MIMO Channel Measurement Campaign in Subway Tunnels

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Abstract—**The recent construction of the new L9 subway line in Barcelona, Spain has provided the opportunity to study the impact of different antenna configurations on the maximum channel capacity inside subway tunnels. In this work the authors present the design tradeoffs inside different kind of tunnels in terms of antenna spacing and applied diversity technique for a 2x2 MIMO system at C-Band. These design tradeoffs are the conclusion of the measurement campaign carried out during last year at L9 subway tunnels.**

I. Introduction

In [1], the authors have presented a complete set of raw-data obtained from a measurement campaign inside subway tunnels at 5.8GHz. This measurement campaign was carried out during last year and took place at the L9 subway line tunnels in Barcelona, Spain.

The study developed in this work follows the steps presented at [2], [3], [4] and [5] where the dependence of the maximum theoretical channel capacity with the excited and propagated 'wave-guide' modes inside the tunnel is shown. Due to the dependence of the excitation of these modes with the transmitter and receiver placement inside the tunnel, antenna spacing of the Multiple Element Antenna (MEA) and different polarization of the antennas the authors have carried out an analysis of the impact on the maximum capacity of the polarization diversity and the antenna spacing of the MEA.

Considering a multi-element antenna system with 2 transmitting antennas and 2 receiving antennas and a quasi-static channel at each point of the tunnel the channel matrix H can be obtained by the measurement system presented at [1] and the maximum theoretical capacity at each point of the tunnel can be computed by Eq. 1.

$$C = \log_2 \det(I_2 + \frac{\rho}{2} H_0 H_0^H) \quad (1)$$

where I_2 is a 2x2 identity matrix, ρ is the received Signal to Noise Ratio (SNR) and H_0 is computed by Eq. 2.

$$H_0 = H\sqrt{\frac{4}{\|H\|_F^2}} \quad (2)$$

In order to compare with the SISO case the average receive SNR of a single antenna system or SISO SNR [6] is computed by the Eq. 3.

$$\rho_0 = \rho\frac{\|H\|_F^2}{4} \quad (3)$$

TABLE I
Tunnel Environments

Tunnel	Path Distance [m]	Height [m]	Width [m]
TST	297	4.77	9.54
BST	292	4.65	9.54
BBT	157	4.65	9.54

where ρ is again the SNR at the receiver. This work presents the considered scenarios at section II [1], the raw-data processing and the considered parameters on the study at section III and the design tradeoffs mentioned above at section IV. At the end, a brief discussion about the results is done in order to discuss some of the authors' conclusions.

II. Tunnel Scenarios

This section is devoted to describe the different tunnel structures and MEA structures considered during the analysis mentioned at section I. All of them are described at [1], therefore in this work there is only a brief description of them, focused on the main parameters.

A. Tunnel Environments

The considered tunnels are classified by their longitudinal section shape in two different kinds of tunnels and by their cross section shape in two different tunnels. All of them are summarized in Table I with the used acronyms on this work and their main parameters.

The acronyms refer to the different parts of the tunnel depicted at Fig. 1 where TST is the top straight tunnel, BST is the bottom straight tunnel and BBT is the bottom bended tunnel of that figure. As one can see the TST is an arched tunnel and the BST and the BBT are quasi-rectangular tunnels.

B. MEA Structures

A 2 antenna structure was adopted for the transmitting and receiving MEA considering a 2x2 MIMO system. This structure was a combination of two rectangular patch antennas centered at 5.8GHz with 5% of bandwidth at 15dB return loss. The MEA allowed to change the antenna spacing between 2λ and 6λ and the polarization of the transmitting and receiving set-up. Table II shows the different experiments which took place inside the tunnels described at section II-A and Fig.

Fig. 1. Tunnel scenarios of the L9 subway line in Barcelona, Spain.

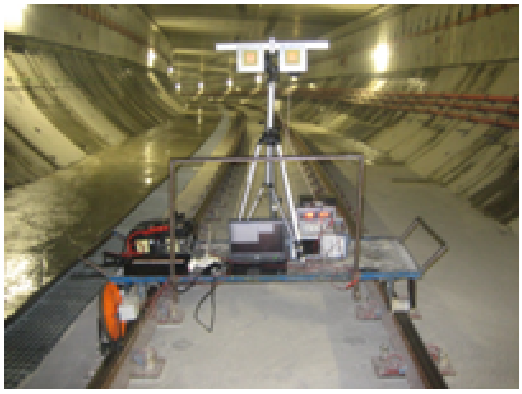


Fig. 2. MEA receiver real implementation inside L9 subway tunnel.

TABLE II
MEA CONFIGURATIONS

Polarization	Tunnel	Antenna Spacing
HH	TST	2λ,4λ,6λ
	BST	4λ,6λ
	BBT	2λ,4λ,6λ
VV	TST	2λ,4λ,6λ
	BST	4λ,6λ
	BBT	2λ,4λ,6λ
VH	TST	4λ,6λ
	BST	4λ,6λ
	BBT	2λ,4λ,6λ

2 shows a real implementation of the MEA structure at the receiver.

The HH, VV and VH acronyms refer to a Horizontal-Horizontal configuration of both patch antennas at the transmitter and the receiver, Vertical-Vertical polarization and Vertical-Horizontal polarization.

III. DATA PROCESSING

A. Considered MIMO Parameters

Assuming the quasi-static behavior of the channel [7], [8], the channel matrix H can be characterized by a single tap for each sub-path of the multipath environment. Therefore the measurement system presented at [1] provided a sampled channel matrix $\hat{H}$ at every 25cm along the different tunnel longitudinal sections. In order to avoid the presence of the propagation path loss and other propagation effects, this channel matrix was normalized by the Frobenious normalization presented at [9] and computed by the Eq. 2 for each sampled matrix $\hat{H}$. The maximum theoretical capacity is given by Eq. 1. where ρ was fixed to 10dB.

B. Considered Experiments and Results

At this point, the maximum theoretical channel capacity has been computed by Eq. 1 for the relevant scenarios presented at Table I by the sampled channel matrix $\hat{H}$.
Fig. 3 shows the maximum theoretical capacity evolution along the BST when a 2λ antenna spacing and HH polarization are configured on the transmitting and receiving MEAs, both of them placed at the center of the tunnel. This figure also shows the SISO case when ρ_0 defined by Eq. 3 is considered as SISO SNR [6], providing information about the impact of the spatial diversity application inside a quasi-rectangular tunnel (BST) on the maximum theoretical capacity. Although the increment on that capacity is far away of the expected at a rich scattering scenario a slight improvement on the MIMO behavior has been observed.

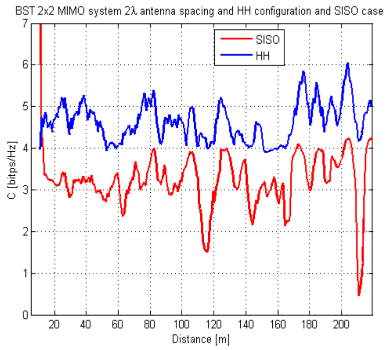
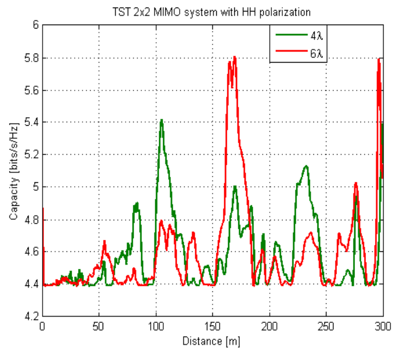


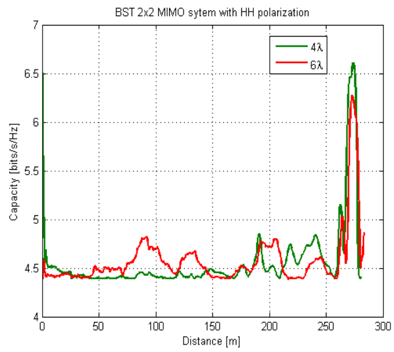
Fig. 3. Maximum theoretical capacity distribution along distance in the BST considereing the SISO case and certain configuration of the transmitting and receiving MEAs.

Fig. 4 shows the different maximum theoretical capacity distribution along distance in two different tunnels and different antenna spacings. This figure also shows the maximum theoretical capacity distribution along distance in two different tunnels when a 6λ antenna spacing is considered at the transmitting and receiving MEAs and VH polaization is configured at both MEAs.

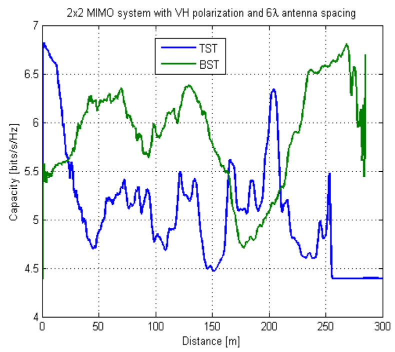
Fig. 4(a) and Fig. 4(b) show the impact of the antenna spacing for a certain configuration of the transmitting and receiving array on the maximum theoretical capacity. In both figures the maximum theoretical capacity shows a slight increment when the antenna spacing is higher than 4λ and the antenna spacing influence on the capacity seams to be higher for the TST scenario.
The effect of the obstacles inside the TST produces a fluctu-



(a)



(b)



(c)

Fig. 4. Maximum theoretical capacity distribution along distance for different scenarios. (a) TST, 2x2 MIMO system with HH polarization and different antenna spacing (4λ and 6λ). (b) BST, 2x2 MIMO system with HH polarization and different antenna spacing (4λ and 6λ). (c) TST and BST, 2x2 MIMO system with VH polarization and 6λ antenna spacing.

ation on the maximum theoretical capacity distribution which can be explained by a richer scattering scenario when the presence of obstacles is considered.

A change on the tunnel shape at the end of the BST tunnel produces a considerable fluctuation on the maximum theoretical capacity. This fluctuation can be explained by the excitation of a new set of modes along the new shape by the impinging wave.

Fig. 4(c) shows the impact of the spatial diversity and polarization diversity application inside the quasi-rectangular tunnel and the arched tunnel (TST). The TST curve shows the effect of a change on the receiving MEA when one the elements is disconnected and a MISO situation is considered.

This figure shows how the MIMO behavior has a better performance in a quasi-rectangular tunnel than in a arched tunnel, although there is a certain capacity gain in both cases. However this improvement on the maximum theoretical behavior is far away from the expected improvement in a rich scattering scenario.

IV. Design Tradeoffs

The presented results at section III-B provide some insight about the optimal choice for different conifguration parameters of a MEA working in subway environments at C-band. This section summarizes these optimal configuration of the parameters taking into account that the diversity techniques have a low impact on the maximum theoretical capacity inside tunnels [8], [10], [11], [12].

A. Spatial Diversity and Antenna Spacing

Once a spatial diversity technique is assumed with a 2x2 MIMO system working inside the different environments presented at Table I the results presented at III-B show the low impact of the antenna spacing on maximum theoretical capacity inside tunnels. This antenna spacing provides an increment, showing a different behavior when the tunnel changes its cross section.

B. Polarization Diversity Technique

The spatial diversity technique has been shown as a low effective method to increase the maximum theoretical capacity of the tunnel channel. Therefore although the number of antennas increases the maximum theoretical capacity this method is not enought to provide a high increment in that capacity.

In that way the diversity polarization could be a complementary design parameter in order to increase the maximum theoretical capacity, even its impact over that capacity has appeared as cross sectional depenedent.

V. Conclusions

A two design guidelines of a 2x2 MIMO system working inside a real subway tunnel such as the L9 subway line tunnel in Barcelona are presented in this work. The authors have studied the impact of the antenna spacing and the polarization diversity technique applied in the maximum theoretical capacity for a certain position of the transmitter and receiver antenna array.

The study has lead to conclude that there is a low impact on the maximum theoretical capacity when a spatial diversity technique is applied. The impact of the 2x2 MIMO system spatial diversity is reduced to a slight increment on the maximum theoretical capacity compared with the SISO case. Moreover, combining polarization and spatial diversity the increment experimented by the maximum theoretical capacity is far away from the expected in a rich scattering scenario. This low impact effect is even worst in arched tunnels.

The study also concludes that the antenna spacing has a low impact on the maximum theoretical capacity even there is a slight increment on it when the antenna spacing is increased. Due to the wavelength is on the order of $5cm$ and the receiver antenna spacing is limited by the width of the train then the antenna spacing should be as high as possible, fitting the mentioned constrain.

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