are thus widely used in secured and robust networks for public authorities, disaster rescue, transportation, unmanned vehicles, sensor networks, or military communications [1, 2].

As shown in [3], the accumulated throughput in a MANET with N nodes can however not grow larger than $O(\sqrt{N})$ when the messages are forwarded in a unicast multi-hop fashion. This means, such networks scale poorly with an increasing number of nodes. Besides this, also the necessary network organization introduces a growing overhead. As each node can move independently and in any direction, the links between nodes may change frequently. The multi-hop forwarding thus requires sophisticated routing algorithms. Especially in large dynamic networks where the topology is constantly changing, routing information has to be shared among all nodes in the network to establish and maintain correct and up-to-date routing tables [2, 4, 5]. The overhead introduced by sharing routing information can thus lead to a significant decrease in network performance (e.g. long delays, throughput degradation, connectivity problems, and others). In case of a proactive routing strategy, typically *Hello* and *Topology-Control (TC)* messages are distributed. The TC messages are broadcast (or multicast) messages sent from each node to all (or a subset of) other nodes in the MANET. Hence, effective and efficient broadcasting is very important to implement reliable and efficient routing strategies.

With cooperative transmission protocols, the scaling behavior can significantly be improved: Information theoretical work has shown that a scaling law of $O(N \log N)$ is achievable [6]. The proposed cooperative transmission method of *distributed hierarchical multiple-input multiple-output (MIMO) transmission* is, however, of high complexity and difficult to implement in practice. In order to improve the scaling behavior of practical MANETs, some other cooperative approaches have been developed. Examples are *multistage cooperative broadcast* [7] and *barrage relaying* [8]. These cooperative approaches focus on broadcast (or multicast) instead of unicast communication. Thereby, all nodes which were able to correctly decode the message transmitted by a source node in a first time slot support the transmission in the next time slot by re-transmitting the same message simultaneously. Nodes that could decode the message in the second time slot start to re-transmit it in the following time slot and so on until all intended nodes receive the message successfully. In order to achieve a diversity gain, [7] proposes to use a distributed transmit diversity scheme such that the different signal contributions add up in power at the receiving nodes and the messages spread through the network quickly. Barrage relaying [8] follows a similar approach but applies a specific phase dithering scheme in addition to turbo-like error correction. Each transmitting node pseudo-randomly dithers its carrier phase, such that the superposition of these signals induces a time-varying channel characteristic at the receiving nodes. An error correction code is then used to extract time diversity provided by the time-varying fading channel.

Compared to classical broadcasting, such cooperative communication methods can achieve large gains by reducing the required number of time slots to spread messages to all (intended) nodes. Improving the efficiency of broadcasting in a MANET can also enhance the scaling behavior of the network when unicast traffic is considered. This is because the overhead introduced by routing is one main reason for the poor scalability. Establishing and updating routing tables is often based on broadcasting. Having a more efficient spreading of the routing information thus results in more resources available for transmitting unicast messages. Therefore, cooperative transmission schemes can improve the performance of MANETs in various ways:

- To quickly spread messages to multiple (multicast) or all (broadcast) other nodes in the network.
- To efficiently establish and refresh proactive routing tables in a MANET, specifically to distribute Hello and TC messages.
- To distribute the message of a source node to its neighborhood to form a virtual MIMO (VMIMO) cluster that can further improve the performance by spatial multiplexing (cf. distributed hierarchical MIMO transmission [6]).

Contribution: In this paper, we focus on the implementation of a demonstration system to study different cooperative transmission and broadcast techniques and the gains that can be achieved with them in practice. The developed system is based on multiple software-defined radios (SDRs), is very flexible, implements single-carrier quadrature amplitude modulation (QAM), orthogonal frequency division multiplexing (OFDM) as well as filter bank multi-carrier (FBMC) modulation, and allows for comparison of all combinations of the implemented modulation and cooperation schemes. Using this demonstration system, we develop, implement, and study practical and efficient MANET broadcasting schemes based on cooperative transmission protocols (e.g., distributed transmit diversity schemes) for multi-carrier systems.

In a first step, we study a distributed Alamouti scheme [9] and extend it to a combination with signal-to-noise ratio (SNR) aggregation for cooperative broadcasts in a single-carrier setup. With SNR aggregation, each receiver node stores two or more observations of the broadcast message and, eventually, combines them to enhance the probability of successful decoding.

In a second step, we show that the system is very flexible and scalable regarding both the number of participating nodes and number of multi-carrier tones. Furthermore, we outline how these schemes can drastically improve the broadcasting in MANETs.

2 Design and Setup of the Demonstration System

To build a scalable and flexible MANET demonstration system, different hardware platforms and development environments have been investigated to find the most suitable selection. Thereafter, first a simulation environment has been developed to prove that the signal processing and principal signal chains are working as expected. Second, the software has been adapted on real hardware using SDRs. Last, some measurements have been conducted to prove the concept and show that the demonstration system can be used to verify and demonstrate various cooperation schemes.

Within this section, the system model used for the demonstration system and a brief overview of the state of the art will be provided. Thereafter, the hardware and software setup will be explained in detail. The section will end by discussing the transmitter and receiver implementation.

2.1 System Model

For the demonstration system we consider a distributed multiple-input single-output (MISO) system consisting of multiple source nodes TX_n, $n = 1, 2, \ldots, N$, and a single destination node RX, all equipped with a single antenna as shown in Figure 1. Distributed MISO systems are often considered to be a promising approach in MANETs as several nodes can assist each other in transmitting data and thus increasing the range and reducing the outage probability.

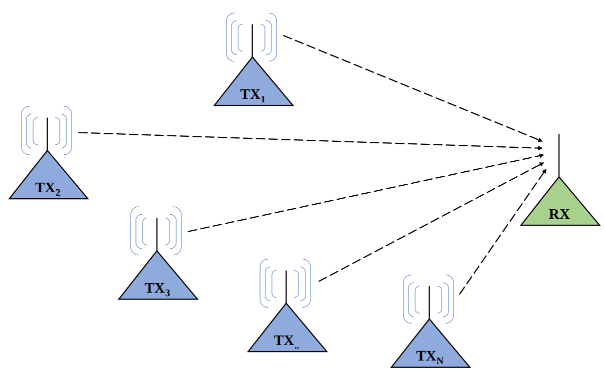

Fig. 1. System model for the demonstration system.

The transmit symbol vector $\mathbf{x} \in \mathbb{C}^{1\text{x}N}$ comprises the symbols of all cooperating nodes. The structure of $\mathbf{x}$ depends on the cooperation scheme used by the nodes (e.g. distributed transmit diversity or distributed beamforming). The single antenna receiver RX observes the received symbol $y \in \mathbb{C}^{1\text{x}1}$ with

$$y = \mathbf{h}^{\mathrm{T}} \cdot \mathbf{x} + n, \tag{1}$$

where $\mathbf{h} \in \mathbb{C}^{1\text{x}N}$ is the channel vector assuming a narrowband channel model in the equivalent baseband, comprising the complex channel taps between each transmitter and the receiver. The scalar $n \in \mathbb{C}^{1\text{x}1}$ models additive white Gaussian noise.

The demonstration system is designed such that it allows to study different forms of transmit cooperation combined with different modulation schemes, as e.g., single-carrier modulation, OFDM, and FBMC. Thereby, we are particularly interested in cooperation techniques that apply transmit diversity.

2.2 State of the Art

In literature, different transmit diversity techniques are proposed to mitigate the effect of short term fading. Examples of such techniques include delay diversity schemes [10], space-time codes, space-frequency codes, phase roll diversity schemes [11]. In the following, we focus on space-time codes. We distinguish roughly between orthogonal space-time block codes (OSTBCs) [9, 12], non-orthogonal space time block codes (NOSTBCs) [13, 14], and trellis codes [15]. In a first step, we are going to study the use of distributed OSTBCs with the help of our demonstration system.

The first orthogonal space-time block code was the *Alamouti code*, a transmit diversity scheme for two transmit antennas [9]. Tarokh et al. generalized the principle of this scheme in [12], where they proposed space-time block codes from orthogonal designs. Theses codes can be designed for any number of transmit antennas and they achieve the full transmit diversity gain. The maximum-likelihood (ML) decoding is very simple and of very low complexity. The most important disadvantage is, that OSTBCs for more than two antennas do not achieve the full rate, i.e. they lead to a rate loss. For more than four antennas the maximum rate is only 0.5 (for $n = 3$ and $n = 4$ transmit antennas, there are OSTBCs achieving a rate of $R = \frac{3}{4}$).

In this paper, we apply a distributed transmit diversity scheme based on the Alamouti code. The goal is to implement an efficient cooperative broadcasting scheme.

A similar multi-antenna diversity demonstration system which utilizes the Alamouti scheme on USRP boards is described in [16]. The authors have successfully implemented a complete communication system using SDRs, MATLAB and GNU Radio. However, the focus of their work was on the implementation aspects using two SDRs and not on the scaling behaviour of MANETs. Hence, only a single SDR equipped with two antennas was used on the transmit side and another SDR on the receiving side.

One very important aspect to achieve transmit diversity through the use of space-time block codes (STBC) like the Alamouti scheme is knowledge about the channel impulse response (CIR) at the receiver. The channel estimation performance of a MIMO-OFDM system based on the Alamouti scheme is studied in [17]. However, no measurements on hardware have been performed.

MATLAB in combination with SDRs seems to be a popular approach to build up a demonstration system with low costs. Measel et. al. also implemented an OFDM-MIMO demonstration system utilizing the Alamouti scheme [18]. Unlike the focus of this paper, their demonstration system was implemented to characterize already existing communication systems but not to investigate cooperative broadcast techniques with respect to the scalability of MANETs.

Horváth and Bakki implemented a prototype transmission link for FBMC [19]. They also used the USRP SDR platform from Ettus Research for the transmitter and receiver. Moreover, they performed some measurements regarding the power spectral density, the peak-to-average power ratio, and the bit error rate (BER) to validate their system design. In contrast to this paper, they focused on a SISO system and not on a MISO system. Their main aim was the realization of an FBMC transmission testbed based on one link.

Dziri et al. implemented a comparable real-time FBMC transmission link [20]. In addition to [19], they also implemented a channel, hence built up a more sophisticated transmission model. Comparable to the demonstration system presented in this paper, they used MATLAB to develop the software and the USRP SDR platform from Ettus Research. But in contrast, they stuck to a SISO model and did not further consider any diversity scheme. Their focus was to solve some practical problems, mainly time and frequency synchronization as well as channel estimation and equalization.

2.3 Space-Time Coding

Space-time coding means to code data across both space and time to achieve transmit diversity. A simple scheme is to use a repetition scheme with two time slots. In time slot 1, only transmit antenna 1 is transmitting symbol α, in time slot 2, the same symbol α will be transmitted by antenna 2. This can be described in matrix notation:

$$\begin{aligned}\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} &= \begin{pmatrix} x_{11} & x_{21} \\ x_{12} & x_{22} \end{pmatrix} \cdot \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} \\ &= \begin{pmatrix} \alpha & 0 \\ 0 & \alpha \end{pmatrix} \cdot \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}.\end{aligned} \tag{2}$$

Note, that due to the time-slotted approach, the data rate is only 1/2. The receiver will combine the two signals using the maximum-ratio combining approach to maximize the SNR of the received signal:

$$\begin{aligned} y &= y_1 \cdot h_1^* + y_2 \cdot h_2^* \\ &= \left(|h_1|^2 + |h_2|^2\right) \alpha + h_1^* n_1 + h_2^* n_2. \end{aligned} \tag{3}$$

2.4 Alamouti Scheme

To overcome the drawback of rate reduction, two symbols have to be transmitted in two time slots. This is achieved by a transmit symbol vector $\boldsymbol{x}_1 = (\alpha_1, \alpha_2)^{\mathrm{T}}$ in a first time slot and $\boldsymbol{x}_2 = (-\alpha_2^*, \alpha_1^*)^{\mathrm{T}}$ in a second. The receiver observes $y_1 \in \mathbb{C}^{1\mathrm{x}1}$ in the first time slot, and y_2 in the second; both are stacked in a vector $(y_1, y_2)^{\mathrm{T}}$.

The resulting matrix notation for this is

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \sqrt{\frac{E_s}{2}} \cdot \begin{pmatrix} \alpha_1 & \alpha_2 \\ -\alpha_2^* & \alpha_1^* \end{pmatrix} \cdot \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}, \tag{4}$$

which can be rewritten as

$$\begin{pmatrix} y_1 \\ y_2^* \end{pmatrix} = \sqrt{\frac{E_s}{2}} \cdot \begin{pmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{pmatrix} \cdot \begin{pmatrix} \alpha_1 \\ \alpha_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2^* \end{pmatrix} \tag{5}$$

$$\mathbf{y} = \sqrt{\frac{E_s}{2}} \cdot \mathbf{H} \cdot \boldsymbol{\alpha} + \mathbf{n}. \tag{6}$$

Decoding will be performed by multiplying with $\mathbf{H}^{\mathrm{H}}$:

$$\begin{aligned}
\mathbf{r} &= \mathbf{H}^{\mathrm{H}} \cdot y && (7)\\
&= \sqrt{\frac{E_s}{2}} \cdot \mathbf{H}^{\mathrm{H}}\mathbf{H} \cdot \boldsymbol{\alpha} + \mathbf{H}^{\mathrm{H}}\mathbf{n} && (8)\\
&= \sqrt{\frac{E_s}{2}} \cdot \begin{pmatrix} h_1^* & h_2 \\ h_2^* & -h_1 \end{pmatrix} \cdot \begin{pmatrix} h_1 & h_2 \\ h_2^* & -h_1* \end{pmatrix} \cdot \boldsymbol{\alpha} + \mathbf{H}^{\mathrm{H}}\mathbf{n} && (9)\\
&= \sqrt{\frac{E_s}{2}} \cdot \begin{pmatrix} |h_1|^2 + |h_2|^2 & 0 \\ 0 & |h_1|^2 + |h_2|^2 \end{pmatrix} \cdot \boldsymbol{\alpha} + \mathbf{H}^{\mathrm{H}}\mathbf{n}. && (10)
\end{aligned}$$

Thus, two independent channels are established which gives about 4 dB improvement compared to the repetition scheme in order to achieve the same data rate [21].

Considering a frequency offset of both transmitters with respect to the local oscillator of the receiver, (4) can be rewritten as

$$\begin{aligned}
\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} &= \sqrt{\frac{E_s}{2}} \cdot \begin{pmatrix} x_{11} \cdot e^{j\omega_1 t} & x_{21} \cdot e^{j\omega_2 t} \\ x_{12} \cdot e^{j\omega_1 (t+T_s)} & x_{22} \cdot e^{j\omega_2 (t+T_s)} \end{pmatrix} \cdot \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n2 \end{pmatrix} && (11)\\
&= \sqrt{\frac{E_s}{2}} \cdot \begin{pmatrix} \alpha_1 \cdot e^{j\omega_1 t} & \alpha_2 \cdot e^{j\omega_2 t} \\ -\alpha_2^* \cdot e^{j\omega_1 (t+T_s)} & \alpha_1^* \cdot e^{j\omega_2 (t+T_s)} \end{pmatrix} \cdot \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}, && (12)
\end{aligned}$$

where T_s is the slot duration. Assuming that the frequency offset is so small that the phase shift that occurs due to the frequency offset between time slot 1 and time slot 2 can be neglected, i.e.

$$e^{j\omega_1 t} \approx e^{j\omega_1 (t+T_s)} \tag{13}$$

and

$$e^{j\omega_2 t} \approx e^{j\omega_2 (t+T_s)}, \tag{14}$$

equation (11) can be rewritten as

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \sqrt{\frac{E_s}{2}} \cdot \begin{pmatrix} h_1 \cdot e^{j\omega_1 t} & h_2 \cdot e^{j\omega_2 t} \\ h_2^* \cdot e^{-j\omega_2 t} & -h_1^* \cdot e^{-j\omega_1 t} \end{pmatrix} \cdot \begin{pmatrix} \alpha_1 \\ \alpha_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}. \tag{15}$$

As described above, decoding can thus be performed by multiplying with $\mathbf{H}^{\mathrm{H}}$:

$$\begin{aligned}
\mathbf{r} &= \mathbf{H}^{\mathrm{H}} \cdot \mathbf{y} && (16)\\
&= \sqrt{\frac{E_s}{2}} \cdot \mathbf{H}^{\mathrm{H}}\mathbf{H} \cdot \boldsymbol{\alpha} + \mathbf{H}^{\mathrm{H}}\mathbf{n} && (17)\\
&= \sqrt{\frac{E_s}{2}} \cdot \begin{pmatrix} h_1^* \cdot e^{-j\omega_1 t} & h_2 \cdot e^{j\omega_2 t} \\ h_2^* \cdot e^{-j\omega_2 t} & -h_1 \cdot e^{j\omega_1 t} \end{pmatrix} \cdot \begin{pmatrix} h_1 \cdot e^{j\omega_1 t} & h_2 \cdot e^{j\omega_2 t} \\ h_2^* \cdot e^{-j\omega_2 t} & -h_1^* \cdot e^{-j\omega_1 t} \end{pmatrix} \cdot \boldsymbol{\alpha} + \mathbf{H}^{\mathrm{H}}\mathbf{n} && (18)\\
&= \sqrt{\frac{E_s}{2}} \cdot \begin{pmatrix} |h_1|^2 + |h_2|^2 & 0 \\ 0 & |h_1|^2 + |h_2|^2 \end{pmatrix} \cdot \boldsymbol{\alpha} + \mathbf{H}^{\mathrm{H}}\mathbf{n}. && (19)
\end{aligned}$$

Hence, small frequency offsets between the different local oscillators can be corrected at the receiving side. Estimation of the time-variant channel impulse response will be performed in two steps:

1. estimation of the complex channel coefficient and
2. estimation of the frequency offset.

Combining both estimates can be considered as a time-variant CIR.

2.5 Hardware Setup

For the measurements, three different SDRs of type Ettus Research USRP B210 are used, each connected to a computer. Two SDRs are configured as transmitters, one as a receiver. For the initial measurements, the SDRs are connected to the Ettus Research 8-channel clock distribution system CDA-2990 (called OctoClock). This system generates a 10 MHz reference signal which is used to derive the carrier frequency and the sampling timing. Additionally, a one-pulse-per-second (PPS) signal is generated and distributed to the SDRs for timing alignments (cf. Figure 2). The two SDRs are configured to start transmitting at a certain instant of time. Based on the PPS-pulses, the receiver is configured to start 0.01 s prior to the transmission. This ensures that the receiver will not miss the start of a burst, also in case of jitter. Due to the connecting cables between OctoClock and SDRs, the range of the setup is limited to the lengths of the cables.

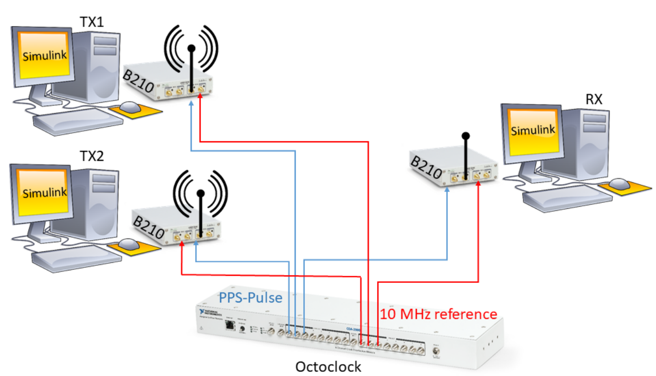

Fig. 2. Demo System Architecture.

2.6 Software Setup

Development Environment In order to have a user-friendly interface, a high-performance interface to the SDR, and a powerful programming language, we have chosen a combination of three different programming tools:

Simulink: The Simulink environment is part of MATLAB and offers a graphical user interface which allows to monitor and change signal parameters and settings during runtime of the measurement. It is therefore the preferred solution for the user interface. Moreover, it offers the possibility to integrate MATLAB and C++ code, which both will be needed, too.

MATLAB: MATLAB is very well suited to implement algorithms and signal processing. A lot of functions are provided by various toolboxes which simplifies the development. In addition, figures can easily be generated during runtime of the measurement which eases the development and debugging process. Therefore, all signal processing functionality is implemented using MATLAB blocks in Simulink.

C++: As a C++ API is provided for the SDRs, an interface between MATLAB and the SDR is programmed using C++. This allows access to sophisticated functions of the SDRs like synchronization to external pulses and reference frequencies. The C++ interface can be included in Simulink and MATLAB using MEX-functions.

Configuration Relevant settings of the SDRs (such as frequency offsets, gains, etc.) can be controlled from the Simulink user interface. All other settings are defined in appropriate initialization-f iles which are called at the software's startup. In these files carrier frequency, length of training sequences and data, interpolation and decimation factors, etc. are set.

2.7 Modulation

In the current implementation, different modulation schemes are implemented. The setup allows to select between a single-carrier 4-QAM modulation scheme, a multi-carrier OFDM and an FBMC scheme using 4-QAM and Offset-4-QAM on the subcarriers.

2.8 Transmitter Implementation

The transmitter implementation consists of the burst generation, i.e. combining training data and payload, coding according to the Alamouti scheme, and pulse shaping using rectangular pulses. The complex baseband sequence will then be passed to the SDR interface where the signal is mixed to carrier frequency and transmitted. For the demonstration system, the payload data is always the same which allows for simple BER and packet error rate (PER) calculations at the receiving side.

2.9 Receiver Implementation

PPS pulses are used for coarse synchronization and the start of sampling is aligned on the rising edge of the PPS pulse. This ensures that full bursts are sampled and no data will be missed. The SDR mixes data to a low intermediate frequency. Mixing to baseband and applying a matched filter is then performed in MATLAB.
Since for the Alamouti scheme two transmitters are active and therefore CIRs and carrier frequency offsets have to be estimated for both of them, all further signal processing blocks are implemented twice. The explanations will concentrate on one chain as both chains are working similarly. The main difference is that they use different training sequences and, for the staggered burst structure, the offset values are different (i.e. the time difference between the training sequence and the start of the data block has to be adjusted).

Parameter Estimation The parameter estimation, such as carrier frequency offset estimation, timing estimation, and estimation of the CIR has to be done differently for single-carrier and multi-carrier modulation schemes. For single-carrier schemes, the estimation is mostly done in time domain, whereas in multi-carrier schemes, the estimation is typically done in frequency domain, resulting in a complex channel coefficient per subcarrier.

For the single-carrier system, which we will consider in the following sections, maximum length sequences (m-sequences) are used to perform the estimation of carrier frequency offset, timing, and CIR. In order to facilitate the estimation, three sequences are used, two at the beginning of the burst (used for timing and CIR estimation as well as coarse frequency offset estimation) and one at the end of the burst (used for fine frequency offset estimation). As multiple transmitters are used, orthogonality between the training sequences of the different transmitters has to be ensured. This can be done using orthogonal sequences, transmitted simultaneously, or using a time-division multiplexing approach to transmit the training sequences of the different receivers in a staggered manner (see Figure 3). Since the used m-sequences are not perfectly orthogonal, i.e. the cross-correlation between the two training sequences is not zero, there will be some interference in the simultaneous mode which degrades the estimation, especially in cases of large carrier frequency offsets.

For the multi-carrier schemes, pilot tones are often used to estimate the channel transfer function and the carrier frequency offset. The orthogonality between the pilots of the different transmitters can be achieved by using a frequency-division multiplexing approach, e.g. by assigning every $N-$th carrier to one transmitter and interpolating the channel transfer function. This approach works fine in case the coherence bandwidth of the channel is larger than the spacing between the pilots.

Decoding Once frequency offset and complex CIR are estimated, the Alamouti decoding can be performed. This scheme can also be extended to more than two

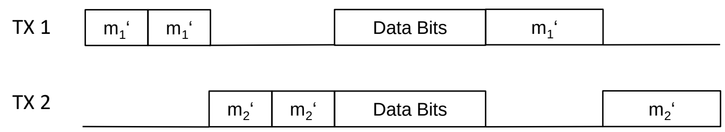

Fig. 3. Burst Structure: "Staggered".

nodes. The requirement for this is that an orthogonal transmit diversity scheme is applied. The Alamouti decoding block will use the estimates from both chains and output symbols according to the time-slotted Alamouti scheme where two symbols are transmitted in two adjacent time slots. To ensure that both signal chains are working properly, BER and PER will be calculated per chain and in total. Finally, demapping is performed and the transmitted and received values are compared in order to calculate BER and PER.

3 Measurement Results

In order to prove the aforementioned concepts, several measurements have been performed. In this section, the test scenarios are presented which shall be the base for further measurements. Thereafter, some details are provided for the measurement results for the single-carrier QAM configuration of the demonstration system. For the measurements, the SDRs are positioned in a shape of a right-angled triangle where the receiver is positioned in the corner of the right angle. The path between TX1 and RX is a grazing line of sight, as measurement equipment is positioned in between. The path from TX2 to RX can be considered as a line-of-sight channel. The distance between both transmitters and the receiver is about 1.32 m and 1.1 m, respectively.

3.1 Test Scenarios

We investigate the broadcast (BRC) of MANETs in four different scenarios:

- Scenario 1 (reference, 1 transmit node and single burst decoding): One transmitter sends a packet in a short burst. The receiver decodes based on the single burst.
- Scenario 2 (BRC, SNR aggregation, one transmit node): One transmitter repeatedly sends the same burst. The receiver stores two or more observations of this burst and combines them to enhance the probability of successful decoding.
- Scenario 3 (cooperative BRC, distributed transmit diversity, single burst decoding): Two transmitters send the same broadcast data, either using the distributed Alamouti transmit diversity scheme, or each one alone.
- Scenario 4 (cooperative BRC, distributed transmit diversity, SNR aggregation): Two transmitters send the same broadcast data repeatedly, either using distributed transmit diversity or each one alone. The receiver stores several observations and combines them for successful decoding.

3.2 Results

In the following sections, the main results will be discussed.

Scenario 1 Several measurements for different SNR levels have been performed. An example of the resulting BER per packet is shown in Figure 4 for an average SNR of approximately 8.1 dB. Thereby, each one of 4001 packets is decoded separately and no channel coding is used; the channel is estimated using a training sequence. The PER, averaged over all 4001 packets, is about 96%, i.e. only 4% of the received packets are successfully decoded, i.e. without a bit error.

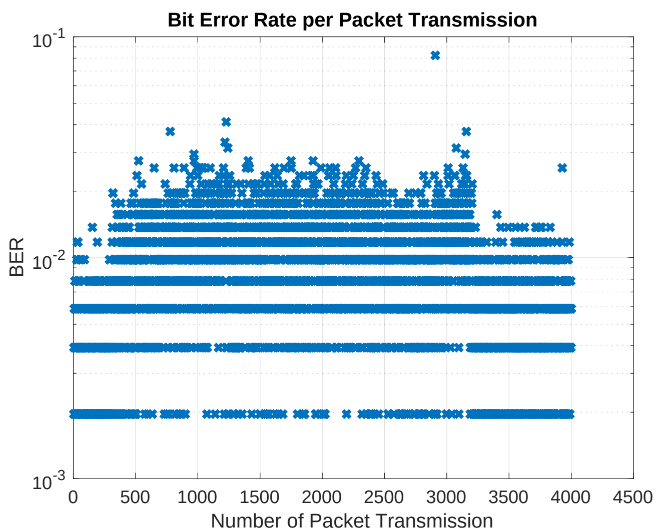

Fig. 4. BER for each of 4001 transmitted packets, Scenario 1, mean SNR ≈ 8.1dB.

Scenario 2 One representative result is given in Figure 5 for the same measurements as used in Scenario 1. It shows the significant improvement compared to the experiment in Figure 4 for the SNR aggregation based on two coherently combined packets, i.e. packet 1 is combined with packet 2 before decoding, packet 2 is combined with packet 3 before decoding, then packet 3 with packet 4 and so on. For the coherent combining, the estimated CIR is used. The average PER is decreased to about 21%. Taking all results into account, it can be concluded that the SNR aggregation used for this scenario is an efficient technique to enhance the BER and PER performance in a broadcast significantly.

Scenario 3 For Scenario 3 we consider a very low SNR case measured with the demonstration system. Node 1 and Node 2 are using the distributed Alamouti

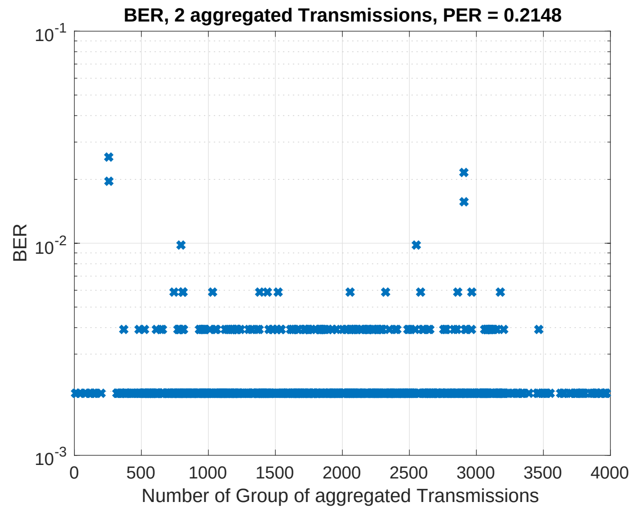

Fig. 5. BER for coherently aggregated packets (consisting of two coherently combined observations), Scenario 2, mean SNR ≈ 8.1dB.

scheme, or each node transmits alone. For Node 1 transmitting, the receive SNR is about -4 dB, for Node 2 it is about -2 dB and for the distributed Alamouti transmission of both nodes it is about 0 dB.

As it can be seen in Figure 6, the BER can be significantly reduced by the use of the distributed transmit diversity. For all three cases the BERs are high and the PERs are 100% (i.e. no error free packet could be detected) because of the very low SNR. In comparison, the distributed Alamouti approach shows by far the lowest BER, due to a diversity as well as a power gain (two nodes transmit jointly and no sum power constraint is limiting the sum transmit power).

The fact, that the Alamouti scheme outperforms both SISO schemes is true as long as good estimates of the channel are available. This can be seen from the following two measurements. In a first case (Case 1) the channel estimation is performed in a low SNR-regime whereas in a second case (Case 2) the channel estimation is performed in a high(er) SNR-regime.

Table 1. PER for SISO and Alamouti scheme.

	PER	
	Case 1	Case 2
SISO: TX1 only	81.41%	79.10%
SISO: TX2 only	93.03%	51.74%
Alamouti: TX1 and TX2	94.03%	18.52%

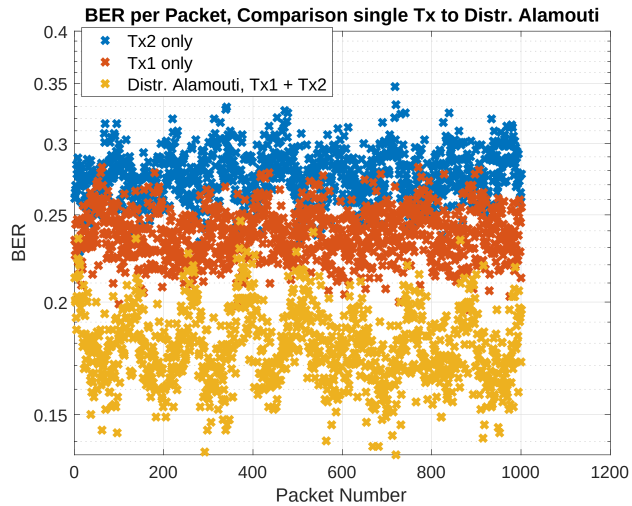

Fig. 6. BER for each of 1001 transmitted packets, Scenario 3, low SNR.

As it can be seen in Table 1, the Alamouti scheme outperforms both SISO schemes in case good estimates of the complex CIR can be achieved, i.e. the SNR of the training sequences is sufficiently large. This has been achieved by transmitting the training sequences with a higher transmit power than the payload of the message.

Scenario 4 In Scenario 3, the resulting BER is very high and the PER equals 100% even for the distributed Alamouti transmission - due to the very low receive SNR. To further reduce the PER, we combine SNR aggregation with the distributed Alamouti scheme. Figure 7 shows the corresponding PER versus the group size N_g for aggregated transmissions (i.e., the number of combined packet observations). For group size $N_g = 1$, each packet is decoded separately, for $N_g = 2$, two packet observations are coherently combined, etc. The same measurements as in Scenario 3 are used, i.e. the receive SNR values are as stated there.

Although the packet error rates drop strongly in all three cases, the distributed Alamouti approach shows by far the best performance. However, due to the low SNR a high number of observations have to be combined to achieve low packet error rates. For instance, in order to achieve a PER below 10%, for the distributed Alamouti case 27 packet observations have to be combined. In comparison, in case only Node 1 is transmitting, already 63 packets, and in case of Node 2 even 153 packets have to be combined to achieve PER $< 10\%$.

Summary of the Results To conclude, the transmission can be significantly improved in terms of a BER and PER reduction by using the SNR aggregation

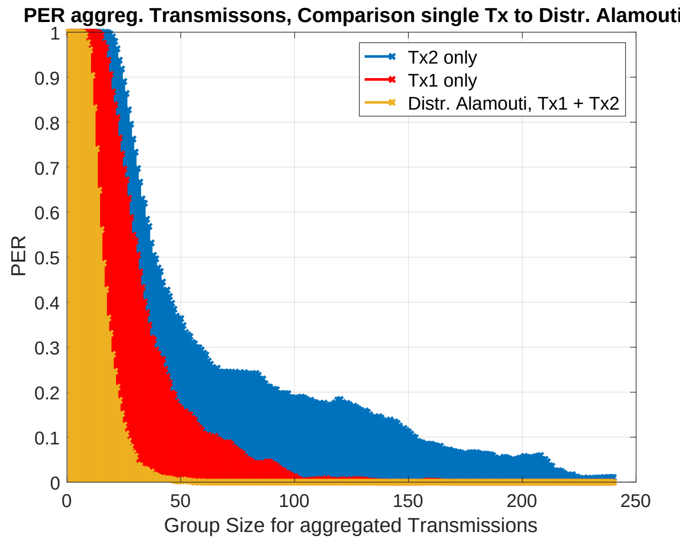

Fig. 7. PER vs. number of coherently combined packets; low SNR case.

and the Alamouti diversity scheme. The benefits of SNR aggregation become clearly visible in the first two scenarios. The benefits of the Alamouti diversity scheme become obvious in the third measurement scenario. The last scenario shows, that the SNR aggregation in combination with the Alamouti diversity scheme is even more beneficial.

3.3 Scalability of the Demonstration System

Currently, the demonstration system consists of three SDRs. One of the major drawbacks of the B210 SDRs is that only USB-connectivity is supported. This means that the SDR devices have to be connected to a PC, which requires a large number of PCs to set up a larger demonstration system, or much more expensive SDRs providing an Ethernet interface.

In order to overcome this issue, a Raspberry Pi, which is a single board computer, can be used. Data to be transmitted can be sent to the Raspberry Pi via Ethernet which is then forwarded to the SDR over the USB interface. Therefore, one PC can be used to control a large number of transmitters. A TCP/IP server is running on the Raspberry Pi and a TCP/IP client in MATLAB on the PC. Thus, the user interface only requires minimal change, i.e. the SDR interface has to be replaced by the TCP/IP client interface. A proof of concept has been performed and the results have shown that this is a suitable approach for further phases of the project.

4 Future Work

4.1 Scaling Behaviour of MANETs

As sketched in Section 1, one major drawback of MANETs is their scaling behaviour with increasing number of nodes and, correspondingly, routes. Currently, no sophisticated solution exists on how to overcome this issue. One of the major goals of the implemented demonstration system and its planned extensions is to investigate different methods and techniques to improve exactly this. Therefore, it is foreseen to further investigate the use of OSTBCs as well as NOSTBCs like Linear Scalable Dispersion Codes (LSDCs). Moreover, it is nearby to consider Space-Frequency Block Codes, too. In our future work we will also consider synchronization issues in order to implement the system without the OctoClock synchronizer.

4.2 Adaptability of the Demonstration System

The implemented Simulink environment has been designed in a modular way for simple exchange of modulation schemes, parameter estimation algorithms, and cooperative diversity schemes. With this model it has been shown that exchanging the modulation with only slight adaptations is possible. The distributed MISO scheme still allows for a diversity gain.
The simulation environments are implemented with a user interface in such a way that simulations can be run on a PC and the same user interface can be used to perform real transmissions using SDRs.

4.3 Further Measurements

All measurements shown above have been performed for the single-carrier scheme. The measurements shall be repeated for OFDM and FBMC modulation schemes. We expect that with OFDM and FBMC an efficient use of larger bandwidth and higher data rates can be achieved. A comparison between the spectra of the generated signals shows that the edges for the FBMC spectrum are much steeper than for the OFDM spectrum which corresponds to the theoretical expectations proving that the signal processing in our implementation is working correctly.

5 Conclusion

This paper describes how to set up and implement a MANET demonstration system which allows to perform measurements and to gain hands-on experience on cooperative transmit diversity schemes in combination with further signal-processing like the SNR aggregation approach for broadcasting.
Furthermore, the scalability and adaptability of this demonstration system have been proven. For the latter, Simulink environments have been implemented utilizing single-carrier as well as multi-carrier modulation schemes (OFDM and

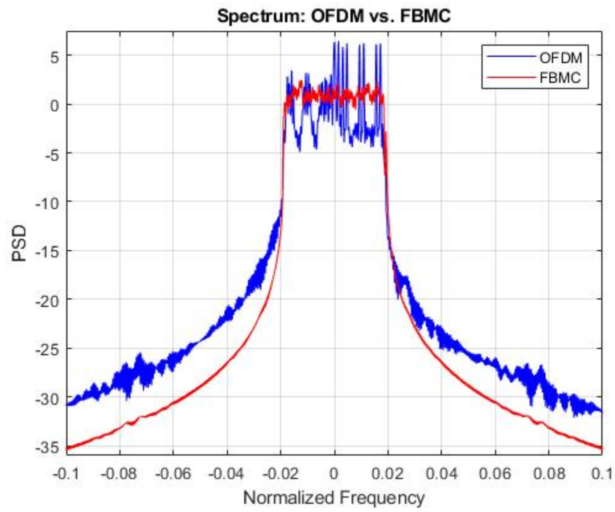

Fig. 8. Comparison between the OFDM and FBMC Spectrum.

FBMC). These environments can be directly deployed to the SDRs in order to perform real-time measurements.

First measurements using the demonstration system in its single-carrier configuration have been performed investigating the benefits of the described burst structure and SNR aggregation. One crucial result is that the Alamouti diversity schemes significantly outperform SISO schemes as long as the estimation of the complex CIR is possible with the necessary quality. Additionally, SNR aggregation can be used to further reduce the PER. Again, the Alamouti diversity scheme shows by far the best results.

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