Propagation in Subway Tunnels: SISO and MIMO Channel Characterization

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Abstract: - This paper first describes experimental results on the characterization of the propagation in subway tunnels. A first set of experiments have been carried out in Paris subway to determine the path loss, the long term and short term fading and the masking effect produced by a train. Then a wide band analysis has been performed both for a SISO (Single Input Single Output) and for a MIMO (Multiple Input Multiple Output) transmission. The improvement of the channel capacity which can be expected with MIMO techniques is outlined.

Key-Words : - Propagation, MIMO, Tunnel, channel capacity

1 Introduction

For railways applications, there is now an important demand to increase the capacity of the transmission between the train and a base station. Indeed, to ensure and to improve the control-command and especially of subways, a high bit rate is necessary. In Europe, a bandwidth around 900 MHz has been devoted to railways (GSM-R) but is not large enough to ensure all the functionalities needed by the railway operator. Since in many cases, the subway is underground, it could be possible to use the tunnel as an oversize waveguide supporting a number of modes. In this case, one can expect that space time coding techniques [1] will improve the channel capacity [2], even if the spread of the direction of arrival of the rays is small. However, the correlation between the antennas belonging either to the fixed or mobile base is an important factor playing a leading part in the channel performance [3].

A predictive model of the propagation based on a ray tracing or a ray launching technique can be used but the presence of curves, changes in the tunnel cross section, the presence of lamps, cables and other distributed small obstacles may modify the channel impulse response. This is the reason extensive measurements have been carried out in Paris subways to determine the narrow band and wide band characteristics of a SISO transmission; i.e. by considering only one transmitting and one receiving antenna. The influence of another train between the fixed antennas and the mobile ones, acting as an important mask, is also investigated either in a one way or in a two way tunnel.

The last part of this paper deals with the improvement that one can expect by means of a MIMO technique, four fixed and four mobile antennas being considered.

2. SISO channel characterization

Narrow band and wide band analysis will be successively considered.

2.1 Narrow band analysis

Since the final objective is to increase the space diversity to get a small correlation between antennas, the first idea is of course to implement omni directional antennas, at least in the horizontal plane. However, the environment is quite different as in indoor for example, because most of the energy propagates along the tunnel axis. Preliminary measurements have shown that the mean angular spread is smaller than 40°. A compromise must thus been found between the gain which can be expected by using directive antennas and the diversity gain. Taking this value of the
angular spread into account, the fixed antennas are horns, having a gain at 900 MHz of about 10 dBi. For the SISO experiment, the horn was put at a height of 1.7 m, near the track.

On the train, it was not possible to install antennas on the roof and the only possible solution was to use patch antennas placed just behind the windscreen. The continuous curve in Fig. 1 represents the variation of the received power in a one way tunnel versus the position of the train, the distance varying in this case between 500m and 900 m from the transmitter. In this part, the tunnel is nearly straight, 5m high and 6m wide. It clearly appears that the mean power decreases exponentially with the distance, the slope of the regression line being 12dB/100m. The distance between two successive measurements is on the order of 5cm and any "short term fading", i.e. with an occurrence probability on the order of the wavelength, appears. On the contrary, there are wide and deep fadings but ten meters apart, at least.

A masking train was placed between 230m and 300m but any change in the mean received power is observed in this wide tunnel.

2.2 Wide band analysis

The channel impulse response was measured for various distances between the transmitter and the receiver. The channel sounder makes the cross correlation between the transmitted and received pseudo random sequence. Its bandwidth is equal to 35 MHz and its centre frequency is 900 MHz.

An example of the received signal on four different patches in the train is shown in Fig. 3. If the shapes of the received pulses are compared to the emitted one, any additional echo appears. In other word, the channel can be considered as flat within this frequency bandwidth, which is itself much greater than the necessary bandwidth of the expected transmission. In the presence of a masking train, any appreciable difference occur on the shape of the impulses response, the additional delays due to the multiple reflections and diffraction on the train being too small to be discriminate by the channel sounder.

Fig. 1 Received power versus distance in a one way tunnel in the presence of a masking train or not.

Fig. 2 Received power in a two way tunnel, curved in the first part and straight far away.

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This assumption of a flat channel will thus be used for analyzing the MIMO configuration.

3. Characterization of the MIMO channel

After a brief description of the experiments and of the data processing, the distribution function of the channel capacity which can be expected is presented.

3.1 Description of the measurement set up

Four horn antennas were put on the platform, along a line parallel to the track at a height of about 2 m. The distance between the horns can be easily changed and two intervals will be considered: 90 cm and 2.1 m. On the train, four patches antennas, 30 cm i.e. one wavelength apart, are placed along a horizontal line, behind the windscreen.

The train stops every 2 m and the 4x4 complex impulse responses are stored. Taking the assumption of flat fading into account, the elements of the \( H \) transfer matrices reduce to a complex number, which is the peak value of the I, Q impulse response. In order to make a statistical analysis of the channel capacity when the train moves on a distance of few hundred meters, the mean path loss must be subtracted. Indeed, the objective of this approach is to emphasize the improvement brought by MIMO techniques, compared to the SISO configuration, but, of course, by keeping constant the mean signal to noise ratio.

As it has been seen previously, the received power exhibits an exponential decrease with distance. By computing first the average power of each \( H \) matrix, it is thus possible to normalize each element such that the mean signal to noise ratio remains constant, whatever the distance between the transmitting and receiving antennas.

3.2 Field distribution

It has already been outlined that the field amplitude does not vary rapidly from one point to another one if they are one or few wavelengths apart. Nevertheless, by considering a large interval of few hundred meters, the global field distribution follows a Rayleigh distribution.

This appears in Fig. 4 representing the cumulative density function of the field amplitude, normalized to the regression line, thus by subtracting the mean path loss. The mean field amplitude on few hundred meters is normalized to 0 dB. Four configurations have been tested: For configurations 1 and 2, the train moves in a one way tunnel, while for configurations 3 and 4, the waves propagate in a two way tunnel.

3.3 Channel capacity

The maximum channel capacity by using multiple antennas on the transmitting and receiving site, is given in [1] and is an extension of the Shannon theorem. If \( \rho \) is the mean signal to noise ratio on
each receiving antenna, the capacity $C$, expressed in bits/s/Hz, is calculated from formula (1):

$$C = \log_2 \left| \text{det} \left(I + \rho H H^h\right) \right|$$  \hspace{1cm} (1)

Where $I$ is the identity matrix and the upper script $h$ means the hermitian conjugate of the $H$ transfer matrix.

Extensive measurements have been carried out both in the one-way and in the two-way tunnel, 100 successive complex transfer matrices being stored from different positions of the train. Results are presented in Fig. 5 by assuming a signal to noise ratio of 10 dB. Let us first consider the case of the one-way tunnel. Configurations L and M correspond to a distance between the horns on the platform of 90 cm and 2.1 m respectively.

As a comparison, the curve noted Rayleigh in Fig. 5 has been obtained from $H$ matrices whose elements are chosen to fulfill the condition of i.i.d. Rayleigh channels. Of course, this optimum configuration in which the capacity is 11 bits/s/Hz for a probability of 0.5 cannot be reached practically due to the correlation between the antennas, both on the platform and on the train. Nevertheless, the mean capacity reaches 7 bits/s/Hz and 9 bits/s/Hz in a one-way and in a two-way tunnel respectively.

4. Conclusion

From experimental data, the main characteristics of the propagation in a subway tunnel have been derived. It has been shown that an important increase of the channel capacity can be obtained even in such a wave guide structure, the dispersion of the angle of arrival on the receiver being rather small. Indeed, the transverse dimensions of the tunnel being much greater than the wavelength, many modes are supported, the various changes in the geometrical configuration avoiding that only one mode becomes dominant.

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References: