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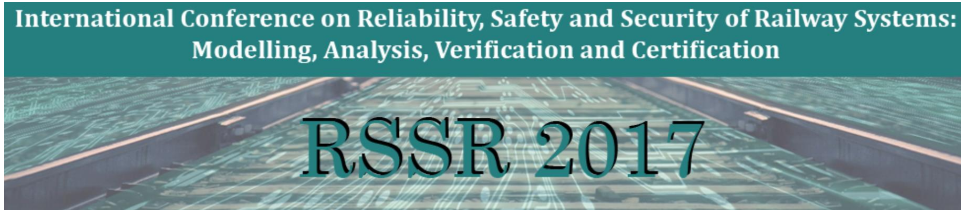

LTE SYSTEM DESIGN FOR URBAN LIGHT RAIL TRANSPORT (LRT)

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Gianluca MANDÒ
Technical Directorate,
Thales Italia SpA, Italy
gianluca.mando@thalesgroup.com

Giovanni GIAMBENE
Dipartimento di Ingegneria dell'Informazione e
Scienze Matematiche, University of Siena, Italy
giambene@unisi.it

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- Tramway Control System (TCS)
- Existing radio communication solutions for railway signalling
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Light Rail Transit (LRT) and Tramway Control System (TCS) (1/2)

Tramways:

- Are creating environmentally-sustainable cities, enforcing the concept of **sustainable mobility** within smart cities
- **Share their ways with other vehicles (buses, cars, and pedestrians)**
- Safety in tramways is based on the principle that **the train movement is fully controlled by the driver**, no level of automation is allowed

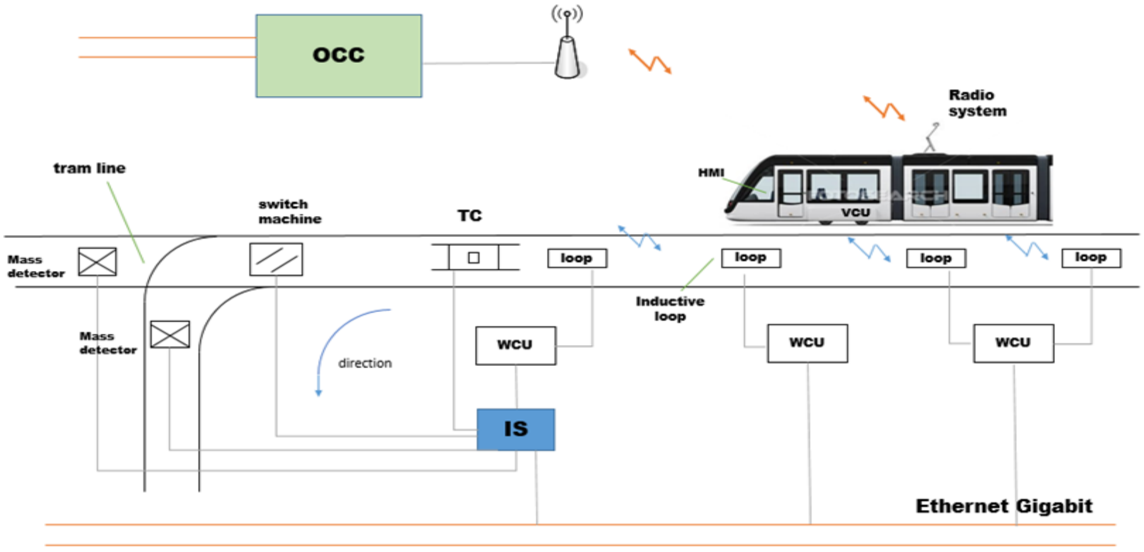
Tramway Control System:

- Is the **signalling** and control system that provides supervision and control over tramway and LRT networks, including routing and headway management
- Is 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 signalling 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 signalling, communications and comfort

Light Rail Transit (LRT) and Tramway Control System (TCS) (2/2)

General TCS architecture

- Interlocking System (IS)
- Operational Control Centre (OCC)
- Wayside Communication Unit (WCU)



Radio Communications Services for Urban Transport Systems (1/2)

Radio communication services for urban transport systems

- **Connectivity** is one of the key issues for **urban guided transport systems**
- Moving vehicles are connected to ground-based infrastructure by **radio communications** that allow a broad range of signalling options than legacy inductive systems
- In the past, radio systems have been based on either analogue technology dedicated to voice or low-bandwidth digital technology
- There is the need of adopting **new digital mobile technologies with high capacity** for urban guided transport systems (train control signalling, passenger security, and non-critical applications).

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Radio Communications Services for Urban Transport Systems (2/2)

These services can be classified into three main categories:

- **Safety-critical services**: signalling traffic
- **Operational non-safety services**: passenger information, CCTV video, IoT
- **Non-critical applications for infotainment**: Internet access for passenger, advertisement, etc.

These services have different Quality of Service (QoS) requirements

- **Safety-critical services QoS requirements:**
  - Low throughput (up to 100 kbps)
  - Strong requirements in terms of security and reliability
  - Availability (at least) 99,99%
  - Packet loss rate lower than 10^{-3}
  - Delay lower than 200 ms

Existing radio communication solutions for railway and urban guided-transport

Radio communication solutions

- **GSM-R**
  - Dedicated GSM network for railways
- **TETRA**
  - For public safety applications, but low bit-rate
- **Wi-Fi**
  - For local wireless networks with limitations in the support of mobility
- Necessity of the convergence towards a **new broadband railway communication system** that aggregates traffic flows (voice, TCS, CCTV and other services), handling them with proper QoS levels and security policies

LTE is a candidate for railway communications

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LTE Features overview

- **Peak data rate** of 300 Mbps in downlink (DL) and 75 Mbps in uplink (UL)
- **Fully packet-switched IP-based** mobile communication standard
- **Enhanced support for mobility**
- **Inter-working with previous technologies**
- Advanced multiple access scheme: **OFDMA** in DL and **SC-FDMA** in UL
- **Adaptive Modulation and Coding** (**AMC**): **QPSK, 16-QAM** and **64-QAM** modulation schemes
- Advanced **MIMO** spatial multiplexing techniques
- Enhanced support for **end-to-end Quality of Service** (QoS)

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LTE QoS support

- The QoS level in the LTE Evolved Packet System (EPS) is based on the bearer established between the Packet Data Network Gateway (PDN-GW) and the UE

- All the packet flows that are mapped to the same bearer receive a common QoS treatment (e.g., scheduling policy, queue management policy, shaping policy, radio link control configuration)
  - Each bearer is assigned with a **QoS Class Identifier (QCI)** and an **Allocation and Retention Policy (ARP).**
  - **A QCI refers to a set of packet forwarding treatments** (e.g., scheduling weights, admission thresholds, queue management thresholds, and link layer protocol configuration) preconfigured by the operator for each network element. **There are 9 QCIs levels.**
  - **ARP is used in the CAC** phase to decide if a bearer establishment/modification request can be accepted or rejected in case of resource limitation.

QCI table and related QoS requirements

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QCI	Bearer Type	Application Example	Packet Delay	Packet Loss	Priority
1	GBR	Conversational VoIP	100ms	10^{-2}	2
2		Conversational Video (Live Streaming)	150ms	10^{-3}	4
3		Non-Conversational Video (Buffered Streaming)	300ms	10^{-6}	5
4		Real Time Gaming	50ms	10^{-3}	3
5	NON-GBR	IMS Signaling	100ms	10^{-6}	1
6		Voice, Video, Interactive Games	100ms	10^{-3}	7
7		Video (Buffered Streaming) TCP apps (web, email, ftp) Platinum vs. gold user	300ms	10^{-6}	6
8					8
9					9

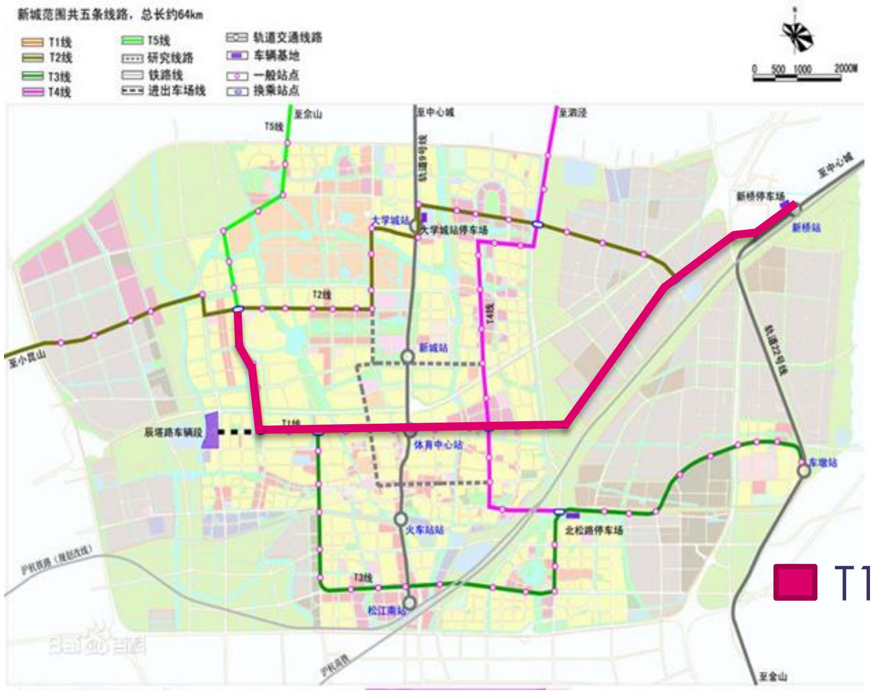
The QCI table specifies values for the priority handling, acceptable delay budget and packet loss rate for each QCI label

Comparison of existing radio communication technologies for railway applications

	GSM-R	TETRA	Wi-Fi	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 / Preemption	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

Real LRT line scenario of Songjiang Line T1

Simulating a dedicated LTE mobile network for a real city tram line – Songjiang (Shanghai) tram line T1



Songjiang Tram Line	Line T1
Length (km)	15.659
Stations	23
Trains	15
OCC (Operational Control Centre)	1

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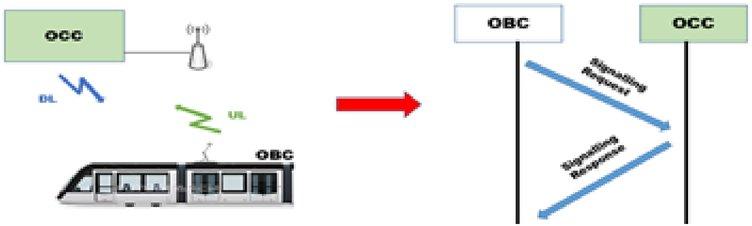
Signalling model for our scenario

Evaluating the end-to-end performance for signalling traffic between the trains and Operational Control Centre (OCC)



DL signalling traffic (OCC → Train) consists of:

- Train position request
- Passenger Information
- Driver Login Answer
- Time synchronization answer

UL signalling traffic (Train → OCC) consists of:

- Train position answer
- Route Request
- Train Diagnostic Telemetry
- Time synchronization request

Signalling traffic model (UL and DL)

Parameter	Value
Packet size	200 bytes
Data rates	1.6 kbps
Transport Layer Protocol	TCP
Application level traffic model	CBR
Packet Loss Rate requirements	10^{-3}
Mean e2e delay requirements	50 ms

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NS-3 simulator and LENA module

Ns-3 simulator

- Is an open-source discrete-event simulator (Linux environment) we have used to simulate our LRT scenario
- ns-3 can model **different** kinds of communication **networks** and it offers the advantage of being **modular**
  - IP level simulator
- Being ns-3 and open-source software, we can **use existing modules** and modify their code for our purpose
  - The work carried out in this paper has been based on the **ns-3 LENA** (LTE-EPC Network simulAtor) **module** that is well-suited to simulate our LRT scenario with an LTE-based network
  - **A train is modeled as a User Equipment (UE) with multiple traffic flows (there is no LTE relay onboard)**.

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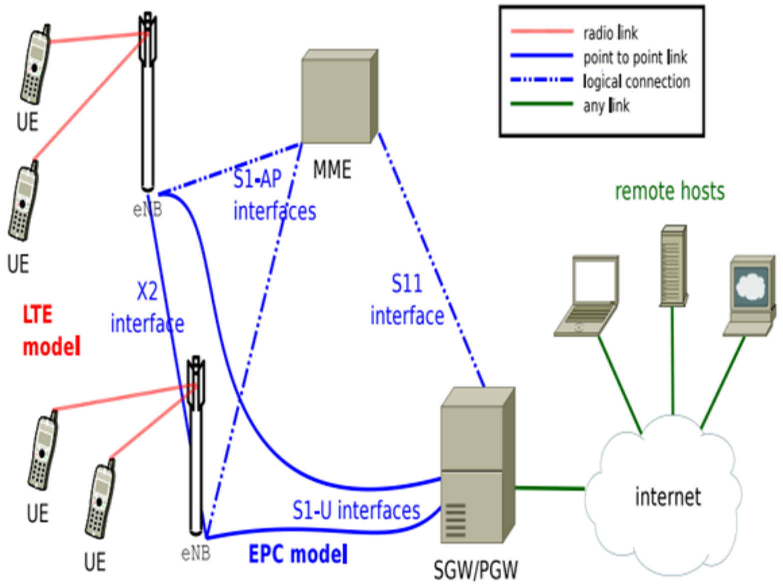
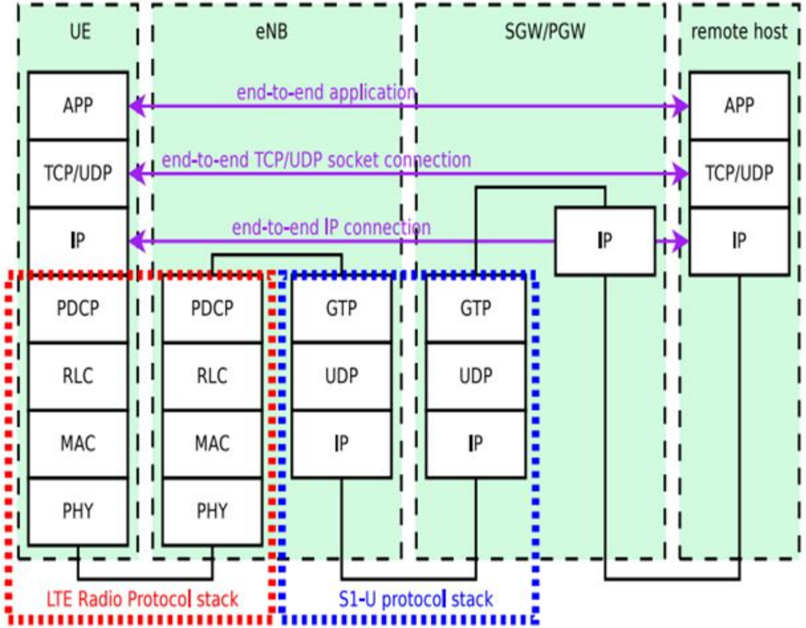
NS-3 LTE LENA Module

- Overview of the LENA module including the LTE radio access and the network (EPC, Evolved Packet Core)



- Data plane protocol stack



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NS-3 LTE LENA Module (cont'd)

Possible target applications

- Uplink and downlink scheduling
- Radio resource management algorithms
- Inter cell interference coordination solutions
- Mobility management
- End-to-End QoS provisioning

Limitations

- As for handovers, only **intra-frequency X2-handovers** are supported
- **No QoS aware scheduler** is implemented for **uplink**; only Round Robin is available

Simulator implementation

LENA simulation output

- Simulation output results can be at different layers: IP, RLC, PDCP, MAC, PHY

Output using FlowMonitor module

- The module installs probes in network nodes to track the packet exchanged by the nodes
- FlowMonitor captures e2e IP traffic (layer 3)
- Packets are classified according to the flow they belong to
- Any retransmission caused by layer 4 protocols (e.g., TCP) will be seen by the probes as a new packet

Data collected for each flow from simulations:

- **Mean packet delay:** $\overline{delay} = \frac{delaySum}{rxPackets}$
- **Packet loss rate**: $PLR = \frac{lostPackets}{rxPackets+lostPackets}$

LTE simulation parameters

Simulation parameters

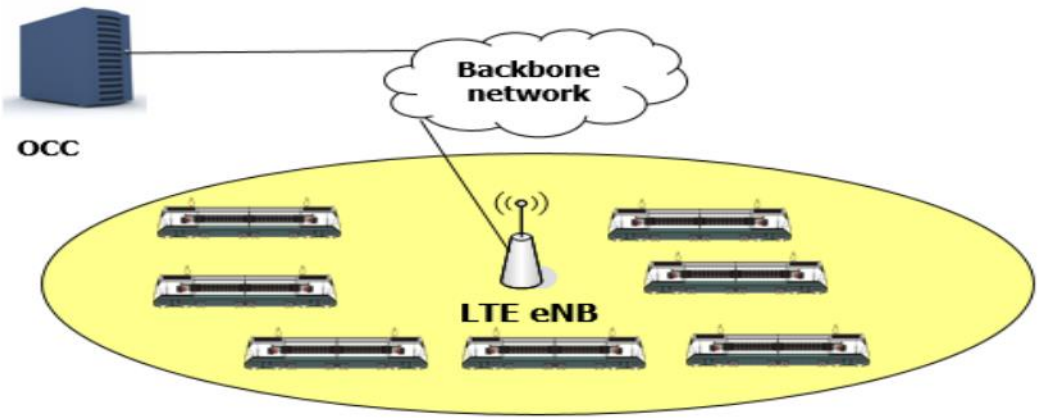
Parameter	Value
LTE bandwidth	5 MHz
Number of RBs	25
Downlink frequency	@ 2120 MHz
Uplink frequency	@ 1930 MHz
eNB antenna height	50 m
UE antenna height	3.5 m
Propagation loss model	COST231 Hata model
UE mobility model	Waypoint mobility model
eNB antenna gain	18 dBi
UE antenna gain	0 dBi
Type of handover	X2-based handover
Handover algorithm	Strongest cell handover
HOM / TTT	3 dB / 256 ms

UE Cell Edge Throughput	1 Mps
Uplink scheduler	Round Robin (RR)
Downlink scheduler	Priority Set Scheduler (PSS)
Adaptive modulation and coding with different MCS and related SINR threshold values	Piro's Model
Transmission mode	1 (SISO)
eNB Tx power	18-26 dBm
UE Tx power	23 dBm
eNB noise figure	5 dB
UE noise figure	9 dB
UL interference margin	10 dB
DL interference margin	8 dB

Scenario 1: Stationary trains at train depot

Scenario characteristics:

- The simplest use case where all trains are located at train depot and turn on signalling traffic all at the same time (**signalling data rate: 1600 bit/s/train**)
- **Single LTE cell** to cover the train depot
- All the trains are modelled as stationary UEs and are uniformly distributed in the cell



Parameter	Value
eNB transmission power	26 dBm
Cell radius	500 m
Number of trains	15 – 30

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Scenario 1: Stationary trains at train depot

At train depot:

- **UL and DL signalling traffic has been considered together with video traffic**
- Each trains generates one uplink video traffic and receives one downlink video traffic

- **UL and DL video traffic model**

Parameter	Value
Application level traffic model	CBR
Data rate	about 1 Mbps
Packet size	1000 bytes
Packet loss rate requirement	$< 10^{-3}$
Mean e2e delay requirement	< 150 ms
Transport layer protocol	UDP

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Scenario 1: Stationary trains at train depot, mean delay and PLR

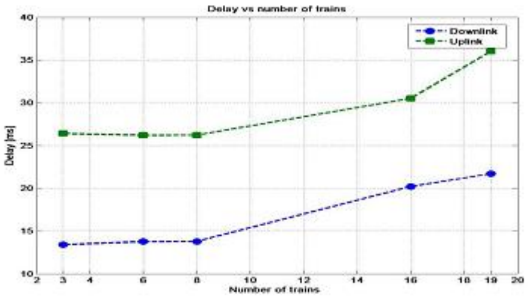
Mean delay

- The mean delay for video is higher than the mean delay for signalling traffic because video traffic entails a higher load

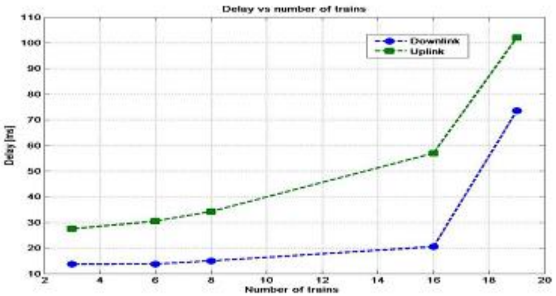
PLR

- 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
- Video PLR requirements are not fulfilled in uplink, while they are met in downlink when there is no congestion in the network.

Signalling traffic



Video traffic



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Cell planning: number of eNBs

Number of eNBs to cover the tram line T1 vs. eNB transmission power level

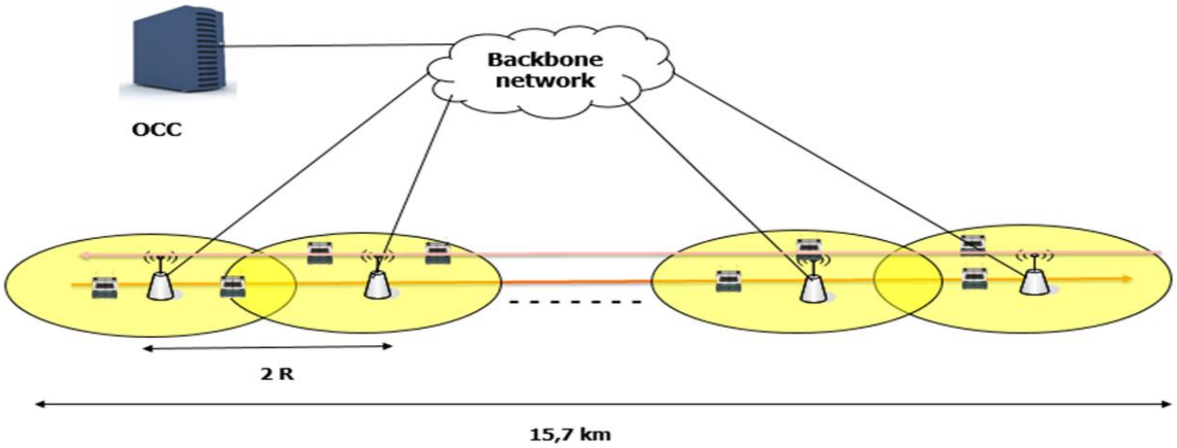
- We assume **there are 2 trains (2 UEs) at cell edge at the same time**
- **Fixing the Cell Edge Throughput (CET)** for a UE, we determine the Modulation and Coding Scheme (MCS) index, which has a corresponding Signal-to-Interference and Noise ratio (SINR) threshold value
- Knowing the SINR threshold and the other link budget terms, we obtain the minimum receiver power P_{min} and the **cell size**, R.
- The number of cells for tram line T1 is obtained dividing the line length by $2R$ ("**linear cell deployment**")

P_{tx} of the eNB [dBm]	R [km]	N_{eNB}
18	0.31	26
20	0.35	22
22	0.41	20
24	0.47	17
26	0.54	15

Scenario 2: Mobility for trains

Normal operation conditions

- Evaluation of the performance when trains are moving along the line thus having **handovers among adjacent eNBs (X2-handovers)** varying:
  - Number of eNBs
  - Number of trains along the line
  - Traffic loads



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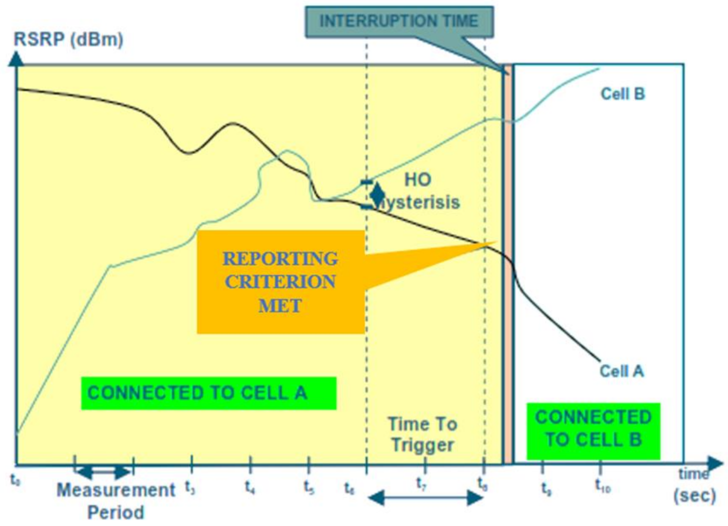
LTE X2 – handover scheme

Strongest cell handover algorithm

- To trigger a handover procedure, the following two conditions must be satisfied depending on the received signal power level (RSRP) from the eNB
  - $RSRP_{target} > RSRP_{serving} + HOM$
  - $HO\,Trigger_{timer} > TTT$



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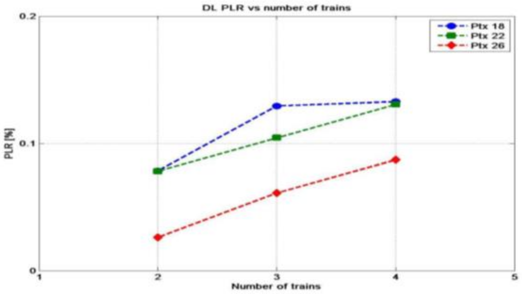
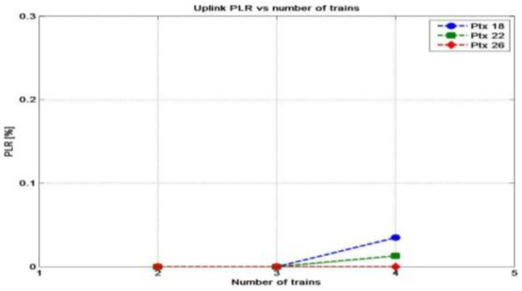
Scenario 2: Handover performance

Results (only signalling traffic case):

- Mean e2e delays are not critical in this simulation scenario
- **PLR increases when trains have mobility**. This increment is mainly due to the **failure of handovers** that the trains trigger when moving across different cells
- PLR increases with the **number of trains**, since more trains trigger handovers at the same time and eNBs do not handle in time the handover procedure
- Downlink PLR is higher than uplink one (congestion at the eNB in managing handovers for many UEs)
- We can conclude that **using higher eNBs transmission powers could improve the PLR performance** with higher transmission costs. However, increasing the eNB transmission power we reduce the number of cells, thus there could be congestion and performance degradation in terms of delay. A trade-off is needed.





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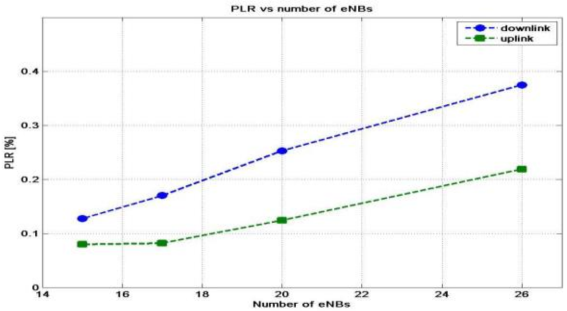
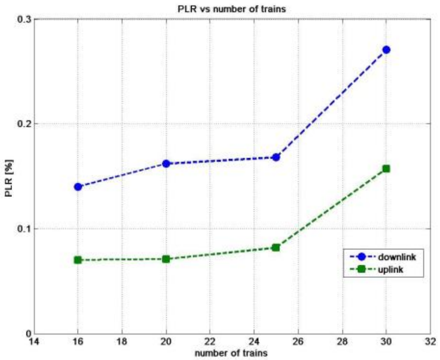
Scenario 2: Impact of number of eNBs and number of trains

Results (only signalling traffic case):

- **The more eNBs are deployed, the higher is the PLR value**
  - Especially for downlink this is due to the more frequent handovers with an increase in PLR
- **The more trains is in the line, the higher the PLR value**
  - This is still due to the more frequent handovers caused by the increment in the number of trains.
  - PLR requirements are met up to 25 trains for uplink and never for downlink





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Scenario 2: Impact of non – critical traffic on signalling (1/2)

Traffic flow configuration

Traffic Flow	UL Video Traffic	DL Video Traffic
Packet size	1000 bytes	500 bytes
Data rate	1 Mbps	500 kbps
Transport layer protocol	UDP	UDP
Application – level traffic model	CBR	CBR
PLR requirement	10^{-3}	10^{-3}
Mean e2e delay requirement	150 ms	150 ms

EPS bearer configuration

Traffic Flow	Signalling Traffic	Video Traffic
Standardized bearer in ns-3	GBR_GAMING	GBR_CONV_VIDEO
QCI	3	2
Priority	3	4
Packet delay budget	50 ms	150 ms
Packet error & loss rate	10^{-3}	10^{-3}
GBR uplink	16 kbps	1 Mbps
GBR downlink	16 kbps	1 Mbps

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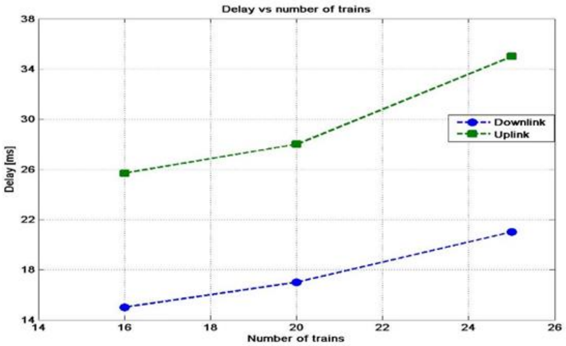
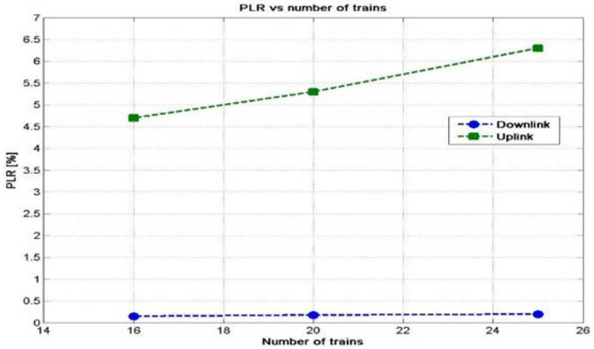
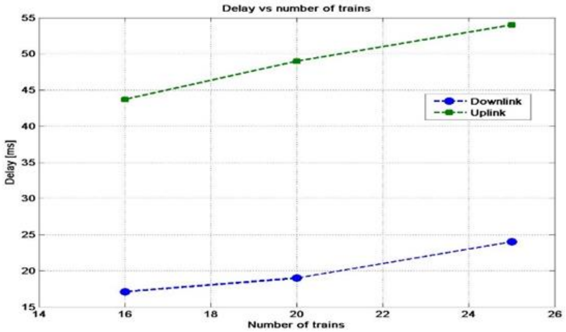
Scenario 2: Impact of non – critical traffic on signalling (2/2)

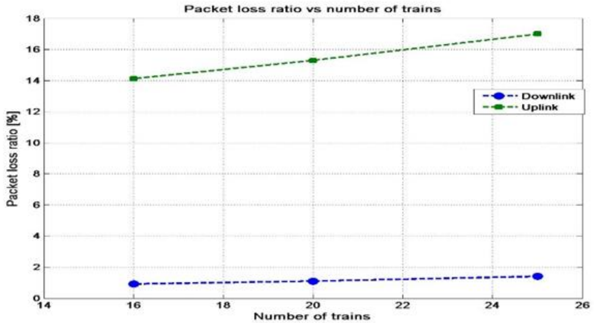
Signalling traffic performance





Video traffic performance





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Conclusions

Results show that:

- Major challenges have been investigated when using an LTE-A network for signalling and other services in urban guided transportation systems
- An ns-3 **simulator** based on LTE MODULE has been built implementing the communications for the railway scenario based on Songjiang T2 LRT line
- We have demonstrated that PLR requirements in stationary conditions are fulfilled independently of the number of trains in the depot, while **PLR performance degrades when mobility is introduced**
- We have evaluated the **impact of non-critical IT traffic** (UDP – based video) on TCP – based signalling
- Safety-critical signalling throughput is not affected by video in stationary scenarios, whereas, in the presence of mobility, handovers degrade the signalling performance that can be guaranteed only if a QoS-aware scheduler is adopted

LTE (in the future LTE-R) technology is a valid candidate for next-generation railway communications

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Next steps

It would be interesting to

- Implement **inter-frequency handover in ns-3** so that a suitable frequency re-use scheme can be adopted in LTE
- Implement **suitable QoS-aware schedulers** for the uplink traffic as those used for downlink traffic in the LTE module
- **Evaluate the performance** when train operators do not have a dedicated LTE network so that LTE resources are shared with commercial LTE traffic.

Thank you

Thank you!

Email: gianluca.mando@thalesgroup.com

Email: giambene@unisi.it

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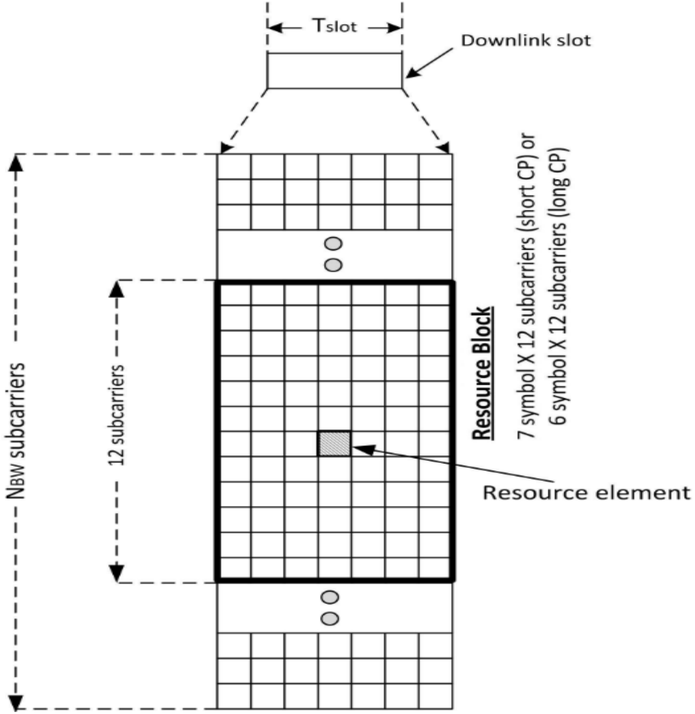
Spare slides

LTE PHY basic characteristic

- **The smallest resource unit for uplink/downlink transmissions is the physical Resource Block (RB)**, which is 180 kHz (= 12 adjacent sub-carriers with spacing of 15 kHz) in the frequency domain and one slot (0.5 ms) in the time domain, corresponding to 6 or 7 OFDM symbols (depending on the cyclic prefix length chosen).



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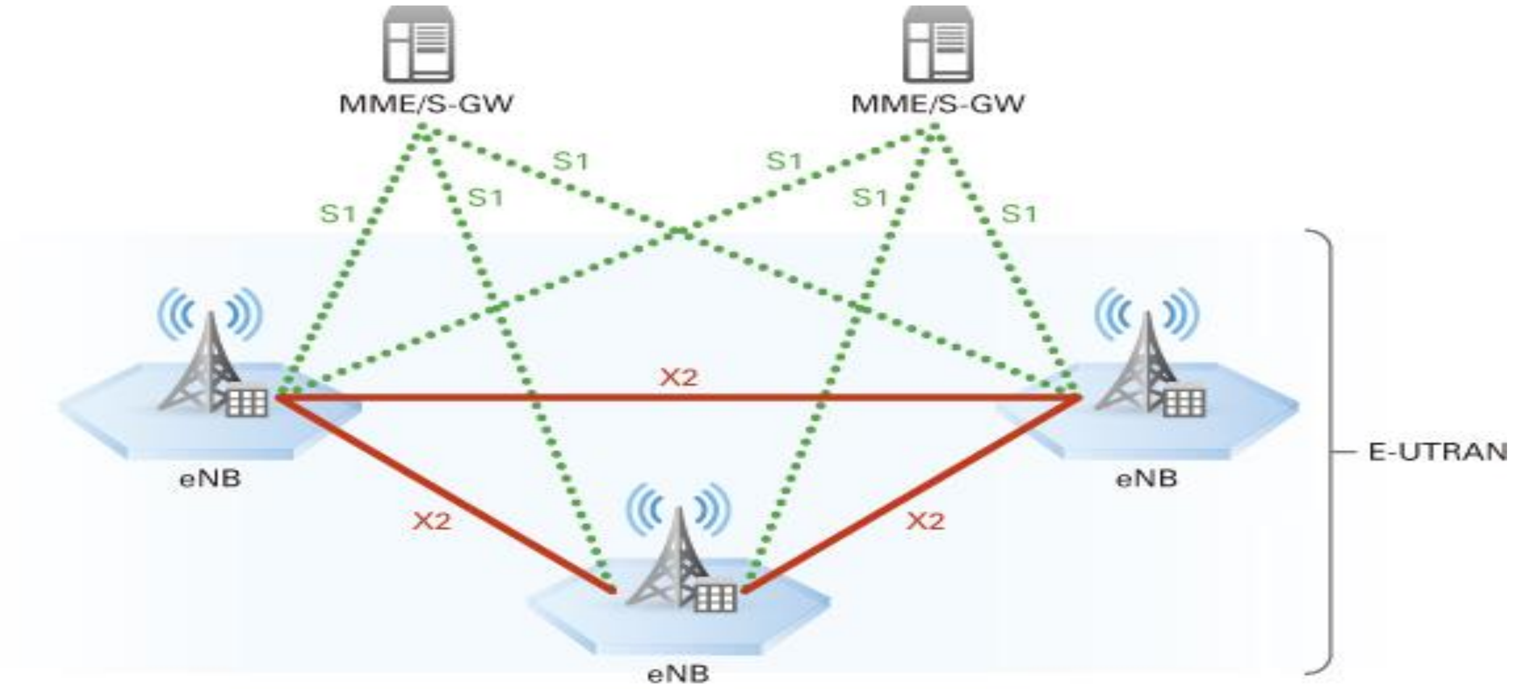
LTE network architecture



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EPS bearers

Guaranteed Bit Rate (GBR)

- Dedicated network resources are permanently allocated (for example, by a CAC function in the eNodeB) when a GBR bearer is established or modified.

Non-Guaranteed Bit Rate (Non-GBR)

- This bearer does not guarantee any particular bit rate. For these bearers, no bandwidth resources are permanently allocated. This bearer can be used for applications such as Web browsing or FTP transfer.