Performance Evaluation of SIMO Techniques in IEEE 802.11p

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Abstract. In this paper, we evaluate the performance of spatial diversity techniques in the scope of vehicular communications, using a IEEE 802.11p multi-antenna flexible and modular implementation. The analysis is based on the well-known Selection Combining (SC) and Equal Gain Combining (EGC) algorithms. The results obtained indicate that employing these techniques improves the system's resilience against the fast fading multipath effect that characterizes dynamic wireless channels. The measurements performed reveal that up to 32% more frames can be decoded when compared to a single antenna system within a Non Line of Sight (NLOS) scenario. We also examine the influence of the modulation type used on the performance of the diversity combining scheme.

Keywords: SIMO · IEEE 802.11p · Vehicular communications

1 Introduction

Vehicular communications have raised interest in the last few years and are currently under intense research and development worldwide. They follow the Dedicated Short Range Communication (DSRC) paradigm and enable a wide range of applications for Intelligent Transportation Systems (ITS), such as road safety, traffic efficiency, real-time traffic information, entertainment and comfort [1]. The communication between wireless nodes in a ITS scenario could be either vehicle to infrastructure (V2I) [2] or vehicle-to-vehicle (V2V) and are based on the IEEE 802.11:2012 - amendment 6, also know as IEEE 802.11p standard [3] for Wireless Access in Vehicular Environments (WAVE). In the United States a 75 MHz bandwidth has been allocated for DSRC in the range from 5.850 to 5.925 GHz, whereas in the European Union 50 MHz has been allocated ranging from 5.855 to 5.905 GHz.

The vehicular environment is highly dynamic and complex due to the large number of moving vehicles and the fast change of the surrounding area. This

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leads to a situation where Radio Frequency (RF) signals can bounce off several obstacles. This scattering implies that many copies of the signal may arrive to the receiver, having travelled along many different paths. When these copies combine, they may add constructively, giving a good overall signal, or destructively, mostly canceling the received signal. This fast fading multi-path effect of the channel is highly frequency selective. This means that some frequencies in a 10 MHz 802.11p channel may be wiped out while others are unaffected. On the other hand the typical vehicular communication suffers from high Doppler shifts due to the relative movement of the nodes [4].

One of the main purposes of vehicular communications is to support safety-related applications. Typically these services demand a robust, very low latency and high-reliable communication system between the involved nodes. This could be a challenge taking into account the problems already mentioned. One way to overcome the fast fading multi-path effect, without violating the standard, is the use of multiple antennas at the receiver, improving the system reliability. In this paper we focus on the study and evaluation of diversity techniques and its impact on communication reliability using the IT2S IEEE 802.11p platform. IT2S is a modular, flexible and multiradio FPGA (Field-programmable Gate Array) based platform designed at IT-Aveiro for research and development on vehicular communications. The flexibility of the IT2S platform, permitted by its modular design, consisting in independent blocks for the RF, baseband PHY and upper layers software, allow us to easily modify the Physical Layer (PHY) in order to include several diversity methods in the reception side. In the context of this work we evaluate the performance of Selection Combining (SC) and Equal Gain Combining (EGC) versus single antenna based on laboratory measurements.

The reminder of this paper is structured as follows: the next section gives a short overview of relevant related work. Section 3 describes the diversity methods used in this work. The technical implementation is described in Sect. 4. Section 5 gives an overview concerning the testbed setup. The measurements results are presented in Sect. 6. In the last section we draw the conclusions and some outlines for future work.

2 Related Work

Nuckelt et al. [4] performed a series of simulations based on several V2V and V2I scenarios. They applied three different diversity techniques: SC, EGC and Maximum Ratio Combining (MRC) with up to four antennas at the receiver. The channel and the 802.11p PHY layer were both modeled in MATLAB. The obtained results shown a slightly improvement for SC and significant increased performance for EGC and MRC with MRC outperforming all other combining techniques. However, the study performed in this work is based on simulations with short packets of 100 bytes, limiting its generality and scope. It would be interesting to analyze the system's performance with bigger frame sizes and different modulations schemes, as well as performing the validation of the results in practice, in order to evaluate the techniques in a real world scenarios.

Real-World measurements can be found in [5,6], where the authors carried out some measurement campaigns with real V2V and V2I scenarios. Several different approaches for diversity schemes have been applied in this work, particularly SC, EGC and MRC. The analysis of the results reveals a better performance of EGC and MRC when compared to SC. Although in [5] the performance of EGC and MRC was very similar. The technical solution implemented for the diversity schemes is very similar to the one described in this paper. However, it yields a very complex and bulky hardware support when compared to our own hardware platforms. On the other hand, in [5], only the automatic gain control (AGC), time and frequency synchronization were implemented in the FPGA. The rest of the forward processing modules were programmed in a digital signal processor (DSP) which results in a high latency system. In contrast, our solution includes all the processing modules that are completely implemented in the FPGA, thus reducing the overall system's latency.

In this work, we present a different approach by applying receive diversity techniques directly to the IT2S modular and compact IEEE 802.11p multi-radio platform which has been adapted for that purpose. Starting from a complete PHY implementation for single antenna we were able to perform the modifications needed in order to achieve receive diversity for different data rates. In fact, the IT2S multi-radio capabilities allow its use in different communication scenarios, namely in simultaneous multichannel communications (as defined in ETSI ITS G5 standards) using single antenna and independent PHYs, as well as in the exploration of diversity techniques using multiple antenna configurations, as discussed in this paper. These capabilities make the IT2S platform adaptable to different communication scenarios depending on the required throughput, signal strength, distance range, etc.

3 Overview of the Diversity Techniques

In this section we provide a short overview about the applied receive diversity schemes.

The main goal of receiving antenna diversity is to take advantage of multiple versions of the transmitted signal that travelled along independently faded paths, and combine them into a single improved signal. Typically we can find in the literature [7] three methods for diversity: spatial, time and frequency diversity. Within the scope of this analysis, we focus on signal diversity obtained by spatial separation of the receiver antennas. So a system called Single-Input Multiple-Output (SIMO) is used to achieve spatial diversity.

The simplest diversity method commonly used is to choose the receiver's antenna with the strongest signal. This method, called Selection Combining (SC), improves reliability, because both signals are unlikely to be simultaneously weak. It is also easily implemented in hardware due to its low complexity. However, it wastes the received power at the antenna that was not selected. This particular method should not be considered as a true SIMO system because, in fact, only one antenna is used each time a received frame is processed. A potential better method uses the incoming independently faded signals from both antennas in order to combine them coherently, resulting in a single signal with improved Signal to-Noise Ratio (SNR). According to [6] a linear diversity combiner with two antennas could be defined by

$$Y_{n,k} = \alpha y_{n,k}^{(ch0)} + \beta y_{n,k}^{(ch1)} \quad (1)$$

where α and β are the weighting factors, which in our case are set to one thus leading to a method called Equal Gain Combining (EGC). $y_{n,k}^{(i)}$ represents the received data at antenna (i) at time n and subcarrier index k. This technique requires two dedicated RF frontends for each antenna which increases the hardware complexity and power consumption but yields better performance than SC.

4 Implementation of the Diversity Techniques

In this section, we give a detailed description on the system architecture implemented in a FPGA for both diversity schemes evaluated.

4.1 Selection Combining

The Fig. 1 depicts the complete block diagram for the SC method solution. All the blocks represented are implemented in the FPGA except the RF frontends. This solution is a quick and simplified adaptation of the existing reception (RX) chain for single antenna. Obviously this model can be further optimized in terms of resources, but for a simple proof of concept it works perfectly well for the SC analysis. The incoming frame is initially processed by both RF front ends. During the firsts short training sequences of the preamble, the Received Signal Strength Indication (RSSI) is measured for each branch and fed to the corresponding AGC

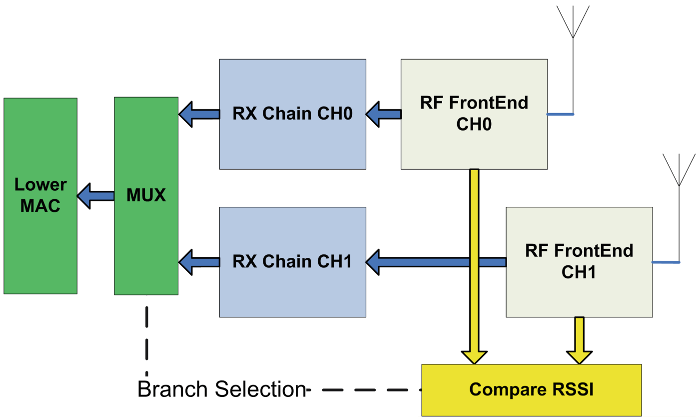

Fig. 1. Selection combining block diagram.

module. At the same time a comparator checks both RSSI values and chooses the higher one. Finally the output of the comparator forces the multiplexer to link the selected RX chain branch with the Lower MAC block for further frame processing. This simple process is repeated for each received frame.

4.2 Equal Gain Combining

The Fig. 2 shows the block diagram of the RX chain used for the EGC technique with two antennas. All the blocks included in this diagram are implemented in the FPGA. Once again this solution is a modification of the existing RX chain for a single antenna. In the first block time and frequency synchronization is performed individually by both branches. Then the received time-domain signal is transformed back to the frequency-domain using a 64-point Fast Fourier Transform (FFT). At this point the resulting samples of each branch are delayed until they are perfectly aligned with respect to the start of an OFDM symbol. The equalizer performs the channel estimation based in the long training sequences in order to determine the equalization factors: phase and amplitude. Then the subcarrier samples are phase compensated [5] by the equalizer in both branches, according to

$$\hat{y}_{n,k}^{(ch0)} = y_{n,k}^{(ch0)} exp(-j arg H_k^{(ch0)}) \quad (2)$$

$$\hat{y}_{n,k}^{(ch1)} = y_{n,k}^{(ch1)} exp(-j arg H_k^{(ch1)}) \quad (3)$$

where $H_k^{(i)}$ represent the equalization factors at antenna (i) and subcarrier index k. This operation ensures that the samples are suited to be combined coherently. Note that the amplitude compensation is only performed in the next step.

The following block is the Diversity Combiner. This module combines the two branches based on

$$\hat{\mathcal{Y}}_{n,k} = (|H_k^{(ch0)}| + |H_k^{(ch1)}|)(\hat{y}_{n,k}^{(ch0)} + \hat{y}_{n,k}^{(ch1)}) \quad (4)$$

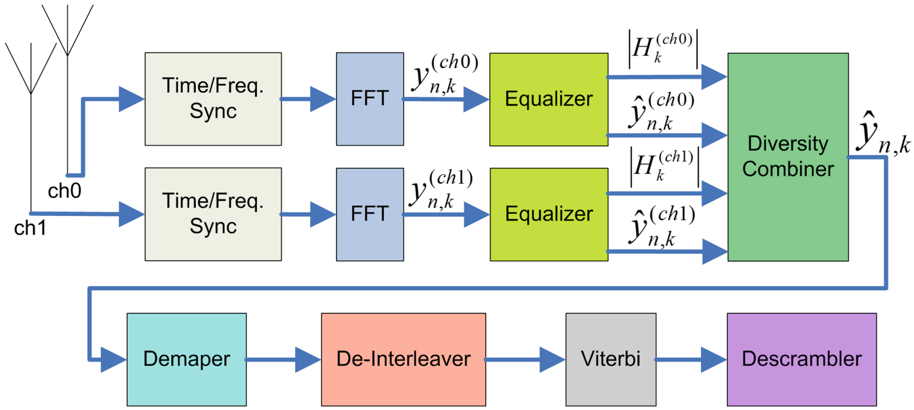

Fig. 2. Equal Gain Combining block diagram.

resulting in a single set of sub-carrier samples per OFDM symbol. The Demaper converts the I/Q vectors back to a bit stream. After de-interleaving, the binary sequence is decoded by a forward error correction block based on the Viterbi's algorithm. Finally the data is descrambled in order to retrieve the original frame.

5 Experimental Setup

In this section we present a summary of the testbed environment. The IEEE 802.11p hardware platforms used in our measurements includes two 5.9 GHz custom made RF frontends, two 10 bit AD/DA (Analog to Digital and Digital to Analog converter) processors and a FPGA module fitted in a Xilinx Spartan-6 XCSLX150-2CSG484C. The digital baseband PHY was modelled in VHDL (VHSIC Hardware Description Language) and implemented in the FPGA. The platforms were totally developed from scratch and are compliant with the 802.11p standard. We have full access to both analog and digital PHY layers, which represents a great advantage and flexibility over closed black box commercial solutions.

The Fig. 3 depicts the block diagram of the used multiradio platform. In this architecture the PHY layer is divided in two sub-layers: digital PHY and analog PHY. In this context the digital PHY sub-layer is implemented in the FPGA module. Apart from processing the transmitted and received data frames, the FPGA module is also responsible for managing the configuration, control and communication of both AD/DA processors and RF modules. It also provides interface with the GPS (Global Positioning System) module and includes a Universal Serial Bus (USB) interface for connecting the upper layers running in a single board computer. The GPS module provides location and time synchronization.

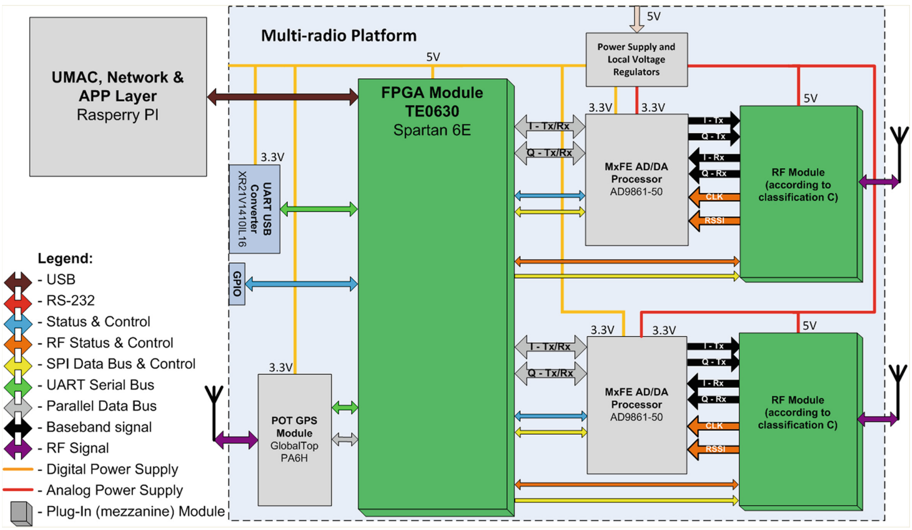

Fig. 3. Complete block diagram of the multi-radio hardware platform.

The AD/DA processor is an integrated converter and defines the interface between the digital and analog PHY sub layers. It is responsible for converting the OFDM modulated baseband signals from the digital domain to the analog domain (and vice versa). This processor also includes two auxiliary ADC (Analog to Digital Converter) channels in order to sample signals such as RSSI or the Power Amplifier (PA) emitted power (both signals generated by the RF module) for monitoring and control purposes. The RF module implements the analog PHY sub-layer according to the IEEE 802.11p standard for the 5.9 GHz class C wireless communication band. The module's main task aims to convert the I/Q components of the OFDM signals from baseband to radio frequency (and vice versa) and perform its transmission (or reception) to the medium. This custom module incorporates all the key components (transceiver, filters, PA, RF switch, etc.) for proper operation over the 5.9 GHz range. For these measurements and tests we used two hardware platforms, each one connected to a Raspberry PI via USB. The Raspberry PI is a small single board computer running one application with configurable parameters for transmission and the other one was programmed to act as a sniffer, collecting the detected and correctly decoded 802.11p packets. The transmitter was equipped with only one RF module while the receiver included two RF modules for diversity tests. In the laboratory room the distance between transmitter and receiver was about 7 m. The transmitter's antenna was placed right behind a set of metal cabinets, in a configuration of Non Line of Sight (NLOS) relatively to the position of the receiver's antennas (refer to Fig. 4). This setup creates a richly environment of scattered replicas of the transmitted signal which can be exploited by the diversity techniques. The set of antennas used were monopoles suited for the 5.9 GHz operation band. The distance between the two receiver's antennas was about 50 cm. Furthermore the equipment was tuned in the 172 channel which corresponds to a center frequency of 5.86 GHz. For all the measurements the constant transmitted power programmed was about 3 dBm. The transmit power was calibrated in order to obtain a Packet Error Ratio (PER) close to 50 single antenna in NLOS configuration. Thus, in this mode, we can more easily highlight the performance of the spatial diversity schemes under test in this work. At each transmission trial we

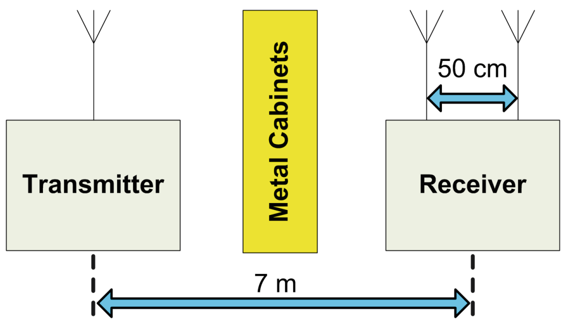

Fig. 4. Testbed setup layout.

sent a thousand packets of 1004 bytes, including the SIGNAL field, SERVICE bits, MAC header and payload. At the receiver side we measured the number of successfully decoded frames per trial.

6 Experimental Results

The Fig. 5 represents the number of successfully decoded packets obtained for a single antenna receiver within NLOS and Line of Sight (LOS) regimes. In this particular test we sent 1000 frames at 6 Mbits/s for different transmitted power values in a laboratory environment. The results for LOS regime indicate a perfect reception rate, except for slightly performance decrease at −3 dBm resulting in a PER of 4.8%. On the other hand in the NLOS regime we can observe a perfect reception rate above 9.8 dBm. Bellow this value there is an important performance degradation in terms of received frames. This is precisely the point were we can enable and take advantage of the receive diversity techniques.

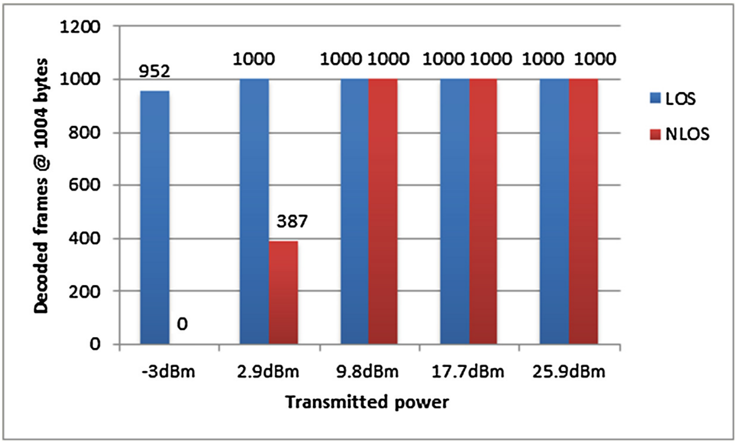

Fig. 5. Single antenna measurements results.

The values in Fig. 5 depicts the average value of 10 measurement runs performed for each parameter setting. Three modulation schemes have been chosen for this performance evaluation: BPSK with coding rate 1/2 (3 Mbits/s), QPSK with coding rate 1/2 (6 Mbits/s) and 16-QAM with coding rate 1/2 (12 Mbits/s). For each transmission run 1000 frames of 1004 bytes were transmitted and the corresponding number of successfully decoded frames at the receiver was measured. According to the chart of Fig. 6, a moderate performance improvement can be observed for all modulations of the SC scheme compared to the single antenna configuration (named antenna ch0). In fact, we observed during the tests that the SC system often opted by the antenna ch1, discarding the signal at antenna ch0. This behavior clearly shows that antenna ch1 constantly picked-up a stronger signal than antenna ch0, within this particular testbed configuration.

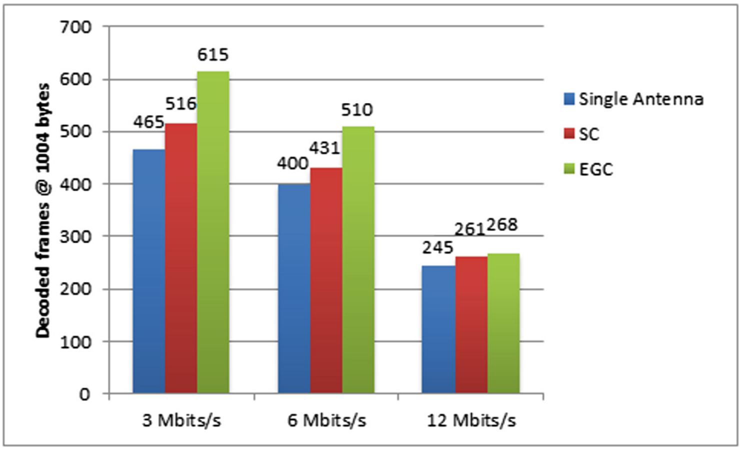

Fig. 6. Multiple antenna measurements results.

In the best scenario, which corresponds to 3 Mbits/s, the SC technique was able to decode up to 11% more frames than the single antenna setup. Results for EGC scheme indicate a significantly increased performance, especially for 3 and 6 Mbits/s, when compared with the single antenna. This is an expected result because the EGC technique takes advantage of the signals from both antennas in order to combine them into a single signal with improved SNR, thus leading to an increased number of successfully decoded frames. In this case the EGC scheme was able to decode up to 32% more frames when compared to the single antenna results for 3 Mbits/s.

Another interesting observation on the results is that the overall number of decoded frames decreases with the increase of the data rate. In particular at 12 Mbits/s (16-QAM) which denotes only a slightly performance improvement for SC and EGC modes. This can be explained by the fact that higher modulations are more sensitive to the fast fading multi-path effect in NLOS configuration resulting in a higher Error Vector Magnitude (EVM) that cannot be significantly compensated by the diversity techniques employed in this work. So, in this testbed setup, SC and EGC performed better at lower modulations schemes.

7 Conclusions and Future Work

In this paper we presented the evaluation of two different spatial diversity combining techniques. SC and EGC were implemented in our IEEE 802.11p IT2S platforms. Several laboratory measurements have been carried out in order to analyze the resulting performance gain of these techniques when compared with the single antenna setup. The presented results show that the system performance is improved if SC or EGC are applied. More specifically we have shown that with the use of SC, up to 11% more packets can be decoded. EGC performed even better, with up to 32% more frames decoded compared to a single antenna for 3 Mbits/s, resulting in a more robust and reliable communication system. We also shown that the performance of the spatial diversity schemes applied depends on the type of modulation used.

For future work we will take into consideration the use of MRC diversity technique, where the factors α and β (in Eq. 1) are weighted according to the SNR estimated for each branch. We also intend to carry out some real world experiments with moving vehicles, equipped with our platforms, at different speeds within V2V and V2I scenarios. We will consider several environments such as open space (LOS), tunnel and city with different traffic conditions.

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