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Advantages of simple MIMO schemes for robust or high data rate transmission systems in underground tunnels

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Abstract—Robust, reliable and high data rate transmission systems are key components of underground information systems particularly in the case of driverless ones. In this context, wireless systems must be able to maximize data rate and/or robustness while avoiding increases in transmitting power and/or in transmission bandwidth. MIMO techniques are today well known in the scientific community for indoor applications where the propagation channel experiences multipath effects. The work presented in this paper concerns the evaluation of conventional MIMO techniques such as the Alamouti code, spatial multiplexing, and linear precoding in tunnels environments usually considered as correlated channels. After the choice of the best suited channel model and antenna configuration, the simulation of the physical layer based on Wi-Fi IEEE802.11a/g standards gives rise to the comparison of the MIMO algorithms.

Index Terms—MIMO, space-time code, spatial multiplexing, linear precoding, underground tunnels, channel correlation

I. INTRODUCTION

INTEGRATING the railway transport systems requires mobility of information. Nowadays, there is an increase of complexity of information systems in the field of transport. Several types of data must be carried on the same medium and required different system performance and QoS. In this context, wireless systems are key solutions to carry at the same time with different priorities, data related to infrastructure, traffic, operation and rolling stock management. In the field of mass transit, driverless underground systems are one of the best examples of such deployments (New-York, ligne 1 in Paris, Malaga...). These systems should provide robustness, reliability and high throughputs in order to answer at the same time, on uplink and downlink, the safety and the QoS requirements in the case of video and audio streams related to surveillance systems or passenger information. In this context, MIMO (Multiple Input Multiple Output) systems seem to address this issue. Indeed, by exploiting the spatial dimension (provided by the multiple antennas at the transmitter and the receiver) MIMO systems are able to mitigate signal fading due to the multipath that occurs during a wireless transmission. Therefore the quality and the reliability of reception is improved. MIMO systems can also offer an increase in data rate by multiplexing data onto the multiple

transmit antennas. Thus these MIMO systems should be able to provide at the same time high data rate, QoS, robustness, adaptability, and to use with parsimony radio resources in complex propagation environments as underground tunnels.

This work is a first contribution in the development and optimization of new innovative train-to-ground communication systems. The objective of the paper is to evaluate some MIMO algorithms in the context of transmissions in tunnels. The systems parameters of the physical layer are chosen to be as close as possible from those of IEEE802.11a/g standards [1]. Indeed, some of the systems deployed in the world by underground operators are based on such existing wireless standards in the 2.4 and 5.8 GHz bands. The study has to demonstrate the ability of MIMO systems to increase robustness/coverage and/or data rate in such a transmission scenario. The first step is to provide MIMO channel models that will be included in the physical layer simulation chain. Two analytical channel models are studied. Their inputs are channel impulse responses (CIR) simulated by a 3D ray-tracing software. Different antenna configurations in the tunnel are considered. An analysis based on the MIMO channel capacity leads to the choice of the best antenna configuration and of an accurate channel model. Finally, the physical layer is modeled and three MIMO algorithms are investigated: the well-known Alamouti Space Time Block Code (STBC), spatial multiplexing (SM), and a combination of linear precoding (LP) and spatial multiplexing. The paper is organized as follows. Section II briefly presents the principles of propagation in underground tunnels. Then, the channel modeling process and the correlation based models are detailed in section III. Two extreme channel configurations are chosen, offering low and high correlation degrees. Section IV is devoted to the description of the transmission/reception chains. An evaluation of their performance in terms of block error rate (BLER) versus E_b/N_0 ratio is given in section V. Finally we conclude and give some perspectives.

II. PROPAGATION IN TUNNELS

Free propagation in tunnels is possible when the transverse dimensions of the tunnel are large compared to the wavelength. The tunnel can be compared to an oversized lossy waveguide. In this case, the modal theory [2] shows that only

the hybrid modes, denoted EH_{mn} (where m and n stand for the mode order), are able to propagate.

Some experimental works in underground tunnels [3] in the 900 MHz band showed that, in the case of short range communications, MIMO channel capacity can be increased for specific antennas configurations. Moreover, it was recently demonstrated that the concept of spatial diversity must be replaced by the concept of modal diversity [4]. In this context, MIMO techniques appear as a very interesting solution for transmission in underground tunnels.

III. CHANNEL MODELING

A. Introduction

MIMO system performance is linked to the correlation level existing between the multipath components (MPC) in the channel. Consequently, it is crucial to be able to model MIMO channels to evaluate MIMO system performance through numerical simulations. It is possible to consider general models such as 3GPP, WINNER or WiMAX ones [5]-[7]. Another kind of channel models dedicated to MIMO configurations exist. Their aim is to model the parameter influencing MIMO channel capacity. They are generally separated in two subcategories [8] regarding the channel parameters considered: *physical models* or *analytical models*. The two categories are based on double-directional complex channel impulse responses (CIR) between transmit and receive antennas or second order statistics characterizing the channel.

Physical channel models characterize an environment describing the double-directional multipath wave propagation between the location of the transmit (Tx) and the receive (Rx) antenna arrays [9], [10]. They model geometrical wave propagation parameters (directions of departure (DoD) and arrival (DoA), delays of the MPC) in deterministic [11], [12] or stochastic ways [13]-[18]. They need an accurate description of the geometry of the propagation scene.

Analytical channel models offer greater flexibility and highlight the correlation phenomenon which occurs in the MIMO channel and degrades performance. Channel CIR are exploited to compute statistical properties like the spatial correlation of the channel. Without any polarization diversity and in the NLOS (Non Line of Sight) case, the matrix \mathbf{H} of the MIMO channel can be written as (1):

$$\mathbf{h} = \mathbf{R}_{\mathbf{H}}^{\frac{1}{2}} \mathbf{g} \quad (1)$$

where \mathbf{h} is a vector of \mathbf{H} , $\mathbf{R}_{\mathbf{H}}$ denotes the channel correlation matrix, and \mathbf{g} is a $(N_{\text{Rx}} \times N_{\text{Tx}} \times 1)$ vector with i.i.d. Gaussian elements with zero mean and unit variance.

The main drawback of this representation lies in the number of real parameters ($(N_{\text{Rx}} \times N_{\text{Tx}})^2$ coefficients). The *Kronecker model* [19] and the *Weichselberger model* [20] reduce the size of the MIMO correlation matrix by breaking up it, in order to translate the propagation environment with accuracy.

The Kronecker model assumes that the Tx and Rx correlations (\mathbf{R}_{Tx} and \mathbf{R}_{Rx} respectively) are independent, so the channel correlation matrix $\mathbf{R}_{\mathbf{H}}$ can be separated using the Kronecker product, introducing the Kronecker model in (2):

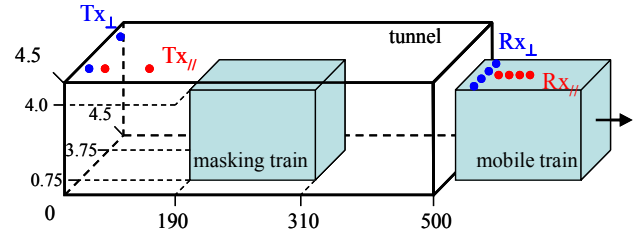


Fig. 1. Antennas configurations

$$\mathbf{h} = (\mathbf{R}_{\text{Tx}} \otimes \mathbf{R}_{\text{Rx}})^{\frac{1}{2}} \mathbf{g} \Leftrightarrow \mathbf{H} = \mathbf{R}_{\text{Rx}}^{\frac{1}{2}} \mathbf{G} \mathbf{R}_{\text{Tx}}^{\frac{1}{2}} \quad (2)$$

where \mathbf{G} is an i.i.d. unit variance matrix ($N_{\text{Rx}} \times N_{\text{Tx}}$).

The Kronecker model is widely used for its simplicity and the reduced size of data it involves (only $N_{\text{Rx}}^2 + N_{\text{Tx}}^2$), when the joint DoD-DoA spectrum is separable. Subsequently, this model can not reproduce the coupling between the two ends of the system, so it will not be recommended to model specific channels like “keyhole” one. In this case, the Weichselberger model which introduces a coupling matrix between the Tx and Rx correlations is best suited (3).

$$\mathbf{H} = \mathbf{U}_{\text{Tx}} (\mathbf{\Omega} \circ \mathbf{G}) \mathbf{U}_{\text{Rx}}^T \quad (3)$$

where $\mathbf{R}_{\text{Tx/Rx}} = \mathbf{U}_{\text{Tx/Rx}} \mathbf{\Lambda}_{\text{Tx/Rx}} \mathbf{U}_{\text{Tx/Rx}}^H$ ($\mathbf{\Lambda}_{\text{Tx/Rx}}$ containing the corresponding eigenvalues), \circ denotes the Schur-Hadamard product, and $\mathbf{\Omega}$ ($m \times n$) is the coupling matrix equals to (4):

$$\mathbf{\Omega}_{mn} = \sqrt{E_{\mathbf{H}} \left[\left| \mathbf{U}_{\text{Rx},m}^H \mathbf{H} \mathbf{U}_{\text{Tx},n} \right|^2 \right]} \quad (4)$$

B. Channel modeling

The Kronecker and the Weichselberger models have been chosen to model the 2x4 MIMO channel in a tunnel with a masking train (Fig. 1). In this work we consider that the channel will not vary during the transmission of a coded block.

The two Tx antennas are 3 m spaced while the four Rx antennas are separated by 1 m each. Two configurations regarding the tunnel longitudinal axis are modeled: $\text{Tx}_{//} \text{Rx}_{//}$ and $\text{Tx}_{\perp} \text{Rx}_{\perp}$. These two configurations have been simulated using a 3D ray-tracing software [21] at 2.4 GHz, considering an uniform radiation pattern for each antenna element. For the considered frequency band, the 3D ray-tracing software indicates that the mean path delay, smaller than 3 ns, is much smaller than the symbol duration (4 μs for the OFDM symbol, and 50 ns for the equivalent single-carrier symbol). Consequently, we have focused on narrow band channel models. The Rx and Tx correlation matrices have been deduced from the obtained simulated CIR. The results in terms of mean channel capacity (5) over the interval [310, 500] m which corresponds to the transmitter-receiver distance are plotted in Fig. 2.a) and Fig. 2.b) for the $\text{Tx}_{//} \text{Rx}_{//}$ and $\text{Tx}_{\perp} \text{Rx}_{\perp}$ configurations, respectively. Lower and upper channel capacity bounds are added on Fig. 2 using a totally correlated and an uncorrelated Rayleigh channel, respectively.

The mean channel capacity curves show that full space diversity is reached when the Tx and Rx antenna axis are oriented perpendicular to the tunnel longitudinal axis ($\text{Tx}_{\perp} \text{Rx}_{\perp}$ configuration). In this case, the mean channel capacities

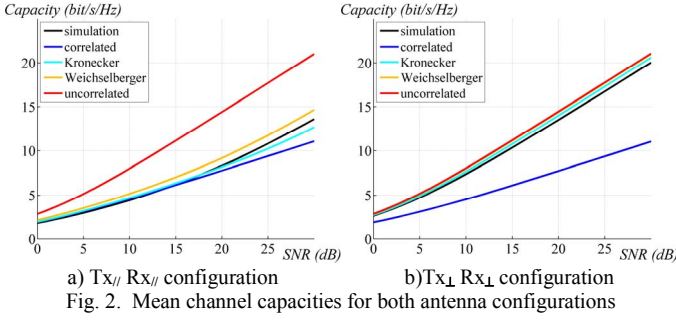


Fig. 2. Mean channel capacities for both antenna configurations

obtained with the Kronecker and the Weichselberger models are closed to the uncorrelated one.

$$C = \log_2 \left[\det \left(\mathbf{I}_{N_{Rx}} + \frac{\rho}{N_{Tx}} \mathbf{H} \mathbf{H}^H \right) \right] \quad (5)$$

The mean channel capacity obtained for the configuration $Tx_{//} Rx_{//}$ with both models is close to the totally correlated one. In this case, the interest to use such a technology is reduced compared to the SISO configuration. Indeed, the weak spatial diversity brought by the MIMO channel will not allow a high gain for MIMO systems. These two configurations show that the mean channel capacity results obtained for the Kronecker and the Weichselberger models are close to the models obtained using the channel matrix computed from the simulated CIR. Thus, we choose to use the Kronecker model in the rest of the paper, discarding the effect of a coupling between the Tx and Rx correlations.

IV. TRANSMITTING/RECEIVING SIMULATION CHAIN DESCRIPTION

In this section, three different MIMO schemes are investigated. The number of antennas, equal to two at the transmitter and to four at the receiver, has been fixed to keep a good compromise between performance and complexity of the system. The physical layer is close to the one proposed in IEEE802.11a/g Wi-Fi standards [1]. Perfect synchronization and channel knowledge is assumed at the receiver.

The MIMO schemes are all based on the space-time bit-interleaved coded modulation (STBICM) scheme. This simple scheme is a very efficient solution to obtain high diversity and coding gain on a MIMO channel. It is an extension of the bit-interleaved coded modulation (BICM) structure that is the concatenation of a channel encoder, a bit interleaver and a bit-to-symbol mapper. The channel code captures the time and space diversities inherent to the MIMO channel. The BICM scheme involves a 1/2 rate recursive systematic convolutional code with constraint length $K=7$, and defined by the generator polynomials $g_0 = 171_8$ and $g_1 = 133_8$. A random bit interleaving is performed over a 1536 bytes length block of coded data. Finally each block is modulated using a 4-PSK (Phase Shift Keying) modulation or a 16-QAM (Quadrature Amplitude Modulation) according to the Gray mapping. The modulation order is chosen to obtain a spectral efficiency equal to $\eta = 2$ bit/s/Hz, whatever the MIMO scheme, in order to compare their performance. The BICM scheme is followed by the selected MIMO scheme. At the receiver, the MIMO

detection that depends on the algorithm involved at the transmitter is performed. This stage is followed by the inverse operations of mapping, interleaving and channel coding.

A. Alamouti based system

The first one, depicted Fig. 3, involves a conventional Alamouti STBC at the transmitter while the receiver consists in a Maximum Ratio Combining (MRC) [22]. In case of uncorrelated MIMO channel, this scheme achieves the maximal order of diversity equal to $N_{Tx} \times N_{Rx}$ since no time diversity is visible from the point of view of channel code (the channel is assumed to be constant over one coded block). To achieve a spectral efficiency equal to 2 bit/s/Hz and because of the non-full rate of the Alamouti code, the 16-QAM is chosen.

B. Spatial multiplexing based system

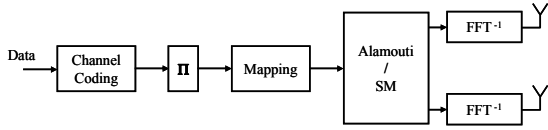
The spatial multiplexing, illustrated Fig. 3, involves a simple serial to parallel multiplexing of encoded data. Thanks to a full-rate equal to the number of transmit antennas, the modulation order can be reduced to four to achieve $\eta = 2$ bit/s/Hz. Thus a 4-PSK Gray-mapped modulation proposed in the standard is implemented. At the receiver the MIMO detection is performed by a MMSE (Minimum Mean Square Error) equalizer. In case of uncorrelated MIMO channel, the MMSE equalizer can only exploit a diversity order equal to $N_{Rx} - N_{Tx} + 1$ and consequently it is unable to achieve the maximal order of diversity equal to $N_{Tx} \times N_{Rx}$.

C. Linear precoding based system

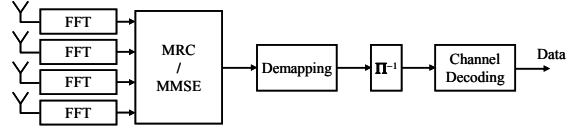
In order to improve BER performance, the BICM may be concatenated with an efficient full-rate linear space-time code: a linear precoding or equivalently a space-time spreading (see Fig. 4.a). The goal is to fully exploit the transmit space diversity, without giving up the high capacity and high coding gains provided by the STBICM scheme. We recall that the channel matrix is unknown at the transmitter. Linear precoding involves a linear combination of the complex symbols. Moreover, it spreads the complex symbols over p time periods. Then, thanks to a space interleaver (or space mapper) Π_s , the mixed symbols are allocated to different antennas at different time periods according to the DLST (Diagonal Layered Space Time) structure [23]. To fully exploit the transmit space diversity, the symbols coming from the same precoding process have to be transmitted on different antennas. Hence the precoding size equals to the number of transmit antennas $p=N_{Tx}$. A larger precoding size is not useful since no time or frequency diversity exists. In our application, we choose a Hadamard precoding matrix defined recursively by

$$D_M = \frac{1}{\sqrt{2}} \begin{pmatrix} D_{M/2} & D_{M/2} \\ D_{M/2} & -D_{M/2} \end{pmatrix} \text{ with } D_1 = 1 \quad (6)$$

The receiver, illustrated in Fig. 4.b), is divided in two main elements: a MIMO equalizer, which processes jointly linear precoding and MIMO signal demapping, and a channel decoder, improving the information on the coded bits and estimating the information bit sequence. The iterative process is based on the exchange of soft values between these two

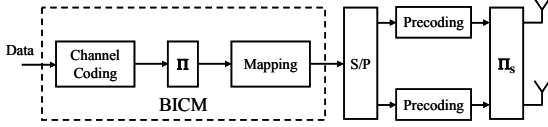


a) Transmitting module using Alamouti or spatial multiplexing (SM)

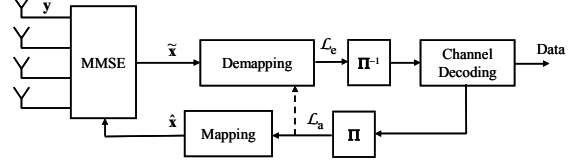


b) Receiver using MRC or MMSE equalizer

Fig. 3. Alamouti / SM based simulation chain associates with a MRC receiver / MMSE equalizer



a) Transmitting module combining spatial multiplexing and linear precoding



b) Turbo receiver: MMSE turbo-equalizer

Fig. 4. Spatial multiplexing and linear precoding based simulation chain associates with a MMSE turbo equalizer

elements. This exchange is maintained thanks to soft mapper/demapper converting LLRs required by the channel decoder to and from complex symbols. Thus this information exchange is realized according to the Turbo principle [24]. The MIMO equalization is based on the MMSE criterion with interference cancellation. Detailed information can be found in [25][26]. It can be shown that, in case of uncorrelated MIMO channel, such a system can achieve the maximal diversity order equal to $N_{Tx} \times N_{Rx}$. Moreover, this structure benefits from the full rate of the linear precoding like the spatial multiplexing scheme. Thus a 4-PSK Gray-mapped modulation proposed in the standard is implemented to achieve $\eta = 2$ bit/s/Hz.

V. PERFORMANCE EVALUATION

In this section, the performance of the three previous 2x4 MIMO schemes are simulated at 2.4 GHz in the tunnel environment described and modeled in the section III for both antennas configurations ($Tx_{//} Rx_{//}$ and $Tx_{\perp} Rx_{\perp}$), in terms of block error rate (BLER) as a function of E_b/N_0 ratio.

A. Alamouti / spatial multiplexing based systems

Fig. 5.a) shows the BLER results for the Alamouti STBC and the SM scheme. The curve labeled “SISO Rayleigh” represents the performance of the same BICM scheme with a 16-QAM modulation over a Quasi-static Rayleigh fading SISO channel. This SISO scheme achieves the same spectral efficiency equal to 2 bit/s/Hz.

In section III, we have shown that the $Tx_{//} Rx_{//}$ antenna configuration corresponds to a mean channel capacity close to the totally correlated MIMO channel. In this configuration, the SM scheme leads to poor performance, worst than the SISO one, even for high E_b/N_0 values. Indeed, the spatial correlation of the channel does not enable the separation of the spatially multiplexed data flows at the receiver. The channel decoder can not recover from the errors generated at the output of the MMSE equalizer. On the contrary, the Alamouti scheme offers a small gain compared to a SISO configuration: it exists a factor 2 at $E_b/N_0 = 12$ dB. Indeed the property of orthogonality brought by the Alamouti scheme allows for the optimal exploitation of the channel diversity, even if this one is weak.

In the uncorrelated $Tx_{\perp} Rx_{\perp}$ configuration, the SM and Alamouti schemes improve performance reducing the BLER by a factor greater than 100 compared to a SISO transmission/reception chain. Alamouti scheme provides best results for high E_b/N_0 values.

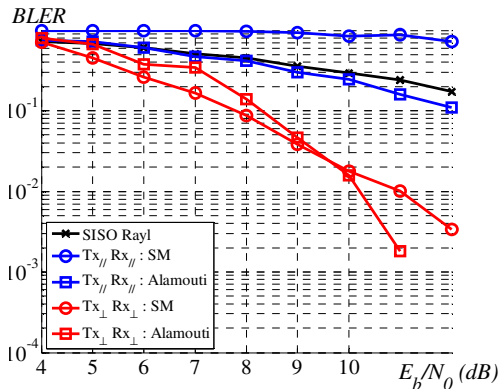
B. Linear precoding based system

Fig. 5.b) presents the BLER performance obtained with the association of SM and linear precoding with a MMSE turbo equalizer at the receiver. The curves labeled “ideal” represent the performance obtained when a genie gives perfect information feedback on the coded bits in the MMSE equalizer. This performance corresponds to a perfect equalization process, for which no spatial interference remains at its output.

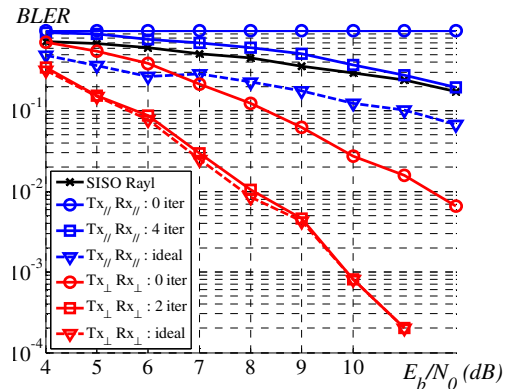
As obtained with the two previous classical MIMO schemes, the transmission performance is better in the $Tx_{\perp} Rx_{\perp}$ configuration than in the $Tx_{//} Rx_{//}$ one. For the $Tx_{//} Rx_{//}$ configuration, which can be compared with a totally correlated channel, and after four iterations, the turbo-equalizer is not able to totally recover from the spatial interference generated by the spatial multiplexing (the ideal curve is not attained). Thus, in this specific configuration ($Tx_{//} Rx_{//}$) and for the number of iterations we considered, the MIMO system does not bring any performance gain compared to the SISO system. On the contrary, when the channel is uncorrelated like in the $Tx_{\perp} Rx_{\perp}$ configuration, only three iterations are necessary for the turbo-equalizer to converge towards its ideal performance. It demonstrates the interest of the combination of linear precoding and spatial multiplexing in a MIMO system.

VI. CONCLUSION

The paper has focused on the performance evaluation of some MIMO schemes in confined environments like tunnels. The first step was to propose a statistical channel modeling in order to facilitate the simulation of the physical layer based on IEEE802.11a/g standards. The modeled channels enable a mean capacity analysis regarding the antennas configuration in the tunnel. This analysis has shown a great dependency of the capacity towards the antenna configuration. The $Tx_{\perp} Rx_{\perp}$ configuration (perpendicular to the tunnel longitudinal axis)



a) Alamouti and spatial multiplexing (SM) schemes



b) spatial multiplexing (SM) associated with linear precoding scheme

Fig. 5. Block Error Rate versus E_b/N_0 ratio using the IEEE802.11a/g Wi-Fi standards like chain

leads to high capacity, close to the uncorrelated MIMO channel. In such conditions of transmission, the Alamouti STBC naturally exploits the spatial diversity inherent to the MIMO channel, just like the linear precoded SM scheme. Moreover, the linear precoded SM scheme takes advantage of the uncorrelation to perfectly separate the multiplexed data flows. Thus for both schemes BLER performance is improved compared to the SISO case.

On the contrary, in the $Tx_{//} Rx_{//}$ configuration the Alamouti STBC can only benefit from the limited spatial diversity. The linear precoded SM scheme leads to poor performance, worse than the SISO case for the considered number of iterations.

In future works, an adaptive algorithm between the Alamouti STBC and the linear precoded SM scheme will be investigated to optimize the performance in all the possible antennas configurations.

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