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ENSURING LONG-TERM DATA INTEGRITY

ETCS Data Integrity Requirements Can Be Fulfilled Even under Unfavorable Conditions with the Proper LTE Mechanisms

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The European Train Control System (ETCS) is the leading signaling system for train command and control. In the future, ETCS may be delivered over long-term evolution (LTE) networks. Thus, LTE performance offered to ETCS must be analyzed and confronted with the railway safety requirements. It is especially important to ensure the integrity of the ETCS data, i.e., to protect ETCS data against loss and corruption. In this article, various retransmission mechanisms are considered for providing end-to-end ETCS data integrity in LTE. These mechanisms are validated in simulations, which model worst-case conditions regarding train locations, traffic load, and base-station density. The simulation results show that ETCS data integrity requirements can be fulfilled even under these unfavorable conditions with the proper LTE mechanisms.

Communication Technologies for ETCS

Railway signaling is gradually migrating from trackside colored-light signals toward fully digital in-cab signaling systems with automatic train control [1]. ETCS, which is the leading digital signaling system, is gaining significant international popularity. In Europe—for regulatory reasons—ETCS is deployed on all new and modernized railway lines. In other countries around the world, ETCS is often chosen for technical and economic reasons [1].

Communication between ETCS elements is currently provided by Global System for Mobile Communications-Railways (GSM-R). These two elements—ETCS and GSM-R—form the European Railway Traffic Management System (ERTMS). Despite being designed specifically for railways, GSM-R is already an outdated technology. Its shortcomings have been widely recognized in the literature and technical reports [2], [3]. The major issues of GSM-R are 1) insufficient capacity, 2) inefficient usage of network resources, and 3) limited support for data communication. For example, bursty ETCS data traffic is delivered over circuit-switched data calls. Thus, each ETCS-equipped train requires a dedicated data call that continuously occupies radio and backbone resources as long as that train is operating. ETCS messages are relatively infrequent and short, so the network resources reserved for these ETCS data calls are underutilized. Therefore, alternative technologies, which would bring higher capacity and efficiency, are being considered to replace GSM-R in the future [1]–[5].

LTE is one of the likely candidates to replace GSM-R [4], [5], since it offers many advantages in terms of capacity and data-transmission capabilities [6]. Moreover, LTE [and LTE-advanced (LTE-A)] is the latest family of Third-Generation Partnership Project (3GPP) standards. Thus, it has much lower obsolescence risk than any earlier standards, such as the Universal Mobile Telecommunications System. Besides, since both GSM and LTE are 3GPP standards, interworking mechanisms between these two networks are well defined [6]. This means that migration from GSM-R to LTE would be easier than migration to other technology.

Although the first proposals to replace GSM-R with LTE had already emerged by 2010 [7], [8], the literature on this topic is still relatively scarce. Most of the publications on LTE in a railway environment are focused on transmission performance under high-speed conditions—tackling problems caused by Doppler shift [9]–[11] and by frequent base-station handovers [12], [13]. However, these publications only considered LTE as a commercial network for the passengers on board the train—not as a replacement for GSM-R. This is a significant difference because, in the latter role, LTE must fulfill specific ERTMS and ETCS requirements on transmission performance and reliability. Therefore, despite the well-known benefits of LTE, this technology has to be explicitly validated in railway scenarios.

Only a few research works explicitly analyzed LTE as a possible network for the future ERTMS. Notably, publications by Liem and Mendiratta [14], Calle-Sanchez et al. [5], and Zayas et al. [15] considered LTE as a solution for providing voice communication in ERTMS-based railways. Then, in publications by Sniady and Soler [4] and Sniady et al. [16], LTE was considered as a network for ETCS communication. It has been established that LTE fulfills the ETCS requirement on message transfer delay under various conditions. However, one of these studies [16] also revealed that a densely deployed LTE network may not fulfill ETCS requirements on data integrity. ETCS data loss exceeded the maximum acceptable value. Hence, data protection mechanisms in LTE, such as retransmission, must be investigated further.

The goal of this article is to analyze the performance of the built-in LTE retransmission mechanisms and compare them with an end-to-end retransmission mechanism dedicated to ETCS. This analysis should show if ETCS data integrity can be ensured in LTE, even if the underlying physical transmission is unreliable.

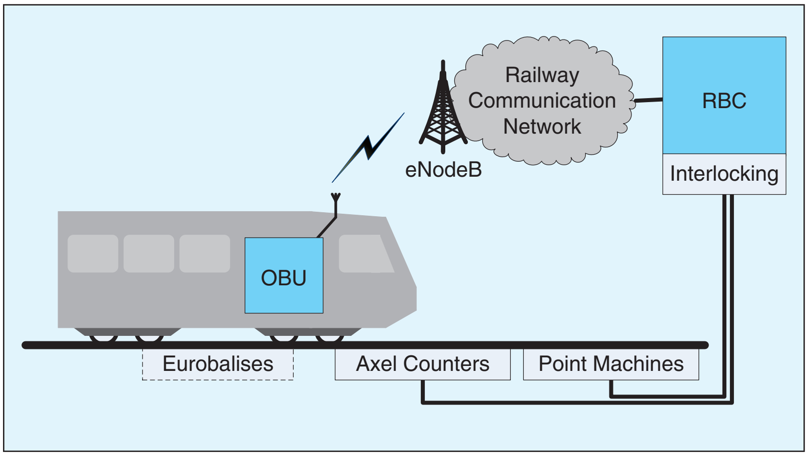

FIGURE 1 The ETCS architecture. The ETCS Level 2 is shown because it is the level that will be used in Denmark.

ETCS and Its Transmission Requirements

The ETCS architecture (Level 2) [1] is shown in Figure 1. The main ETCS logic is placed in the radio block center (RBC) server. The RBC decides how trains are allowed to move in its supervised area. To make its decisions, the RBC must have real-time information about the supervised area.

Each ETCS train is equipped with an onboard unit (OBU). The OBU is responsible for informing the RBC about train location, speed, and direction. This is done through ETCS location update messages sent from the OBU to the RBC. The RBC must also be informed about the state of interlocking elements, such as axel counters and point machines (this is provided over nonstandardized wired interfaces). Based on all that information, the RBC can make decisions on which trains can be allowed to drive. These decisions are communicated to the OBU via ETCS movement authority (MA) messages. It should be noted that more types of messages are exchanged within the ETCS (e.g., configuration messages during system start). However, location update and MA are the most important and the most frequent ones because they provide the core functionality of the system (i.e., management of train movement). The ETCS also includes Eurobalises, which are passive elements used by trains for establishing their position along the tracks.

The goal of ETCS is to ensure safe and efficient train movement. To fulfill this goal, reliable low-delay communication between the ETCS elements is required. If ETCS data are corrupted, lost, or cannot be delivered within a certain time period, the system loses information about train locations and their movement state. Thus, a potentially dangerous situation occurs. In such a case, trains must be preventively stopped until communication is restored. This is highly undesirable, since it causes timetable disruptions. Moreover, any uncontrolled state always poses a safety risk.

Due to these safety and efficiency concerns, the underlying network must fulfill strict requirements on the performance of ETCS message transmission. Currently, in the GSM-R network, ETCS messages are delivered over circuit-switched data calls. Hence, ETCS requirements, so far, are defined only for circuit-switched transmission [17]. LTE, on the other hand, is a packet-switched network. The performance offered by LTE cannot be compared directly with the current requirements. Thus, in this article, tentative ETCS requirements for packet-switched transmission are used, as defined by the Banedanmark (Rail Net Denmark) Signalling Programme [17].

There are two requirements that are relevant for this article. First, the probability of an end-to-end ETCS data loss cannot exceed 1×10^{-4}. Second, the average end-to-end ETCS message delay cannot exceed 500 ms (with 95% probability; for a message size of 128 B). Other ETCS requirements are related to the delay of various network procedures (e.g., registration) and are out of scope in this article.

Previous research showed that the average ETCS delay in an LTE network is below 50 ms [4], [16]. Thus, it is an order of magnitude smaller than the maximum acceptable delay of 500 ms [17]. This large difference creates a delay budget, which can be used by retransmission mechanisms. Thus, thanks to these mechanisms, it should be possible to prevent a data loss without exceeding the maximum acceptable delay.

Packet Loss Prevention in a Railway LTE Network

An LTE network consists of a wireless radio access network and a wired backhaul network. Due to its nature, the radio part of the network is much more prone to disruptions and, as a consequence, transmission errors. These disruptions can be caused, for instance, by noise, interference, or signal shadowing. To minimize errors in the wireless transmission, LTE continuously adapts the modulation and coding scheme (MCS) used on the radio link. The goal is to choose an MCS that provides the highest possible throughput, while keeping the transmission error probability acceptably low.

The radio link adaptation in LTE is configured with a specific error probability target—usually 10% [6]. This target is not 0% for two reasons. First, no modulation or coding scheme is robust enough to ensure completely error-free transmission. Second, a limited amount of radio transmission errors is actually desired to get a higher radio throughput [6]. The higher the error target is, the less conservative (less robust) the chosen MCS. This increases the error probability at the radio link. However, at the same time, the successful part of the transmission has much higher throughput than it would have with a conservative approach. An error probability target of 10% maximizes the radio throughout [6].

Since a packet loss is always expected at the radio link, LTE must provide countermeasures: retransmission mechanisms at the media access control (MAC) and the radio link control (RLC) layers [18], as shown in Figure 2.

MAC Layer Retransmissions

The MAC layer uses a hybrid automatic repeat request (HARQ) mechanism. It is a default retransmission mechanism that protects all traffic transmitted over the LTE radio link.

Whenever an LTE node sends a radio transport block, it expects to receive HARQ feedback from the receiver: an acknowledgment (ACK) in the case of successful reception or a negative ACK (NACK) if the received block is erroneous and cannot be decoded. When the sender node receives an NACK, it attempts to retransmit the radio block. The retransmission may have higher redundancy (more error-correcting bits) to increase the probability of successful reception. Moreover, it may use a more robust MCS.

To decode the frame, the receiver combines the signals received in each retransmission attempt. This also increases the probability of a successful data decoding, compared with a mechanism that would treat every retransmission attempt independently.

RLC Layer Retransmissions

The RLC layer may operate in transparent mode (TM), unacknowledged mode (UM), or acknowledged mode (AM). In TM, the RLC simply forwards the packets the between the upper and lower protocol layers.

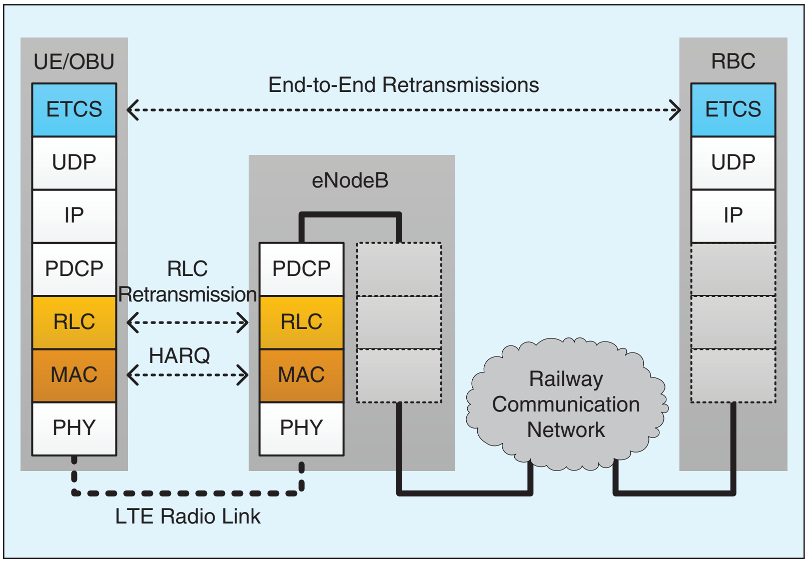

FIGURE 2 A simplified LTE protocol stack. Three available retransmission mechanisms are shown at the MAC layer, at the RLC layer, and at the application layer (i.e., ETCS layer). PDCP: packet data convergence protocol. IP: Internet protocol.

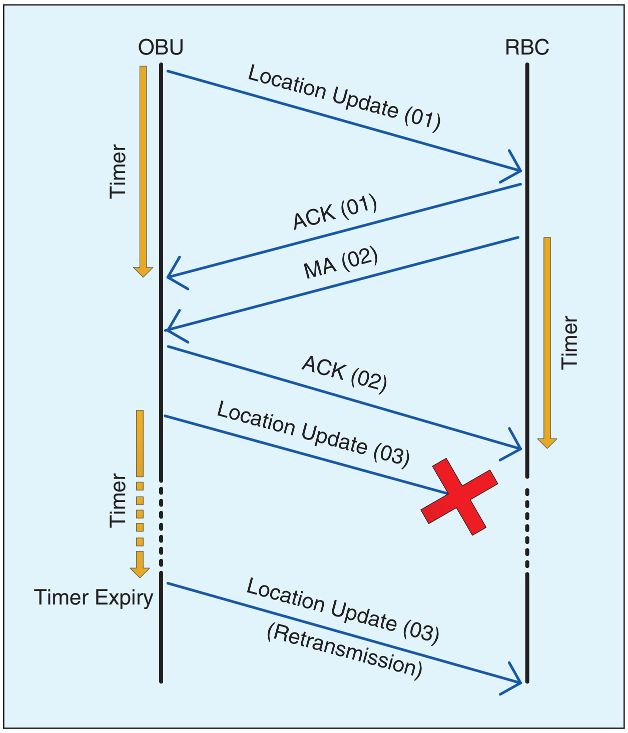

FIGURE 3 An example of an ETCS OBU–RBC message exchange with the end-to-end retransmission mechanism. The first two messages (location update 01 and MA 02) are delivered successfully before their retransmission timers expire. The third message (location update 03) is lost by the underlying transport network and does not arrive at the RBC. When the retransmission timer at OBU node expires, the location update 03 message is retransmitted.

In UM, the RLC layer provides additional segmentation of packets forwarded from the upper layer. Then, at the receiver, RLC reassembles the packets from the segments delivered by the MAC layer. Besides this, the UM RLC ensures an in-sequence delivery of packets, which may arrive out of order from the MAC layer.

On top of UM functionality, AM adds an additional retransmission mechanism, which is engaged if the MAC's HARQ retransmissions fail. The RLC mode is configurable independently for each evolved packet system (EPS) bearer. Thus, traffic that is sensitive to a packet loss can be delivered over AM, while other traffic is delivered over UM or TM.

Additional ETCS Layer Retransmissions

These two retransmission mechanisms at the MAC and RLC layers protect only the radio link. Thus, they cannot prevent packet losses—caused by congestion, buffer overflows, transmission errors, or other random errors—in other parts of the network. Furthermore, mechanisms at MAC and RLC layers have a limited number of retransmission attempts. If all of the attempts are unsuccessful, the packet is irreversibly lost. Hence, another end-to-end protection layer might be required.

In the model proposed here, this additional protection is provided by retransmissions at the application layer (ETCS). This mechanism within the protocol stack is shown in Figure 2, while an example of the mechanism operation is shown in Figure 3. Whenever an ETCS node sends a message, a timer is started. The sender node expects to receive a 5-B ACK from the receiver node. If the ACK does not arrive before the timer expires, the sender attempts to retransmit the message. It is possible to configure the timer duration as well as the maximum number of retransmission attempts.

This end-to-end retransmission mechanism provides a similar functionality as EuroRadio data link layer. EuroRadio is used in the GSM-R network to increase transmission reliability and security [1]. A similar end-to-end retransmission mechanism could also be provided by the transmission control protocol (TCP) transport protocol, if this was used instead of the user datagram protocol (UDP). However, most TCP procedures, such as flow control, congestion control, and slow-start, would be redundant for the infrequent low-rate ETCS. In addition, TCP would introduce more overhead due to the larger headers. Besides, in the case of a packet loss, TCP retransmits the same packet. By using the retransmission mechanism at the application layer (ETCS), it is possible to retransmit the lost packet with updated information (e.g., with an updated train position). Thus, in this work, UDP is used as a transport protocol, and the retransmissions are handled by the application layer.

Simulation Scenarios and Cases

As presented in the previous section, there are multiple retransmission mechanisms available in LTE. The performance of these mechanisms is evaluated using computer-based simulations. The goal is to compare effectiveness of these mechanisms and to verify whether they provide sufficient end-to-end ETCS data integrity—even in the worst-case scenario in terms of train locations and traffic load.

Simulation Setup

The simulations were conducted using OPNET Modeler version 17.5 PL3 [19]. The setup was based on an example using the Copenhagen, Denmark, main train station, and it followed a scenario presented in a previous publication [16]. In this simulation setup, the station was covered by an LTE radio network (currently, the station is covered by a GSM-R network). To model the worst-case conditions, the simulated radio network consisted of ten densely deployed eNodeBs (i.e., ten radio cells). The eNodeBs were placed linearly—following the shape of the station tracks. The station is approximately 1-km long, so the distance between eNodeBs was 100 m, as shown in Figure 4. Such inter-eNodeB separation meant that a train passing through the station at a typical speed of 60 km/h would have to perform an intercell handover every 3 s. Therefore, it is unlikely that more eNodeBs would be deployed, since passing trains would have to perform handovers even more frequently—resulting in more signaling overhead.

In the simulations, 40 trains were placed at the station. This is the upper bound for the number of trains expected simultaneously at the station in the peak hour in 2030 [4]. Thus, 40 is the worst-case assumption, and there should be fewer trains in everyday operation.

In the simulations, each train was modeled as LTE user equipment (UE). All of the trains were placed at a distance of 50 m from the nearest eNodeB, as shown in Figure 4. This train distribution was the least favorable from the radio transmission point of view because most of the trains were located at the cell edges. As a consequence, radio transmission had to use relatively high power to counteract path loss between trains (UEs) and eNodeBs. At the same time, trains associated with two different eNodeBs were in close vicinity of each other. This caused significant interference between transmissions in the neighboring cells.

All trains (UEs) in the simulation were modeled as stationary. This simplification was made for two reasons. First, thanks to the fixed positions, it was possible to execute simulations multiple times, ensuring that the UEs remained in the same unfavorable positions (at the cell edges). Therefore, any change in the observed simulation results were only due to the change in chosen parameters and mechanisms, not due to the randomness of UE positions. Second, most of the trains at the station

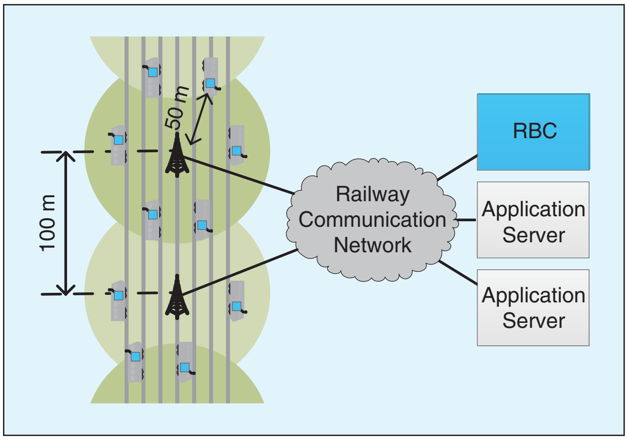

FIGURE 4 A schematic view of the simulation topology. The green circles depict an approximate cell range. For clarity, only the middle section of the station is shown, with two out of ten eNodeBs.

stand by the platforms or drive at low speed. Therefore, their speed is of relatively little importance for the transmission performance.

Other parameters used in the simulation are presented in Table 1. The main objective for the radio network configuration was to ensure coverage over the whole station with the minimum reference signal received power above −92 dBm (railway radio coverage requirement [17]).

Application Mix

The LTE network was used for communications between the OBUs and application servers, including the RBC. Five applications were provided by the network. Due to the purpose of this work, only the performance of ETCS signaling was analyzed. The remaining applications were used solely to generate background traffic. The timing and data rates were chosen so that the modeled applications generate realistic traffic that may be seen in the future railway network. The five applications were defined as follows (based on [16]).

- ETCS signaling: Each OBU was sending a 128-B message to the RBC every 30 s, on average. Similarly, the RBC was sending a 128-B message to each of the OBUs every 30 s, on average. These messages could be location updates, MAs, or other ETCS message types (e.g., configuration data and train specification data). The average time between messages was set to 30 s following assumptions given in [24, p. 155]. ETCS messages had a constant size of 128 B, according to the size specified in the ETCS requirements [17]. However, in ETCS, the message size varies, and it is usually smaller. Hence, the 128-B message size is considered as the worst-case scenario.
- Video transmission from selected trains to the control center (represented by one of the application servers): Video is proposed as a service for monitoring train interiors for security purposes. The video

application generated a 1,000-kb/s uplink stream (per train).

- Interphone (internal railway telephony) between train drivers and the control center: A single call generated uplink and downlink streams, each with a bit rate of 64-kb/s [voice stream bit rate generated by the International Telecommunication Union (ITU) G.711 codec]. The assumption was that each train driver makes a voice call to the control center every 900 s, on average. The call duration was 20 s, on average.
- Voice announcements were assumed to inform onboard passengers about the current traffic situation. This was simulated by an application generating a 64-kb/s downlink stream (ITU G.711 codec). Announcements were transmitted every 900 s, on average. Each announcement provided brief information about traffic disruption, changes in the travel schedule, and so on. Hence, the announcements were short, and each lasted 5 s.
- Discreet listening for security purposes: The application generated a continuous uplink stream with a bit rate of 64 kb/s from each train (ITU G.711 codec).

The five applications differ in transmission requirements and their importance for train operation. Thus, a quality-of-service (QoS) mechanism is required to differentiate between them. In LTE, the QoS mechanism is built around the concept of an EPS bearer [6]. Every UE uses one or more EPS bearers. Each of these bearers is specified by a QoS class indicator (QCI), which predefines the most important transmission parameters for packets carried by the bearer, e.g., guaranteed bit rate (GBR), scheduling priority, packet error loss target, and delay target [25]. To ensure certain QoS, sensitive applications (e.g., ETCS) can be assigned to a high-priority GBR bearer. Other applications are carried over low-priority best-effort bearers (non-GBR).

In the simulation model, three bearers were defined for each train. As shown in Table 2, ETCS packets were carried over a dedicated bearer of QCI 3. According to the standard [25], an LTE network should provide the following performance to a bearer of QCI 3:

- GBR (in this scenario, set to 16 kb/s)
- scheduling priority 3 (relative to other bearers)
- delay lower than 50 ms
- packet error loss rate below 10^{-3}.

However, these are only performance targets. The network aims at providing such performance, e.g., by

TABLE 1 The simulation parameters.

Parameter	Value
Frequency band[1]	5.9 GHz (5 MHz bandwidth)
eNodeB maximum transmission power	36 dBm
eNodeB antenna height[2]	10 m
eNodeB antenna gain[3]	15 dBi
UE antenna height[2]	4 m
UE antenna gain[3]	1 dBi
Path-loss model[4]	UMi
Multipath channel model[5]	ITU Pedestrian A
Link adaptation error target	0.01%
LTE transmission mode[6]	Transmit diversity (TM2) (eNodeBs with 2 × 2 antennas, UEs with 1 × 2 antennas)
UE category	1

1: An assumption was made that part of the 5.9-GHz ITS band could be assigned for railway purposes [20]. 5 MHz is the LTE bandwidth closest in size to the 4-MHz bandwidth used by GSM-R.

2: eNodeB antennas were assumed to be placed near the ceiling of the station building, while UE antennas were placed on the train roofs.

3: eNodeB and UE antenna gains were selected within a typical range as given in [21, p. 223].

4: ITU-R M2135 Urban Micro (UMi) [22] was chosen, since it models an urban scenario with buildings higher than location of eNodeB. This is the case at the Copenhagen main train station. Moreover, this path-loss model supports 5.9-GHz frequency. The simulation chooses between line-of-sight and non-line-of-sight cases based on line-of-sight probability as defined in [22]: $P_{LOS} = \min(18/d, 1) \cdot (1 - \exp(-d/36)) + \exp(-d/36)$, where d is the distance between eNodeB and UE in meters.

5: The ITU Pedestrian A multipath channel model was chosen because the trains (UEs) were considered stationary.

6: Transmit diversity was chosen because it offers improvement in the received SNR (in contrast to other MIMO modes, which improve throughput) [23]. Hence, transmit diversity should contribute to a lower error rate of the radio transmission.

TABLE 2 The EPS bearer configuration.

EPS Bearer	ETCS	Voice	Default Bearer
Application(s)	ETCS	Interphone and voice announce	Other
QoS Class Identifier (QCI)	3	2	9
Bearer type	GBR	GBR	Non-GBR
Guaranteed bit rate (uplink)	16 kb/s	64 kb/s	—
Guaranteed bit rate (downlink)	16 kb/s	64 kb/s	—
Allocation retention priority	1	5	9
Scheduling priority[1]	3	4	9
Delay budget[1]	50 ms	150 ms	300 ms
Packet error loss rate[1,2]	10^{-3}	10^{-3}	10^{-6}

1: Values of these parameters are defined in a 3GPP standard [25]. Moreover, these values are only performance targets and are not strict requirements.

2: Maximum error loss rate in a noncongested network.

configuring packet schedulers and link layer accordingly, but the network does not guarantee them under all circumstances [25]. This is because, in some situations, e.g., in the case of very poor radio conditions, neither scheduling nor link layer retransmissions are able to countermeasure a large packet loss.

Simulation Scenarios and Configuration Cases

Using the described simulation setup, three scenarios were prepared. The scenarios differed in the traffic load. This difference was created by varying the number of video streams transmitted in the uplink (from the train).

- *Scenario 1 (light traffic load)*: No video traffic was sent in this scenario. The average utilization of LTE physical uplink shared channel (PUSCH) was 1.46%.
- *Scenario 2 (medium traffic load)*: Video streams were sent from four trains (10% of all the trains). The average utilization of PUSCH was 35.24%. Note that the average utilization was not uniformly distributed among the cells. In the cells that carried the video streams, the average uplink utilization was 65.79%.
- *Scenario 3 (traffic overload)*: Video streams were sent from all 40 trains. The average utilization of PUSCH was 98.87%. In a real-world situation, simultaneous video streams from all trains are unnecessary. It would be enough if a train station security supervisor could see simultaneously just a few chosen video streams. However, the purpose of the scenario with 40 video streams is to model overload conditions, when the LTE uplink shared capacity is exceeded.

Each of the three scenarios was analyzed in five cases—summarized in Table 3—which differed in the configuration of the retransmission mechanisms:

- *Case A*: Only the MAC retransmission mechanism was enabled (three attempts allowed).
- *Case B*: The MAC and RLC retransmission mechanisms were enabled (three attempts allowed at each layer).
- *Cases C1–C3*: The MAC, RLC, and ETCS retransmission mechanisms were enabled. At the MAC and RLC layers, three retransmission attempts were allowed. At the ETCS layer, between one (Case C1) and three (Case C3) retransmission attempts were allowed. The ETCS retransmission timer was set to 500 ms.

Simulation Results

Each of the three scenarios was analyzed in each of the five retransmission configurations. Thus, 15 cases were considered in total. Each simulation case was executed at least 70 times, with varying random seed numbers, until stable results were observed. Each simulation run lasted 15 min.

The probability of an end-to-end ETCS data loss observed in the simulations is shown in Figure 5.

***Table 3* The maximum allowed retransmission attempts in the analyzed configuration cases. A dash means that the retransmission mechanism was off.**

Case	MAC Layer (HARQ)	RLC Layer	ETCS Layer
A	3	—	—
B	3	3	—
C1	3	3	1
C2	3	3	2
C3	3	3	3

Scenario 1

The first series in Figure 5 shows the results recorded in Scenario 1, which modeled a very lightly loaded network. In the configuration Case A, the probability of an ETCS data loss was 7.08×10^{-4}. In this configuration, ETCS traffic was not protected with any retransmission mechanism apart from the default HARQ (on the MAC layer). If three HARQ attempts were insufficient to deliver a packet, then it was irreversibly lost. Also, if the packet loss occurred elsewhere than at the radio link, it was impossible to recover the lost data. Therefore, as expected, the data loss probability in Case A was the highest among all the configuration cases.

In Case B, thanks to RLC retransmissions, the data loss probability fell to 3.02×10^{-6} (a reduction of 99.6%). The observed data loss was below the maximum loss acceptable by ETCS, which is 1×10^{-4} (marked with the red dashed line in Figure 5). Thus, in Scenario 1, an RLC retransmission mechanism was sufficient to fulfill ETCS data integrity requirement. In Case C, no data loss was observed—even with only one end-to-end retransmission attempt (Case C1).

Scenario 2

The second series in Figure 5 shows the results from Scenario 2, in which four video streams were transmitted in the network. These video streams were used to monitor trains' interiors for security purposes. In a real-world situation, four streams from a single station should be sufficient to provide security for the train passengers. Thus, this is the most realistic scenario regarding the network traffic.

The ETCS data loss probability was higher than in Scenario 1, but it followed the same tendency across various configuration cases. In Case A, the data loss probability was 1.4×10^{-3}. In Case B, thanks to RLC retransmissions, it was lowered to 5×10^{-6} (reduction by 99.6%). Thus, similarly as in Scenario 1, the data protection provided by RLC was sufficient to fulfill ETCS data integrity requirement. In Case C, when at least one end-to-end retransmission was allowed (Case C1), ETCS data loss was not observed at all.

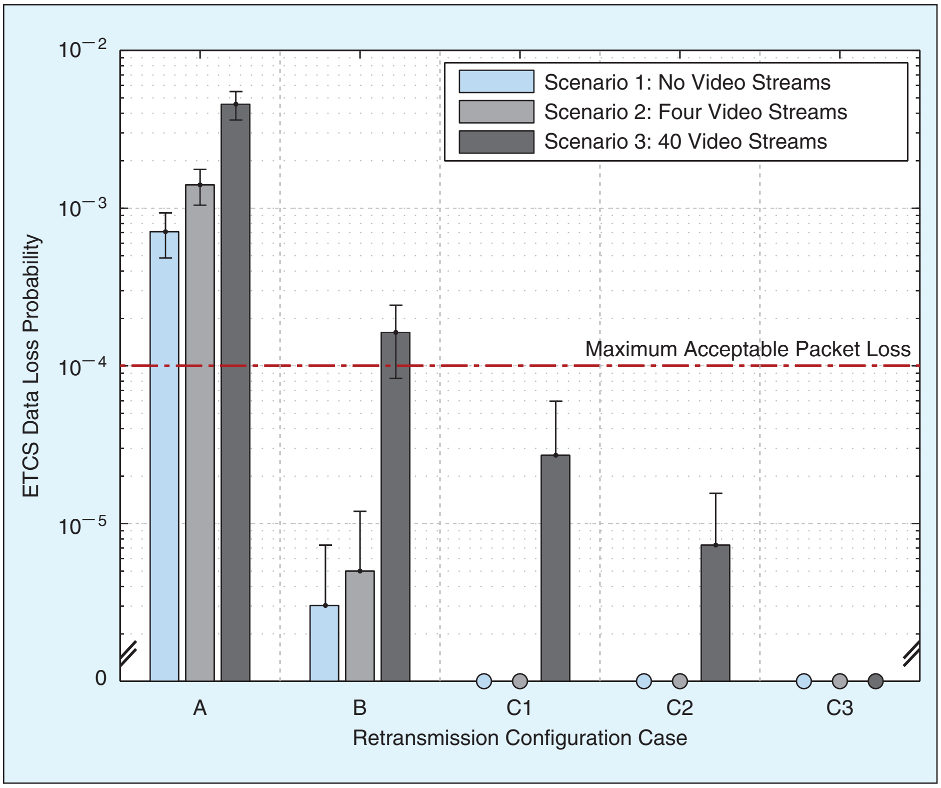

FIGURE 5 The ETCS end-to-end data loss probability in LTE network operating in one frequency band (with 95% confidence intervals).

Scenario 3

In Scenario 3, the network was overloaded with 40 uplink video streams. This traffic overload significantly increased the ETCS data loss probability, as shown by the third series in Figure 5. In all of the cases, the probability of data loss was above the probabilities observed in the previous two scenarios.

In Case A, when only HARQ retransmissions were used, the ETCS data loss probability was 4.56×10^{-3}. Then, in Case B, RLC retransmissions lowered the data loss probability to 1.63×10^{-4}. Although the data loss was reduced by 96.4% compared with Case A, it remained above 1×10^{-4}. Thus, in this overload scenario—opposite to Scenarios 1 and 2—RLC retransmissions were not sufficient to fulfill the ETCS data integrity requirement.

In Cases C1–C3, an ETCS end-to-end retransmission mechanism was added on top of MAC and RLC retransmissions. When one end-to-end retransmission attempt was allowed, the data loss fell to 2.71×10^{-5}, i.e., below the ETCS maximum acceptable limit. In Case C3, when three retransmission attempts were allowed, no data loss was observed.

The recorded packet loss values are high, but they are in the same range as values observed in LTE lab tests and field trials. In particular, in trial results published by Anehill et al. [26], the measured cell-edge packet loss was 4×10^{-3}. Also, in other field trials [27], the packet loss was found to be between 3×10^{-4} and 2×10^{-3}. Therefore, considering the worst-case assumptions made in the presented simulations, the observed values are realistic.

Discussion of the Results from the Three Scenarios

At the RLC layer, data packets are split into smaller segments to fit into the current radio frame size. This segmentation mechanism amplifies the packet loss. This is because, even if only one of the segments is lost, the whole ETCS packet is discarded, and ETCS data are lost. Moreover, it is possible that a radio frame carries segments from more than one packet. Then, a single lost frame can cause a loss of more than one packet. Therefore, even a small loss at the lower layers [physical (PHY) layer, MAC, and RLC] may cause higher packet loss at the application layer.

In the simulations, the trains (UEs) were concentrated at the cell edges. Due to that, there was a significant level of intercell interference, which degraded radio transmission and caused radio frame drops. As a consequence, the data (packets) carried by the dropped frames were also lost. This was the main cause of the ETCS data loss.

The more video was transmitted in the network, the higher the interference level, and, therefore, the higher the data loss. This is visible, for instance, in Case A: the data loss probability was considerably higher in Scenario 3 than in Scenario 1 due to the difference in the traffic load.

This interference issue could not be solved by the EPS bearer mechanism. This is because eNodeBs manage their respective radio resources independently. Each eNodeB follows the EPS bearer specification (see Table 2) and configures its packet scheduler and link layer in a way that should provide the specified transmission performance for each bearer. Thanks to this, a high-priority ETCS packet will be scheduled before lower-priority traffic. Hence, ETCS is prioritized within each cell, and no other traffic should delay or interrupt ETCS traffic. However, since the eNodeBs are independent, the prioritization does not work between the cells. An eNodeBs is not aware of what type of traffic is transmitted in the neighboring cells. Thus, even though ETCS traffic is prioritized by the eNodeB and is transmitted ahead of other traffic, the radio frames carrying an ETCS packet can still be heavily interfered by transmissions in the neighboring cells.

As proven by configuration Case A, the radio frame loss due to the interference was so high that it could not be solved effectively by the HARQ retransmissions. Therefore, the retransmissions at the higher layers were necessary.

The retransmissions at the RLC layer prevented most of the data loss. As visible in Case B—under low and medium traffic load—the network fulfilled ETCS data loss requirement. In Scenario 3, the data loss exceeded the acceptable value, but only slightly. Although such overload conditions should not occur in a properly dimensioned network, a good ETCS performance must be guaranteed regardless of the network load. To achieve that, the end-to-end retransmission mechanism is necessary. In Scenarios 1 and 2, one end-to-end retransmission attempt was sufficient to recover all data lost in the network. In Scenario 3, three end-to-end attempts were required.

It is worth noting that even if RLC retransmissions recovered all the data lost on the radio link, the end-to-end retransmissions would be still necessary. This is because data loss may occur in other parts of the network. Only the end-to-end mechanism can protect against such losses.

Besides using the retransmission mechanisms, another strategy for lowering ETCS data loss is to directly address its main cause, the intercell interference. In LTE, this can be achieved with various interference-avoidance mechanisms, such as [23].

- Intercell interference coordination (ICIC), which is based on the partial frequency reuse concept. ICIC allows eNodeBs to coordinate which part of the frequency spectrum is used by each eNodeB near the cell edge. Thus, the interference at this vulnerable location is significantly reduced.
- Coordinated multipoint (CoMP), which allows multiple eNodeBs to simultaneously receive/transmit to an UE that is close to the cell edge. The UE receives a combined signal from these few eNodeBs. Thus, thanks to CoMP, the signals from the neighboring eNodeBs improve reception instead of introducing interference.
- Carrier aggregation (CA), which is used to increase transmission bandwidth by aggregating multiple LTE frequency channels. The aim of this mechanism is to increase throughput, but CA can also be used to balance the traffic load across a wider frequency range. Thus, it may lower the interference.

By implementing these mechanisms, the intercell interference would be reduced, and the data loss on the radio link would be significantly lowered.

Consequences for ETCS Operation

Failures and delays in ETCS communication have different consequences depending on the circumstances when they occur. The most disruptive are communication failures that force a running train to slow down or stop. As the train is running, it repeatedly receives the MA updates from the RBC. Every new MA informs the OBU about the new end-of-MA (EoMA) point, i.e., the point where the train must stop. As the train approaches the EoMA, the RBC prepares a new MA and sends it to the OBU (depending on ETCS implementation, the RBC may send MA on the OBU request). If the new MA is not delivered at the appropriate time, the train must slow down and eventually stop to not overrun the EoMA point. Therefore, the closer the train is to the EoMA, the higher the risk that ETCS data loss will disrupt the train movement.

To minimize the risk of travel disruptions, the MA message is sent to the OBU some time before the train approaches the current EoMA. According to a technical report by ERTMS User Group [28], the MA update should take between 4 and 5 s, on average. However, signaling systems are designed under the worst-case assumption that the MA update takes up to 12 s. If the MA update time is shorter than 12 s, the train operation will not be affected negatively, i.e., no unnecessary braking will be made. During the MA update, approximately 2.5 s are consumed by the internal operations of the RBC and the OBU [28]. Hence, the delay in the communication network cannot exceed 1.5 s on average and 9.5 s maximum.

In the simulated LTE network, in the configuration with retransmission mechanisms off (Case A), the maximum MA transfer delay was 1.7 s. Simulation results show that up to three end-to-end retransmission attempts were necessary to countermeasure the data loss in the network. Therefore, in the worst case, assuming three retransmissions and a 500-ms timeout, the maximum MA transfer delay should be as follows:

$$\text{Attempts} \times \text{Timeout} + \text{MaxDelay} \approx 3.2\ \text{s}.$$

This worst-case MA delay of 3.2 s is shorter than the maximum delay of 9.5 s. Therefore, even in an overloaded network, the modeled LTE network should offer ETCS performance that guarantees uninterrupted train operation.

However, besides the intercell interference, there are also other things that may affect the reliability of ETCS communication. In the railway context, the primary challenge is sufficient radio coverage, which must be guaranteed despite difficult conditions—long distances requiring continuous coverage, high-speed UE mobility, and underground tunnels. These issues were discussed in the previous publications [5], [9], and [29], and, therefore, they were out of scope of this work. Another cause of communication problems may be external factors that cannot be controlled by the mobile network or its configuration—for instance, strong and long-lasting electromagnetic interference, software failure or hardware failure. These types of problems may be only addressed with the proper network architecture using redundant hardware, redundant frequency bands, and multipath solutions [30].

Conclusions

ETCS signaling is one of the critical railway applications. Reliable delivery of ETCS messages ensures that the railway signaling system is in a controllable and safe state. ETCS data integrity is one of the most important railway requirements on the underlying communication network.

Ensuring data integrity in a wireless network may be challenging, especially when the transmission resources are shared between various applications. Therefore, this article analyzed ETCS data integrity in a railway LTE network under the worst-case conditions: densely deployed base stations, excessive traffic load, high train concentration, and unfavorable train positions at the cell edges.

The simulation results demonstrated that ETCS data loss probability can be significantly reduced using radio and end-to-end retransmissions. Due to that, the modeled LTE network fulfilled ETCS data integrity requirements despite the worst-case conditions.

All in all, a carefully designed LTE network is capable of fulfilling ETCS transmission requirements set by the railway industry.

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