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# Performance of LTE in High Speed Railway Scenarios

## Impact on Transfer Delay and Integrity of ETCS Messages

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**Abstract.** GSM-Railways (GSM-R) is an obsolete mobile technology with a number of shortcomings in terms of capacity and capability. These shortcomings become a major issue for railways as GSM-R may limit the number of running trains in some areas and it cannot support advanced data services. Hence, alternative technologies, such as LTE, have to be considered as a future railway communication technology.

This paper presents an analysis of transfer delay and data integrity of European Train Control System (ETCS) messages transmitted over LTE network. The analysis is made using OPNET models of a high speed railway line and LTE systems.

**Keywords:** GSM-R, ETCS, LTE, railway signaling.

## 1 Introduction

Communication networks are inevitable elements of modern railways. This is because communication networks are fundamental for vital railway services such as train command-control systems and railway emergency call. These services greatly improve railway safety and efficiency (e.g. by ensuring that trains always obey signals and by providing more detailed information to train drivers, what allows reaching higher speeds and maximize track occupancy) [1].

GSM-R is one of the most important communication networks for railways due to its growing popularity across Europe and other places around the world, where it substitutes legacy national railway communication technologies [1][2]. Despite that, GSM-R has some major shortcomings in terms of capacity and capability, which are directly inherited from the commercial GSM. Hence, the question arises if railways could replace GSM-R with a more modern mobile technology, such as LTE.

The next two sections present an overview of the shortcomings of GSM-R and benefits of LTE that could be advantageous in a railway environment. In the following part of the paper, an LTE network is analyzed on an example of one of the main Danish railway lines (Snoghøj-Odense). Using OPNET Modeler, a set of simulation scenarios is investigated, where ETCS railway signaling on the line is delivered over

an LTE network. Simulation results are compared with ETCS requirements concerning data transfer delay and data integrity [3].

## 2 Shortcomings of GSM-R

The first major issue of GSM-R is that it offers only circuit-switched transmission. This mode of transmission is less efficient than packet-switched. Especially when considering that one of the main applications of GSM-R is delivery of bursty, low-rate ETCS data messages. The lack of packet-switched transmission leads to very low utilization of the GSM-R network [1].

Another major problem with GSM-R is its insufficient capacity, i.e. a small number of channels available for user transmission. This is a consequence of the combined effect of the circuit switched transmission paradigm and the reduced band of radio spectrum assigned. In areas with high train concentration such as central train stations there are problems with providing sufficient number of channels to serve all the trains that are to operate there simultaneously [4]. Railway companies try to overcome this problem by implementing special operational rules, such as those proposed by Banedanmark – the manager of the Danish national rail network [3], e.g.:

- train drivers are required to turn off GSM-R radio while they are at a longer stop.
- train traffic supervisors need to constantly control the number of trains in a given GSM-R cell and ensure that there are free channels available for incoming trains.

Such solutions are impractical, prone to error and they cannot solve the capacity problem entirely. This means that the capacity of the GSM-R network becomes a bottleneck limiting the number of trains to be operated in a given area. Desirably, the only limitation should be related to the capacity of the railway infrastructure.

Finally, the last shortcoming of GSM-R is its very limited support for data communication. The maximum transmission rate per connection is limited to just 9.6 Kbit/s [1], what is sufficient only for applications with very low demands. Apart from that, message delay is in the range of 400 ms [1], what is too high to allow any interactive real-time application. Lastly, long connection setup time, which is in the range of 7 seconds [1], heavily impacts applications that require rapid setup, e.g. applications for emergency situations.

These shortcomings (the lack of packet-switched transmission, limited capacity and limited support for data communication) show how outdated GSM-R technology is from a telecommunication point of view. This is especially apparent if GSM-R is compared with commercial mobile networks, which already underwent few major evolutions from the original GSM technology. The most significant standards released in Europe, after GSM were GPRS, UMTS and LTE. These new standards brought various improvements in the capabilities of the mobile networks [5]. Railways could benefit from these modern technologies. It is especially important considering that some commercial mobile operators already consider shutting down their GSM networks, so GSM is a technology becoming quickly obsolete. In the beginning of 1990's it was decided to build the railway communication technology on the basis of

an already available, well-established mobile communication standard [1]. That is one of the main reasons why GSM was chosen for railways. Hence, now when GSM is being slowly abandoned by commercial operators, one of the main reasons for adopting GSM-R by railways becomes invalid.

The technology that should be considered as the most likely alternative to GSM-R is LTE. This is because it brings number of benefits over previous mobile communication technologies – both GSM and the later UMTS. These benefits concern such improvements as a more efficient core network, reduced packet delay and a high throughput radio access [5]. Details of these improvements are described in the following section. Apart from the technical benefits, LTE is the most modern mobile communication standard that is being deployed commercially around the world. That is advantageous in terms of economy, because of the reduced obsolescence span.

### 3 Benefits of LTE

There are over 20 years of development separating GSM and LTE technologies, what makes them very different in many aspects. However, here, the focus is put on a few main advantages of LTE that could be highly beneficial from the railway perspective.

The key element differentiating LTE from GSM-R is that an LTE network is based on packet-switched transmission. It is the first mobile technology adopting the all-IP approach abandoning circuit-switched transmission. Packet switched transmission is more flexible in managing available network resources. Thanks to this, it increases network utilization and reduces waste of limited network resources. Despite the lack of circuit-switched mode, LTE includes Quality-of-Service mechanisms that provide packet differentiation. This could be applied to protect railway safety-critical applications such as ETCS [5].

Another advantage of LTE network is the reduced packet delay, which is one of the crucial requirements for providing ETCS messages. This is achieved by simplifying the network architecture. The LTE network has less logical and physical elements and they are all based on a common technology (IP).

Finally, LTE offers much higher throughput over its radio access thanks to a more advanced radio interface. It consists of a number of improvements that increase spectral efficiency of LTE in comparison to older technologies (GSM and UMTS):

- Advanced multiplexing – Orthogonal Frequency Division Multiplexing (OFDM).
- More advanced modulation – up to 64 Quadrature Amplitude Modulation (QAM).
- Sophisticated transceiver – Multiple Input Multiple Output (MIMO) technology.

The additional throughput can be consumed in various ways: to serve more users, to provide more applications or to provide bandwidth-demanding applications, which cannot be provided over the low-rate GSM-R radio interface.

Summing up, LTE brings important improvements over GSM-R. But the question that needs to be answered is whether it can also fulfill all the railways requirements in terms of performance and reliability, in order to become a viable alternative to GSM-R.

## 4 LTE as a Railway Communication Technology

The general question of whether LTE can be a railway communication technology has been divided into three smaller questions:

### 4.1 Can LTE Support Safety-Critical Railway Applications, Such as ETCS?

GSM-R was designed to provide two fundamental services: transmission of The European Train Control System (ETCS) messages and voice communication for railways. ETCS is a digital wireless railway signaling system that replaces legacy national signaling systems used around Europe. Its main goal is to provide safe and efficient command-control system that ensures international interoperability. ETCS becomes widely adopted across Europe thanks to its technical benefits, but also due to the European Union directives, which oblige railways to adopt it.

Thus, any railway communication technology that could be considered an alternative to GSM-R needs to support ETCS, i.e. it needs to fulfill all the transmission requirements for reliable and timely delivery of ETCS messages. These requirements concern parameters such as [6]:

- Received signal power.
- End-to-end delay.
- Data rates.
- Probability of connection loss.
- Maximum break during handover.
- Bit error rate.
- Connection establishment delay.
- Connection establishment failure probability.

The requirements listed above concern circuit-switched transmission of ETCS messages. Thus, for LTE based ETCS transmission, there is a need to redefine these requirements to packet-switched transmission. This redefinition has not been finalized by the International Union of Railways (UIC). However, the Danish Signaling Program defined tentative requirements for packet-switched transmission of ETCS messages which are published in [3]. These requirements concern parameters such as:

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

## **4.2 Can LTE Support All the Advanced Voice Functionality Provided by GSM-R?**

Voice communication is still a very important service for railways. Railway communication technology needs not only to provide point-to-point calls as commercial mobile telephony does, but also to provide railway-specific features such as group calls, broadcast calls, call prioritization and advanced addressing based on location or function (e.g. calling a train dispatcher responsible for a given area). The main problem here is the lack of a single widely accepted technical solution for providing voice communication over LTE [7].

## **4.3 Can LTE Bring Real Improvements for Railways in Terms of Capacity and Supported Applications While Still Fulfilling the Requirements of ETCS?**

It should be verified whether the benefits of LTE listed in the previous section bring an actual improvement for railways and whether QoS mechanisms are efficient enough to use LTE for combining safety and non-safety applications.

# **5 OPNET Simulations**

Since we have already gathered and analyzed sufficient data, we focus this paper on answering the first of the previously presented questions: whether LTE can fulfill packet-switched requirements on the delivery of ETCS messages [3]. We will focus on the other questions in following papers.

There are two factors that could limit performance of an LTE network in a railway environment: train speed (User Equipment speed) and LTE network load. In the following part of the paper the first of the two limiting factors is analyzed, i.e. relation between train speed and performance of LTE network.

The proposed simulation scenarios model a high-speed railway line, where it is required to provide continuous, reliable connectivity between train On-Board Unit (OBU) and Radio Block Controller (RBC) - ETCS server supervising train movement. In such scenario, performance of LTE transmission may be limited by the train speed. Thus, the purpose of these simulations is to verify whether LTE can fulfill the ETCS requirements at high train speeds.

The modeled scenarios are based on a railway line between Snoghøj and Odense (Denmark). An overview of the line is shown in Figure 1. It is one of the most important railway lines in Denmark for both national and international traffic. Currently, the line is operated at speeds up to 180 km/h [8]. In the future, the line may be upgraded to allow higher travel speeds up to 200 km/h or more [9]. However, speeds up to 500 km/h are considered in the simulations as this is the top speed that needs to be supported according to requirements for GSM-R [6].



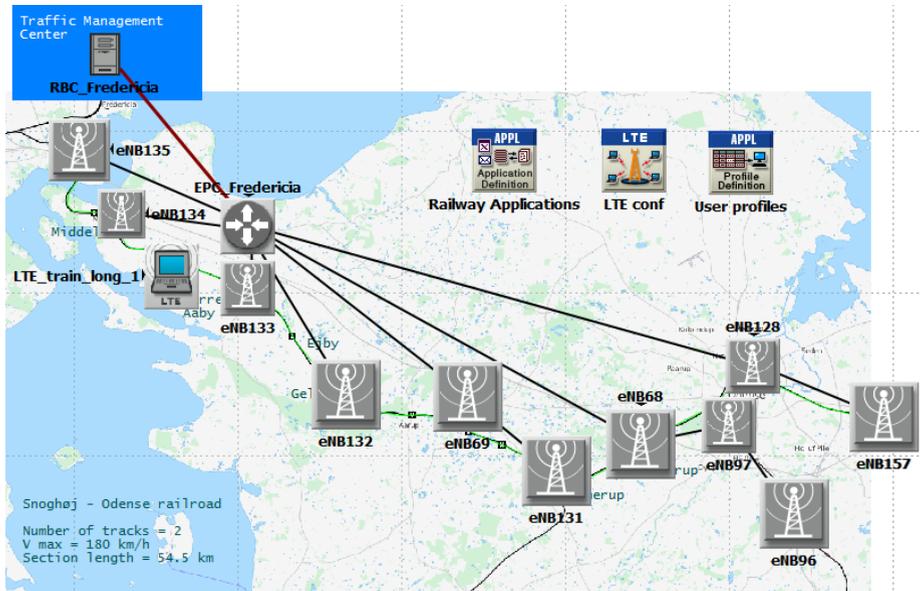
**Fig. 1.** Snoghøj-Odense railway line with the location of intermediate train stations  
Map source: [10]

Snoghøj-Odense is a double-track line with length of 54.5 km. In order to provide LTE coverage over the whole line it is required to set up multiple eNodeBs. This means that trains need to perform multiple handovers between LTE cells while travelling over the line. In the OPNET simulation 11 eNodeBs are placed. Their location follows the proposed location of 11 real GSM-R BTSs, which are planned to be deployed along the Snoghøj-Odense line by Banedanmark [11]. Each eNodeB has three LTE sector antennas operating in a 5 MHz bandwidth. LTE supports 1.4MHz, 3MHz, 5MHz, 10MHz, 15MHz and 20MHz bandwidths [5]. The 5 MHz bandwidth has been chosen as it is the closest to the size of GSM-R bandwidths in Europe, where GSM-R operates in 4 or 7 MHz bandwidths [1].

The eNodeBs are connected to Evolved Packet Core (EPC), which, in the OPNET model, simulates the LTE network backbone and includes functionality of a number of separate nodes from the LTE standards: Mobility Management Entity (MME), Home Subscriber Server (HSS), Serving Gateway (GW), and Packet Data Network Gateway (PDN GW). EPC provides connectivity with the Radio Block Controller (RBC). This network topology is shown in Figure 2.

There are up to 15 trains passing through the line in the peak hour [8]. Assuming that all of them are equipped with ETCS On Board Units (OBUs) then each train is a mobile terminal, which uses the LTE network to communicate with the RBC.

Every OBU sends an ETCS message to the RBC at time intervals following exponential distribution with a mean value of 30 seconds. Also the RBC sends an ETCS message to each of the OBUs at time intervals following an exponential distribution with a mean value of 30 seconds. These time values are based on the assumption that a movement authority and a position update messages are transferred every single minute. In our model, ETCS messages have constant size of 128 bytes according to the size specified in the ETCS requirements [3].



**Fig. 2.** Topology of the LTE network along the Snoghøj-Odense railway line

Two scenarios are considered:

**Scenario 1.** There is a single train travelling back and forth on the line. The purpose of this scenario is to measure performance of delivery of ETCS messages in terms of delay and data integrity in an unloaded network.

**Scenario 2.** Additional trains are introduced simulating train traffic in the peak hour. There are 15 trains travelling over the line per hour (total for both directions). The purpose of this scenario is to investigate how 14 additional trains affect transmission of ETCS messages by the initial single train.

Each of the two scenarios contains 13 subcases with train speeds between 25 km/h and 500 km/h. Each case was executed 20 times with varying seed numbers. The length of each simulation run was 4 hours.

## 6 Simulation Results

Two sets of simulation results are analyzed for each of the scenarios: one concerning the transfer delay of ETCS messages, while another concerning integrity of the delivered ETCS messages.

### 6.1 Transfer Delay Analysis Results

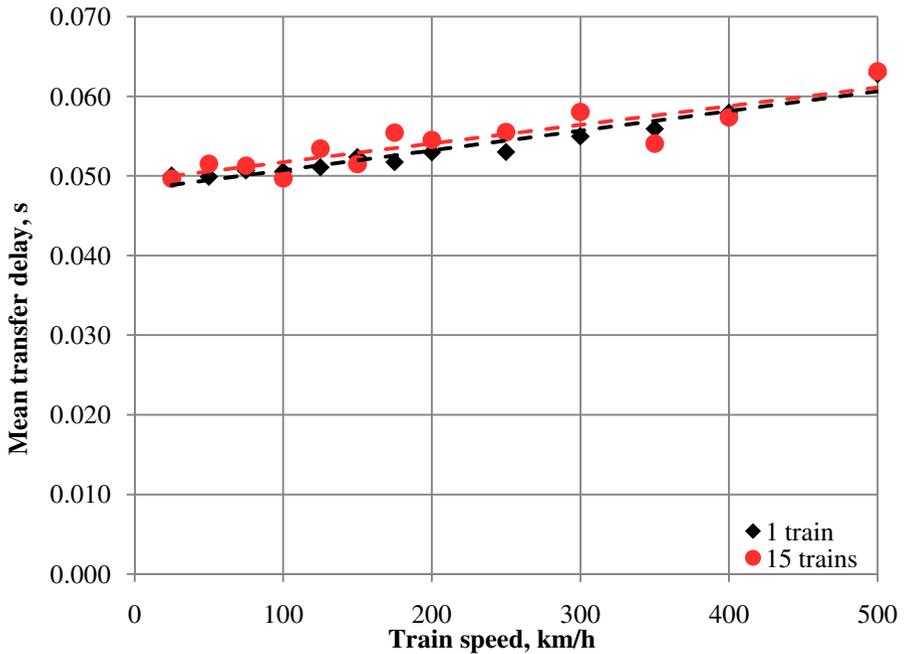
According to the requirements presented in [3] the mean transfer delay of 128 byte ETCS message is required to be lower than 0.5 s. Moreover, 95% of ETCS messages have to be delivered within 1.5 s.

Simulation results concerning ETCS message delays are presented in Table 1. All of the recorded values fulfill these transfer delay requirements:

- Mean transfer delay is in the range of 0.05 – 0.07 s
- 100 % of messages is delivered within 1.5 s

**Table 1.** Transfer delay of ETCS messages delivered over LTE network

Train Speed [km/h]	Single train scenario		15 train scenario	
	Mean transfer delay [s]	Messages delivered within 1.5 s [%]	Mean transfer delay [s]	Messages delivered within 1.5 s [%]
25	0.050	100 %	0.050	100 %
50	0.050	100 %	0.052	100 %
75	0.051	100 %	0.051	100 %
100	0.051	100 %	0.050	100 %
125	0.051	100 %	0.053	100 %
150	0.052	100 %	0.051	100 %
175	0.052	100 %	0.055	100 %
200	0.053	100 %	0.055	100 %
250	0.053	100 %	0.056	100 %
300	0.055	100 %	0.058	100 %
350	0.056	100 %	0.054	100 %
400	0.058	100 %	0.057	100 %
500	0.063	100 %	0.063	100 %



**Fig. 3.** Mean transfer delay of ETCS messages in relation to train speed

Furthermore, as it can be seen in Figure 3, the mean delay of ETCS messages slightly increases with the train speed. However, as the delay increase is not significant, the ETCS requirements are fulfilled even at high train speeds.

Lastly, results obtained in both scenarios (single train and 15 trains) are comparable. This means that the modeled LTE network provides sufficient resources to support ETCS signaling over the Snoghøj-Odense line, with its maximum frequency of 15 trains per hour.

## 6.2 Data Integrity Analysis Results

Another set of simulation results concerns data integrity. There are four requirements on the ETCS message delivery in this regard [3]:

- Probability of data loss  $< 10^{-4}$
- Probability of data duplication  $< 10^{-5}$
- Probability of data being out-of-sequence  $< 10^{-5}$
- Probability of data corruption  $< 10^{-6}$

It has to be noted that an LTE network provides retransmission mechanisms over the radio link (at the MAC layer and the RLC layer) [5]. Moreover, the data is protected by retransmission mechanisms at the end-to-end transport protocol (the TCP layer). Thus, the successful delivery of messages (lack of data loss, duplication, out-of-sequence delivery or corruption) can be measured both at the radio link and at the end-to-end connection as shown in Table 2.

**Table 2.** Data integrity of ETCS messages delivered over LTE network

Train Speed [km/h]	Ratio: delivered error-free packets / sent packets:			
	Single train scenario		15 train scenario	
	<i>LTE radio link (RLC layer) [%]</i>	<i>End-to-end connection (TCP layer) [%]</i>	<i>LTE radio link (RLC layer) [%]</i>	<i>End-to-end connection (TCP layer) [%]</i>
25	99.9995 %	99.974 %	99.9993 %	99.958 %
50	99.9990 %	99.985 %	99.9986 %	99.896 %
75	99.9994 %	99.953 %	99.9984 %	99.958 %
100	99.9992 %	99.969 %	99.9993 %	99.958 %
125	99.9993 %	99.948 %	99.9982 %	99.844 %
150	99.9989 %	99.908 %	99.9989 %	99.898 %
175	99.9990 %	99.907 %	99.9986 %	99.773 %
200	99.9990 %	99.886 %	99.9980 %	99.792 %
250	99.9991 %	99.881 %	99.9983 %	99.779 %
300	99.9988 %	99.828 %	99.9977%	99.702 %
350	99.9986 %	99.783 %	99.9982 %	99.801 %
400	99.9980 %	99.679 %	99.9976 %	99.734 %
500	99.9971 %	99.567 %	99.9952 %	99.564 %

As it can be seen in the “LTE radio link” column in Table 2, over 99.99% of packets are delivered successfully over the LTE radio link and these do not require retransmission. The remaining packets are retransmitted by the RLC layer which works in the acknowledged mode, what means that the Automatic Retransmission Request (ARQ) feature is enabled [5]. Looking at the results concerning the end-to-end connection, also shown in Table 2, it can be seen that over 99.5% of packets are delivered successfully without the need for retransmission. The remaining 0.5% of packets are retransmitted by the mechanisms of the TCP layer. It should be noted that the retransmission mechanisms at the RLC and the TCP layers are not correlated. Thus, an erroneous packet can be retransmitted by the TCP layer while its retransmission could have been already requested by the RLC layer.

Thanks to the combined multilayer error detection and correction mechanisms, 100% of the ETCS messages are delivered correctly to the ETCS application layer, what fulfills the data integrity requirements.

Figures 4 and 5 show the percentage of successful (error-free) packet transmissions in relation to train speed over the radio link and over the end-to-end connection, respectively. As it can be seen in the figures, with increasing train speeds the success rate of the transmission is decreasing. However, in all the cases, regardless of the train speed, the network was able to timely recover. This was shown in the transfer delay analysis where no packets were delayed more than 1.5 s.

Finally, as in the case of transfer delay, the results obtained in both scenarios (single train and 15 trains) are comparable. Thus, the network had no problem to serve ETCS traffic generated by the trains on the line.

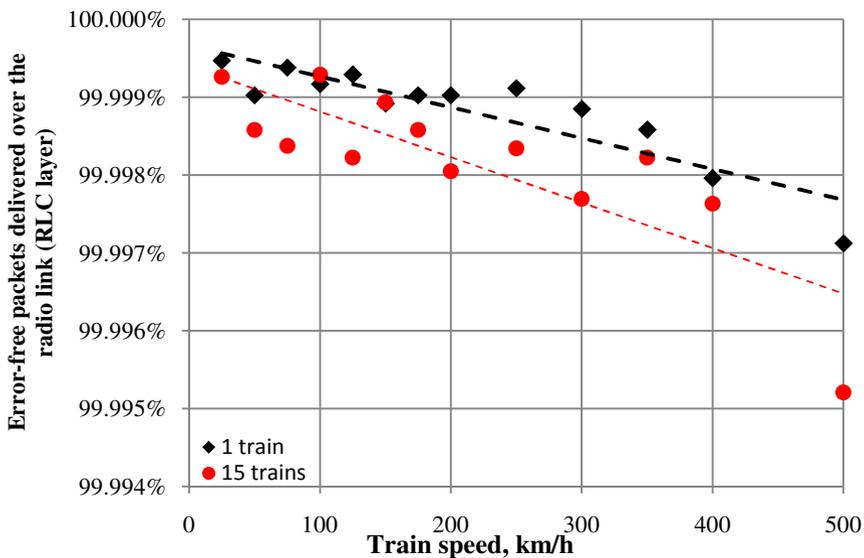
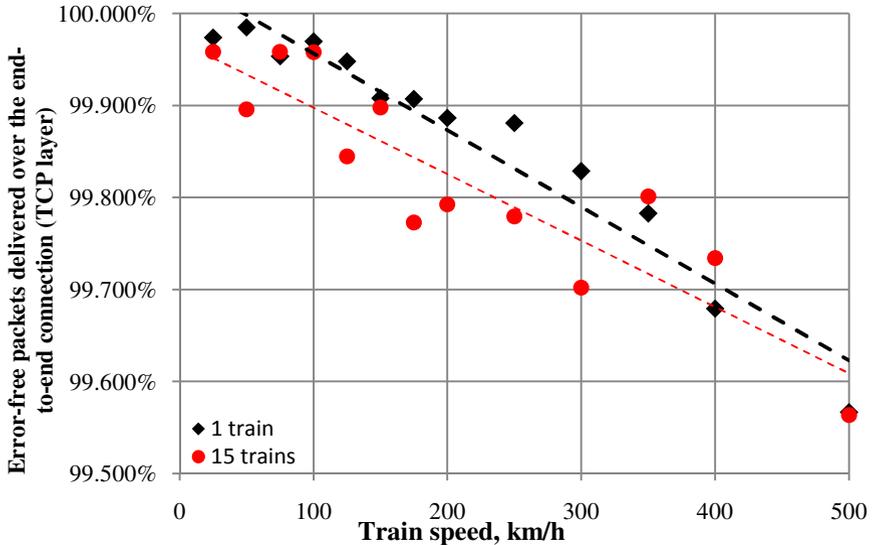


Fig. 4. Ratio of the delivered error-free packets to the sent packets over the radio link (at RLC layer) in relation to train speed



**Fig. 5.** Ratio of the delivered error-free packets to the sent packets over the end-to-end connection (at TCP layer) in relation to train speed

## 7 Conclusions

This paper presented an OPNET simulation model of a railway line where GSM-R network, which is used for providing ETCS signaling between train OBU and RBC, was substituted with the more modern LTE network.

Simulation results show that the modeled LTE network has no problems in providing connectivity between train OBU and RBC. This fulfills ETCS transmission requirements in terms of delay and data integrity. Increasing the train speed decreases the quality of the OBU-RBC communication. Nevertheless, the ETCS requirements are still fulfilled at any investigated speed in the range from 25 km/h to 500 km/h.

What is more, the recorded transfer delays, which are one order of magnitude lower than the limits set by the ETCS requirements, suggest that the LTE network has resources to serve many more users or to provide additional applications for the existing users.

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