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Evaluation of ETCS performance with LTE as alternative railway communication network using OPNET

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Abstract
GSM-Railways (GSM-R) is a communication mobile network designed to fulfill specific communication needs of railways. GSM-R is being widely deployed across Europe and other countries around the world for providing railway voice and train control services (ETCS). Despite that, GSM-R already shows various shortcomings in terms of capacity and support for additional data services. This triggers the issue whether railways could greatly benefit from an alternative communication technology. One of the possible alternatives is LTE. In our work we analyze delivery of railway services over an LTE network. This work is done using OPNET as simulator for modeling real life railway scenarios and communication infrastructure. These scenarios take advantage of OPNET features allowing modeling an end-to-end LTE network, as well as trains movement over an exemplary real life railway line.

Introduction
Communication technologies have always played a crucial role in the railway system due to its size, long distances, large number of employees and passengers and their constant mobility [1]. For many years communication technologies for railways were proprietary solutions, designed for specific countries or even specific railway companies. Such a situation, where every country operates its own set of communication systems, created a great obstacle for international train operation. Railway international incompatibility is especially problematic in Europe, which consists of many, relatively small countries. In order to make railway competitive against other means of transport, international train interoperation is essential.

This need led to development of the European Rail Traffic Management System (ERTMS), which main purpose is to increase railway interoperability across Europe. ERTMS replaces legacy national railway signaling and communication technologies introducing an integrated, fully-digital wireless train management system [1].

GSM-R, which is part of ERTMS, is the first international mobile communication network dedicated for railways. GSM-R is designed to provide two essential railway services: transmission of the European Train Control System (ETCS) messages and voice communication for railways. The ETCS system provides in-cab signaling and train movement supervision. Thanks to these, ETCS reduces the risk of train driver error [1]. Moreover, it increases track occupancy [1]. Thus, GSM-R, as a basis for ETCS, contributes to the safety and the performance of railways.

In spite of the above, GSM-R shows various shortcomings in terms of capacity and data transmission capabilities. Due to these, GSM-R becomes a bottleneck of railway operation and the element which slows down innovation in railways. That is why there is a need for further research on alternative railway communication technologies.

The technology that should be considered as the most likely alternative to GSM-R is LTE. LTE has various benefits over previous mobile communication technologies – both GSM and the later UMTS. These benefits include improvements such as a more efficient core network, reduced packet delay and a high throughput radio access [2].

The following section of the paper presents details on GSM-R shortcomings and how these can be addressed with LTE. The rest of the paper describes the railway requirements on communication networks and how LTE can be validated as a possible railway communication technology using OPNET.

LTE addressing GSM-R shortcomings
There are three major shortcomings of GSM-R, which are a motivation for research on alternative technologies for railway communication.

The first shortcoming of GSM-R is the low network resource utilization. This is a consequence of the fact that GSM-R offers only circuit-switched based transmission. This is an issue, because one of the main applications of GSM-R is delivery of bursty, low-rate ETCS data messages. Since GSM-R is based on circuit-switched based transmission, ETCS connections continuously occupy network resources even when these are not utilized [1]. In contrast to GSM-R, LTE is based on packet-switched based transmission [2]. Thanks to packet-switched based transmission, network resources can be flexibly shared between ongoing connections. As a result, network utilization in LTE increases, compared to GSM-R.

The second shortcoming is the insufficient capacity of GSM-R networks. Railway operators acknowledged that this is a huge issue at big train stations, depots and shunting yards with high train concentration [3]. In such areas there is a shortage of communication channels what means that GSM-R may not be able to provide connectivity for all of the trains. Hence, GSM-R may become an obstacle for train operation. There are three sources of this problem: an inflexible radio interface, circuit-switched based transmission and limited frequency spectrum assigned to railways [4]. LTE eliminates the first two of the listed problem sources. Apart from the previously mentioned packet-switched based transmission, LTE introduces a high throughput radio interface. This interface includes advanced multiplexing (OFDMA and SC-FDMA), higher modulation (64 QAM) and improved transceiver (MIMO) [2]. As a consequence, LTE offers much higher spectral efficiency, which should solve the capacity issue of GSM-R.

Finally, GSM-R supports only the most basic data services. This is because, GSM-R connections are limited to 9.6 Kbit/s, packet delay over the network is in range of 400 ms and connection setup time is approximately 7 s [1]. Due to these limited connection parameters, it is impossible to offer modern interactive and multimedia data services over GSM-R. LTE offers much higher throughput, low packet delay and faster network procedures. Thanks to these improvements in LTE, railways could introduce a range of new modern data services, which would improve railway operation (e.g. by making it safer with video surveillance) and make it more attractive for the customers (e.g. Internet access and cargo tracking) [5]. This is important if railways are to be competitive with other means of transport.

LTE as alternative railway communication technology

Based on the listed advantages of LTE over GSM-R, a hypothesis has been formulated that LTE can be a valid alternative to GSM-R. This may be an obvious conclusion in the telecommunication industry, but in the railway industry GSM-R is considered as state-of-art, innovative technology, currently being deployed as part of railway infrastructure in a growing number of countries. GSM-R shortcomings are belittled for economic and political reasons. This is why it is important to demonstrate that LTE is technically capable of solving the communication problems existing in GSM-R and that it could enrich railway services.

However, it has to be remembered that LTE is a technology designed for commercial mobile networks. Thus, initially, LTE has not been intended for networks, such as the railway communication network, which main purpose is delivery of safety-critical applications with high Quality-of-Service (QoS) constraints. The most prominent example of such applications is ETCS. As mentioned previously, ETCS provides critical information for the train drivers (about speed limits, movement authority, etc.) and supervises train movements. Thus, ETCS affects not only the customer satisfaction (as it is the case with the applications in commercial networks) but affects directly the people safety.

This is why, in our work, we want to verify that LTE can be an alternative technology for safety-critical railway communication networks. In order to achieve this goal we identified two main elements which need investigation. Firstly, the performance of ETCS signaling delivered over LTE has to be analyzed and confronted with the ETCS requirements. These requirements are introduced in the next section of the paper. Secondly, QoS provisioning mechanisms need to be analyzed in order to ensure that LTE networks can simultaneously provide applications with different QoS requirements (e.g. safety-critical and best-effort).

ETCS requirements

The International Union of Railways (UIC) defined requirements on communication networks for ETCS signaling [1]. However, these requirements were developed with focus on GSM-R. Therefore these concern only circuit-switched based networks. That is why, there is a need to redefine the ETCS requirements for packet-switched case. This redefinition is not finalized by UIC, but the Danish Signaling Program published tentative requirements, which concern parameters such as [4]:

- Received signal power.
- End-to-end data transfer delays.
- End-to-end data integrity: probabilities of packet loss, duplication, out-of-sequence delivery and corruption.
- Network attach procedure delay.
- Packet Data Protocol (PDP) context activation delay.

Factors affecting ETCS transmission

The performance of ETCS signaling over an LTE network is affected by various factors, which should be analyzed:

- Train speed – the higher the train speed, the higher the frequency of handover between base stations. Every handover operation introduces some disturbance in the communication, which results in higher delay and higher probability of packet loss. Moreover, the higher the train speed, the lower the radio signal quality, due to frequency error (Doppler effect) and less precise channel estimation.

- eNodeB density & eNodeB transmission power – the higher the eNodeB density (number of eNodeBs deployed along the railway line), the lower transmission power is required to provide sufficient network coverage. On the other hand the higher the eNodeB density, the more handovers have to be performed.

- Traffic load – traffic load in a railway LTE network is increasing with the number of users (trains). In turn, this results in increasing the ETCS message delay, due to queuing mechanisms.

- QoS mechanisms – in case of a network with heterogeneous traffic (safety-critical, priority and other applications) packet admission and prioritization mechanisms are essential. These mechanisms directly affect transmission performance.

How these factors affect fulfillment of the ETCS requirements has to be answered.

OPNET simulation-based approach

A simulation-based approach has been chosen to answer the challenge of analyzing ETCS performance and QoS mechanisms in LTE railway networks. An alternative would be to perform measurements on a trial LTE network deployed along a railway line. However, this is unrealistic due to the costs, time and the lack of available radio spectrum in which these tests could be performed. Moreover, measurements do not provide the flexibility of simulations, which allow validation of various topologies and architectures.

From the range of available network simulation tools it has been decided to use OPNET Modeler. There are multiple reasons for that:

- OPNET offers the possibility of simulating a full end-to-end LTE network. In OPNET Modeler, there are built-in models of eNodeB, Evolved Packet Core (EPC) node, External Application Servers and various User Equipment (UE). These models include the full protocol stack from the physical layer up to the application layer as shown in Figure 1.

  Analyzing ETCS performance it is important to focus on end-to-end statistics, in the same way as the requirements are defined for an end-to-end transmission. In case of ETCS, end-to-end means between the ETCS On-Board Unit (OBU) and the Radio Block Controller (RBC). OBU is the ETCS element within the train, while RBC is an ETCS server supervising train movements in a given area. Hence, it is important that the simulation models not only the wireless link, but the whole network with all the intermediate nodes as well as the whole protocol stack. Only such simulation model can produce realistic results which can be compared with the ETCS requirements to fulfill.

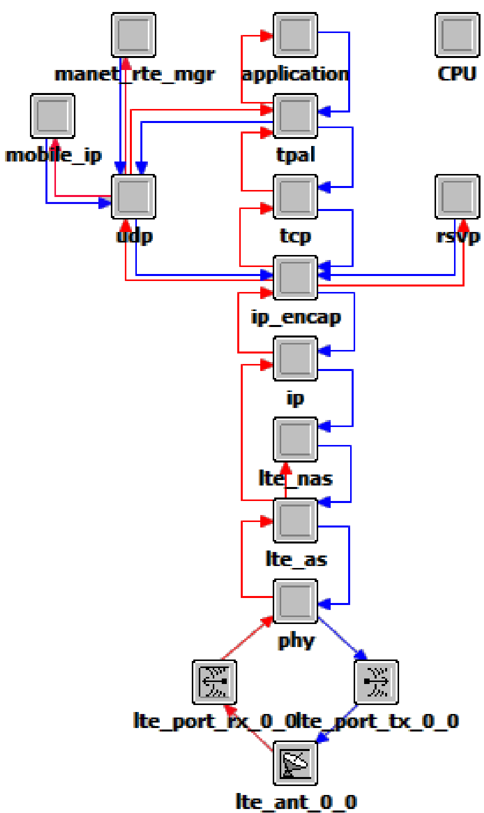
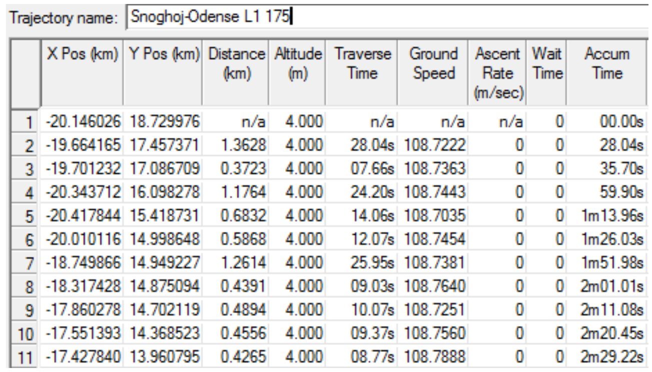


Figure 1. LTE UE node model.

- OPNET Modeler includes the feature of node movement modeling. In order to model a realistic railway scenario, wireless node movement is essential. In OPNET Modeler it is possible to precisely define the trajectory of each node as shown in Figure 2. This feature is used to model trains movements along the railway tracks.



Trajectory name: Snoghoj-Odense L1 175

	X Pos (km)	Y Pos (km)	Distance (km)	Altitude (m)	Traverse Time	Ground Speed	Ascent Rate (m/sec)	Wait Time	Accum Time
1	-20.146026	18.729976	n/a	4.000	n/a	n/a	n/a	0	00.00s
2	-19.664165	17.457371	1.3628	4.000	28.04s	108.7222	0	0	28.04s
3	-19.701232	17.086709	0.3723	4.000	07.66s	108.7363	0	0	35.70s
4	-20.343712	16.098278	1.1764	4.000	24.20s	108.7443	0	0	59.90s
5	-20.417844	15.418731	0.6832	4.000	14.06s	108.7035	0	0	1m13.96s
6	-20.010116	14.998648	0.5868	4.000	12.07s	108.7454	0	0	1m26.03s
7	-18.749866	14.949227	1.2614	4.000	25.95s	108.7381	0	0	1m51.98s
8	-18.317428	14.875094	0.4391	4.000	09.03s	108.7640	0	0	2m01.01s
9	-17.860278	14.702119	0.4894	4.000	10.07s	108.7251	0	0	2m11.08s
10	-17.551393	14.368523	0.4556	4.000	09.37s	108.7560	0	0	2m20.45s
11	-17.427840	13.960795	0.4265	4.000	08.77s	108.7888	0	0	2m29.22s

Figure 2. Exemplary node trajectory.

- Additionally to the node-movement feature, OPNET Modeler provides a dynamic model of the LTE physical layer, which takes into account instantaneous node locations and estimates radio signal properties. Moreover, the model includes Link Rate Adaptation which based on the estimated link conditions choses the appropriate Modulation and Coding Scheme (MCS).

- What is more, OPNET Modeler's LTE implementation models EPS Mobility Management (EMM), which includes network attach and registration, cell search, cell reselection and advanced handover procedures.

- OPNET Modeler provides a set of application models, which can be used to generate traffic that represents the currently existing and the possible future railway applications. Examples of these are ETCS signaling and video surveillance.

- Finally, OPNET Modeler provides eNodeB Failure and Recovery Support which allows forcing eNodeB to fail at a chosen simulation time. This feature is essential in analysis of resilience mechanisms.

Simulation scenarios

In order to investigate ETCS performance under different conditions (train speed, traffic load, etc.) we propose two OPNET simulation setups:

- The first one is the open railway line simulation setup, which is shown in Figure 3. This setup is supposed to be used for investigation of the effects of train speed and eNodeB density on ETCS signaling performance. This is why this setup models an open railway line (a line between the stations) where trains can reach high speeds. Moreover, the modeled line should be long in order to make it suitable for deployment of many eNodeBs. This is important for investigation of the handover effects.

  Taking into account these needs, the Snoghøj-Odense railway line has been chosen as source of data for this

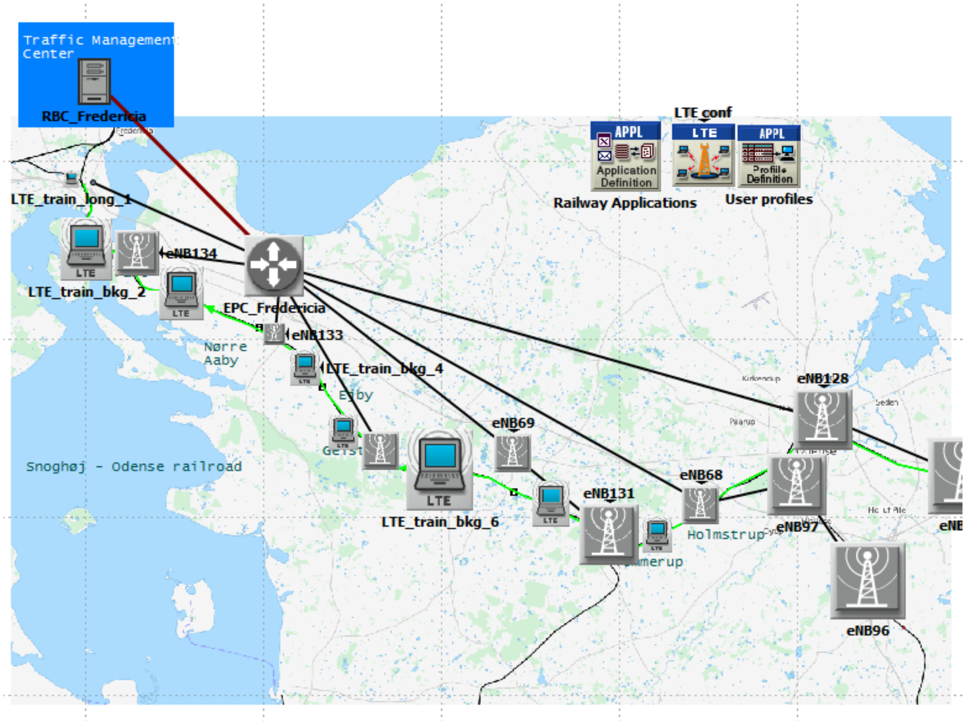


Figure 3. Open line scenario.

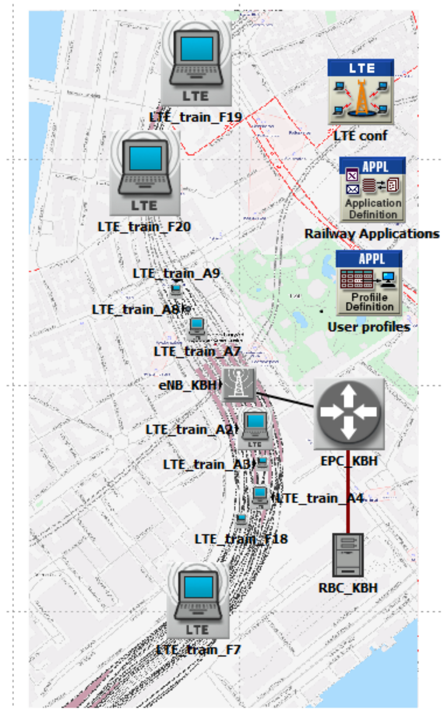


Figure 4. Station scenario.

simulation setup. It is one of the most important lines in Denmark, because it is the only line connecting the West and the East parts of the country. Currently it is the line with the highest allowed driving speed in Denmark that is 180 km/h. The line is 55 km long which means that at least 10-15 eNodeBs are required to provide coverage over the whole line (in practice even more eNodeBs may be required).

- The second simulation setup, which is shown in Figure 4, models a train station scenario. This setup is supposed to be used for analysis of the traffic load effects and QoS mechanisms. In this case, it has been chosen to model a train station with shunting and depot areas, because these are the places where the train concentration (user concentration) is the highest. It means that here the traffic generated by the trains will be the biggest. Moreover, more applications types are used at the train station, e.g. shunting specific applications, which are not used on the open line.

  It has been chosen to base this simulation setup on Copenhagen Main Station. This is because it is the biggest train station in Denmark with the highest number of arrivals and departures per hour. Moreover, it is the location which cannot be easily covered with a GSM-R network due to the mentioned capacity limitations of GSM-R. Thus, it is a good location to demonstrate the advantages of LTE.

The two OPNET simulation setups are used as frameworks in our current work. The setups can be modified and adapted to various simulation scenarios that help to answer the previously listed research goals.

Current results

Based on the first scenario, the Snoghøj-Odense line, we have already reported in [6], that the modeled LTE network provides OBU-RBC connectivity that fulfills ETCS requirements on message delay and data integrity. In that paper we concentrated on impact of train speed on ETCS transmission. Our results showed that the higher the train speed, the longer the message delay is and the more packets are being lost or corrupted. Nevertheless, the ETCS requirements are still fulfilled at any investigated speed in the range from 25 km/h to 500 km/h and with different scenarios from 1 to 15 running trains.

Besides, we have analyzed in [7] the relation between the number of eNodeBs, the impact on ETCS and the relation with the power consumption. The results show that the increasing eNodeB density reduces the transmission power, but also negatively impacts the transfer delay and data integrity of ETCS messages. This comes as an effect of such elements as:

- The increased frequency of the handovers, during which packet transmission is disturbed.
- The increased signaling overhead due to the handover procedures.
- The increased probability of packet/acknowledgement loss during a handover.
- The growing interference from the neighboring LTE cells.

This can be a valuable analysis for infrastructure manager and operators in the pre-deployment analysis phase. The collected results allow finding the optimum number of eNodeBs for a particular railway line.

Future work: heterogeneous access networks

Performance, efficiency and resilience are the key requirements for railway communication networks. In order to address these challenges we would like to propose an innovative approach to the railway radio access architecture. The idea is to introduce a two level heterogeneous radio access network, where railway lines are simultaneously covered by a macro radio cell and a number of micro radio cells.

This heterogeneous architecture should bring various benefits. Firstly, it should improve transmission performance. This is because trains would choose between macro or micro cells depending on its driving speed. In case of fast driving trains which would be connected through the macro cell, the number of handovers is reduced. In turn, this improves the transmission performance as the handovers contribute to the delay and increasing transmission disruptions (packet loss, corruption, etc.). On the other hand, the stationary trains would be connected through the micro cells. These cells could operate in new high frequency band increasing the capacity of the overall system. Thus, this architecture would address the problem of limited railway radio spectrum in the low frequency band. Furthermore, the introduction of a two-level radio access network is also beneficial from the point of view of network resilience. The second radio access network could protect against interference and node or link failures in the access network.

OPNET Modeler has been chosen as the tool for analysis of the heterogeneous access network architecture. This is because it allows modeling and easy comparing between various deployment strategies.

Future work: voice communication for railways

The next step in verification of LTE as an alternative to GSM-R networks is analysis of voice communication in LTE. Despite the rapidly growing importance of data services, a lot of railway procedures are still dependent on voice communication. Furthermore, some voice services, such as Railway Emergency Call, are also important elements contributing to the railway safety.

It has to be noted that LTE dramatically changes voice communication in mobile networks. It is the first network that abandons circuit-switched backbone, which, mostly unchanged since the initial GSM standard, has been used for providing voice calls in all previous network technologies (GSM and UMTS standard families). Hence, in LTE a new voice communication system has to be introduced. Most probably, the majority of the mobile operators will decide to support Voice over LTE (VoLTE) standard which depends on IP Multimedia Subsystem (IMS) for providing voice call signaling.

From the railway point of view, it is important to verify VoLTE in terms of providing advanced railway voice services. GSM-R offers several railway-specific features such as location dependent addressing, functional addressing and call prioritization. Thus, whether VoLTE can provide these railway features and that it can do that fulfilling time requirements (e.g. setup call delay) needs to be proven. For this purpose we intend to build an OPNET model of IMS, which will be used to verify VoLTE architecture in respect to the railway requirements.

Conclusions

This paper presented communication challenges faced by the railways in Europe and other countries adopting ERTMS. The communication subsystem of ERTMS – GSM-R is inefficient and limited in terms of capacity and data transmission. This is why railways need to introduce modern communication technology such as LTE.

In our work we analyze whether LTE is capable of becoming a railway communication network fulfilling the specific railway requirements. This work is mainly done using OPNET Modeler. This is because OPNET Modeler offers a capable simulation environment with a range of features that allow building realistic railway communication scenarios. Mainly, OPNET allows modeling an end-to-end LTE network with the entire protocol stack and the most important LTE mechanisms. Moreover, node mobility plays a crucial role in railway modeling and it is a feature well implemented in OPNET Modeler.

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http://www.dtu.dk/subsites/robustrails/English.aspx

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