Feasibility of LTE for Train Control in Subway Environments Based on Experimental Data

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***Abstract*—Modern railway transportation systems need a reliable communication infrastructure providing very high data rates and low latencies for applications such as communications-based train control (CBTC) or video surveillance. In this paper, the suitability of the Long Term Evolution (LTE) standard for subway environments is evaluated using a propagation model based on real channel measurements. An LTE deployment with several subway stations is simulated using the ns-3 discrete-event network simulator to evaluate both the system performance and the fulfillment of the quality of service (QoS) requirements of representative services such as CBTC, closed-circuit television (CCTV), voice over IP (VoIP) and file transfer. Several parameters and procedures of the LTE system are adapted to the subway environment: the LTE network is configured using a QoS-aware scheduler, hence critical services are prioritized; the handover procedure is tuned to avoid ping-pong effects; and inter-cell interference coordination techniques are also applied.**

***Index Terms*—LTE, CBTC, ns-3.**

I. Introduction

The railway industry is evolving their conventional signalling systems to communication-based systems demanding reliable and fault-tolerant infrastructures. Examples of these modern communication-based signalling systems are the communications-based train control (CBTC) system and the European Rail Traffic Management System (ERTMS). In this work, we will focus on the CBTC system as it is more common in subway environments.

CBTC systems require a communications infrastructure that gives support to their quality of service (QoS) needs, being a low latency the most critical one. Also, additional services are being deployed in public transportation systems that demand high data rates, e.g., closed-circuit television (CCTV). However, these throughput demands cannot be satisfied by legacy communication systems such as GSM for Railways (GSM-R).

In subway scenarios, IEEE 802.11 wireless local area network (WLAN) deployments are considered as the communication infrastructure for CBTC [1]. The main advantages of Wi-Fi are its low cost and the usage of the freely available industrial, scientific and medical (ISM) radio bands. However, to support long-range and high-mobility scenarios, Wi-Fi deployments require several access points supporting the latest standard amendments such as the IEEE 802.11k/r/v. Nonetheless, interoperability among different manufacturers implementing these amendments is still unclear. Additionally, managing the interference caused by other devices as well as that produced by neighbour access points is yet another issue.

The 3GPP Long Term Evolution (LTE) and the LTE-Advanced (LTE-A) standards are good alternatives for communications in subway environments. The disadvantages of LTE are its higher equipment cost and the licensing costs associated to the frequency bands. On the other hand, LTE provides mobility support, flexible QoS configuration, long range communications, etc. Also, LTE allows for sharing the deployed infrastructure with the passengers.

In this work, we study the viability and performance of LTE for supporting the needed services in subway environments. We use the LTE module of the ns-3 network simulator [2] to check if the QoS requirements of all the applications are met. Instead of relying on simulated channels, we obtained a simplified channel model from subway measurements carried out in the Madrid Metro [3]. Although previous works focused on the simulation of CBTC traffic, none of them uses a specific channel model for subway scenarios nor the results from a measurement campaign. In [4], the OPNET simulator was used to study the LTE time-division duplex (TDD) performance with different QoS configurations. In [5], commercial channel simulators were considered to test an integrated train-to-ground communication system. The performance of CBTC in Wi-Fi deployments is also evaluated with the ns-3 simulator in [6].

II. QoS in Subway Communications

Based on previous works [4] [5], we identify the following applications and requirements for subway communications:

- CBTC: Bidirectional communication between trains and the wayside server. This application requires a low data rate but a low delay (between 50 ms and 150 ms).
- CCTV: The train sends a video stream to the central monitoring system, which requires a high throughput but tolerates delays up to 500 ms.
- Voice communication: As CBTC, voice over IP (VoIP) requires low delay communications with low data rate.
- File update: bulk data transfer to the train. It is a low-priority, best effort transmission.

In LTE, traffic packets are classified into different bearers based on each packet header. LTE defines the so-called QoS class identifiers (QCIs) to configure QoS requirements of the bearers. Each QCI defines a priority, a packet delay budget, and a tolerated packet error ratio (PER). Also, some QCIs support a guaranteed bit rate (GBR) for each bearer.

The ns-3 simulator allows us to use the 9 QCI values defined in LTE Release 8. However, the provided QoS-aware schedulers only consider the assigned GBR value of each bearer and ignore the remaining parameters. We have also enhanced the schedulers to take into account the priority of each bearer as explained in Section II-A.

A. ns-3 LTE Scheduler Enhancements

The ns-3 LTE model was first published in 2011 and it has been actively developed and enhanced since then [2], [7]. Although the ns-3 LTE model supports only frequency-division duplex (FDD), the whole LTE protocol stack is implemented, including an Evolved Packet Core (EPC) model providing end-to-end Internet Protocol (IP) connectivity. The model includes design documentation [8] and is open source, as the rest of the ns-3 simulator.

Several scheduler implementations are provided, such as the well-known proportional fair (PF) and maximum throughput (MT) opportunistic schedulers as well as other QoS-aware schedulers [7]. Only the downlink (DL) scheduler is currently implemented in ns-3, whereas the uplink (UL) employs a simple round robin (RR) scheduler. Also, the QoS-aware schedulers only prioritize some users over others, but do not consider different flows from the same user. In our scenario we need to prioritize the CBTC flows over the others.

Given that all of our users have the same priority, our approach consists in modifying the PF scheduler to include a flow prioritization mechanism. First, a resource assignment to each user is performed by a fair algorithm. Then, these resources are shared between the different flows of each user taking into account the QoS requirements. We also implemented the PF scheduler for the UL, taking into the account the additional restriction that the assignment of resource blocks (RBs) to each user equipment (UE) must be contiguous in frequency, as required by the single-carrier FDMA (SC-FDMA) modulation. We perform this assignment in an iterative way:

- Calculate the PF metric for each RB and UE that can transmit in that RB.
- Select the UE that has the best metric in more contiguous RBs.
- Assign some of the adjacent RBs to the UE depending on the UE data requirements.
- Go to the first step until no more RBs can be assigned.

The LTE standard defines the logical channel prioritization (LCP) procedure that must be performed by the UEs to prioritize the logical channels (LCs) in a predictable way [9]. We implemented this mechanism because the ns-3 implementation performed this process in a non-standard way using a RR algorithm. We also added the LCP procedure to the PF DL scheduler, thus providing the required QoS awareness.

Each LC is configured by setting the *priority*, *prioritisedBitRate* and *bucketSizeDuration* parameters. The LCP mechanism ensures that the *prioritisedBitRate* is provided to the LCs in priority order. The *bucketSizeDuration* parameter limits the amount of prioritized data the LCs can transmit continuously. Given that the way the QoS parameters of a bearer are mapped to these parameters is not standardized, we configured the LCP to ensure that the required bit-rate of high priority LCs is always satisfied.

III. Simplified Channel Model

In this article we develop, from a previous measurement campaign [3], a simplified channel model suitable to perform system level simulations. Such a measurement campaign was conducted in a modern subway station and its entrance tunnel in the Madrid Metro. The so-called GTEC Testbed [10] was employed for the measurement process: a node was placed at the subway station in the role of an Evolved Node B (eNodeB) to cyclically transmit an LTE signal with a bandwidth of 10 MHz (50 RBs) at a carrier frequency of 2.6 GHz, while the receiver node was connected to the train antennas. The eNodeB employed a vertically polarized 90º sector antenna and transmitted with a power of 18.5 dBm. At the receiver, two vertically polarized 30º sector antennas were attached to the train front window.

During the measurements, the eNodeB was placed at the middle of a 100 m length station. The signal was acquired from an approaching train, starting the measurements at a distance of 145 m from the eNodeB. For this paper, we only considered the measurements up to the middle point of the station, where the transmitter was located. The considered measurement trajectory can be divided into a tunnel section of 90 m, and a station section of 55 m.

From the measurement campaign results, we obtained a path loss model and a fading model suitable for the system level simulator. These models only depend on the distance between the eNodeB and the UE. Also, to simulate FDD transmissions, we need to consider different channel realizations for the DL and UL, as the UL carrier frequency is different from that of the DL. In the measurement campaign, the same carrier frequency was used for both receive antennas. Thus, we decided to use the measurements from antenna 1 for the DL and those from antenna 2 for the UL.

A. Path Loss Model

The signal propagation characteristics change when the train moves from the tunnel to the station. Hence, in our previous work [3], a log-distance path loss model with two breakpoints was proposed. Note that the impact of the antenna radiation patterns was not removed from the model. Fig. 1 shows the received power at each antenna and the estimated path loss model applied to the transmit power. Note that the path loss exponents are negative in the first section due to the directivity of the receive antennas and their relative angles with respect to the transmit antenna. Also note that the quasi-periodic oscillations can be explained by a 2-ray channel model.

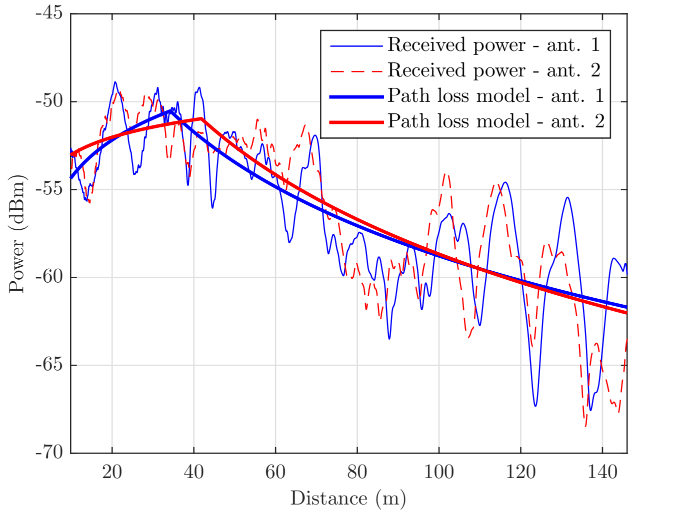

Fig. 1. Received signal power (smoothed) vs distance and the corresponding path loss model estimation.

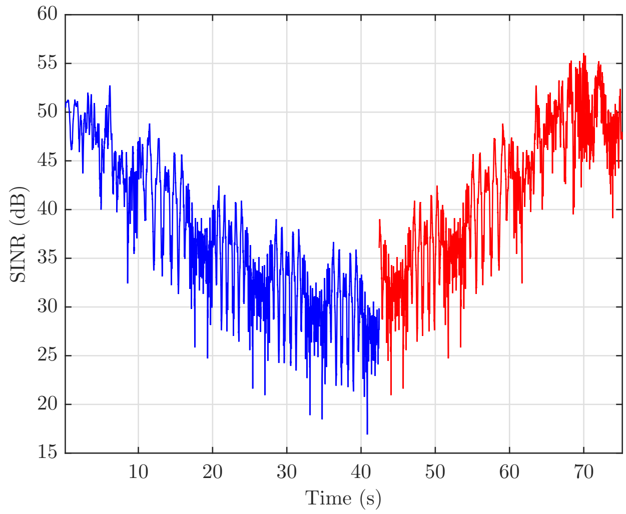

Fig. 2. DL SINR versus time for an UE performing a handover. Blue and red lines represent the SINR for the first and second eNodeBs, respectively. The distance travelled by the UE is 1130 m.

TABLE I
PATH LOSS MODEL CONFIGURATION.

Antenna	L_0	d_0	d_1	d_2	n_0	n_1	n_2
1	90.78	0.0292	34.27	∞	-0.709	1.773	-
2	80.14	0.0239	41.87	∞	-0.329	2.037	-

A log-distance path loss propagation model with three distance fields is implemented in the ns-3 simulator [8] and is defined with respect to the distance d as follows:

$$\mathrm{PL}(d) = \begin{cases} 0 & d < d_0 \\ L_0 + 10n_0\log_{10}(\frac{d}{d_0}) & d_0 \leq d < d_1 \\ L_0 + \beta_{1,0} + 10n_1\log_{10}(\frac{d}{d_1}) & d_1 \leq d < d_2 \\ L_0 + \beta_{1,0} + \beta_{2,1} + 10n_2\log_{10}(\frac{d}{d_2}) & d_2 \leq d, \end{cases}$$

where $\beta_{i,j} = 10n_j\log_{10}(d_i/d_j)$; d_0, d_1 and d_2 are the distance fields; n_0, n_1 and n_2 are the path loss exponents; and L_0 is the path loss at d_0. The considered parameters are specified in Table I. The parameters had to be adapted since the formulation of the channel model in [3] is slightly different.

B. Fading Model

The ns-3 simulator includes a fading model based on traces of power spectral density (PSD) values with RB granularity. This model was modified so that it depends on the distance between transmitter and receiver. The channel traces are extracted from the recorded data and are processed to remove the large-scale fading (i.e., the path loss term), hence the average power is one along the path followed by the train. This way, the path loss model can be applied to the traces in the simulation.

As we only have traces for a maximum distance of 145 m, we need to extend these traces to perform simulations with trains that are farther away in the tunnel. In order to do so, we follow a simple approach: when the distance between the UE and the eNodeB exceeds the maximum distance in the measurement data, we repeat cyclically the traces of the initial 55 m of the tunnel section. Note that, as explained before, a path loss depending on the distance is still applied.

Fig. 2 shows the DL signal-to-interference and noise ratio (SINR) for an UE moving from an eNodeB station to another and performing a handover. The combined path loss and fading effects can be seen with the eNodeB transmit power being fixed at 18.5 dBm. Also, the noise figure of the receiver is set to 2.07 dB to match the results obtained in the measurements. Notice that the UL SINR results would be different as the power control mechanism is enabled in our simulations.

IV. LTE DEPLOYMENT AND CONFIGURATION

In this paper, we consider a scenario with three identical and consecutive subway stations with a separation of 1104 and 1522 m, respectively. These are approximately the distances between “La Almudena” station of the Madrid Metro (where the measurement campaign was conducted) and the adjacent stations. We consider the same transmitter setup for all the stations, with the eNodeBs located at the center of each platform and connected between them through an X2 interface to allow the handover process. A central server is connected to the simulated packet data network gateway (PGW) node of the EPC with a point-to-point connection at 100 Gbit/s and without delay. This central server will send all the DL packets and receive the UL packets.

Four trains and two parallel tracks are considered in the simulation scenario. Two trains move on one track departing from the first and second stations. The other two move on the other track in opposite direction departing from the second and third stations. This way, the second station will have two trains leaving and two trains arriving. We model a train trip by setting way-points at different positions with a given velocity. The train departs from its initial station accelerating until a speed of 19.44 m/s ($\approx$ 70 km/h) is reached. The speed is maintained until the train starts to brake when approaching the destination station. Inside the station, the train moves at a constant speed of 5.55 m/s ($\approx$ 20 km/h) before stopping at the end of the station. A constant acceleration of 1 m/s^2 is

TABLE II
APPLICATIONS CONFIGURATION.

Application	DL (kbit/s)	UL (kbit/s)	Packet Size (bytes)	QoS priority	Transport protocol
CBTC	4.8	8	200	1	UDP
CCTV	0	2000 (mean)	variable (traces)	9	UDP
VoIP (G.711)	68.8 (max)	68.8 (max)	172	2	UDP
File update	1000	0	256	9	TCP

considered between way-points regardless of whether the train accelerates or brakes.

A. QoS Configuration

The different applications considered with their assigned data rates and QoS priorities are shown in Table II. The CBTC application is configured with the maximum priority to send packets of 200 bytes every 333 ms for the DL and 200 ms for the UL. The CCTV application is configured to send a video with subway train surveillance footage from the trains to the control room. To simulate this video source, we transmit traces of this video footage encoded in H.264 with an average bit-rate of 2000 kbit/s. These traces contain the size of each packet and the time instants to send them. The lowest priority is assigned to this flow, so it does not affect the CBTC and VoIP flows. The VoIP application is configured with the G.711 codec parameters, i.e., 50 packets per second are sent with a size of 160 bytes plus 12 bytes for the RTP header. Also, the duration of active and silence periods is modeled using exponential distributions. The active period has a mean duration of 175 ms, whereas the silence period distribution has a mean of 325 ms. A priority of 2 is assigned to VoIP and the bearer is configured with the needed GBR. Finally, the file update application simulates a constant transmission of data to the trains with a data date of 1000 kbit/s. This data transmission does not affect the other applications as the lowest priority is assigned to this flow.

All the applications use Unacknowledged Mode (UM) Radio Link Control (RLC) to avoid the use of the automatic repeat request (ARQ) mechanism. However, hybrid automatic repeat request (HARQ) was enabled for all the transmissions as it only adds a delay of 24 ms in the worst case.

B. Frequency Reuse

As shown in Fig. 2, there is a high channel variability in the tunnel, where the UEs may experience a very high interference level from vecinity stations, degrading their SINR and increasing the probability of undesired handovers. Also, the eNodeB will see the interference from UEs at the cell edge. Therefore, using Inter-Cell Interference Coordination (ICIC) techniques is required to mitigate these problems. We considered the *Hard Frequency Reuse* ICIC technique, which is already implemented in the ns-3 simulator, because is the one that reduces the interference the most at the expense of a reduced bandwidth and consists in splitting the bandwidth in sub-bands and assigning each sub-band to a cell, thus limiting the transmissions in each cell to the assigned sub-band. In our case, 50 RBs are divided into sub-bands of 16, 16 and 18 RBs. However, even with this technique, there is a residual interference affecting the DL signal because LTE DL control channels are transmitted at fixed positions. In our case, when the UEs are at the cell edge, bursts of errors appear due to the interference from adjacent cells. The loss of these control channels causes the loss of both the complete subframe for the DL transmission and the scheduling information for the oncoming UL subframe.

C. Handover Customization

The LTE handover process is controlled by the source eNodeB and assisted by the UE, which sends measurement reports to the source eNodeB to decide whether a handover should be performed. Large signal-to-noise ratio (SNR) variations at the cell edges, as those shown in Fig. 2, can provoke ping-pong handovers, yielding multiple handovers instead of a single one. We have decided to use the *Strongest cell* handover algorithm implemented in the ns-3 LTE module, which has the following parameters:

- **Hysteresis**: The difference in dB between the Reference Signals Received Power (RSRP) of the source and destination cells. We use the default value of 3 dB.
- **Time-to-trigger**: The hysteresis condition should be satisfied during this time before the handover is triggered. We increased the default value from 256 ms to 640 ms.

A high time-to-trigger parameter helps to avoid the ping-pong handovers but delays the handover process. If the handover is delayed too long, a radio link failure can be triggered, increasing the delay of the handover process and the probability of packet loss. We incremented the time-to-trigger value as it was required to avoid the ping-pong handovers but also avoiding radio link failures in all the simulations.

V. SIMULATION RESULTS

The duration of the simulations is 110 s, the transmit power of the eNodeBs was set to 18.5 dBm and the noise figure of both the eNodeBs and UEs was set to 2.07 dB.

A. Throughput

We performed a simulation to obtain the achievable throughput of each UE over time. We configured two traffic sources for each UE to saturate both the DL and UL with packet sizes of 1000 bytes. Fig. 3 shows the results of the simulation. UEs 1 and 2 start with the complete bandwidth of their cells to end the simulation sharing the second cell. The opposite happens to UEs 3 and 4. We can see how the PF scheduler is assigning the resources to the UEs in a fair way. Also, the differences in the peak throughput is explained by the unequal division of RBs between the cells, as explained in Section IV-B. The average PER obtained in the simulation is $1.1 \cdot 10^{-2}$ for the DL and $2.5 \cdot 10^{-4}$ for the UL. This difference is a consequence of the interference problems in the DL control channels, which could be mitigated by deploying two UEs in each train with their antennas oriented to each direction.

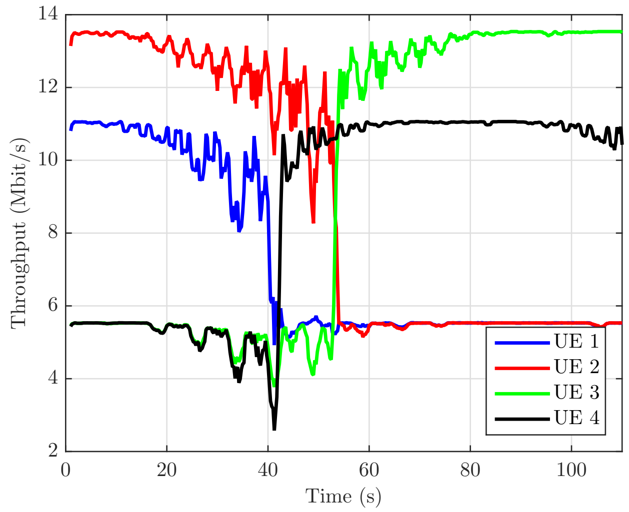

Fig. 3. DL throughput for the different UEs. Smoothing of 1 second.

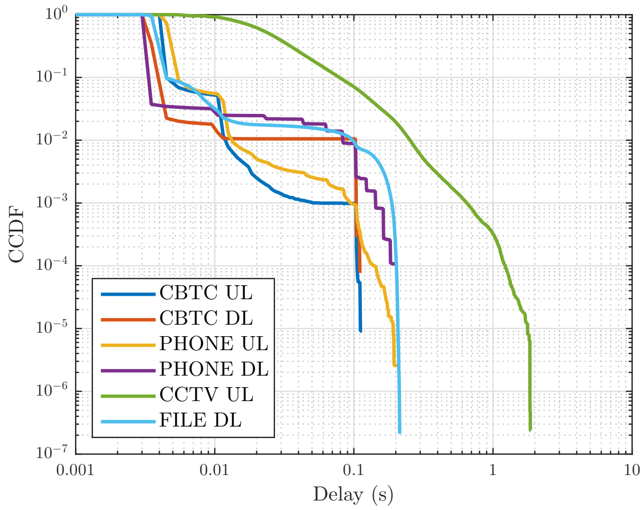

Fig. 4. CCDF of packet delay for different flows.

B. Packet Delay

Fifty runs of the simulation were performed with different random seeds to obtain averaged results of different situations with modified traffic sources for each run. The position of the eNodeBs and the initial positions of the trains are also modified by a random offset of ± 10 m. Otherwise, the trains would experience the same channel realizations at the same time instant in all the simulations.

In Fig. 4, the complementary cumulative distribution function (CCDF) of the packet delay for the different flows is shown. The maximum delay for the CBTC traffic slightly exceeds 100 ms with a probability of 10^{-4} and so we can consider that the delay requirements are fulfilled. Also, VoIP traffic has a maximum delay of 200 ms with low probability. The only problematic case is the CCTV traffic, which has a delay of 1 s with a probability of 10^{-4}. This is because the UL channel model is more challenging than that of the DL (has a slightly higher path loss exponent) and the data rate at some time instants is not enough for the CCTV. Focusing on the CCDF of the CBTC DL traffic shown in Fig. 4, the horizontal line with a 10^{-2} probability indicates that no packets arrived with a delay between 11 and 111 ms, but some outliers arrived with a delay of 111 ms. The reason for these outliers is a delay due to the packet reordering mechanism at the RLC layer. This mechanism has a timer that adds a delay when a packet is lost. In the ns-3 simulator, this timer is fixed to wait 100 ms, which explains the delay of the outliers, which could be modified to reduce the delay in all the flows.

Conclusions

In this work, we evaluated the suitability of LTE in subway environments by performing system level simulations with a propagation model based on real channel measurements. The ns-3 LTE module was configured, adapted and extended to match the subway scenario conditions and to optimize the performance of typical applications such as CBTC and VoIP. In particular, QoS configuration, frequency reuse and handover customization were carried out. From the obtained results, it can be concluded that the QoS requirements of these applications were satisfied.

Acknowledgments

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