The Adoption of Public Telecom Services for the Evolution of the ERTMS-ETCS Train Control Systems: Challenges and Opportunities

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Abstract. The ERTMS-ETCS train control system relies on the GSM-R dedicated radio network for train to ground communications and on terrestrial dedicated network(s) for communications between the control center and the wayside equipments. However GSM-R technology will become obsolete in the next years, has limited capacity to accommodate growing traffic needs and is suffering from interference caused by the LTE. With the introduction of IP technology in the evolution path of the ERTMS-ETCS a number of possible alternatives are being analyzed and, among them we have studied an hybrid telecom system based on public networks (cellular + satellite). Although public cellular services are provided as best-effort, satellite can act as intelligent backup to complement the cellular networks and, all together, provide QoS in line with the ERTMS-ETCS requirements. This paper outlines the results of a specific test campaign to assess the performance of the cellular networks and satellite communications in a 300 km railways line for a cumulative 18,000 travelled Km in 21 days. These results, have been processed to estimate the achievable performance in the rail environment and to pave the way for realizing the multi-bearer solution. An economical assessment of the multi-bearer solution is presented making reference to the local and regional lines for which the deployment of a dedicated network is difficult to justify.

1 Introduction

In [EL1], [EL2] it is envisaged that future railway telecommunication systems will not be based on an unique modern or (futuristic) system, but it will integrate a variety of systems, each of them specialized/oriented to specific services. Services to passengers will be provided by one or more flexible radio systems

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capable of evolving rapidly with the market demands and open to new and more advanced content-oriented applications. Instead, the communication platform for railway management will be oriented towards a unified infrastructure supporting real-time collaboration services. This allows to increase efficiency, speed-up the business processes, improve operational effectiveness, facilitate information exchange and improve the quality of decision making. Effective management of railway operation processes will require highly reliable and stable telecommunication platforms, supporting new operational modes enabling the increasing of the railway traffic capacity while ensuring high security and safety levels. The European Rail Agency (ERA) has already undertaken studies to evaluate possible options for the evolution of the GSM-R that will have to be replaced in the next years. In fact, GSM-R is suffering from technology obsolescence, electromagnetic compatibility with 4G-LTE networks operating in frequency bands close to those of GSM-R, and limited capacity. We observe that, concerning capacity, in addition to the ERTMS-ETCS needs, [SE1], wide-band passenger services (e.g. entertainment) and train equipment monitoring should be carefully considered. To enhance capacity, a first option would be the introduction of the GPRS, as done in the past for GSM. However, this option presents two major weaknesses: sustainability of capital costs associated to upgrades and extensions of the actual GSM-R radio network, especially for low traffic rail lines not yet covered by it, and interference issues. In the definition of a viable solution, two major challenges arise: to comply with the interoperability requirement, as done by the GSM-R today, and, from the train operator side, to protect the investments on the GSM-R. Nevertheless, a migration path to a fully IP-based telecom system is already started, and the incoming 5G could facilitate the evolution towards a full service-based system for all rail applications. Concerning cost reduction, a first breakthrough in economic sustainability is represented by the replacement of proprietary, dedicated networks with public networks, such as the cellular and satellite networks operated by commercial operators. This scenario implies a step-change in the liability process with the introduction of the guaranteed QoS as the most relevant Key Performance Indicator (KPI) in the provisioning of a mobile connectivity service package by a telecom operator(s), the starting point being the existing GSM-R specifications (see after). Considering that in the short term, each telecom bearer may provide best-effort services only, in the framework of the ESA ARTES 20 3InSat project we have investigated, by means of an experimental campaign, the possibility of achieving acceptable QoS on public networks. We consider QoS should be achieved by jointly using several best effort bearers managed by an on-board Multipath Router device (MAR: multiple access router). To further improve QoS we also propose the integration of a QoS guaranteed link provided by Satellite. This is helpful to improve quality in the case(s) of congested or unavailable terrestrial networks and/or to solve possible handover issues in the case of high speed trains. Due to limited space, experimental results presented and discussed in this paper are restricted to the case of terrestrial and, with integrated satellite communication used for transmitting standard signaling messages from train to ground and viceversa.

The test trials also included measurements for different types of communications services to/from train. Some of them have been designed to test the radio networks under very stressful conditions involving transmissions of data packets much longer than the typical signaling messages. As an example we have considered burst emissions of variable length packets even much longer than the standard SMS messaging used for typical signaling. We have also considered the case of the train control centre generating traffic having variable peak rates and characterized by different statistical distributions of the inter-arrival packet times such as the exponential one. Test activities have also included other two differentiated tests: the Radio Access Network end-to-end delay performance test directly performed by Vodafone-IT and the EuroRadio performance test performed by Ansaldo STS. The paper is organized as follows. In Section 2 we review the main issues related to the adoption of public land mobile radio network for supporting railway communication services. In Section 3 we describe the test scenario and we introduce the selected KPI. Results are presented and commented in Section 4 while a discussion on costs are presented in Section 5. Finally, Conclusions are drawn.

2 Main Issues for Railway Management Using Integrated Plmn/Satellite Networks

The adoption of PLMN/Satellite integrated radio networks for railway communications introduces some main concerns which are discussed in this Section.

2.1 Radio Coverage Issues

Design criteria of PLMNs are deeply different from those indicated in [EIR], and in general coverage requirements could be not guaranteed at all, outage probability could be over the prescribed limits and coverage holes could be present along the line. As indicated in [DSI] to improve coverage and link reliability and other performance parameters (see after) these two technical options could be considered.

1. **Multi-radio Technology (MRT):** on board equipment should be able to route messages/calls on any one of the terrestrial radio interface(s) available in the area (i.e. GSM, UMTS, LTE etc.) and/or on satellite. Routing decisions shall be taken on the basis of the current traffic load in the PLMN(s). The on board MAR should also be able to simultaneously select two (or more) radio interfaces for different communication services. As an example voice and/or data services could be routed on two distinct radio interfaces (e.g. GSM for signaling and UMTS for voice).
2. **Connecting to Multiple Radio Networks of Different Operators:** coverage could be improved by exploiting the simultaneous presence of networks of multiple mobile network operators (MNOs) in the same area[1]. In

[1] It should be noted that co-location of Base Stations of different operators works against improvement in radio coverage.

this case the on-board equipment should be able to switch among bearers of different operators and/or to setup and maintain multiple radio links with the different networks. Duplicates of messages have to be detected and discarded by applications used for train control. In this case the re-design of some parts of the Euroradio [ALC] protocol could be necessary, [DSI].

2.2 Handover and Cell-Reselection

Intense voice/data traffic originated by PLMN users may cause traffic congestions that may lead to (temporary) unavailability of radio bearers. This can have strong impact on the train Handover/Cell Reselection performance. To mitigate these problems, priority mechanisms for dropping one (or more) active calls, when the train is executing handover in presence of congestions, should be (possibly) negotiated with the telecom operator. The possibility of reserving radio channels for train communications only at some hours of the day, could be another option to meet handover/cell-reselection requirements.

2.3 Call Setup

In PLMN call setup delays can be related to cell load and could be difficult to control. Specifications in [EIR] consider priority levels in the call setup phase in relation to the call type. It seems difficult to relax call setup requirements even for regional and/or low traffic lines. The MRT and/or simultaneous usage of more than one telecom operator could be helpful to improve call setup objectives. Table 1 lists the main QoS requirements for the existing GSM-R system. We remark that the very demanding requirements in Table 1 refer to

Table 1. QoS parameters for GSM-R (ETCS)

QoS Parameters	**Demand Value**
Call setup time	$\leq$ 10s (100%)
Connection establish failure probability	$\leq$ 1% (100%)
Data transmission delay	$<$ 0.5s (99%)
Error rate	$< 1\%/h$ (100%)
Duration of transmission failures	$< 1s$ (99%)

high speed railway lines and they will be relaxed in the case of regional/low traffic lines[2]. However, the most important one is the time required for emergency call. In this case, the proposed adoption of Satellite is helpful to cope with congestion/unavailability of terrestrial network. In this perspective, the usage of integrated PLMN/satellite networks for railway communications can be seen as a valuable option.

[2] Requirements of radio systems supporting ERTSMS-ETCS over regional/low traffic lines are still under discussion.

3 Scenario and Test Trial

In this Section we present results from a test trial for the standard signaling service based on M2M service of the Vodafone IT public mobile radio network. The test scenario is represented in Figure 1. The trials were performed on the railway

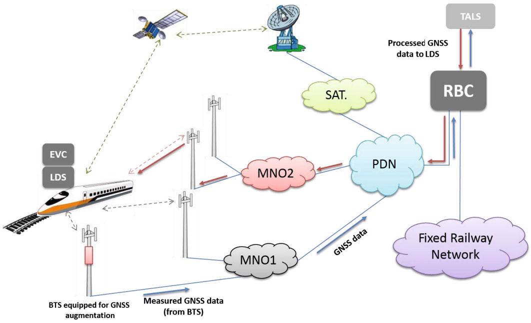

Fig. 1. Test scenario including augmentation sub-network

connecting the towns of Cagliari and Olbia in the Sardinia Island (Italy), in the framework of the ESA ARTES 20 3InSat Project, that foresees realization of a railway testbed for testing satellite navigation and communication technologies for rail applications, under real operational conditions. The line is about 300 km long and the maximum allowed train speed is 150 km/h, actually limited to 130 km/h (which is the maximum speed of the Minuetto Diesel traction trains used on the line). Tests and demonstrations have been performed reaching the maximum speed. During the 4 weeks of the test campaign, two trips per day each lasting 3:50 hours each way, have been performed. The GSM/GPS and satellite antennas were placed on the roof top of the train with unobstructed view to the sky. A power supply unit (PSU) of several batteries has been employed in the case of power outage. Tests have been executed by using the Vodafone 2G/3G public mobile access network, providing seamless handover even to the other mobile networks in case of lack of Vodafone coverage. The satellite link has been provided by Inmarsat Satellite (BGAN configuration). As shown in Figure 1 the on-board equipment includes the Euro Vital Computer (EVC) and a Location Determination System (LDS). Both EVC and LDS functionalities have been emulated by software running on a portable PC. The Radio Block Centre (RBC) emulator has been hosted by a server cluster located at TriaGnoSys lab facilities (Munich-Germany). The GPS antenna was placed on a windows sill outside the lab. To determine train position (train mileage with respect to the head station), the LDS uses data from GPS with differential corrections provided by a local augmentation network deployed along the line. The augmentation network includes two GPS measurement stations (one in Samasti and the other at Decimomannu) which acquire GPS data from satellites, pre-process them and send GPS observations by means of the wired network(s) to the Track Area LDS Server (TALS) in Monaco (see Figure 1). Data are processed by TALS to calculate corrections which are delivered to train using the terrestrial radio network.

3.1 Selected Key Performance Indicators

All data collected in the test trial, have been analysed to extract the following statistics:

1. End-to-End (E2E) delays vs train location (specified in terms of train mileage from the head of the track, in the reported plots illustrating the delay behaviour). The purpose of this statistics is to evidence the presence of (rare) anomalies in the E2E delay related to signal shadowing caused by rail-track infrastructures like tunnels, or coverage holes;
2. Cumulative Distributions of the E2E delay and of the corresponding Jitter;
3. Probability the E2E delay exceeds a threshold (Thr);
4. Packet Loss probability;
5. Mean and Standard deviation of the E2E delay computed using the data sets below the 90% percentile and below the 95% percentile[3].

4 Results

For brevity, only test results concerning the short messaging between train and the control centre are reported here. Test also considered the transmission of augmentation information from the control centre (i.e. TALS) and train. This first test was performed twice for a total duration of 184 min. The main characteristics of the generated traffic are detailed in Table 2. As shown in Table 2 traffic characteristics are different for forward (from Train to Ground) and reverse (from Ground to Train) links. The same tests have been repeated using the Satellite link.

Table 2. Test: traffic characteristics

Stream type	Traffic Source	Traffic Destination	Traffic Type	Inter Departure	Payload Size (Bytes)
1	Ground/RBC	Cab/EVC	UDP	0.33 pkts/sec	300
2	Cab/EVC	Ground/RBC	UDP	0.25 pkts/sec	50
3	Ground/TALS	Cab/LDS	UDP	1.0 pkts/sec	135

[3] Rank order statistics filtering has been necessary to eliminate outliers that could seriously impair the calculation of statistics.

4.1 Terrestrial Network

In Figure 2 the average packet End-to-End Delay versus the train position (in terms of mileage from the head station) is plotted. The mileage has been quantized into bins, each one with a length of 250 meters. In each bin, we report the delays of packets that have been transmitted in the selected bin spatial interval. Purpose of this graph is to evidence the presence of anomalies in the estimated delay that can be related to the rail track characteristics. From analysis and

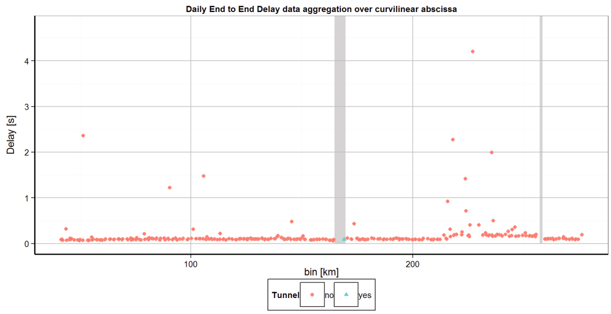

Fig. 2. Daily end-to-end delay versus train location - Terrestrial network, Stream 1

results in Figure 2 it is observed that large values of E2E delay are mainly due to tunnels and orography (physical barriers), causing poor service coverage areas along the rail track. This leads to significant variability of the available bit rate for transmission and/or to connection drops requiring re-setup. Another interesting phenomenon leading to an increase of the E2E delay was the delay in performing handover between different operators (roaming) or handover between 2G and 3G technologies and viceversa.

Forward Link - Train to RBC. The following Tables provide results on the percentiles of the packet E2E delay, jitter and on the probability that the packet E2E delay exceeds a threshold Thr (s). Results have been obtained by aggregating data obtained on the daily basis. The computed Packet Loss is 2.1%. The

Table 3. Percentiles of End-to-End Delay and Jitter (s) - Stream 2

No.Meas./Perc	50	70	80	90	95	99	99,9
E2E Delay	0.11	0.14	0.19	0.47	0.68	5,33	36.00
E2E Jitter	0.00	0.01	0.019	0.08	0.28	2.03	12.68

mean and the standard deviation of the E2E delay obtained by excluding data above the 90 and 95 percentiles are: 0.16s and 0.13s for the 90-th percentile and 0.22s and 0.39s for the 95-th.

Table 4. Probability E2E delay exceeds (Thr)

Dataset/Thr	1	2	5	7	10	12	15
Stream 2	2.87%	1.98%	1.03%	0.77%	0.51%	0.44%	0.33%

Table 5. Percentiles of End-to-End Delay and Jitter (s) - Stream 1 and Stream 3

No.Meas./Perc	50	70	80	90	95	99	99.9
E2E Delay - Stream 1	0.10	0.12	0.16	0.21	0.41	2.13	7.63
E2E Jitter - Stream 1	0.00	0.01	0.011	0.03	0.13	1.19	5.75
E2E Delay - Stream 3	0.1	0.11	0.16	0.19	0.35	2.15	8.15
E2E Jitter - Stream 3	0.00	0.002	0.01	0.02	0.05	0.63	4.02

Table 6. Probability E2E delay exceeds (Thr)

No.Meas./Thr.	1	2	5	7	10	12	15
Stream 1	2.06%	1.04%	0.28%	0.17%	0.06%	0.03%	0
Stream 3	2.07%	1.07%	0.31%	0.15%	0.05%	0.02%	0%

RBC to Train - Reverse Link. Similarly to the previous Section, the following Tables provide results on the percentiles of the packet E2E delay and jitter for Stream 1 and Stream 3 traffic types on the reverse link. Table 6 indicates the probability that E2E delay is greater than Thr. The packet loss for Stream 1 traffic is 3.40% and mean and standard deviation of the E2E delay computed on the 90 and 95 percentile datasets are: 0.12s, 0.05s (90-th) and 0.15s, 0.2s (95-th), respectively. Finally, the packet loss for Stream 3 is 3.40% and mean and standard deviation of the E2E delay computed on the 90 and 95 percentile datasets are: 0.11s, 0.04s (90-th) and 0.14s, 0.17s (95-th). Results for the two streams are not very different. In fact, signaling messages doesn't cause a significant increase in traffic in the terrestrial network. Table 7 summarizes the main results of the terrestrial network tests. The probability that E2E delay is larger than 2s has been evidenced. Results in Table 7 are taken from previous Tables for the three streams.

Table 7. Summary of test results - Terrestrial network

Forward-Link (Train/EVC to Ground/RBC)	
Stream 2 - Probability E2E delay > 2 s	1.98%
95% **Probability E2E max value**	679 ms
95% **Probability E2E mean value**	215 ms
95% **Probability E2E std dev. value**	390 ms
Packet Loss	2.05%
Reverse-Link (Train/EVC to Ground/RBC)	
Stream 1 - Probability E2E delay > 2 s	1.04%
95% **Probability E2E max value**	410 ms
95% **Probability E2E mean value**	147 ms
95% **Probability E2E std dev. value**	174 ms
Packet Loss	3.40%
Stream 3 - Probability E2E delay > 2 s	1.06%
95% **Probability E2E max value**	352 ms
95% **Probability E2E mean value**	141 ms
95% **Probability E2E std dev. value**	169 ms
Packet Loss	3.40%

4.2 Satellite Link

Tests with the satellite link have been repeated for 5 times for a total test duration of about 991 minutes. Figure 4.2 shows the measured packet E2E delay as a function of the train position. As expected E2E delay is increased with

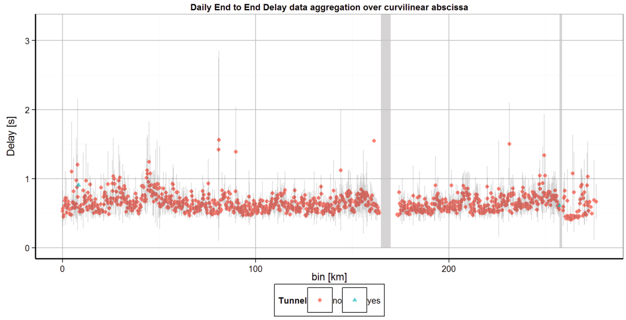

Fig. 3. Daily end-to-end delay as a function of the railway curvilinear abscissa - Integrated Satellite, Stream 1

respect to the terrestrial case, due to the additional (non negligible) propagation delay over the satellite link. Even in this case, significantly large E2E delays can be attributed to the presence of tunnels (in number of 2) and to orography, resulting in poor service coverage areas along the railtrack. When using satellite, we have experienced problems along the terrestrial interconnection path from the Inmarsat Gateway (England) and the control center (Ground/RBC in Munich) leading to an increase of delay from train-to-ground connection.

Forward Link (from Train to Ground) - Satellite The following Tables provide results on the percentiles of the packet E2E delay, jitter and on the probability the packet E2E delay is greater than Thr. As expected the probability that E2E delay is greater than 1s is significantly high due to both the additional satellite propagation delay and also to problems related to the terrestrial interconnection path from the Inmarsat Gateway (England) and the control center (Ground/RBC in Munich). The packet Loss is 1.02% and the mean and the standard deviation of packet delay evaluated by filtering data at 90 and 95 percentiles are: 1.09s, 0.43s (90-th) and 1.13s and 0.46 (95-th), respectively.

Table 8. Percentiles of End-to-End Delay and Jitter (s) - Stream 2, Satellite

No.Meas./Perc	50	70	80	90	95	99	99.9
E2E Delay	1.22	1.42	1.54	1.63	1.78	2.59	6.17
E2E Jitter	-0.02	0.27	0.54	0.90	1.13	1.56	4.32

Table 9. Probability that delay exceeds (Thr), Satellite

No.Meas./Thr.	1	2	5	7	10	12	15
Stream 2	67.8%	3.1%	0.14%	0.08%	0.05%	0.04%	0.03%

Table 10. Percentiles of End-to-End Delay and Jitter (s) - Stream 1 and Stream 3. Satellite

No.Meas./Perc	50	70	80	90	95	99	99.9
E2E Delay - Stream 1	0.56	0.69	0.80	0.98	1.16	1.69	4.34
E2E Jitter - Stream 1	0.01	0.06	0.13	0.28	0.43	0.89	2.57
E2E Delay - Stream 3	0.5619	0.7409	0.8525	1.019	1.148	1.707	4,43
E2E Jitter - Stream 3	0.00	0.04	0.12	0.28	0.44	0.76	2.14

Table 11. Probability that delay exceeds (Thr)

No.Meas./Thr.	1	2	5	7	10	12	15
Stream 1	9, 23%	0.61%	0.07%	0.05%	0.03%	0.02%	0.01%
Stream 3	10.52%	0.71%	0.08%	0.05%	0.03%	0.02%	0.01%

Reverse Link (from Ground to Train) - Satellite. The following Tables provide results on the percentiles of the packet E2E delay and the corresponding jitter for stream 1 and stream 3 traffic used on the reverse link including satellite. In Table 6 we indicate the Probability that delay is greater than threshold (Thr). The packet loss for Stream 1 is 1.53% and the mean and the standard deviation of packet delay evaluated by filtering data at 90 and 95 percentiles are: 0.61s, 0.17s (90-th) and 0.64s, 0.23s (95-th), respectively. Instead, for Stream 3 packet loss is 1.76% and the mean and the standard deviation of packet delay evaluated by filtering data at 90 and 95 percentiles are: 0.62s, 0.19s and 0.65s, 0.24s, respectively. The main results of the tests for the integrated satellite link are summarized in Table 12. From previous results it can be observed that satellite

Table 12. Summary of test results - Integrated Satellite link

Forward-Link (Train/EVC to Ground/RBC)	
Stream 2 - Probability E2E delay > 2 s	3.06%
95% **Probability E2E max value**	1780 ms
95% **Probability E2E mean value**	1120 ms
95% **Probability E2E std dev. value**	463 ms
Packet Loss	1.02%
Reverse-Link (Train/EVC to Ground/RBC)	
Stream 1 - Probability E2E delay > 2 s	0.61%
95% **Probability E2E max value**	1160 ms
95% **Probability E2E mean value**	639 ms
95% **Probability E2E std dev. value**	223 ms
Packet Loss	1.53%
Stream 3 - Probability E2E delay > 2 s	1.06%
95% **Probability E2E max value**	1150 ms
95% **Probability E2E mean value**	650 ms
95% **Probability E2E std dev. value**	235 ms
Packet Loss	1.76%

integration has the (obvious) undesired effects of increasing the E2E delay but packet loss probability is significantly reduced in every case with respect to the terrestrial link. This is due to the increased availability, QoS and better coverage provided by the satellite.

5 Cost Assessment

Public telecommunication services represent a cost efficient solution for the economical sustainability of the ERTMS-ETCS platform on local and regional lines. To evaluate the costs of an hybrid (cellular-satellite) multi-bearer solution we have assumed the average price of cellular and satellite services offered by telecom operators and the cumulative data traffic exchanged between the train and the Radio Block Center according to the ETCS standard. The traffic is routed mainly through the cellular networks for approximately 80% of the time and the satellite is used, as a backup for the remaining 20% of the time. This share is arbitrary and results from a trade off on the availability of the cellular network in typical local and regional lines. A fleet of 100 trains (70 operating simultaneously) and an amortization period of 5 years have been considered to estimate the total operation costs incurred to ensure the service. Under these assumptions the average cost x train x month is about 900 euro and it includes the costs for equipping the trains with the multipath router, the satellite/cellular antennas, plus the communication fees for the providers of the telecom services. These costs are independent from the length of the rail line and vary only with the number of operational trains. Therefore the real benefits depend on the typology of the line, the number of operational trains and the line capacity. However for the local and low traffic lines (about 50% of the total European network length) this solution may be particularly convenient compared to traditional GSM-R networks that would imply up-front investments not economically sustainable for low traffic lines. Furthermore, the M2M based solutions are expected to grow exponentially in the near future and the cellular networks will improve their coverage and capacity with the incoming 5G standard. As a consequence the unitary cost for the transmission of ETCS messages is expected to drop. Similarly, the satellite communications networks will provide more bandwidth at lower cost and, most importantly, satellite operators can dedicate capacity for such services in order to guarantee the emergency call and group calls that, being the most demanding in terms of set up time, cannot be guaranteed with the best-effort services of the cellular networks.

6 Conclusions

We have investigated the performance of cellular and satellite public networks in the railways environment for supporting an hybrid telecom solution as candidate alternative to the GSM-R for the ERTMS-ETCS evolution. The proposed solution consists of a multi-bearer system making use of a combined cellular-satellite system with on board intelligent routing to select the bearer and guarantee the

Quality of the Service that is required by the ERTMS-ETCS. The case of the regional/low traffic lines has been analyzed and resulted attractive from the economical point of view since the investments to deploy a dedicated GSM-R network can be avoided. This solution could accelerate the modernization of these lines most of which are obsolete and costly to operate. The test campaign has been carried out along a 300 Km line crossing big cities, rural areas, tunnels and bridges and the tests have been repeated for 21 days totaling some18 thousands km travelled distance. The data have been processed to derive the most important parameters and the results in terms of packet loss and E2E delays are encouraging. Further work is on progress to develop and validate the multi-bearer routing algorithms and to define the process for homologation and certification a service-based solution in the frame of the ERTMS-ETCS evolution.

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