Integrated Public Mobile Radio Networks/Satellite for Future Railway Communications

Franco Mazzenga, Romeo Giuliano, Alessandro Neri, Francesco Rispoli

Abstract

European train control system adopts GSM-R for communications between train and the command/control center. GSM-R technology is quite old and will be replaced in the near future by other technologies offering lower cost solutions especially for regional and local lines. This paper investigates a new telecommunication solution based on multi radio bearers using cellular and Satellite public networks as an alternative to the deployment of a dedicated infrastructure.
A test campaign on a 300 km of rail line (about 10,000 km of tests) has been carried out to evaluate the performance of cellular and Satellite networks in a railways environment. Test trial results presented and discussed in this paper have been used to assess the performance of multipath TCP protocol to effectively support multi-bearer communications. The discussion on the economical benefits and the potential industrial implications of the proposed solution concludes the paper.

Keywords

Railway communications and train control, European Rail Traffic Management System/European Train control System, Public Land Mobile Network, Satellite communications, Machine-to-Machine communications, Multipath TCP.

I. Introduction

TELECOMMUNICATION systems are fundamental for railway applications to connect passengers as well as to improve safety, security and efficiency in the train management process. In [1], [2], it is envisaged that future railway communication systems will integrate a variety of systems, each of them oriented to specific services. Services to passengers will be provided by several radio systems according to the market demands and to advanced content-based applications. Instead, the communication platform for railway management will be based on an unified infrastructure supporting (real-time) collaborative services, so to improve operational effectiveness and facilitate information exchange. Management of railway operations 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 [3]. The European Rail Agency (ERA) has undertaken studies to evaluate options for the evolution/replacement of the GSM-R. The GSM-R is suffering from technology obsolescence, electromagnetic compatibility with 4G (LTE) networks and limited capacity [4]. Capacity improvement is important [5] to support broadband future advanced control services such as train monitoring based on real time video captured from the train's cabin.
In the definition of a viable solution, two major challenges arise: to comply with the interoperability requirement and, from the train operator side, to protect the investments on the GSM-R. Anyway, a migration path to a fully IP-based system is started, and 4G and the incoming 5G could facilitate the evolution towards a full service-based system for every rail application, [6]. Concerning cost reduction, a first significant breakthrough in economic sustainability is represented by the replacement of proprietary,

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dedicated networks with commercial public land mobile networks (PLMNs) and Satellite. The use of public telecommunication infrastructure(s) allows to rapidly extend the existing automated train control procedures (such as European Rail Traffic Management System/European Train control System, ERTMS/ETCS, and Communications Based Train Control [7]) for improving rail traffic capacity for local/regional lines where the deployment of a dedicated radio infrastructure is expensive in terms of both CAPEX and OPEX. Furthermore, public networks can be considered as low cost and effective enablers for the rapid deployment of the modern railway information system such as that proposed and investigated in the InteGRail project, [8].

This innovative scenario would imply a step-change in the liability process with the introduction of the guaranteed QoS in the provisioning of mobile connectivity services by telecommunication operators. Considering that in the short/medium term radio bearers provided by public networks will offer best-effort services only, in the framework of the ESA 3InSat project [9] we have evaluated the possibility of achieving acceptable QoS through public networks and its economical feasibility.

In this paper we evaluate the performance for train control system adopting PLMNs for signaling. The considered system jointly uses all the available best effort bearers, which are intelligently managed by an on-board Multipath Router device, i.e. the multiple access router (MAR). The MAR adopts multipath TCP (MPTCP) protocol, [10]. To further improve performances, we propose the integration of a guaranteed QoS link provided by Satellite in case of unavailable or congested PLMNs. Experimental data concerning the end-to-end delay and link availability are presented and discussed in this paper for both terrestrial and Satellite links. These data have been used to evaluate the overall end-to-end delay for the (typical) message exchange procedure between the train and the control center based on the MPTCP protocol. Results can be used by the railway operator to infer on the achievable QoS for the typical train control procedures. The paper is organized as follows. In Section II we review the main issues related to the adoption of PLMNs for railway communications. In Section III we detail the proposed architecture for the integrated PLMN/Satellite communication infrastructure based on multi-bearer management and the MPTCP protocol. In Section IV we describe the testbed scenario, the data obtained from the experimental campaign and MPTCP simulation results. The discussion on the costs for the proposed public infrastructure are presented in Section V. Finally, conclusions are drawn.

II. Main issues for the adoption of PLMNs for railway communications

Some of the main issues related to the adoption of integrated PLMN/Satellite radio networks for railway communications are discussed in this Section. Before going into detail, it is helpful to review the GSM-R requirements.

A. *Summary of EIRENE requirements*

GSM-R improves traditional GSM in terms of extended voice and data services and increased reliability. Specifications in [11] establish the main requirements of a (generic) radio bearer for supporting ERTMS/ETCS communications. From [11], the railway radio network shall be designed to fulfill the following requirements:

1) **cell-coverage specifications**: coverage probability of 95% based on a coverage level of 38.5 dBmV/m (-98 dBm) for voice and non-safety critical data; coverage probability of 95% based on a coverage level of 41.5 dBmV/m (-95 dBm) on lines with ETCS levels 2/3 for speeds not greater than 220 km/h;
2) **Handover and cell-reselection specifications**: the handover success rate shall be at least 99.5% over train routes under design load conditions.
3) **Call setup time and priority specifications**: class 1 (fast set-up) 1-2 s, class 2 (normal set-up) $<$ 5 s, class 3 (slow set-up) $<$ 10 s.

Furthermore, connection establish failure probability shall be lower than 1% for 100% of time, the data transmission delay shall be kept below < 0.5s for 99% of time with an error rate of lower than 1% per hour and duration of transmission failures $< 1s$ for 99% of time. The previous figures apply only to high

speed railway lines.
Discussions among railway operators for extending the previous radio link requirements to local/regional lines are still ongoing. Until now, no figures have been agreed. Nevertheless, due to reduced train speed and low/medium traffic volumes, it is widely believed that these values will be relaxed. This strongly motivates studies on the usage of integrated PLMN/Satellite networks, [9].
It is not immediate to "re-phrase" the previous requirements to the PLMN scenarios since they should account for two related aspects: *i.* availability of radio bearers along the line; *ii.* achievable communication performances given the available radio bearers. Requirements in [11] have been issued by implicitly assuming the (proprietary) radio network has been properly deployed along the railway. In the public scenario the number of available bearers can change over the railway and then the achievable performances. This fact may render the requirements' definition very complicated or even impossible. In addition, since the public radio infrastructure is given in practice, the possibility for the railway operator to improve link performance could be limited (see next Section for a discussion).
Thus, we believe that performance requirements issued by railway regulators should directly refer to the manage and control procedures implemented by the train signaling system. In the following we refer to the typical position report (PR)/movement authorization (MA) "two-way" message exchange procedure between the European Vital Computer (EVC) and Radio Block Center (RBC), which is the basic step to implement (more complex) train control procedures such as the passage of a train to/from a high speed line to a legacy line, the manage/control of train movement along the line etc. as detailed in [5]. In general, the message exchange period depends on the considered procedure and can vary from seconds up to tens of seconds. Anyway, the overall end-to-end delay should not exceed k seconds[1] for the $x\%$ of time. In this case, the railway operator should verify (possibly by simulation and/or extensive experimental campaigns) the respect of these requirements before the line can be declared suitable to support rail signaling using PLMNs and Satellite.

B. *Technological aspects for improving radio link performance*

As outlined above, due to the (possible) availability of more than one radio bearers while train is moving along the line, improvement of radio link performance could be achieved by (jointly) considering the following technical options:

1) **Adoption of multi-radio technologies (MRT)**: the on-board equipment should route messages on any available terrestrial radio interface(s) (e.g. GSM, UMTS-WCDMA, LTE) and/or on Satellite. Routing decisions could be based on the current traffic load in the PLMN(s) and on Satellite link availability.
2) **Connecting to multiple radio networks of different mobile network operators (MNOs)**: the on board equipment should switch among bearers of different operators and/or setup and maintain multiple radio links with the different networks.

In the following points we summarize other typical remedies to improve coverage, handover/cell-reselection and call setup.

C. *Radio coverage issues*

It is not easy to provide general recipes to mitigate PLMN coverage problems for every railway. Actions to be undertaken depend on the specific rail track and on its propagation environment. During the design phase the actual radio coverage provided by the existing PLMN/Satellite infrastructures over the line should be assessed by measurements and/or predicted by propagation models. The simultaneous presence of multiple MNOs in the area is helpful to improve coverage[2] when the multi-bearer option is considered. In addition,

[1]Usually $k \leq 7$s for the high speed trains in Italy. This limitation could be relaxed for regional/local lines.
[2]It is worth to observe that co-location of Base Stations of different MNOs works against radio coverage improvement.

it should be observed that the single terminal automatically (and seamlessly) roams on networks of other MNOs in the absence of coverage. It should be railway operator's responsibility to install extra base stations to improve coverage in the specific areas along the railway line with consequently installation and maintenance costs. Agreements between mobile and railway operators could be helpful to share costs. Many times, the Satellite can be the only viable option to guarantee/to improve coverage in rural areas where PLMNs provide limited coverage or are absent at all. Finally, when the Satellite link is not available and the costs to improve coverage are too high, the "manual" procedural level could be the ultimate option. In this case, the un-covered zone(s) along the line could be first geo-referenced on a map and when the single train is approaching these zones, manual control procedures (maybe including speed reduction, visual maneuvering, etc.) shall be operated to guarantee safety. However, if the number of coverage holes along the line is high, manual procedures could negatively impact the benefits provided by the automatic train control system.

D. 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 strongly impacting the handover/cell-reselection performance. To mitigate these problems in the presence of congestions, priority mechanisms for dropping one (or more) active calls when the train is executing handover should be (possibly) agreed/negotiated with the MNOs. The possibility of reserving radio channels for train communications only at specific hours of the day, is another option to meet handover/cell-reselection requirements.

E. Call setup

In PLMN call setup delays can be related to cell load and can be very difficult to control. Specifications in [11] consider priority levels in the call setup phase in relation to the call type. It seems to be difficult to relax call setup requirements even for regional/local lines. The MRT and multiple MNOs options could be helpful to improve call setup objectives. However, the time required for emergency call is the most important factor to be accounted for. In this case the adoption of Satellite is mandatory to cope with congestion or unavailability of terrestrial networks. In this perspective, the adoption of integrated PLMN/Satellite networks for railway communications is a valuable option even for safety [12].

III. INTEGRATED PLMN/SATELLITE NETWORK ARCHITECTURE

In Figure 1.a we illustrate the architecture of the integrated PLMNs/Satellite network for train control/management operations considered in this paper. It is assumed the train can be simultaneously connected to one or more PLMNs and Satellite possibly using the available best-effort bearers. The infrastructure in Figure 1.a is used for the PR/MA messages exchange between the on-board EVC and the RBC. In particular, train periodically reports its position to the RBC in the PR message. The interlocking sub-system reports to the RBC the status of the track-side devices. By combining these information, the RBC generates the MA message, which is sent from RBC to the EVC. The lengths of PR and MA packet are of some hundreds of bytes. For example, the MA message length can range between 205 up to 321 bytes.

The train position is provided by the Location Determination System (LDS) using GPS with differential corrections provided by the local augmentation network deployed along the railway line. This network includes GPS measurement stations (ASs), which acquire and pre-process GPS data from Satellites, and send them to the Track Area LDS Server (TALS) by means of wired communication network. Data from ASs are further processed by TALS to calculate differential corrections, which are then delivered to the train by terrestrial or Satellite networks.

A. On-board Multipath Router and Multipath TCP

Following the considerations in [15], to efficiently exploit all the available (best-effort) bearers (i.e. without traffic prioritization), intelligent on-board MAR adopting MPTCP protocol has been considered. The MAR is in charge of managing all the radio communication bearers available in the train area. We can distinguish between two operational modes. In the first one, the MAR can activate and manage all the available terrestrial bearers (with different MNOs and using different technologies by the same MNO). Due to costs, Satellite should be seen as a backup when no terrestrial network is available. In the second mode, MAR can intelligently select one bearer at time among those available to send/receive messages to/from RBC. The bearer selection could be based on information provided by MNO concerning the status of its access network (e.g. network load, available capacity etc.) or run-time measurements. The MAR could simultaneously select two (or more) radio bearers for different communication services such as, for example, GSM for signaling and UMTS for voice even though each MNO can limit the access to just one bearer in its own PLMN. Moreover, the MAR could vary the priority among active bearers based on *i.* the current link status, *ii.* the historical data on the map (i.e. reporting the positions of link outages along the rail track) and *iii.* the cost (i.e. selecting the cheaper link).

Roaming from one MNO to another and/or inter-radio technology handover could cause significant increase in the end-to-end (E2E) delay. Delays on the order of some seconds or more have been recorded during trial. To avoid these drawbacks, MAR should be able to "anticipate" handover/roaming preparation. To this aim, it could exploit the information on the train position provided by the LDS on-board sub-system so to access the database of available base stations/networks along the line.

The MPTCP protocol layer sits above the multi-link management (MLM) layer in Figure 1, which manages link-level connectivity with every available radio technology. MLM should be optimized to exploit all the available radio bearers along the route and switch to Satellite when no cellular network is available. In the simplest and non-integrated implementation, MAR can be equipped with (several) separated modems, managed by MLM, each one with its own SIM card (i.e. one SIM for each PLMN).

IP-based solutions are being currently introduced on rail communications and MPTCP provides a compatible IP interface for multi-bearer devices. The main advantage of MPTCP is to extend IP to multiple link case without requiring any modification to application layer. Alternatives to MPTCP, such as mHIP and Multipath SCTP, are discussed in [15]. The MPTCP allows to efficiently manage the routes on available best effort multi-bearers thus guaranteeing reliable data transfer from EVC to RBC and vice versa. To achieve QoS, MPTCP can switch traffic from congested path to an un-congested one. The MPTCP inherits all the advantage from regular TCP and provides value-added features such as aggregated bandwidth, high reliability and detection of duplicates and discarding. Furthermore, MPTCP is a platform-independent protocol, it enables inverse multiplexing of resources thus increasing TCP throughput. MPTCP has an efficient congestion control mechanism, it can implement a different congestion window for each path and it is able to send (more) packets on the less congested path. The considered MPTCP-based MAR approach is advantageous in the railway environment using both PLMNs and Satellite because of the limited bandwidth requirement that has negligible impact on the operational costs. In addition to throughput gains from inverse multiplexing, links may be added or dropped without disrupting the end-to-end TCP connection. The problem of link handover is solved by abstraction in the transport layer, without any special mechanisms at the network or link level i.e. handover functionality can then be implemented at the endpoints without requiring dedicated functionalities in the crossed sub-networks. The principle protocol architecture of the proposed MAR+MPTCP solution applicable to the considered integrated PLMN/Satellite scenario is shown in Figure 1.b. Railway applications running over the Euroradio protocol layer communicate using the MPTCP/IP layer and MAR for multi-bearer connectivity.

B. Extension of Euroradio protocol to multi-bearer scenario

Exchange of messages among applications in the EVC and RBC are managed by the Euroradio protocol [13] indicated in Figure 1.b. Extension of railway communications to the public radio scenario requires modifications in the Euroradio stack. The Euroradio layer is partitioned into two modules: the Safety Functional Module (SFM) providing services for safe connection set-up and safe data transfer and the Communication Functional Module (CFM) providing the interface with the underlying communication system. The SFM and CFM communicate through the TSAP (Transport Service Access Point). The extension of the Euroradio protocol should focus on the CFM enhancement while SFM sub-layer should be kept unchanged. Currently the CFM sub-layer interfaces with one communication technology and it is designed to: activate the data connection based on packet switching (IP) or circuit switching (as in the case of GSM and GSM-R), to allow data exchange between EVC and RBC and to perform error control and signaling. In our case Euroradio CFM should be extended to interface with the MPTCP/IP layer.

IV. Test trial and MPTCP performance

In this section we describe the test trial and we provide the main achievements of the experimental campaign and then we report the results on the MPTCP performances.

A. *Test description and results*

The test scenario reproduces the scheme in Figure 1.a and is detailed in [14]. Tests have been conducted in the framework of the ESA 3InSat Project [9], concerning the realization of a railway testbed for testing Satellite navigation and communication technologies for railway applications, under realistic operational conditions. The four weeks test campaign has been performed on the 300 km long railway connecting Cagliari and Olbia towns in Sardinia island (Italy). The maximum train speed has been 150 km/h and we have performed two trips per day lasting 3:50 hours each way. The cellular, GPS and Satellite antennas have been placed on the roof top of the train with unobstructed view to the sky. Tests have been executed using the Vodafone IT 2G/3G public mobile access networks providing seamless roaming to other mobile networks in case of lack of Vodafone PLMN coverage. Terrestrial communications have been integrated with Satellite link provided by Inmarsat Satellite (BGAN configuration). The on-board equipment has included the EVC and the LDS. Both functionalities have been emulated by software running on a portable PC. The RBC emulator has been hosted by a server cluster located at TriaGnoSys lab facilities (Munich, Germany). To determine the train mileage with respect to the head station, the LDS uses data from GPS with differential corrections provided by the TALS. The deployed augmentation network includes two GPS measurement stations (one in Samasti town and the other at Decimomannu town). All data collected in the test trial have been analyzed to extract statistics of the E2E delay, jitter and packet loss probability for different types of traffic. For brevity, only results concerning fixed and variable size messages exchange between train and the control center have been reported here. Tests have also considered the transmission of augmentation information from the control center (i.e. TALS) and the train. The main characteristics of the generated traffic are detailed in Table I. As shown in Table I traffic characteristics differ for the Train-to-Ground and the Ground-to-Train directions. Tests have been executed for terrestrial and Satellite cases using UDP protocol provided by Vodafone IT. Thus, test trial could not be used to directly test MPTCP on the field. Nevertheless, as shown in the next Section, results from trial have been used to evaluate MPTCP performance by simulation.

In Figures 2 we plot the probability the packet E2E delay exceeds a threshold value, T_E. Terrestrial and Satellite cases have been reported for packets with fixed and variable size. As expected, due to the (non-negligible) propagation delay over the geostationary Satellite link, the probability the E2E delay on the Satellite link exceeding small T_E is higher than terrestrial link. However, due to smaller probability of congestion of the Satellite link with respect to the terrestrial one, for large T_E Satellite guarantees better performance. In Table II we report the mean and the standard deviation of the E2E delay after having discarded measured data above the 95-th percentile. From extensive analysis of measured data it has been observed that large values of E2E delay are due to the presence of tunnels and orography (i.e., physical barriers), causing poor service coverage areas along the rail track. This leads to a significant variability of the available bit rate for transmission and/or connection drops, which require re-setup. A significant increase of the E2E delay has been experienced during handover between different operators (i.e. roaming) or handover between 2G and 3G technologies and vice versa. Using Satellite, sometimes we have experienced problems along the terrestrial interconnection path from the Inmarsat Gateway (England) and the control center (Ground/RBC in Munich). This has led to an increase of the E2E delay from Train-to-Ground connection.

B. *MPTCP analysis and performance*

Very preliminary assessments on the suitability of MPTCP protocol for railway applications have been presented in [15] in terms of (theoretical) link availability, only. In this paper, performance analysis of MPTCP has been carried out by simulation using the cumulative distribution function (CDF) of the E2E delay and the link availability obtained from test trial. We assume MPTCP protocol is used by MAR to transmit the PR message and by RBC to reply with the MA message. We have implemented the MPTCP state machine incorporating the basic scheduling algorithm in [10] i.e. we assume only one available technology is used at time. Transmission is started using the radio bearer with the lowest round-trip-time (RTT) among those available. Another bearer is selected by the scheduler if the acknowledgment message (ACK) is not received within the timeout (TO). In principle, the TOs could be different for each technology. The RTT is the sum of the E2E delays of the two links that are generated in accordance to the experimental statistics of the E2E delay introduced in the previous Section. Furthermore, the message is correctly delivered with probability equal to the link reliability in Table II for terrestrial and Satellite. We assume the two transmission directions (from EVC to RBC and vice versa) are independent. In the case the message is dropped on one of the two directions, we assume the TO in the MPTCP elapses and the scheduler selects another radio bearer among those still available. If no further radio bearer is available we assume the MPTCP link is off and an outage event is recorded. Finally, to evaluate performance we assume that all terrestrial links behave in the same way in terms of E2E delay and link availability.

MPTCP performances have been expressed in terms of the complementary CDF (C-CDF) of the time required to complete the PR/MA messages exchange and in terms of the probability for the procedure to end up successfully. We have excluded from calculation the additional time required for processing the PR message and to generate the MA in the RBC. It is not difficult to adapt results to include (constant) additional time due to message processing.

In Table III we provide the probability the overall PR+MA procedure successfully ends up as a function of the number of available bearers. In Figure 3 we plot the C-CDF of the E2E delay for different TO and number of available technologies for fixed (left) and variable (right) message size. Results prove that MPTCP allows to significantly improve the probability for the procedure to end up successfully and to reduce the E2E delay with the number of available bearers. Curves in Figure 3 show that the probability the time required to complete the procedure (excluding message processing time) exceeds 5 seconds is negligible and this should be compared with the limits indicated in the previous Section. Furthermore, the selection of TO is important to better exploit the availability of more bearers and to avoid the un-necessary increase of the overall procedure time. In fact, results show that due to the improved link reliability the TO should be (adaptively) reduced with the increase of the number of active/available bearers. Finally, it is worth noting that the TO for the Satellite link should be selected to be greater than 1 s.

V. COST ASSESSMENT

This section shows the results of a preliminary cost analysis of an integrated public mobile radio network compared with the cost of a dedicated network. To this aim, we have assumed the average market price of cellular/Satellite connectivity multiplied by the usage rate, ending up with a turn-key service of 900 euro/train/month when considering a five years amortization period. To this operational expenses, a $10,000$ euro/train capex cost has to be summed up for each train for the train equipment. While for the GSM-R an overall turn-key infrastructure cost of $50,000$ euro/km is an accepted value when considering the investments already made. Previous cost estimates have been provided by Ansaldo STS and are based on the studies in [16], [17]. However, the exact values depend on the complexity of the line and availability of telecommunication infrastructures. Anyway, the $50,000$ euro/km represents a realistic assumption for equipping local and regional lines with a dedicated GSM-R infrastructure. Additional costs for network management are 7% per year of the total CAPEX, [9]. Based on previous assumptions, results in Figure 4 demonstrate the economic benefits of the integrated public mobile radio network solution for two railways lines of 200 km and 500 km as a function of the number of circulating trains. The costs of the public mobile radio network solution are dominated by the number of trains and are independent of the length of the line since the infrastructure is already available. Instead, the line length becomes the dominant cost for dedicated networks solutions. As a general trend, the public TLC solution exploits its maximum benefits for low traffic and regional lines for which a dedicated line is difficult to justify even if the investments may be some 30% to 50% lower than the average value assumed in our computations.

VI. Conclusions

This paper proposes a new solution based on cellular and Satellite public networks for reducing the costs of a dedicated telecommunication infrastructure in accordance with the objectives of the future evolution of the ERTMS train control system. The novelty consists of a multi-bearer communication solution based on MPTCP making use of an integrated PLMN/Satellite network with an on-board intelligent routing mechanism to provide the required QoS. This solution is particularly attractive for regional and local traffic lines most of which require huge investments to be upgraded. Our solution may contribute to the adoption of a cost efficient ERTMS system to replace the existing and obsolete equipment. To assess the validity of the PLMN/Satellite solution we have used experimental results obtained from a comprehensive test trial in Sardinia, Italy, for evaluating MPTCP performance. Results in terms of achievable link reliability and E2E delays are encouraging towards the adoption of PLMN/Satellite to export ERTMS/ETCS procedures.

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References

[1] M.T. Fatehi, J. Simon, W. Chang, E.T. Chow, S.C. Burleigh, "Enhanced Communication Network Solution for Positive Train Control Implementation", Rail Conference, Boston, Massachusetts, June 12-15, 2011.

[2] R. Sarfati,"GSM-R is becoming IP ready", UIC ERTMS World Conference, Istanbul, Turkey, 2 April 2014

[3] "Satellite Communication to support EU Security Policies and Infrastructures Concept", available at http://www.pwc.fr/assets/files/pdf/2015/02/pwc_concept_paper_satcom.pdf

[4] F. Pujol, J. S. Marcus, "Evolution of GSM-R", ERA/2014/04/ERTMS/OP Interim Report v1.5, Jan. 2015.

[5] F. Senesi, E. Marzilli, "European train control system", Ed. CIFI, 2007.

[6] Next Generation Train Control 7th FP program, http://cordis.europa.eu/project/rcn/110543_it.html

[7] R. Alvarez, J. Roman, "ETCS L2 and CBTC over LTE Convergence of the radio layer in advanced Train Control Systems", The Institution of Railway Signal Engineers (IRSE) Australasia Technical Meeting, Perth, Australia, 18 October 2013.

[8] InteGRail - Intelligent Integration of Railway Systems, Project no. FP6 - 012526, website: www.integrail.info and www.integrail.eu.

[9] 3inSat EU project, description available online at http://iap.esa.int/projects/transport/3insat

[10] F. Yang, P. Amer, N. Ekiz, "A Scheduler for Multipath TCP", Int. Conf. Comp. Comm. Netw. (ICCCN 2013), Nassau, Bahamas, Jul./Aug. 2013, p.1-7.

[11] GSM-R Operators Group, "EIRENE System and Functional Requirements Specification", V15.3.0. 2012

[12] https://artes.esa.int/projects/satcom-rail-specification-certification-framework-satcom-railway-safety-applications

[13] Alcatel, Alstom, Ansaldo Signal *et al.*, "Euroradio FIS", subset-037, v. 2.3.0, 14 October 2005

[14] F. Mazzenga, R. Giuliano *et al.*, "The Adoption of Public Telecom Services for the Evolution of the ERTMS-ETCS Train Control Systems: Challenges and Opportunities", Communication Technologies for Vehicles, Lecture Notes in Computer Science, Springer International Publishing, Vol. 9066, 2015, p. 177-188.

[15] I. Lopez, M. Aguado, E. Jacob, “End-to-End Multipath Technology: Enhancing Availability and Reliability in Next-Generation Packet-Switched Train Signaling Systems”, IEEE Vehicular Technology Magazine, Vol.9, Is.1, Mar. 2014, p.28-35.
[16] “UIC ERTMS Benchmark Project Final Report”, Update 2010, available at: http://www.uic.org/cdrom/2011/05_ERTMS_training2011/docs/benchmark/ERTMSFinalReport2010.pdf
[17] “Study to develop tailor-made solutions for use of innovative financing to support deployment of ERTMS, in particular along nine core network corridors”, PWC 2015, Brussels, Belgium, 20 January 2015, available at: http://ec.europa.eu/transport/themes/infrastructure/events/doc/2015-workshop-innovative-financing-ertms/presentations.pdf.

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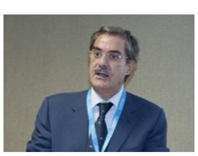
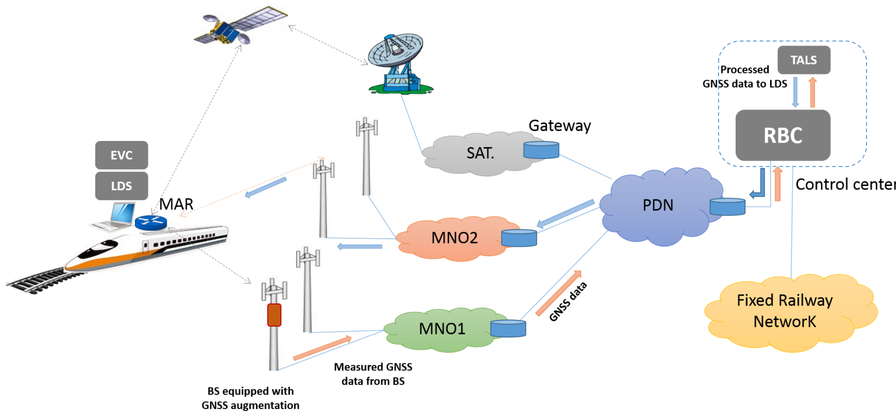
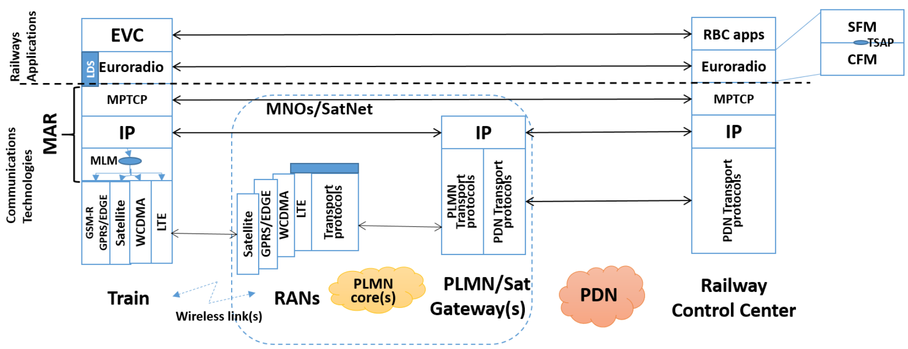


Francesco Rispoli graduated in Electronic engineering (Polytechnic of Turin) in 1978 and holds a Master in applied electromagnetism at the University of Rome “la Sapienza” in 1980. From 2011 is with Ansaldo STS Innovation Unit - Satellite projects, coordinating the development of new technological platforms for satellite-based train control systems. He is leader of the European satellite working group on Next Generation Train Control project and he is board’s director of Galileo Services for rail applications. He is the general director of Radiolabs.

FIGURES



(a)



(b)

Fig. 1. Reference telecommunication infrastructure for integrated PLMN/Satellite for railway communication: principle architecture *(a)* and protocol architecture for the considered MAR+MPTCP *(b)*.

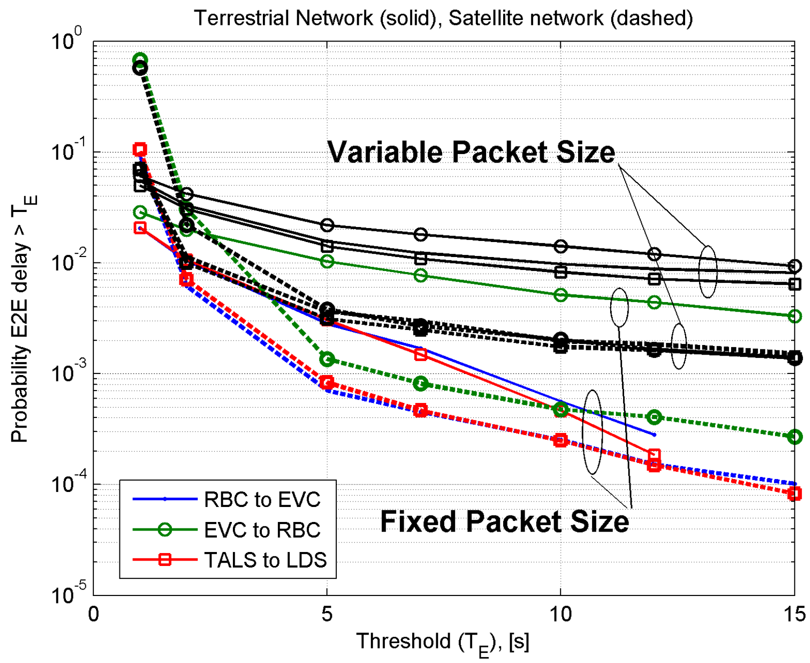


Fig. 2. Probability the E2E delay is greater than threshold – fixed and variable packet size.

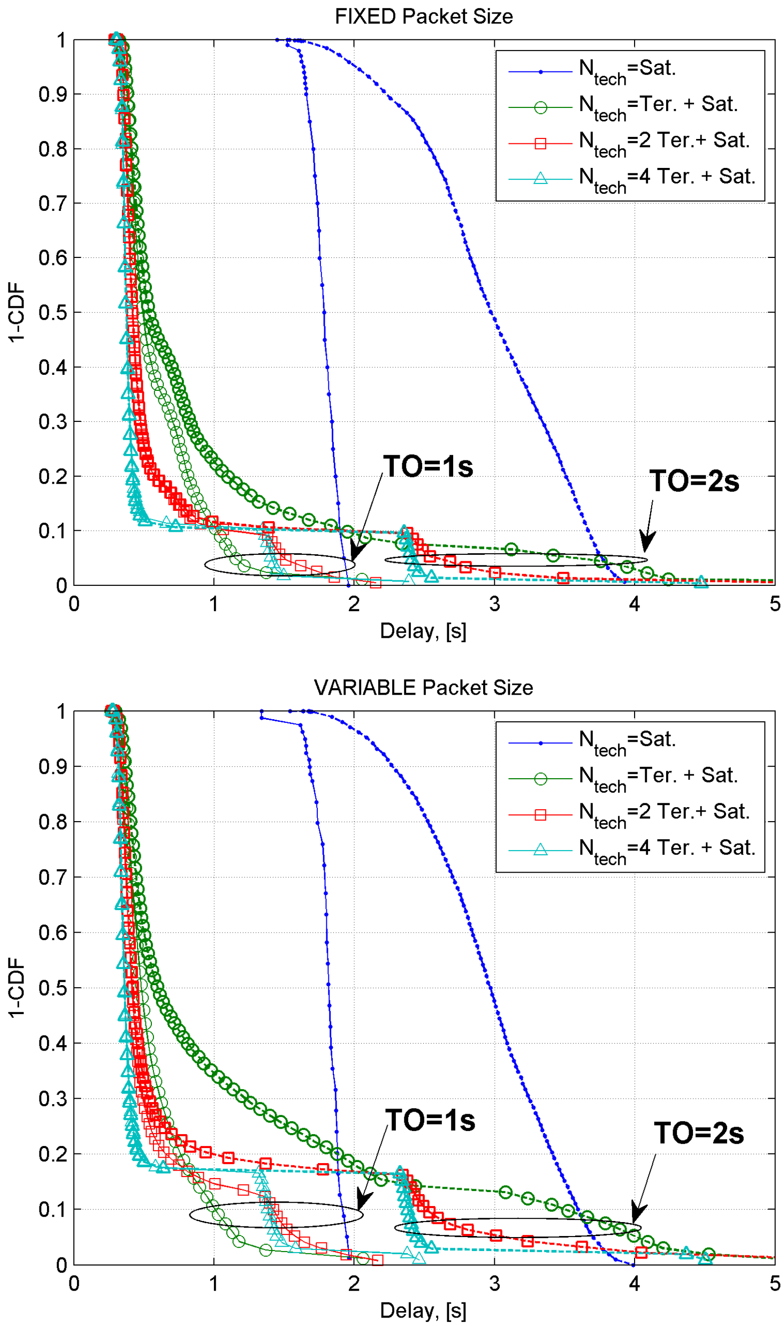


Fig. 3. MPTCP performance: C-CDF of the E2E delay for different TO values and number of available bearers, fixed and variable packet size.

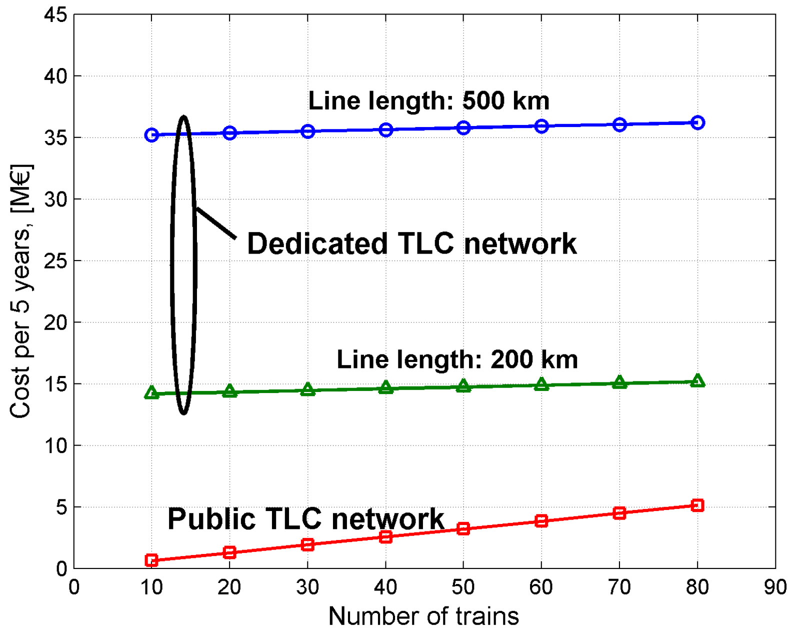


Fig. 4. Cost analysis: Dedicated vs Public TLC network.

TABLES

TABLE I. TRAFFIC CHARACTERISTICS OF THE TEST TRIALS

Test parameters and traffic features					
Fixed packet size					
Stream	Traffic Source	Traffic Destination	Traffic Type	Inter-departure time	Payload Size (Bytes)
1	RBC	EVC	UDP	constant, 0.33 pkts/s	300
2	EVC	RBC	UDP	constant, 0.25 pkts/s	50
3	TALS	LDS	UDP	constant, 1.0 pkts/s	135
Variable packet size					
1	RBC	EVC	UDP	exp, 1.0 pkts/s avg	exp, 1000 avg
2	EVC	RBC	UDP	exp, 1.0 pkts/s avg	exp, 200 avg
3	TALS	LDS	UDP	exp, 1.0 pkts/s avg	exp, 500 avg

TABLE II. MEAN AND STANDARD DEVIATION OF THE E2E DELAY (95-TH PERCENTILE) AND LINK AVAILABILITY.

Link type	Terrestrial		Satellite	
	Fixed packet size	Variable packet size	Fixed packet size	Variable packet size
RBC-to-EVC				
Mean E2E delay (s)	0.15	0.26	0.64	0.64
Std. E2E delay (s)	0.17	0.69	0.22	0.23
Link Availability	96.60%	94.20%	98.47%	98.72%
EVC-to-RBC				
Mean E2E delay (s)	0.22	0.33	1.13	1.03
Std. E2E delay (s)	0.39	1.10	0.46	0.42
Link Availability	97.95%	96.35%	98.97%	99.02%
TALS-to-LDS				
Mean E2E delay (s)	0,14	0,23	0,65	0.62
Std. E2E delay (s)	0,17	0,60	0,24	0.21
Link Availability	96.43%	94.55%	98.24%	98.96%

TABLE III. PROBABILITY TO HAVE THE PR+MA PROCEDURE SUCCESSFULLY COMPLETED. LEGEND: T=n, n TERRESTRIAL LINKS ARE AVAILABLE, S=1, ONE SATELLITE LINK ALWAYS AVAILABLE.

	T=0, S=1	**T=1, S=1**	**T=2, S=1**	**T=3, S=1**	**T=4, S=1**	**T=5, S=1**
FIXED PACKET SIZE						
TO=0.5s	0%	58.47%	88.16%	97.23%	99.35%	99.86%
TO=1s	0%	81.10%	97.58%	99.77%	99.97%	99.99%
TO=2s	39.46%	93.88%	99.38%	99.94%	99.98%	100%
VARIABLE PACKET SIZE						
TO=0.5s	0%	51.44%	85.01%	95.39%	98.87%	99.62%
TO=1s	0.43%	65.63%	93.09%	98.69%	99.58%	99.92%
TO=2s	53.78%	90.51%	98.31%	99.73%	99.93%	99.99%