LTE System Design for Urban Light Rail Transport

Gianluca Mandò[1](✉) and Giovanni Giambene[2]

[1] Thales Italia SpA, Via Lucchese, 33, Osmannoro, 50019 Florence, Italy
gianluca.mando@thalesgroup.com
[2] Dipartimento di Ingegneria dell'Informazione e Scienze Matematiche, Università degli Studi di Siena, Via Roma, 56, 53100 Siena, Italy
giambene@unisi.it

Abstract. This paper deals with the performance of LTE-A (Long Term Evolution-Advanced) cellular networks for supporting operational, safety-critical signaling, and standard IT services for urban transportation. Our interests have been focused on Light Rail Transit (LRT) signaling performance for the Songjiang (China) tramway project. Several stationary and mobility use cases have been considered and mean end-to-end delay and Packet Loss Rate (PLR) key performance indicators have been evaluated. Simulation results highlight that, in stationary conditions, LRT signaling performance requirements are fulfilled, while PLR performance degrades when mobility is introduced. Furthermore, we have evaluated the impact of non-critical IT traffic (e.g., UDP-based video) on TCP-based signaling by demonstrating that signaling throughput is not affected by video in stationary scenarios, whereas, in the presence of mobility, handovers degrade signaling performance, which can be guaranteed only if a QoS-aware scheduler is adopted. In conclusions, our results demonstrate that LTE-A can safely support operative and non-critical applications in urban transportation scenarios, where strong connectivity requirements are crucial.

Keywords: Light rail transit · Safety-critical signaling · LTE

1 Introduction

Reliability, availability and safety play a crucial role for the increasingly use of public transport systems. In this paper, we analyze all major challenges that wireless communication systems are facing today in order to guarantee signaling services for train control, passenger safety, and to allow the coexistence with other new, non-critical applications [1]. Today, traffic control and management of public transportation systems are mainly provided by wireless communication technologies such as GSM-R for railways, TETRA, and WiFi in metro applications. But, if we consider today communication needs for rail transport, we realize that the above technologies have some limitations, mainly due to their inefficiency and limited capacities, thus paving the way to the introduction of new mobile digital technologies.

In this paper, after a brief summary of the existing radio systems used in public transport, we evaluate LTE technology performance for Light Rail Transit (LRT) applications [2]. After defining the main elements of a typical tramway control system, we

A. Fantechi et al. (Eds.): RSSRail 2017, LNCS 10598, pp. 17–33, 2017.
https://doi.org/10.1007/978-3-319-68499-4_2

will describe the simulation of a real urban tram line (Songjiang Line 1 [3]) by using the Ns-3 network simulator [4] and evaluate the performance of an LTE infrastructure for transmitting both control signaling and video traffic.

2 Radio Communications for Urban Transport

Public transport systems can be divided in two main categories, such as: railway transport and Urban Guided Transport (UGT) [5]. The former refers to wheeled vehicles running on rails and is also commonly referred to as train transport. The latter is a public transport system in an urban area with motorized vehicles operated on a guideway (i.e., the vehicles follow a determined trajectory for all or part of their journey). These are, therefore, metro, subways, trams, and LRTs.

Connectivity is one of the key issues for these transport systems. In fact, a moving vehicle cannot obviously be connected to ground-based infrastructure by any other mean than legacy inductive systems or radio communications. In the past, such radio systems have been based on analogue technology, dedicated to voice and not suitable for carrying data. Nowadays, due to the necessity to provide more operational and safety services for train control, passenger security, and new non-critical applications, there is a lot of interest in introducing new digital mobile technologies for urban guided transport systems. In what follows, a survey is presented on the main services provided by radio communication systems for transport systems. Then, a very quick view is given on the state-of-the-art of radio communication technologies for railways and UGT systems.

2.1 Radio Communications Services for Transport Systems

Safety and non-safety services, which are provided today in transport systems through communication technologies, have different Quality of Service (QoS) requirements. They can be classified into three main categories:

- **Safety-critical signaling** for the safe movement of trains and operations. It can be distinguished in two categories: signaling related to the safety of the train itself and public safety signaling, also including voice communications. They generally require a low throughput (up to 100 kbps), but have strong requirements in terms of security, reliability, availability (at least 99.99%), robustness (typically a packet error rate of 10^{-3} for a 200-byte packet) and timing (delay constraints lower than 500–800 ms) [1].
- **Operational non-safety services** for non-critical services for train operation support. They do not have a direct impact on the safety and efficiency, but aim to improve internal railway operations. These services consist of passenger information (to provide contents related to the train location, stations, latest updates on delay and traffic disruption), Closed Circuit TV (CCTV) for security and Internet of Things (IoT) for sensing, communicating and aggregating all information.
- **Non-critical applications for infotainment** that are devoted to providing services to train passengers (e.g., Internet access, advertisement, and movie streaming).

2.2 LTE as a Future Communication Solution for Railway Applications

Today, train operators receive an increasing data traffic demand for signaling, operations, and to provide travel comfort by offering more services to passengers through real-time multimedia data. Technologies such as GSM-R and TETRA, which are ETSI (European Telecommunications Standard Institute) standards, provide an insufficient data rate if we consider today's communication needs for urban transport, while WiFi technologies, although achieving high data rates, have limitations in mobility support and because of interference. LTE is a 4G wireless technology whose standardization started in 2008 by the 3rd Generation Partnership Project (3GPP). Its architecture consists of Base Stations, called eNodeBs (eNBs), which allow connectivity between User Equipment (UE) and Core Network, called Evolved Packet Core (EPC). The introduction of LTE in railway and urban guided transport is an open research issue that is gaining more and more interest from the railway industry.

In a few years, GSM communication systems will be decommissioned as the public communication market is evolving toward LTE. As a consequence, GSM-R also has a foreseeable end of its lifetime [6]. A new system is thus required to fulfill railway operational needs with the capability of being consistent with LTE, offering new services, but still coexisting with GSM-R for a certain period of time. In view of both the performance and the level of maturity of LTE, LTE-Railway (LTE-R) will likely be the next-generation LRT communication systems. Table 1 provides a comparison of LTE with other wireless technologies.

Table 1. Comparison of existing radio communication technologies.

	GSM-R	TETRA	WiFi	LTE
Operational voice support	Yes	Yes	VoIP	VoLTE
Data support	< 10 kbps	< 28.8 kbps	> 10 Mbps	> 10 Mbps
All IP (native)	No	No	Yes	Yes
Vital traffic support	Yes	Yes	No	Yes
P2T/call setup time	1 to 5 s	250 ms	100 ms	100 ms
Handover mechanism	Standard	Standard	Proprietary	Standard
Priorities/pre-emption	Yes	Yes	4 QoS classes/No	9 QoS classes/Yes
Available frequencies	900 MHz UIC	400 MHz PMR	2.4/5 GHz	400 MHz to 3.5 GHz
Cell range	10 km	25 km	< 1 km	1 km
Maturity	End by 2025	Mature	Widely adopted in urban areas	Emerging

3 LRT and Tramway Control System

LRT and tramways are playing an ever more important role in creating environmentally-sustainable cities, enforcing the concept of sustainable mobility within the smart cities contextual environment. It is a kind of urban transportation system for which automation systems for service operation are actually not applied, since these trains share their ways with other vehicles, like buses, cars and even pedestrians. Indeed, the safety in tramways is based on the principle that the train movement is fully controlled by the driver: railway operation is under his responsibility and no level of automation is allowed. Tramway Control System (TCS) is the signaling and control system that provides supervision and control over tramway and LRT networks, including routing and headway management. TCS is a complete signaling and control system that optimizes performances, providing an unprecedented level of supervision and control over tramway and LRT networks, including routing and headway management. It is a modular and scalable system made up of three main building blocks:

- **Traffic Manager** (TM) at the Operation Control Center (OCC) for real-time vehicles localization and circulation management;
- **Interlocking System** (IS), which manages LRT signaling alongside and in the depots. It is usually a fault-tolerant system with a high grade of SIL (Safety Integrity Level) that controls line switches, track circuits, axle counters and signals.
- **On Board Computer** (OBC) to manage on-board signaling, communication and comfort.

The general TCS network architecture (see Fig. 1) consists in a transmission system based on a Gigabit Ethernet Backbone connecting the OCC to the stations and in a radio system to connect the OCC to the trams. Furthermore, TCS allows a safe management of the tram movement at the depot, where electrical switches are monitored and controlled by using the same TCS equipment foreseen for the switch area management in the main line. The main functions of TCS are: automatic vehicle localization, priority management at road and crossing area, train regulation, timetable management, junctions and depot management, and passenger information.

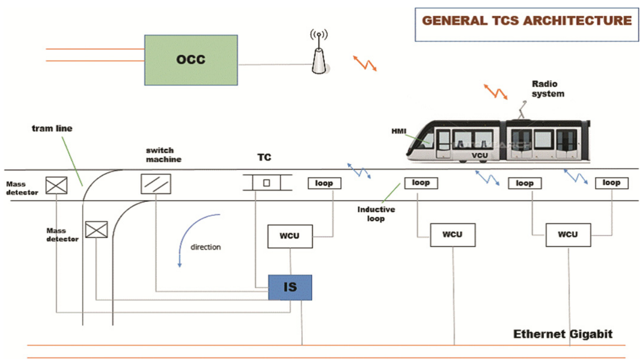

Fig. 1. General TCS architecture.

4 Simulation Approach and Results

For the simulation study carried out in this work, we have assumed an LTE cellular network for the Songjiang Tram Line T1. The details of Songjiang tram lines are provided in Table 2 [3].

Table 2. Characteristics of T1 and T2 tram lines.

Songjiang tram lines T1 & T2	Lines		Total
	Line T1	Line T2	
Length (km)	15.659	15.24	30.941
Stations	23	22 (one station is reserved for future)	45
Trains	15		30
OCC	1		1

First of all we are interested in evaluating the performance in terms of mean end-to-end (e2e) delay and packet loss rate of the signaling traffic from trains to OCC and back, and then we will add a non-critical bandwidth-demanding traffic in order to evaluate the impact of this traffic on signaling traffic. Line T1 is 15.659 km long with 23 stations. At first, 16 trains are provided on the line, but this number will increase to 30 trains during the years. Each train reaches the maximum speed of 70 km/h and its average speed is about 30 km/h. This line is double track; after having reached a terminus point each train goes back to the other terminus. Multiple cells are need in order to cover the whole line T1 with an LTE network. A link budget analysis is then required in order to find the cell range and the number of eNBs to be deployed to cover the target area. We assume that the designed LTE network is dedicated entirely to train traffic.

We model trains as LTE User Equipments (UEs), while the OCC is modelled as a Remote Host and traffic flows are generated in both uplink and downlink directions. We consider the following performance indicators:

- **The mean end-to-end delay (e2e delay)**, calculated as the ratio of the sum of all end-to-end delays for all received packets of a data flow to the number of received packets;
- **The Packet Loss Rate (PLR)**, calculated as the ratio of lost packets to the sum of lost packets and received packets, where lost packets refer to those that were transmitted, but have not been reportedly received or forwarded for a long time.

Transmission Control Protocol (TCP) is used as the transport layer protocol for signaling traffic. TCP provides reliable and ordered delivery of stream of IP packets from one sender to one receiver. LRT signaling traffic is on top of TCP and is intended as the sum of the following traffic flows in downlink:

Traffic position request (32-byte packet size) + Passenger information (128-byte packet size) + Driver logic answer (16-byte packet size) and Time synchronization answer (16-byte packet size).

In uplink, signaling is the sum of the following traffic flows:

Train position request (32-byte packet size) + Route request (16-byte packet size) + Train diagnostic telemetry (32-byte packet size) + Time synchronization request (8-byte packet size).

Both downlink and uplink signaling traffic are modelled (at application level) as a Constant Bit Rate (CBR) traffic having 200-byte packets and data rate of 1600 bps. CBR traffic flows are modelled as ON/OFF traffic processes.

On-board video surveillance is on top of User Datagram Protocol (UDP) that is another common transport layer protocol used in today's Internet. UDP is connectionless and does not provide any sort of reliability, rate limiting or congestion control mechanism to the applications using it, such as video streaming. Table 3(a) summarizes the characteristics of traffic sources and their QoS requirements defined by the train operator. The second phase of this work involves the study of the impact of non-critical traffic (video modelled as CBR traffic having 1000-byte packets and data rate of 1 Mbps) on signaling. Table 3(b) illustrates video traffic characteristics and QoS requirements.

Table 3. Traffic characteristics and QoS requirements for signaling (a) and video (b) traffic.

Traffic Flow	Signalling Traffic
Packet size	200 bytes
Data Rate	1.6 kbps
Transport layer protocol	TCP (New-Reno version)
Application-level traffic model	CBR
Packet Loss requirement	10^{-3}
Mean E2E delay requirement	50 ms

(a)

Traffic Flow	Video Traffic
Packet size	1000 bytes
Data Rate	1 Mbps
Transport layer protocol	UDP
Application-level traffic model	CBR
Packet Loss requirement	10^{-3}
Mean E2E delay requirement	150 ms

(b)

4.1 Simulator Implementation

We have implemented the LTE scenarios of Songjiang Tram Line T1 using the Ns-3 simulation environment [4]. Ns-3 is an open-source discrete-event network simulator under the GNU GPLv2 license. Ns-3 is primarily used on Linux systems, although support exists for Windows systems as well. To implement the LTE scenario, we have used the Ns-3 LENA (LTE-EPC Network simulAtor) module [7]. LENA is a free open-source LTE network simulator developed by the Centre Tecnològic de Telecomunicacions de Catalunya (CTTC). The LTE model supports Radio Resource Management (RRM), Inter-Cell Interference Coordination (ICIC), dynamic spectrum access and QoS-aware packet scheduling. At radio level, the granularity of the model is at the level of Resource Blocks (RBs), which are the fundamental units of resource allocation. Packet scheduling is done on a Transmission Time Interval (TTI) basis (= 1 ms). An eNB can transmit on a subset of the available RBs, interfering with other eNBs transmitting on the same RBs. The simulator is designed to manage tens of eNBs (each controlling a cell) and hundreds of UEs (corresponding in this case to trains). The simulator can be used to simulate many IP packets flows, but in the LTE simulator, scheduling and radio resource management do not directly work with IP packets, but rather with

Radio Link Control (RLC) packets, obtained by segmentation and concatenation of IP packets at the RLC layer.

4.2 Results: Stationary Trains at Train Depot

This scenario implements the simplest use case where all trains are located at the train depot and turn on signaling traffic all at the same time (data rate 1600 bit/s/train). This situation corresponds to a real case when all trams are started at the same time in the depot (the operational services are activated in the morning) (Fig. 2).

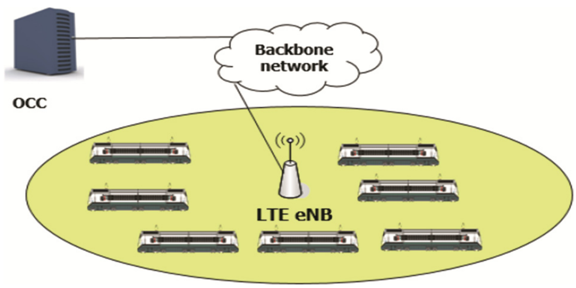

Fig. 2. Stationary trains at train depot.

We consider covering this area with only one eNB with a cell radius of approximately 1 km; thus, all the trains are connected to this cell and exchange data with the OCC. All the trains are modelled as stationary nodes and they are uniformly distributed in the cell. Each simulation run lasted 10 min and was repeated 10 times with different seed numbers in order to achieve reliable results. The main simulation parameters are shown in Table 4 below.

Table 4. Simulation parameters of the stationary scenario.

Parameter	Value
LTE Bandwidth	5 MHz
eNB/UE antenna height	50 m/3.5 m
Cell radius	1 km
eNB/UE antenna gain	18 dBi/0 dBi
eNB/UE Tx Power	26 dBm/23 dBm
Number of trains	15, 20, 25, 30
Simulation repetitions	10

In this scenario, we have found that the mean e2e signaling delay in relation to the number of trains at the train depot is approximately constant in all investigated cases and is below 14 ms and 23 ms (respectively for downlink and uplink) for a number of trains up to 30 at the depot. Uplink delay is a bit higher than downlink because the uplink radio resource scheduling is different from downlink [8]. As for PLR, we have verified that it is negligible for both uplink and downlink, thus fulfilling the requirements of the train operator.

Furthermore, within this depot scenario we have also investigated the impact of non-critical traffic on LRT signaling. In other words, OCC sends a further video flow modelled with 1 Mbps data rate. Both flows share the same LTE resources so that a QoS provisioning mechanism is required in order to prioritize and protect signaling. In LTE, the QoS mechanism is provided using EPS bearers, which carry packet flows between the UEs and a specific packet data gateway (P-GW). Hence, in order to guarantee some specific QoS requirements for a specific application, a dedicated bearer will be established for that application. All the details of each traffic type are summarized in Table 3. Unfortunately, the Ns-3 simulator for LTE only supports QoS-aware schedulers for downlink traffic, while only the Round Robin (RR) scheduler is implemented for uplink. Figure 3 shows the mean delay for signaling traffic for both uplink and downlink in relation to the number of trains. We have supposed that not all the trains activate signaling and video traffic, but only a selected number of them. Due to the congestion of LTE air interface resources caused by video, we noticed an increment of the mean e2e delay for signaling with respect to the case without video. The signaling PLR is still almost zero: the PLR of signaling is not affected by the video even if the number of trains increases. This is an important result since it suggests that in a scenario with stationary trains, the introduction of a non-critical application does not influence the QoS of signaling, which is a vital traffic for train operation and safety.

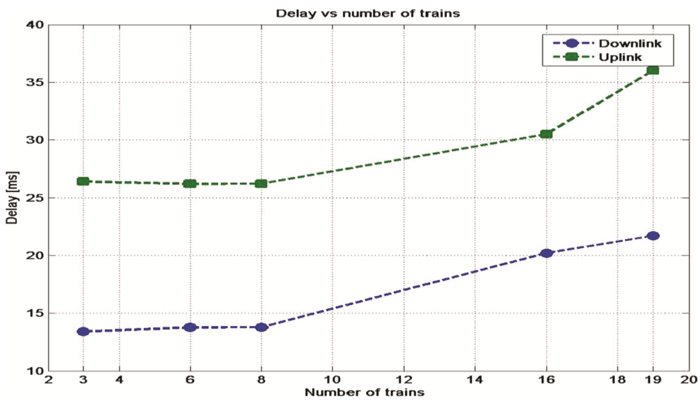

Fig. 3. Signaling traffic delay in relation to the number of trains.

Figure 4 presents the mean delay performance for video. As we can see, due to its high throughput, the mean delay for video is higher than the signaling one.

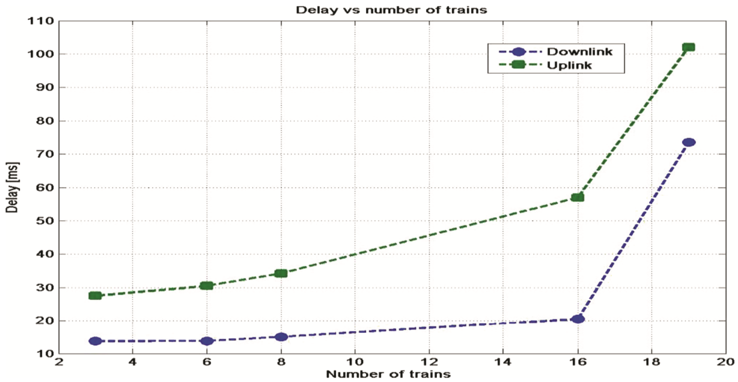

Fig. 4. Video delay in relation to the number of trains.

As for video PLR, it is almost zero in the downlink case until 16 trains are considered at the train depot, since the capacity of an LTE cell is sufficient to support all these traffic flows and a target bit rate is used by the scheduler for each traffic. In the case with 19 trains, the cell capacity is not sufficient so there are packet losses due to congestion. Video PLR requirements defined in Table 3 are not fulfilled in uplink, while they are met in downlink when there is no congestion in the network.

4.3 Results: Cell Planning

The number of eNBs that are needed to cover the tram line with cells of radius R depends on the eNB transmission power according to the link budget analysis. In particular, we use the following equation to determine the cell size R:

$$R[km] = 10^{\left(P_{tx}+G_{tx}-L_{tx}-P_{min}+G_{rx}-IM-L_{rx}-x\right)/z} \quad (1)$$

where:
R is the cell radius
P_{tx} is the transmission power (dBm)
G_{tx}, G_{rx} are transmitter and receiver antenna gains (dB), respectively
L_{tx}, L_{rx} are the losses (dB) at transmitter and receiver, respectively
P_{min} is the minimum receiver power (dBm)
IM is the interference margin (dB)
x, z are terms that depend on the pathloss.

For a given number of trains in transit into the line, we simulate some scenarios where the number of eNBs varies, accordingly to the transmission power, and we evaluate the performance of signaling traffic in terms of mean end-to-end delay and packet loss rate for the communications between trains and OCC. We assume to consider the worst-case conditions for interference: values of the interference margins for both uplink and downlink are chosen as the worst values within a typical range for LTE systems [8].

Furthermore, the noise figure values are chosen as the worst ones for a conservative performance evaluation. Table 5 summarizes the main assumptions and simulation parameters for this scenario. By applying the simulation parameters of Table 5 to Eq. (2) below, we can characterize the path loss L_p in dB as a function of the distance d between transmitter and receiver as:

$$L_p[dB] = 46.3 + 33.9 \times \log_{10}(f) - 13.82 \times \log_{10}(h_b) - F(h_M) + C + [44.9 - 6.55 \times \log_{10}(h_b)] \times \log_{10}(d), \quad (2)$$

where

$F(h_M) = \left[1.1 \times \log_{10}(f)\right] - 0.7 \times h_M - \left[1.56 \times \log_{10}(f)\right] - 0.8$, for medium cities
C is a constant term equal to 0 dB for medium cities
f is the carrier frequency [MHz]
h_b is the eNB antenna height above the ground [m]
h_M is the UE antenna height above the ground [m]
d is the distance between the eNB and the UE [km].

Since uplink is commonly more critical than downlink for the link budget, we determine the cell size R, referring to uplink coverage. In order to define the proper parameters for determining the cell radius R, we can refer to the expected Cell Edge Throughput (CET) or to the minimum receiver power level, P_{min}. Fixing the CET for a single user, we determine the minimum Modulation and Coding Scheme (MCS) index, which has a corresponding Signal-to-Interference and Noise Ratio (SINR) threshold value. Thus, knowing this SINR threshold, the receiver noise figure and the thermal noise, which depends on the number of RBs we assume to allocate to the UE at cell edge, we obtain the minimum receiver power P_{min}, and then R is simply given by (1).

Table 5. Simulation parameters.

Parameter	Value
LTE bandwidth	5 MHz
eNB/UE antenna height	50 m/3.5 m
eNB/UE antenna gain	18 dBi/0 dBi
Type of handover/Handover algorithm	X2-based handover/Strongest cell
CET	1 Mbps
Type of uplink scheduler	Round Robin (RR)
Type of downlink scheduler	Priority Set Scheduler (PSS)
Adaptive modulation and coding	Piro's model
UL/DL receiver sensitivity	−100 dBm/−96 dBm
eNB/UE Tx power	18–48 dBm/23 dBm
eNB noise figure/UE noise figure	5 dB/9 dB
UL/DL interference margin	10 dB/8 dB
Number of trains	16
Tramway line length	15.7 km

Since in our simulation scenario we randomly place 16 trains along the line (8 trains move in a direction and the other 8 trains move in the opposite direction), we can suppose that at most there will be 2 trains at the edge of a cell at the same time. This is only an assumption we have done for our work, but it is of considerable importance in order to define the cell edge throughput and the corresponding number of resource blocks to be allocated to each user. Knowing the CET and the total bandwidth (= 5 MHz in our case, corresponding to 25 RBs), if we consider to have 2 UEs at the cell border, the network could not allocate more than 12 RBs per UE (= train). Assuming an uplink CET of 1 Mbps and allocating 12 RBs, the corresponding MCS index is 6 that corresponds to use a QPSK modulation.

In our Ns-3 simulator, only even MCS indexes from 0 to 28 (out of 30) are considered according to [9]. Each MCS index corresponds to a certain SINR threshold value. So that, knowing the required MCS index to fulfil the CET condition, we can find the corresponding SINR value used by the simulator and the minimum received power P_{min}. In Fig. 5, the MCS level is shown as a function of the SINR level, as implemented in the Ns-3 simulator for the Adaptive Modulation and Coding (AMC) scheme [9].

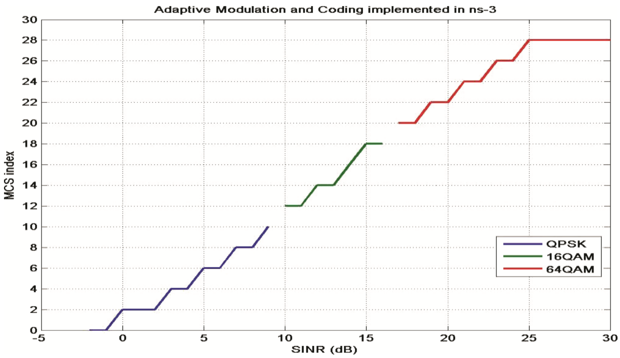

Fig. 5. AMC levels implemented in Ns-3.

In Fig. 6, we provide the graphs for uplink and downlink cell radius. As expected, the higher is the transmission power, the larger is the cell radius. Furthermore, considering the maximum transmission power for UEs equal to 23 dBm, we notice from Fig. 6 that the maximum cell radius is about 0.5 km if we consider the more stringent condition of uplink coverage. This demonstrates that the LTE system is uplink limited. Then, knowing the cell radius, the number of eNBs, N_{eNB}, to be deployed along a tram line according to a linear cellular model is obtained as follows:

$$N_{eNB} = \lceil Length/(2 \times R) \rceil, \tag{3}$$

where h is the total tram line length and $2R$ is the distance between two eNBs (linear cellular model).

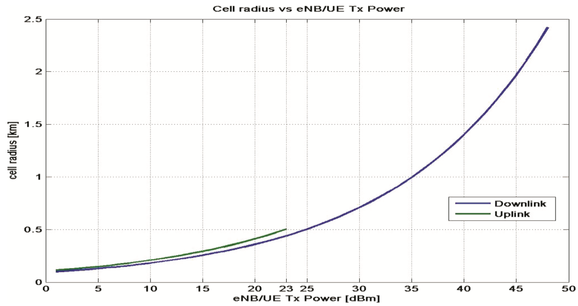

Fig. 6. Cell radius vs. eNB/UE transmission power.

According to the uplink coverage, since the maximum UE transmission power is fixed to 23 dBm, the cell radius is quite small and this has consequence on the minimum number of required eNBs. As shown in Fig. 6, if we limit to have 23 dBm UE transmission power, the cell radius should be about 0.5 km. However, since in uplink and downlink we have considered different values for noise figure and interference margin, we note that the downlink cell radius is smaller than the cell radius calculated for uplink for eNB transmission power of 23 dBm. This entails the need to use a higher eNBs transmission power, specifically the one matching 0.5 km cell radius. Reducing the eNBs transmission power until the minimum value of 18 dBm, we will deploy more eNBs along the track due to the shorter cell radius. Table 6 shows the possible values of eNBs transmission power (in steps of 2 dBs) with the corresponding cell radius *R* and the corresponding number of eNBs to cover the entire line.

Table 6. Selected eNB transmission power.

$P_{tx}[dBm]$	$R[km]$	N_{eNB}
18	0.312984	26
20	0.358709	22
22	0.411115	20
24	0.471178	17
26	0.540015	15

4.4 Results: Impact of Train Mobility, Handover Performance

We are now going to evaluate the signaling performance when trains move along the tramway line. With the purpose of evaluating the impact that mobility and handovers have on signaling traffic performance [10, 11] in relation to the number of trains and varying the number of eNBs, we firstly consider a simple scenario where few trains are moving along the track and different transmission powers are considered, i.e., different numbers of eNBs are deployed along the track. As shown in Fig. 7, we assume a linear deployment of the eNBs with an inter-eNB distance of 2*R*. Trains are moving in the same direction and each train is randomly distributed and travels at a constant speed crossing different eNBs and coming back.

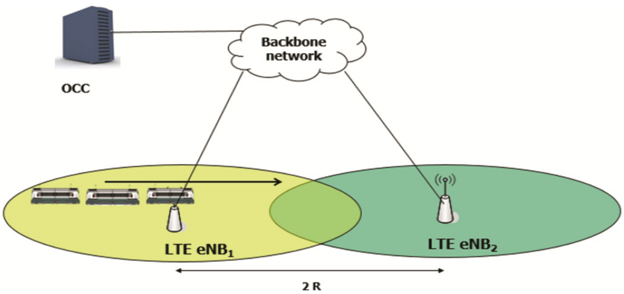

Fig. 7. Handover scenario.

From simulation results not shown here, we have obtained that the mean e2e delays for downlink and uplink for different transmission powers and numbers of trains are not sensitive to the increase in the number of trains and are below 14 ms and 22 ms, respectively, up to 4 trains. Let us now consider the PLR results in Figs. 8(a) and (b). As shown in these graphs, PLR increases when trains have mobility. This increment is mainly due to the handovers that the trains trigger when moving across different cells. Moreover, PLR increases with the number of trains, since more trains trigger handovers at the same time and eNBs do not handle properly the handover procedure and data forwarding. We also notice that the downlink PLR is higher than the uplink one. Regarding this scenario, we can conclude that using higher transmission power for each eNBs could improve the performance at the cost of higher total transmission power in the network. However, increasing the eNB transmission power we reduce the number of cells, thus there could be too congestion and this entails a performance degradation.

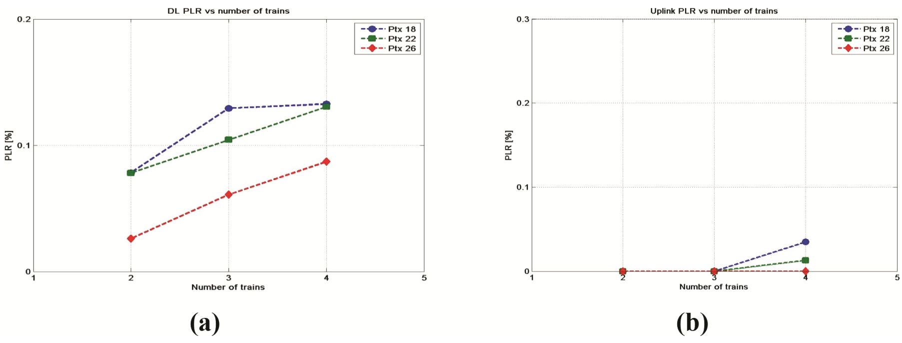

Fig. 8. Downlink (a) and uplink (b) PLR vs. number of trains and eNB transmission power.

4.5 Results: Impact of the Number of eNBs on Signaling Traffic

In order to evaluate the impact that the eNB deployment has on LRT signaling in an LTE access network, we have fixed the number of trains to 16 in the simulation scenario. Besides, we set different eNB transmission powers, corresponding to different cell radii and numbers of deployed eNBs to cover the entire line. Furthermore, we consider a linear deployment of the eNBs with an inter-eNB distance of $2R$. Half of the trains moves in one direction, instead the other half moves in the opposite direction, as shown in Fig. 9. Each train is randomly distributed along the tramway line and after reaching a terminus point comes back to the other one and then stops at its starting point. Considering the same simulation parameters, as in Table 5, each simulation run is repeated 10 times, changing the seed numbers in order to achieve reliable results.

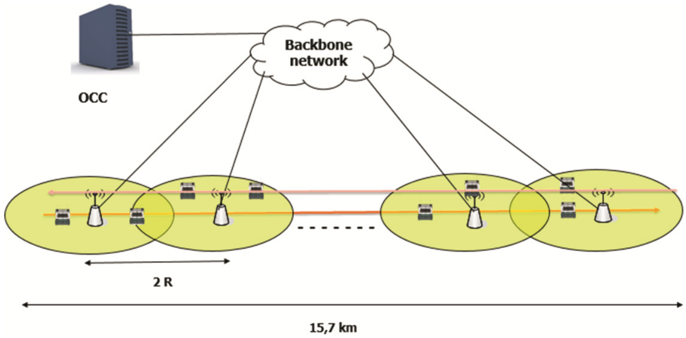

Fig. 9. Simulation scenario topology.

Even if the mean e2e delay is not strongly affected by the number of eNBs deployed, our results show a slight increment in delay for both downlink and uplink when more eNBs are placed. This behavior is mainly due to the more frequent handovers as they will delay transmission and reception of packets. In Fig. 10, instead, we note that the more eNBs are deployed, the higher is the PLR value: this is again due to the more frequent handovers with an increase in packet losses, especially for downlink. Therefore, a trade-off is needed between the total transmission power (and the consequent number of eNBs) and the performance requirements.

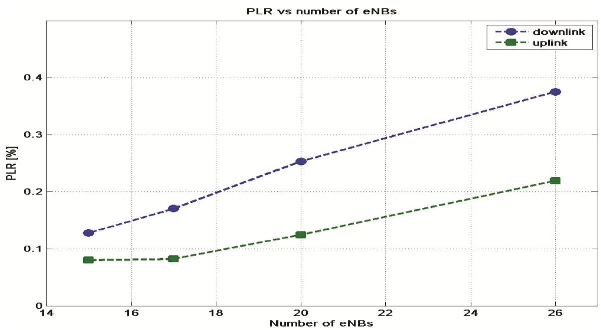

Fig. 10. PLR vs. number of eNBs.

4.6 Results: Impact of the Number of Trains on Signaling Traffic

In this simulation scenario, we consider a deployment with 15 eNBs (considered as a good trade-off solution) and evaluate the performance in relation to the number of trains in the line. We consider the same simulation parameters as in Table 5. Each simulation run is repeated 10 times, changing the seed numbers in order to achieve reliable results.

Even if the number of trains does not strongly affect the mean e2e delay, it has a negative impact on packet loss rate. Indeed, as it can be seen in Fig. 11, the more trains are in the line, the higher the PLR value is; this is mainly due to the more frequent handovers caused by the increment in the number of trains.

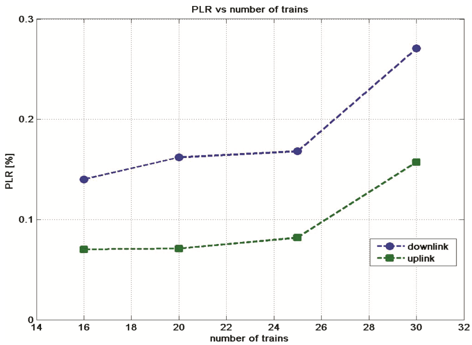

Fig. 11. PLR vs. number of trains.

PLR requirements are met for uplink up to 25 trains and never for downlink. Furthermore, since in the Ns-3 simulator only intra-frequency handovers are supported, additional interference is present in our model, since all eNBs transmit on the same frequency (in real scenarios, there is frequency differentiation among adjacent cells and inter-frequency handovers are adopted).

4.7 Results: Impact of Non-critical Traffic on Signaling

Finally, we are interested in evaluating the impact that non-critical video (500-byte packet) has on signaling when trains are moving. This UDP traffic is modelled as CBR having a data rate of 500 kbps. Compared to the stationary case, there is an increment for both mean e2e delay and PLR: the mean delay continues to match the delay constraint, while the PLR requirement is not met. Figure 12, obtained by varying the number of trains, shows that the PLR of signaling traffic in uplink is significantly degraded, because a QoS-aware scheduler is not used in uplink. Finally, as for the video performance, the mean end-to-end delay and PLR increase with the number of trains, with downlink performance approximately one order of magnitude better than uplink one, because of the use of a QoS scheduler.

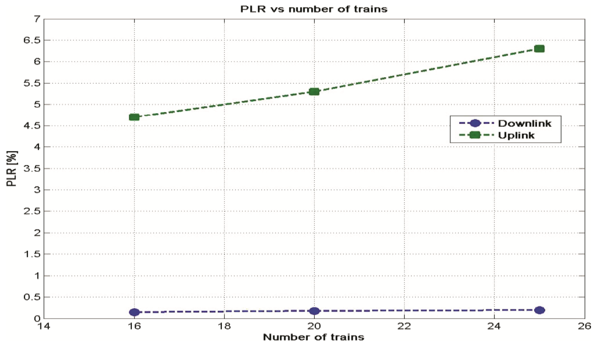

Fig. 12. Signaling traffic PLR vs. number of trains.

5 Conclusions and Future Work

In this paper, we have investigated major challenges faced in urban transportation when using an LTE-A cellular network for safety-critical signaling and standard IT services. Our interests have been focused in evaluating LRT signaling performance using LTE for the citywide Songjiang tramway project. A simulator of LTE railway communications has been built, based on the Ns-3 environment; we have considered several operational scenarios involving time-critical (TCP-based) signaling by differentiating between stationary and mobility use cases. For what concerns PLR in stationary conditions, requirements are fulfilled independently of the number of trains in the depot, while the PLR performance degrades when mobility is introduced. In a second simulation session, we have evaluated the impact of non-critical IT traffic (UDP-based video) on TCP-based signaling. We have obtained that safety-critical signaling throughput is not affected by video in stationary scenarios, whereas, in the presence of mobility, handovers degrade signaling performance that can be guaranteed only if a QoS-aware scheduler is adopted. Results have also shown that QoS requirements are met if there is no congestion in the LTE network.

In conclusions, we have shown that LTE-A radio resources can be safely shared between time-critical and time-non-critical applications, thus allowing the simultaneous use of safety-critical signaling with non-critical traffic such as video surveillance, ticketing, and passenger information. Hence, LTE technology is a good candidate for unified communications in next-generation urban rail infrastructures.

References

1. Bertout, A., Bernard, E.: Next generation of railways and metros wireless communication systems. In: Proceedings of IRSE ASPECT (2012)
2. Sniady, A., Soler, J.: Performance of LTE in high speed railway scenarios. In: Berbineau, M., Jonsson, M., Bonnin, J.-M., Cherkaoui, S., Aguado, M., Rico-Garcia, C., Ghannoum, H., Mehmood, R., Vinel, A. (eds.) Nets4Cars/Nets4Trains 2013. LNCS, vol. 7865, pp. 211–222. Springer, Heidelberg (2013). doi:10.1007/978-3-642-37974-1_17

3. Thales: LRT & Tramway Solution for Optimised Operations and Maintenance. https://www.thalesgroup.com/sites/default/files/asset/document/lrt_tramway_brochure_ld_0.pdf
4. Ns-3 Tutorial: https://www.nsnam.org/docs/release/3.24/tutorial/ns-3-tutorial.pdf
5. Furlan, L., Schmidt, H.: Importance of interchangeability for urban guided transport. Eur. Transp. Res. Rev. **3**(2), 95–101 (2011)
6. Sniady, A., Soler, J.: An overview of GSM-R technology and its shortcomings. In: Proceedings of the 12th International Conference on ITS Telecommunications (2012)
7. Ns-3 Models: https://www.nsnam.org/docs/release/3.24/models/ns-3-model-lib.pdf
8. Holma, H., Toskala, A.: LTE for UMTS: Evolution to LTE-Advanced, 2nd edn. Wiley, Chichester (2011)
9. Ns-3 LTE PHY layer: https://www.nsnam.org/docs/release/3.24/models/html/lte-testing.html#adaptive-modulation-and-coding-tests
10. Sauter, M.: From GSM to LTE-Advanced: An Introduction to Mobile Networks and Mobile Broadband. Wiley, Chichester (2014)
11. Racz, A., Temesvary, A., Reider, N.: Handover Performance in 3GPP Long Term Evolution (LTE) Systems. In: Proceedings of Mobile and Wireless Communications Summit (2007)

http://www.springer.com/978-3-319-68498-7

Reliability, Safety, and Security of Railway Systems. Modelling, Analysis, Verification, and Certification
Second International Conference, RSSRail 2017, Pistoia, Italy, November 14-16, 2017, Proceedings
Fantechi, A.; Lecomte, T.; Romanovsky, A. (Eds.)
2017, XVIII, 265 p. 80 illus., Softcover
ISBN: 978-3-319-68498-7