Performance of MIMO precoders in tunnels for train-to-wayside communications

Jean-Marc Kwadjane[1], Baptiste Vrigneau[2], Charlotte Langlais[3], Yann Cocheril[1], Marion Berbineau[1]

[1]Université Lille Nord de France, IFSTTAR, COSYS, LEOST, F-59650 Villeneuve d'Ascq, 20 Rue Elisée Reclus,
jean-marc.kwadjane@ifsttar.fr

[2]Université de Rennes1, INRIA-IRISA UMR CNRS 6074 6 rue de Kerampont, 22300 Lannion
baptiste.vrigneau@irisa.fr

[3]Department of Electronics, Institut Telecom-Telecom Bretagne, Brest, France
charlotte.langlais@telecom-bretagne.eu

Abstract

In this paper, we investigate Multiple-input Multiple-output (MIMO) techniques implemented on the PHY layer of IEEE802.11x modems deployed for metro applications in tunnels. We analyze the performance in terms of bit error rate (BER) of three well-known quantized precoders: LTE, max-d_{min} and P-OSM, in coded MIMO systems in subway tunnels in presence of impulsive noise. We consider measured channel models and an impulsive noise distribution obtained thanks to measurements in tunnels and in railways environments. Different levels of correlation in the tunnel and also the channel estimation quality are taken into consideration.

1. Introduction

The transmission of information for the control and command of driverless metros is based on radio devices developed from WIFI COTS (Components On The Shield) modified to fulfill the CBTC (Communication Based Train Control) standard [1]. The data exchanges for the control-command are generally low data rate but with strong requirements in terms of robustness, availability, end-to-end delay. In parallel, a second wireless network, also based on WIFI modems, is considered for non-safety applications like video surveillance of the inside of the train, remote monitoring, etc. These applications are known under the name of CCTV (closed-circuit television) and they require higher and higher throughput and QoS. The deployment of these systems in tunnels constitutes a challenge for transport operators because there is a wide diversity of tunnel size and geometry. In this context, it is really important for signaling industry to be able to evaluate in various conditions of propagation in railway tunnel the well-known multiple input multiple output (MIMO) techniques implemented in new standards (IEEE802.11n, IEEE802.11p, LTE), which can offer in multipath environments diversity gain, throughput gain and array gain [2].

Tunnels can be compared to over-sized dielectric wave guide where infinity of hybrid modes can propagate [3]. The excitation of the hybrid modes strongly depends of the position of the transmitting antenna [4] and in [5] the authors consider that spatial diversity can be compared to modal diversity. The consequence is that in [6], the authors showed that the correlation degree in the tunnel strongly depends on the positions of the antennas on the roof of the train and on the ceiling of the tunnel. The MIMO performances can be destroyed due to spatial correlation in the tunnel [7]. Thanks to the bidirectional train-to-wayside link, it is possible to consider MIMO algorithms with Channel State Information at the Transmitter side (CSIT), such as precoding. [8] showed the influence of correlation in tunnel on MIMO algorithms with and without CSIT. As it is impractical to feedback complete and accurate CSIT, [9] investigated limited feedback precoding techniques performance in tunnel environment, depending on the quality of the channel matrix estimation. Furthermore, recent works have shown that the received signal at the antenna on the roof of a moving train near the catenary suffers from electromagnetic noise interference (EMI) [10] which are well modeled by the symmetric α-stable noise (SαS) [11]. Thus, in [12] we have investigated a theoretical approximation of the error probability of max-d_{min} precoder with impulsive noise. In this paper, the aim is to evaluate the performance of three well-known limited feedback precoders: max-d_{min}, P-OSM and Long Term Evolution (LTE) precoder and to investigate their tolerance to channel correlation in presence of impulsive noise. The paper is organized as follows. The next section presents the system model. Then we briefly describe the channel model obtained with measurements in tunnel. In section 4 we present the transmission chain considered for the evaluation. Section 5 details the system performance in the tunnel. Then the section 6 is devoted to conclusion and future works.

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2.System model

The general input-output relation of the precoded MIMO scheme with n_t transmit and n_r receive antennas is:

$$\mathbf{y} = \mathbf{HFx} + \mathbf{n} \tag{1}$$

where $\mathbf{y} \in \mathbb{C}^{n_r \times 1}$ is the complex received symbol vector, $\mathbf{x} \in \mathbb{C}^{b \times 1}$ is the complex transmitted symbol vector of b streams such that $b \leq \min(n_t, n_r)$ and $\mathrm{E}\left[\mathbf{xx}^H\right] = \mathbf{I}_b$, $\mathbf{n} \in \mathbb{C}^{n_r \times 1}$ is a complex SαS noise vector and $\mathbf{H} \in \mathbb{C}^{n_r \times n_t}$ is the channel matrix, $\mathbf{F} \in \mathbb{C}^{n_t \times b}$ is the linear precoder respecting $\|\mathbf{F}\|_F^2 = E_t$.

CSI has to be estimated from the observations that are likely imperfect due to the noise and temporal variations of the channel. Therefore, we model the channel estimation errors by dividing the channel matrix into two parts:

$$\mathbf{H} = \hat{\mathbf{H}} + \mathbf{E} \tag{2}$$

where $\hat{\mathbf{H}}$ is the estimate of $\mathbf{H}$ and $\mathbf{E}$ is the error matrix. They are mutually uncorrelated and both spatially white with entries distributed according to $\mathcal{N}_c(0,1\text{-}\sigma_e)$ and $\mathcal{N}_c(0,\sigma_e)$ respectively, where σ_e is the variance of channel estimation error.

3.Channel Sounding

Measurements were conducted in the Tunnel of Roux (Ardèche region in the south of France). Measurement configurations and first analyses are presented in [13]. The MIMO channel sounding provides the channel matrices **H** measuring the complex impulse responses between each couple of transmitting and receiving antennas. Due to the small RMS delay spread in this environment regarding the data frame size, the channel matrices **H** are modeled in narrow band using the Kronecker model [14], i.e.

$$\mathbf{H} = \mathbf{\Sigma}_r^{1/2} \mathbf{H}_w \mathbf{\Sigma}_t^{1/2} \tag{3}$$

where $\mathbf{H}_w \in \mathbb{C}^{n_r \times n_t}$ is the iid Rayleigh matrix, $\mathbf{\Sigma}_t \in \mathbb{C}^{n_t \times n_t}$ and $\mathbf{\Sigma}_r \in \mathbb{C}^{n_r \times n_r}$ represent the correlation matrices averaged along the tunnel track at the transmitter and the receiver sides, respectively, computed from **H**. The estimation error can be incorporated in this model adding the error matrix **E**:

$$\mathbf{H} = \mathbf{\Sigma}_r^{1/2} \left(\hat{\mathbf{H}}_w + \mathbf{E}\right) \mathbf{\Sigma}_t^{1/2} \tag{4}$$

In this paper, we consider two 4x4 MIMO configurations related to the spacing between the receiving and transmitting antennas. The first configuration has an antenna spacing of 2λ (λ is the wavelength) and a high average value of the spatial correlation ρ equals to 0.96. The second configuration has a greater antenna spacing (10λ) and the average value of the spatial correlation along the tunnel is equal to 0.57. They correspond to a high and a low correlation scenario, respectively [13]. In such an environment (empty tunnel, no cross section change), there is a geometrical similarity between the environment nearby the transmitting antennas and the one nearby the receiving antennas. So the correlation values are equivalent at both sides. All antennas at transmission and reception sides are vertically polarized.

4.Limited feedback precoding

Precoding can be defined as a signal processing technique using the Channel State Information at the Transmitter side (CSIT) to improve the adaptation of the signal to the propagation channel. In this study, we consider three well known precoders (max-d_{min}, P-OSM, LTE) that achieve the best performance by optimizing the same criterion: maximizing the minimum Euclidean distance. The first one is the max-d_{min} precoder [15] which is optimal in terms of the minimum distance and has good performance in ideal Rayleigh channel. However, it has high complexity due to the required joint maximum likely hood detection. The second one is a Precoded Orthogonalized Spatial Multiplexing (P-OSM) [16] in which the singular value decomposition (SVD) operation is replaced by a simple rotation operation at the transmitter in order to orthogonalize the two transmitted symbols. The maximum likelihood detection process is then greatly simplified. Nevertheless, when the number of transmitting antennas is greater than two, an antenna selection technique must be added. P-OSM has good performance in ideal Rayleigh channel close to the one of the max-d_{min} precoder. The last one is proposed in the 3GPP LTE standard [17]. This precoding technique relies on two code-books: Discrete Fourier Transform (DFT)-based Codebook and Householder-based Codebook. This mathematical technique significantly simplifies the computation of selection criterion. The main advantages of the Release 8 codebooks can be summarized as follows [18]: complexity reduction, nested property, and constant modulus property.

Release 8 codebooks preserve the same average power over all the antennas. This avoids the power imbalance which is undesirable in the transmitter.

To transmit back the CSIT, it is mandatory to limit the size of the information. Consequently, the feedback information is quantized with 7 bits. Hence, the max-d_{min} precoder uses a codebook adapted to the channel statistics and the modulation constellation. The POSM and the LTE precoders are also quantized with 7 bits.

5.System performance analysis

The transmission chain used for the system simulations mimics the Physical layer of Wi-Fi like modems similar to the ones considered for CBTC systems for metro applications. This IEEE 802.11x PHY modem involves a bit interleaved coded modulation (BICM) that is the concatenation of a channel encoder, a bit interleaver and a bit-to-symbol mapper. The channel code is a ½ rate convolutional code with constraint length $K = 7$, and defined by the generator polynomials $g_0 = 171_8$ and $g_1 = 133_8$. The frame of encoded data is then interleaved (random interleaver) and converted to complex symbols belonging to the constellation alphabet of binary phase shift keying (BPSK) modulation, quaternary binary phase shift keying (QPSK) modulation or 16 quadrature amplitude modulation (16-QAM). This BICM scheme is followed by one of the quantized precoding techniques presented in section 4, that adapts b = 2 streams to the 4x4 MIMO channel. The channel decoding is performed using the Cauchy soft detection technique presented in [12]. It is assumed that the SαS noise distribution follows the Cauchy law. This assumption is justified since the estimated parameters of the measured SαS noise are close to that of the Cauchy distribution. For this simulation, 10,000 frames of 800 bits each were transmitted. The channel is quasi-static, so H is assumed constant over the transmission of an encoded data frame. The random variables SαS are generated like in [12].

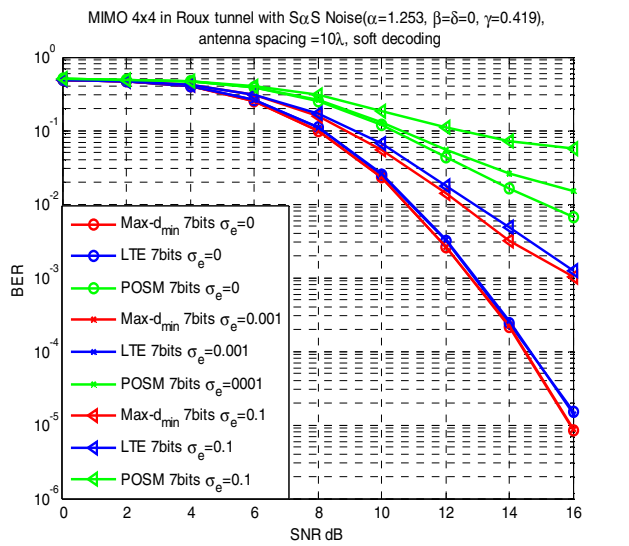

Figure 1. Quantized precoders comparison in measured 4x4 MIMO channel with various quality of estimation of H QPSK in coded system with soft decoding in low correlated channel.

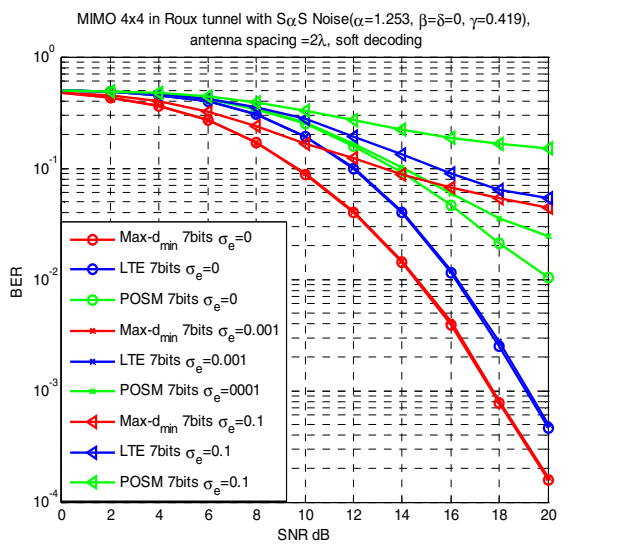

Figure 2. Quantized precoders comparison in measured 4x4 MIMO channel with various quality of estimation of H QPSK in coded system with soft decoding in high correlated channel

Figure 1 and Figure 2 illustrate the impact of imperfect error estimation on communications in MIMO channels depending on the correlation level in presence of impulsive noise. We plot the BER performance in the measured 4x4 MIMO channel obtained in the correlated channel considering an antenna spacing of 10 λ and 2 λ respectively. It can be seen that P-OSM gives poor performance, compared to the two other ones. due to a too small number of quantized feedback bits. The more estimation errors increase, the more the performance degradation for all precoders is significant in these two channels. This demonstrates the impact of the quality of CSIT on precoding techniques performance. More performance degradation is higher for a high correlation value. Figure 2 shows that the max-d_{min} precoder is more resistant than the two others in the high correlated channel. Compared to the max-d_{min}, the impact of correlation is more pronounced for the LTE precoder, even with perfect CSIT, in presence of the SαS noise. The P-OSM is disadvantaged by the antenna selection technique which is greedy in terms of number of bits in the feedback link.

4. Conclusion and perspectives

In this paper we have investigated the PHY layer of IEEE802.11x modems with MIMO algorithms deployed for metro applications. We have evaluated the performance of several MIMO precoding schemes with different CSI quality taking into account various spatial correlation degrees that can be encountered in tunnel scenarios in presence of impulsive noise. Channel estimation errors conduct to significant performance degradation. For a low correlated scenario, the max-d_{min} and the LTE precoders have shown very close performance whatever the channel quality. In the high correlated scenario, the simulation has revealed that the max-d_{min} precoder outperforms the two other precoders.

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