Experimental Evaluation of 4G Technologies in Metro Tunnel Scenarios

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Abstract—In this work, an evaluation of the fourth generation (4G) waveform performance in underground tunnel scenarios has been carried out with the help of hardware testbeds. The equipment for the measurements has been deployed inside the carriage of an underground train, and the antenna elements were located both outside and inside the carriage. The experiments consisted of narrowband and wideband propagation measurements, and over-the-air transmissions for physical layer performance assessment.

I. INTRODUCTION

The so-called fourth generation (4G) wireless communication systems, such as Long-Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMax), allows for delivering mobile wideband Internet access, covering large distances for both low and high mobility conditions. They are based on Orthogonal Frequency Division Multiplexing (OFDM), and designed to combat typical effects of wireless scenarios, such as multi-path propagation. These technologies are candidates for specific environments, such as railway and airport surface communication systems.

One of these new applications is metro transportation, in which both train control and video surveillance can take advantage of the high throughput exhibited by 4G systems. Currently, LTE is already being deployed in metro systems [1] due to the aforementioned advantages. In the literature, works focused on evaluating the behavior of radio signals in railway and tunnel scenarios can be found, with evaluations of radio propagation [2] [3] [4] [5], railway viaduct channel modeling [6], and vehicle-to-vehicle channel modeling [7].

In this paper, the results of a measurement campaign in the metro system of Madrid are presented. A detailed description of the testbeds employed is also provided. The experiments are focused on modeling the radio waves propagation in the tunnel in typical frequencies used in 4G systems. Additionally, the performance of a 4G physical layer transceiver is assessed by means of over-the-air transmissions.

II. MEASUREMENT SCENARIOS DESCRIPTION

The evaluation of 4G technologies in the metro environment requires to carry out measurements in tunnels with different

Fig. 1. Typical tunnel cross sections and narrowband measurement configurations.

types of sections, curves and stations. In metro tunnels the two most common cross sections are the circular (excavated by Tunnel Boring Machine (TBM)), and the arched ones (see Fig. 1). The radius of curves in a tunnel are also relevant, since the propagation losses increase in tunnels with small radius of curvature. The curvature radius range in metro tunnels is typically from 90 m to 1000 m, while the slope of the tunnels is always less than 5.5 %.

Another essential aspect is the presence of stations, leading to the discontinuities very different in size and shape than that of the tunnels. Old metro stations used to be very narrow, while modern stations are wide and pit-shaped with a high ceiling. Thus, the narrow stations can be considered as wide tunnels, but modern large stations are different. Figure 2 represents a modern large station, where the measurements have been done.

A set of measurements have been carried out at the *Ciudad de los Ángeles* station (Line 3 of *Metro de Madrid*) in order to model the propagation in tunnels and stations and to

Fig. 2. The 3D modeled modern metro station.

Fig. 3. Installation of antennas in station and train (MIMO configuration).

assess the performance of a 4G physical layer by means of over-the-air transmissions. In case of the channel propagation measurements, the single-antenna transmitter is placed on the platform of the station (see Fig. 1 and antenna “Tx₂” in Fig. 3), while the single-antenna receiver is placed either inside the cabin of the train with the antennas fixed on the windshield of the front car (see antenna “Rx₁” in Fig. 3) or on the platform (see antenna “Rx_{2_1}” in Fig. 3). For the physical layer measurements, a single-antenna transmitter is placed on the platform of the station (see antenna “Tx₁” in Fig. 3), while two different receivers are employed simultaneously. The first one is installed inside the cabin, with the antennas fixed on the windshield of the front car (see antennas “Rx₁” and “Rx₂” in Fig. 3). The second receiver is placed inside the train and its two antennas are also installed indoors. Notice that no multiple-antenna transmission scheme has been considered.

Narrowband channel propagation measurements were carried out at three different frequencies of 900, 2400, and 5700 MHz; wideband propagation measurements consider 1000 MHz and 2450 MHz; while physical layer measurements were limited to 2400 MHz.

III. TESTBEDS DESCRIPTION

Metro infrastructures require access permissions and specific security requirements must be complied to carry out this kind of measurements. Furthermore, measurements must be

carried out during maintenance periods in a short time-window during night, requiring easy-to-deploy testbeds. The next subsections describe the testbeds employed for the experiments.

A. Physical Layer Testbed

This testbed is similar to the one used in previous works (e.g. [8]), and consists of three USRP B210 boards built from the AD9361 chip by Analog Devices, which supports a continuous frequency coverage from 70 MHz to 6 GHz; full-duplex Multiple Input Multiple Output (MIMO) operation with up to 56 MHz of bandwidth; USB 3.0 connectivity; on-chip 12 bit Analog-to-Digital Converters (ADCs) and Digital-to-Analog Converters (DACs) up to 61.44 Msample/s; automatic gain control; and configurable transmit and receive gain values.

Multi-threaded software based on the Ettus UHD is deployed in laptops connected to the USRP boards. At the receiver, the samples coming out of the two antennas of the USRP are read from the USB and stored first in memory, and eventually recorded in a solid state drive, besides other important logging information. The transmitter reads the signals from files and transmits them cyclically using a single antenna port of the USRP. Such an antenna port is connected to the high-power amplifier and to the transmit antenna.

The last piece of software is responsible of the wideband signal generation and processing, and it is implemented in MATLAB. All the frames transmitted carried six data bursts, each one allocated with four consecutive OFDM symbols and all the available subcarriers, adding up to a total of 24 OFDM symbols per frame. Each burst carried information symbols with different profiles of modulation and channel coding rates, namely, 4-QAM 1/2, 4-QAM 3/4, 16-QAM 1/2, 16-QAM 3/4, 64-QAM 1/2 and 64-QAM 3/4. Channel coding algorithm in all bursts was a tail-biting terminated convolutional code.

As for the receiver, the samples captured by the testbed during the measurement stage are batch-processed with a receiver consisting of frame detection, time and carrier frequency offset synchronization, channel estimation, equalization, and channel decoding. Frame detection and synchronization is computed from the preamble symbol which precedes each frame. This symbol has a three-fold repetition structure in the time domain, which can be exploited to detect its arrival, and obtaining synchronization parameters estimation. For channel estimation and equalization, linear MMSE algorithms have been implemented, estimating the covariance of the channel and the noise from the received signal. The waveforms used during the measurements are standardized 4G physical layer schemes based on OFDM, particularly WiMAX signals, whose parameters are those shown in Table I.

Finally, recall that a single-antenna transmitter and two dual-antenna receivers were used simultaneously for these measurements. The transmitter was placed on the platform in the middle of the station. The first receiver was located in the front carriage, with the antennas outside of the train attached to the windscreen. The second one was inside and in the middle of the train, with the antennas also inside the carriage. The approximate distance between the two receivers is

TABLE I
WiMAX PROFILE FOR PHYSICAL-LAYER MEASUREMENTS.

Sampling frequency	8 MHz
Useful bandwidth	7 MHz
Number of subcarriers	1024
Number of data subcarriers	720
Number of pilot subcarriers	120
Subcarrier spacing	7.81 kHz
Cyclic prefix length	128 samples
Permutation zone	PUSC

(a) Block diagram of the transmitter.

(b) Testbed transmitter and configuration software.

Fig. 4. Narrowband testbed block diagram and prototype.

50 m. The antennas installed outdoors model the rail operator communications infrastructure, while the indoor antennas are aimed to model the signal received by the mobile device of a train passenger.

B. Propagation Measurements Testbed

The modeling of propagation in complex environments, such as tunnels or stations, requires to carry out narrowband and wideband measurements in different conditions and configurations. The deployed testbed consists of a separate transmitter and a receiver. The equipment is able to carry out narrowband and wideband channel sounding measurements in a wide frequency range. The transmitter is shown in Fig. 4. It is a unit covering from 400 MHz to 6000 MHz, with a high output power and a control software built in a PC to be quickly and easily configured. It can generate modulated pulses for channel sounding measurements.

Furthermore, two different types of receivers are required: narrowband and wideband. The narrowband receiver consists of a low-noise amplifier, a portable spectrum analyzer Agilent N9912A, and the control software in a PC. This configuration uses a specially designed software for measurements, which is able to configure the spectrum analyzer with all the parameters of the measurements, to perform several measurements per second, to record the received power level at different frequencies, and to show a real-time graphic of the measurements.

(a) Block diagram of the receiver.

(b) Receiver prototype.

Fig. 5. Channel sounder receiver.

This type of receiver has been installed on the train, attached to a single outdoor antenna, to observe the attenuation along distance in different types of tunnels and curves.

The second type of receiver is a channel sounder used for wideband measurements and modeling of the propagation environment. The block diagram and prototype of the receiver are shown in Fig. 5. The testbed adopts the narrow pulse technique for channel sounding. The transmitter can be Amplitude Modulation (AM) modulated with narrow pulses, up to 15 ns. The receiver is a wideband simple conversion receiver that uses a logarithmic amplifier as envelop detector, and a high performance digital oscilloscope to capture, digitize, and store the delay profile of the received signal. The key parameters for the propagation measurement testbeds are listed in Table II.

IV. EXPERIMENTAL RESULTS

A. Physical Layer Results

The results presented in this section were obtained when the train approaches the station at a constant speed of 18 km/h.

TABLE II
CHANNEL SOUNDER CONFIGURATIONS AND PARAMETERS.

Item	Description
Frequency	980 - 5700 MHz
IF bandwidth	100 MHz
Modulation	Pulse
Pulse width / period	47 / 1500 ns
Tx power	42 dBm
Tx antennas	HG 908P & 2414P Patch antennas
Rx antenna	R&S HL025 Log-periodic antenna
Noise figure	4 dB
Demodulation	Logarithmic detector
Sensitivity	- 90 dBm

Fig. 6. EVM and SNR for indoor antennas.

Fig. 7. EVM and SNR for outdoor antennas.

The recording of the signals starts when the whole train is still inside the tunnel and finishes when the front cabin enters in the exit tunnel of the station. Notice that indoor and outdoor receive antennas are placed 50 meters apart.

All acquired frames were processed to estimate the strength of the received signal and the physical layer throughput, both for the antennas outside and inside the train. First, SNR and Error Vector Magnitude (EVM) values were estimated for each frame. After detection, the strength of the received signal before the frame, which it is assumed to be a silent period, is used as a reference to obtain mean SNR estimations. Also, after channel equalization, the mean squared error of the received symbols compared to the transmitted ones is used to estimate the EVM.

Figures 6 and 7 show the results corresponding to this processing for the indoor and the outdoor antennas, respectively, where the dots represent the mean SNR detected for each received frame. The solid lines are computed by dividing the course of the train in 15 equal sectors, and by obtaining the median SNR and EVM for each sector. It can be appreciated a large difference between the SNR levels observed from the

Fig. 8. Throughput for indoor antennas.

indoor and outdoor antennas. In the first part of the course of the train, the indoor receiver is still inside the tunnel, and a strong attenuation of the signal (the train blocks the signal path) can be appreciated compared to the outdoor front antennas. Once the indoor antennas are inside the station (the train does not block the signal path anymore), the SNR increases and reaches its maximum when the indoor antennas are in front of the transmit antenna, which happens at the end of the measurement. At this point, the outdoor antennas approach the exit tunnel of the station, and the SNR for such outdoor antennas decreases with respect to its maximum, achieved when the outdoor antennas pass in front of the transmit antenna.

Throughput estimations are also obtained. In this case, the transmitted bits are decoded, and for each burst, the ratio of erroneous bits received is measured. Then, the throughput is estimated by two methods. The first one assumes that the bursts with the higher capacity and no errors for each frame were transmitted, denoted as the ideal throughput. The other method assumes that the transmitted burst is picked by means of the mean EVM level detected at the receiver, choosing higher burst profiles for high EVM values, and vice versa.

Figures 8 and 9 show the results corresponding to these throughput estimations, inside and outside the train. The behavior of throughput is very similar to that of the SNR, and similar conclusions can be drawn. Throughput when the indoor receiver is inside the tunnel is close to zero, and as long as the train enters in the station, these values increase. Regarding the outdoor antennas, the throughput is stable around the maximum achievable.

B. Channel Sounding Measurements

Narrowband measurements have been carried out in different types of tunnels, curves and stations. In all cases, the transmitter is installed in the tunnel track and in the station platform, while the receiver is placed on the train. Then, the train moves forward at low speeds (<10 km/h) and the received power is recorded. A representative example of the

Fig. 9. Throughput for outdoor antennas.

Fig. 10. Narrowband measurements at three frequencies in straight and curved tunnels.

Fig. 11. PDPs in the metro station at 1000 MHz and 2450 MHz.

narrowband measurements carried out is shown in Fig. 10. Three different frequencies have been compared in a straight tunnel and a curved tunnel with 500 m Radius of curvature (RoC). As the results shown, the higher the frequency, the lower the attenuation for the tunnel scenario, agreeing with the waveguide theory. From these results, attenuation coefficients for different frequencies are extracted and shown in Table III. On the other hand, wideband measurements offer more details about the radio propagation in the metro stations and tunnels. In this case, the channel sounder transmitter and receiver are installed on the platform of the station to measure the power delay profiles (PDPs) of the channel at the station, the influence of the train, and effects from the tunnel. An example of the results measured in the station (see Fig. 2), at 1000 MHz and 2450 MHz are shown in Fig. 11. From this figure it is easy

TABLE III
ATTENUATIONS AT DIFFERENT FREQUENCIES IN TUNNELS.

Frequency [MHz]	980	2400	5700
Straight tunnel Att. [dB/100 m]	4.05	2.95	2.15
Curved tunnel Att. [dB/100 m]	7.33	6.82	6.05

to see that lower frequency exhibits longer excess delay spread, and more higher order multipath components are present.

V. CONCLUSION

In this work, the performance of 4G waveforms in a metro environment has experimentally evaluated. More specifically, the propagation loss and the PDPs of the channel have been estimated from real measurements, as well as the SNR, the EVM and the throughput exhibited by a 4G waveform. The propagation results agree with the waveguide theory, while the physical layer performance results show that 4G waveforms seem to be good candidates for metro environments. Additionally, the measurement results show that wireless communications directly with passengers inside the train are still a challenge due to the strong attenuation of the train structure.

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