Adaptive MIMO algorithms for train-to-wayside transmissions in tunnels

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Abstract

In order to satisfy vital train-to-wayside transmissions for metro applications, IEEE802.11x modems are deployed along the tracks on an Ethernet network in tunnel. This paper presents possible enhancements of the PHY layer of these systems based on MIMO techniques with and without channel state information at transmitter in order to increase system performance without increasing the number of deployed access points and the transmitted power. The tunnel scenario with a masking train in the case of low and high spatial correlation is modeled thanks to the Kronecker model obtained with a 3D ray tracing tool. We consider the following MIMO schemes: spatial multiplexing, space-time block codes, max-dmin and P-OSM precoders at 5.8 GHz with a targeted Frame Error Rate equals to $3.10^{-2}$for a frame length of 100 bytes. The MIMO algorithms are compared in terms of achieved signal to noise ratio (SNR) versus spectral efficiency.

1. System description and targeted KPI

Driverless metro systems rely on several train-to-wayside wireless communications deployed along the tracks and offering robustness, high data rate and QoS (Quality of Service) for vital (related to train movements) and non vital applications (maintenance, video surveillance of the inside of the trains, passenger information). Today, railway industry offers solutions based on IEEE 802.11a/b/g existing modems operating between 2 and 6 GHz (depending on the country) [1] and deployed along the tracks on an Ethernet network (e.g. the Urbalis system of ALSTOM (Lausanne, Shanghai…) and the Airlink system of SIEMENS (Budapest line M2, New York line 1...). The work presented in this paper is focused on possible enhancement of the Physical Layer of these WLAN systems that could be deployed for vital applications in a tunnel context. Previous works have shown the possible enhancements with simple MIMO techniques [2]. Here, the aim is to show how precoding techniques can provide technically and economically efficient solutions to improve existing systems without increasing the number of deployed access points and the transmitted power with the same final targetedperformance in term of maximum tolerable frame error rate).

The 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 of size 100 bytes 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). The BICM scheme is followed by the MIMO transmit algorithm whose characteristics depend on the available channel state information at the transmitter side (CSIT). In particular, thanks to the bidirectional train-to-wayside link, we can consider MIMO algorithms with partial CSIT, such as precoding. The considered MIMO schemes will be described in the next section. The operational frequency is 5.8 GHz, and the targeted performance indicator is a fixed frame error rate (FER) equals to 3.10^{-2}. With this FER, the objective is to compare the MIMO algorithms in terms of achieved signal to noise ratio (SNR) versus spectral efficiency. The SNR, given by E_b/N_0, is expressed as:

$$E_b / N_0 = \frac{\sigma_x^2}{\sigma_n^2} \times \frac{1}{R_c m} \times N_R \times \frac{N_T}{N}$$

where R_c is the channel code rate, N is the number of transmitted layers (for instance equal to N_T for spatial multiplexing), m is the number of bits per complex symbol, N_T (resp. N_R) is the number of transmit (resp. receive)

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antennas, σ_x^2 is the variance of the complex symbols and σ_n^2 is the variance of the i.i.d complex Gaussian noise samples. The spectral efficiency is given by $\eta = R_c N m$.

2. Tunnel scenario

In [3], the authors have shown the importance of the antennas position in the ideal case (a hollow tunnel) to maximize the channel diversity and its link with the channel correlation. In this paper, a more realistic scenario with a parked masking train between the transmitter and the receiver is investigated (Figure 1). We focus on two antenna configurations: a high correlated one (called EP_1RP_1, with a mean correlation level equal to 0.97) and a low correlated one (called EP_2RP_2, with a mean correlation level equal to 0.53).The channel matrices are computed using a 3D ray-tracing based tool validated in tunnels [4] (considering six reflections and one diffraction).

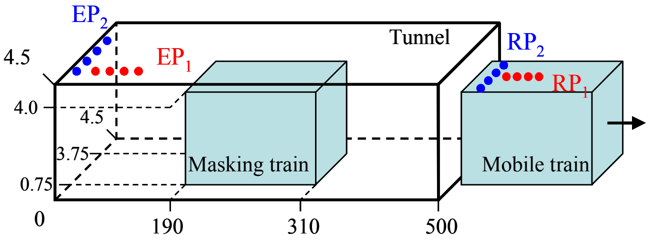

Figure 1. Real scenario: a masking train parked between the transmitter and the receiver in a 1-track tunnel with a square cross-section.

The 4 transmitting antenna elements are 1 m spaced and are placed 20 cm from the tunnel roof and the side wall (all the elements in EP_1, only the first one in EP_2). The 4 receiving antennas are 65 cm and are placed 10 cm above the train roof. The middle of the receiving antenna is aligned with the middle of the train.

Assuming these parameters, we compute the mean behavior of the correlation at both transmitting and receiving sides to model the channel thanks to the Kronecker model [5]. The channel matrices are in narrow band, due to the small RMS delay spread in such an environment regarding the data frame size. In the following, we analyze the performances of several MIMO algorithms in block fading channels for both antenna configurations. Moreover, the results are presented separately according to whether CSI-T is available or not.

3. System performance analysis with and without CSI-T

First, conventional MIMO algorithms without knowledge of CSI-T are investigated. In order to benefit of the high data rate advantage brought by the multiple antennas and the fading environment, full rate MIMO schemes are considered such as spatial multiplexing (SM) and full rate space time block codes (STBC). In the sequel we use a STBC based on Hadamard matrix, belonging to the linear dispersion code family [6], such that, for a 4×4 MIMO channel, the space-time matrix is expressed as $S = \Pi_S T$. Π_S is a matrix of size 16×16 such that each line has only one position, with a non zero value, equal to 1. T is a Toeplitz matrix of size 16×16 with a Hadamard matrix of size 4 on its diagonal. In the case of full rate MIMO schemes, it is well known that powerful receivers, such as iterative receivers, have to be carried out to recover transmitted data and manage spatial interference [7]. In the sequel we focus on turbo equalization based on minimum mean square error interference cancellation (MMSE-IC) that was shown to provide a good complexity-BER performance trade off [11]. The performances for SM and full rate STBC schemes in the EP_2RP_2 4×4 MIMO (uncorrelated) channel configuration, detailed in the section 2, are depicted in Figure 2. For the EP_2RP_2 antennas configuration (uncorrelated scenario), whatever the chosen MIMO scheme, performance is largely improved by 15 dB compared to the SISO (single input single output) case. At high spectral efficiency, the performance of the full rate STBC is degraded compared to the SM scheme. Indeed, the iterative receiver at 6 iterations is not able to perfectly recover all the transmitted layers of the STBC because of the block fading nature of the channel. On the contrary, for low spectral efficiency, the performance of the STBC is improved by 1 dB compared to SM. For the EP_1RP_1 antennas configuration, we observe an error floor of FER performance (not shown) around 10^{-1}. Indeed, the rank deficiency of the channel matrix prevents from recovering the transmitted layers of the full rate MIMO schemes. In this case, the MIMO schemes lead to FER performance degradation compared to the SISO case. Orthogonal space-time matrices with lower rates could be used. Instead, we propose to take benefit of a low rate feedback link channel to implement MIMO algorithms with the partial knowledge of CSI at the transmitter side.

Second, taking into account the knowledge of CSIT allows us to anticipate evolutions of the propagation channel characteristics. This is well-known in the literature as the precoding process. The MIMO channel is decomposed into several independent eigen-subchannels using the SVD (Singular Value Decomposition) technique, and resources are allocated over these sub-channels to optimize a particular criterion (MMSE, SNR, capacity…). In this study, we consider two precoders that achieve the best performance by optimizing the same criterion: maximizing the minimum Euclidean distance. The first one is the max-d_{min} precoder [8] and the second one is precoded orthogonalized spatial multiplexing (P-OSM) [9,10]. In the latter, the SVD operation is replaced by a simple rotation operation at the transmitter in order to orthogonalize the two transmit symbols. The ML detection is then greatly simplified. Nevertheless, when the number of transmitting antennas is greater than two, an antenna selection technique must be added. To match the low rate feedback channel, 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 has to return different parameters [9,10], also quantized with 7 bits. In order to limit the complexity, the channel decoder consists in a hard input Viterbi algorithm with no iterative process. Hence, results are not directly comparable with those given in Figure 2 for no CSIT MIMO schemes. Figure 3 shows FER with spectral efficiency equal to 2 bit/s/Hz for the 2 configurations EP_1RP_1 and EP_2RP_2. When the channel is strongly correlated (EP_1RP_1), the quantization introduces less than 0.4 dB loss of E_b/N_0. The best precoder is max-d_{min} with a gain of 1.5 dB on POSM. For the EP_2RP_2 configuration, the quantization loss is increased and is about 1.2 dB for both precoders. The max-d_{min} precoder is the best with a 1 dB gain on the P-OSM. Indeed, quantization of the feedback with 7 bits can definitively improve FER especially when the channel is correlated and should provide a good alternative to iterative methods.

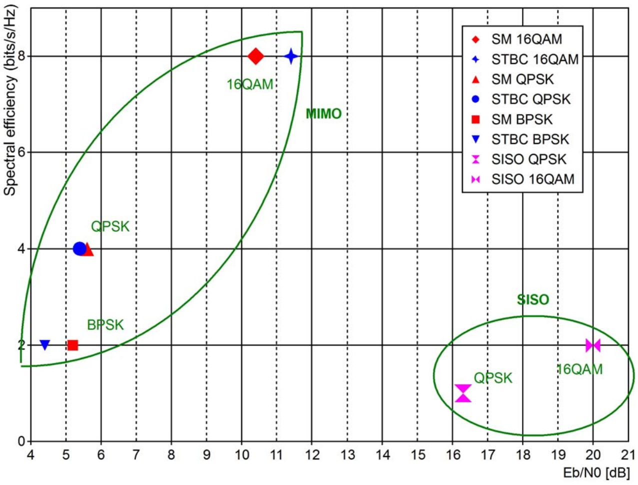

Figure 2. Achieved Eb/N0 (dB) versus spectral efficiency (bits/s/Hz) for the iterative MMSE-IC receiver (6 iterations) for a target FER equal to 3.10^{-2}; EP2-RP2 4×4 MIMO (uncorrelated) @ 5.8 GHz block fading channel and block fading SISO channel.

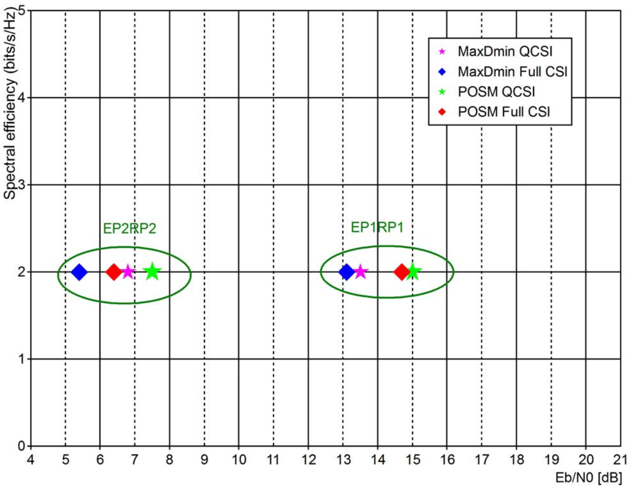

Figure 3. Achieved Eb/N0 (dB) versus spectral efficiency (bits/s/Hz) for the ML receiver for P-OSM and max-d_{min} precoder for a target FER equal to 3.10^{-2}; EP1RP1 (correlated) and EP2-RP2 4×4 MIMO (uncorrelated) @ 5.8 GHz block fading channel.

4. Conclusion and perspectives

In this paper we have proposed to enhance the PHY layer of IEEE802.11x modems deployed for metro applications and we have analyzed performance of several MIMO schemes with and without CSI-T taking into account various spatial correlation degrees that can be encountered in tunnel scenarios. The algorithms are compared with a system point of view, in terms of achieved signal to noise ratio (SNR) versus spectral efficiency for a realistic targeted FER equal to 3.10^{-2}. For an uncorrelated scenario, whatever the chosen MIMO scheme without CSI-T, performance is largely improved by 15 dB compared to the SISO case. At high spectral efficiency, the performance of the full rate STBC is degraded compared to the SM scheme. The iterative receiver at 6 iterations is not able to perfectly recover all the transmitted layers of the STBC because of the block fading nature of the channel. On the contrary, for low spectral efficiency, the performance of the STBC is improved by 1 dB compared to SM. In the correlated scenario, MIMO without CSI-T is not able to improve performance. Hence we have considered precoding techniques with partial CSI-T thanks to a low rate feedback link. With partial CSI-T, we have compared the max-d_{min} and P-OSM precoders, both based on the maximization of the minimum Euclidean distance. In uncorrelated and correlated scenarios, max-d_{min} outperforms P-OSM. However, from a practical point of view, P-OSM is a good alternative to MIMO schemes without CSI-T, even in correlated scenarios, since only a 7 bits feedback is needed and SVD is avoided.

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