Public Land Mobile Networks supporting Regional Train Management

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Abstract—Telecommunications are strategic assets for the design and operation of train control systems based on automatic train protection to prevent errors due to the human factor. The ERTMS/ETCS train control system developed in Europe is considered a world-wide de facto standard. It utilizes a dedicated telecommunication network based on the GSM-R system. This approach is not economically sustainable for low traffic lines due to the cost of building and monitoring the telecommunication infrastructure. This paper presents a novel approach based on a multi-bearer architecture by using existing public telecommunication networks such as cellular and satellite systems. Network availability can be improved by selecting an alternate network in order to guarantee the quality of the service required for the railways application. A procedure to evaluate the performance of a train control system using public networks is also presented. This paper also provides a contribution to the standardization process within the ERTMS/ETCS platform.

I. INTRODUCTION

Telecommunication systems will play an essential role for railway applications to service passengers as well as to improve safety, security and efficiency in the train management process. The vision in [1] envisions 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 and oriented to the specific service to be provided. As an example, services to passengers will be provided by one or more flexible radio systems capable of evolving rapidly with the market demands and open to new and more advanced content-oriented applications. The communication platform for railway management will be probably oriented to a unified communication infrastructure and collaboration services based on real-time information. In this way, it is possible to increase efficiency, speed-up the business processes, improve operational effectiveness, facilitate information exchange and improve the quality of decision making. The management of railway operation processes will require highly reliable and stable telecommunication platforms, so to increase the railway traffic capacity and to ensure high security and safety levels. In practice, the future railway telecommunication platforms will integrate, at one or more protocol stack levels, several communication systems even including public land mobile networks (PLMNs, both circuit and/or packet switched) and satellite [2]. The possibility of using PLMN for railway operation management is of great interest to rapidly extend the advanced rail traffic management and control techniques (based for example on ERTMS/ETCS) to low/medium traffic lines and/or to regional lines, where the deployment from scratch of a dedicated communication infrastructure (based for example on simplified versions of GSM-Railway) would be not cost-effective. However PLMN are not specifically designed in accordance with the EIRENE requirements in [3]. This could limit their applicability for train management and control.

In this paper, we provide a methodology to assess the performance of a train management and control system using PLMNs as well as satellite. The paper is organized as follows. The main requirements of a communication infrastructure supporting railway signaling are summarized in Section II. In Section III we outline the main issues related to the extension of railway operation management over PLMNs. In Section IV we describe the current protocol Euroradio architecture and we consider some extensions to support the future railway operation management based on PLMNs. In Section V we detail our proposed methodology to evaluate performance and costs of the PLMN based solution. We show and comment results in Section VI. Finally, conclusions are drawn.

II. EIRENE SPECIFICATIONS

The GSM-R system [4] extends the traditional GSM network in terms of services and improved reliability and is designed in accordance with EIRENE specification. It is important to note that EIRENE provides the requirements of radio bearer for ERTMS/ETCS: the Euroradio layer is responsible for ensuring the overall safety of the transmission link between train-borne and track-side ERTMS/ETCS applications. The EIRENE document also specifies performance parameters of GSM-R network, regarding:

1) Cell-coverage: coverage probability of 95% based on a coverage level of 38.5 dBmV/m (-98 dBm) for voice and non-safety critical data and 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 lower than or equal to 220 km/h.
2) Handover and cell-reselection: the handover success rate should be at least 99.5% over train routes under design load conditions.
3) Call setup time and priority: class 1 (fast set-up) 1-2 s, class 2 (normal set-up) < 5 s, class 3 (slow set-up) < 10 s.

III. MAIN ISSUES RELATED TO THE RAILWAY MANAGEMENT SERVICES OVER PLMN

The main issues concerning the adoption of PLMN for supporting rail traffic management and control are summarized in this section. In general, it is important to evaluate if PLMN can be successfully used on the low traffic/regional lines to replicate railway services. Low traffic/regional lines can have...
different requirements respect to the High Speed railway lines and this may be helpful to relax the communication system requirements thus allowing the PLMN-based solutions to become viable. To provide services, a service level agreement between the mobile and railway operators shall be necessary. However, the adoption of PLMN to support railway services has to tackle some problems. The most important are now discussed in the following sub-sections.

A. Radio coverage issues

The PLMN deployment is not designed according to EIRENE specifications but in general based on other considerations (e.g. [5]). Thus coverage requirements of the line could not be guaranteed: outage probability could be over the prescribed limits and coverage holes may be present along the railway track. The outage probability (evaluated at the cell borders) for the GSM-R network must be much smaller than a traditional GSM network. For this reason, improvement actions should be taken to respect the requirements. The selection of the action depends on the particular railway track radio conditions. The coverage should be first analyzed and then corrections should be taken. Two scenarios could be considered:

1) Single mobile network operator (MNO): the use of the multi radio technology wherever possible could alleviate coverage issues. In fact, if a zone is not covered by GSM, another technology could be exploited (e.g., TETRA or satellite link). In this case, a multi-technology connection platform should be used in order to select the best available transmission technology for the considered service.

2) Multiple MNOs: in this case coverage improvement could be based on the simultaneous presence of multiple MNOs covering the same area. The main assumption is that, if a zone is not covered by an operator, it could be by another one. The main issue of this approach is the communication between networks of different MNOs: this could be solved with the use of interworking entities at the network level.

Finally, to improve/restore the radio coverage on a specific railway track, it is possible to make agreement with MNOs to add base stations or to use relays cheaper than BSs. This comes at the expense of band and delay problems.

B. Handover and Cell-reselection issues

Radio coverage and public traffic have a strong impact on the Handover/Cell Reselection delay requirements. For example, considering a GSM cell with intense traffic, a train may be not able to execute a handover to a new BS due to unavailability of free channels. Some solutions to this problem could be:

- to implement priority mechanisms at BSs to drop down one or more calls when the network decides the train has to perform handover.
- to increase the number of available channels in the high density traffic cells by increasing the band or asking for the operator to activate GSM-R frequencies (if available in their BSs).
- to increase the number of BSs in order to meet the capacity requirements: this case could be not cost effective for the MNO.

The best solution to select shall guarantee that handover/cell reselection times of public GSM networks are compatible with the regional railway time requirements.

C. Call setup issues

In a public GSM network, the compliance of the delay requirements of the call setup phase is conditioned by the traffic load in both the cell and the network. EIRENE specifications consider some priority levels in the call setup phase in relation to the call type (e.g., emergency calls have the maximum priority). It is necessary to evaluate if under these conditions the requirements can be respected and/or if they are adequate to the regional lines.

IV. System architecture

A. Euroradio protocol

ERTMS/ETCS level 2 system is based on the exchange of information between the on-board European Vital Computer (EVC) and the Radio Block Center (RBC) via the GSM-R network [6]. In particular, Euroradio [7] is the protocol responsible for the safe/secure message exchange between on-board and track-side equipment. The Safety Functional Module (SFM) of Euroradio provides the functions of the safety-related transmission system. The safety services provide safe connection set-up and safe data transfer. The Communication Functional Module (CFM) of Euroradio provides the functionalities to interface the communication system based on circuit switched bearer services such as GSM-R. A CFM entity communicates with its users through one or more Transport Service Access Point (TSAP) by means of transport service primitives.

B. Possible Euroradio extension for future railway operation management

Future train communication networks shall be multi-technology (GSM/GPRS, HSPA, LTE, Satellite, etc.) and multi-operator. In this scenario, the extension of the Euroradio protocol is important. To simplify this process, the SFM module shall be not modified and extensions shall focus only on the CFM module (extended-CFM). In detail, the interface between the SFM and the CFM remains the TSAP so to avoid porting problems and backward compatibility of the already existing railway applications. The CFM interfaces with the communication technology and is designed to implement the functionalities to:

- activate a data connection based on packet switching (IP) or circuit switching (as in the case of GSM and GSM-R);
- exchange data between EVC and RBC;
- perform error control and signalling.
The CFM-extension can be achieved in different ways. One of them is depicted in Fig. 1. The extended-CFM (E-CFM) is composed of functionally separated CFMs, each one specific for the technology (e.g. GSM, GPRS, UMTS-HSPA, UMTS-LTE, etc.). The E-CFM management subsystem in Fig. 1 continuously monitors the radio channel status and reports on the number of available radio links. On the basis of QoS data/measurements, this entity decides which technology to use to establish a safe transmission for the railway messages. Despite its simplicity, the implementation of the E-CFM architecture in Fig. 1 requires the repetition of a lot of functionalities common to all the different technologies. More efficient CFM solutions can be envisaged by grouping all common functionalities. For brevity this aspect is no further analyzed in this paper. To increase channel reliability, the E-CFM could:

1) send the same message using different technologies (GSM, UMTS, etc.);
2) send the same message using the same technology but on channels belonging to different operators (multi-operator case).

In all these cases, a new entity must be inserted in the E-CFM to delete duplicate messages. The new Euroradio architecture shall be as in Fig. 2. The E-CFM can simultaneously connect to various wireless technologies even of different operators to provide a reliable and stable link for the EVC-RBC communication. E-CFM shall be able to select, time by time, the best path offered by the different available bearers (GSM/GPRS, UMTS, Satellite). When EVC or RBC receive more replicas of the same message, mechanisms for intelligently discarding duplicated messages shall be introduced.

V. METHODOLOGY FOR PERFORMANCE AND COST ASSESSMENT

A. Scenario

The reference scenario for the integrated analysis of the communication infrastructure for the railway management is shown in Fig. 3. We assume that the train moves along the railway and that the train speed pattern can be measured. In general, the (resulting) speed pattern is dictated by the EVC-RBC control procedure based on EVC transmitting Position Report (PR) messages and receiving the corresponding Movement Authority (MA) messages from RBC. The train speed is remotely controlled by the RBC in accordance to the status of the line and traffic conditions. When the MA is not received (e.g. a timeout is expired) the train can (autonomously) reduce/change its speed to guarantee safety. As an example, train can stop if no MAs are received for a relatively long time. In the following, it is assumed that the train is always connected to one MNO until the bearer is available. It is also assumed that the BSs positions are not optimized to support train services. Thus radio coverage could be discontinuous (i.e. coverage holes can occur) along the line. The MNO/technology is selected according to an optimal policy to be defined (see after). A pictorial example of the received power and the train speed profile is shown in Fig. 4. The received powers from the BSs of the two MNOs and from satellite are reported as a function of the curvilinear abscissa, indicating the train position over the line. Since the train is connected to one bearer until its received power falls below the reference levels $P_0$, in Fig. 4 the maximum received power among the two MNOs is also indicated. The dashed vertical lines in Fig. 4 indicate the positions along the railway where handovers between MNOs or satellite should occur. For simplicity, we consider hard handover and arbitrarily we also assume that during the handover phase train speed is temporarily reduced and re-starts to increase when handover is concluded. This fact is highlighted by the (exaggerated) variation of the train speed profile in Fig. 4. In the considered example, no coverage holes are assumed, since for each point of the curvilinear abscissa $s$ there is always at least one bearer available (see the maximum received power $\max_k \{P_k(s)\}$, with $k$ identifying the $k$-th MNO. The speed profile in Fig. 4 indicates the (average) train speed at position $s(t_i)$ which has been reached by train at time $t_i$. 

Figure 1. Extended-CFM architecture

Figure 2. Extended Euroradio architecture

Figure 3. Reference scenario

Figure 4. Reference scenario
Indicating with $\Delta$ the sampling interval of the speed profile, we assume that $t_i = i \cdot \Delta$, $i$ positive integer. Then, the train speed at point $s(t_i)$ could be evaluated as:

$$v(s(t_i)) = \frac{s(t_i) - s(t_{i-1})}{\Delta} \quad (1)$$

If $\Delta$ is small enough, the train speed at $s(t_i)$ is equal (in practice) to the instantaneous speed. The train speed profile is regulated by the train movement procedures which use message exchange by wireless link. Considering for example the GSM technology, we assume that one message (PR or MA) can be sent using $L \geq 1$ frames and, for each frame, only one channel is assigned to the train so that $\Delta \geq LT_f$ where $T_f$ is the GSM frame duration (equal to about 4 ms). The train speed profile is used to calculate the time intervals required to train to pass from one MNO to another or to satellite. The time interval required by the train to pass from $s(t_i)$ to $s(t_{i+1})$ is $T_{ij} = t_{i+1} - t_i$. From the example in Fig. 4, it can be observed that the time the train remains connected to MNO 1 is $t_{ex}-t_{es}$ (3’rd window). The $T_{ij}$ are the basic data required to evaluate costs and performance of the integrated communication network as shown in the following.

**B. Cost calculation**

Indicating with $T_{ij}$ the time interval the train is connected to the $i$-th MNO or to satellite before passing to the $j$-th MNO, let be $c_i$ the unitary cost per time of the link on the $i$-th MNO. The overall cost of the communication system for the single train travelling along the line is:

$$C = \sum_{i=1}^{N_{op}} c_i \sum_{j=1}^{N_i} T_{ij} \quad (2)$$

where $N_{op}$ is the number of MNOs (including satellite) and $N_i$ is the number of times the train is connected to the $i$-th MNO. The (2) implicitly assumes that the radio link is always on (circuit mode) even when the train does not use it. If the costs is proportional to the number of messages exchanged during $T_{ij}$, the number of transmitted messages can be easily calculated and then used for cost calculation. In general the cost model depends on the $T_{ij}$. Other and much more complex cost models could be considered.

**C. Outage evaluation**

To evaluate the system performance in terms of the percentage of the communication system is unavailable, $P_{out}$, from the profile of the maximum received power in Fig. 4 we can identify the zones (if exist) along the rail line where no MNO and satellite coverages are available. Assuming that the RBC is aware of no coverage zones, train control procedures specific for no radio coverage cases can be activated (for example the train can proceed at a reduced speed). We indicate with $Q_i$ the $i$-th time duration required for the train to travel the $i$-th no coverage zone. In this case, indicating with $T_{tot}$ the overall time requested by the train to travel along the railway line, the percentage of time $P_{out}$ the radio bearer is unavailable is:

$$P_{out} = \frac{\sum_{i=1}^{N_Q} Q_i}{T_{tot}} \quad (3)$$

where $N_Q$ is the number of radio holes along the railway. By repeating evaluations of (2) and (3) over the same railway line by changing the speed profile, it is possible to evaluate the statistics of $C$ and $P_{out}$ specific for the line. If equations (2) and (3) are recalculated for different railway lines belonging to the same region and for different speed profiles we can obtain the statistics of $C$ and $P_{out}$ over the region.

The proposed procedure can be easily extended to account for realistic traffic conditions in each BS introducing a probability that handover may fail. The handover failures lead to altering the train speed profile in accordance with the specific control procedure applicable in these cases. Thus the time interval $T_{ij}$ need to be recalculated accordingly and so the costs and outage probability.

**VI. RESULTS**

To prove the effectiveness of the proposed procedure we consider the simple synthetic scenario (shown in Fig. 5) of a regional line covered by two public MNOs providing a GSM-900 service (the uplink and downlink frequencies are respectively 900 and 945 MHz). We perform a Monte Carlo simulation to evaluate the $P_{out}$ for the considered scenario in accordance to (3). The positions of the BSs along the line are randomly generated at every trial. The received power is calculated using the Hata COST 231 model [8] for suburban environment, without accounting for shadowing and fast fading effects. The main parameters (reported in Fig. 5) characterizing the synthetic scenario are:

- Cell coverage radius $R$, calculated using the Hata COST 231 model.
- Inter-distance $d_l$ between the centers of two adjacent BSs belonging to the same MNO. It is modeled as an uniform random variable in $[A(1-\alpha), A(1+\alpha)]$, where $A$ is the mean value of $d_l$ and $\alpha < 1$.
- Vertical distance $D$ between the BSs centers and the railway. The module of $D$ is modeled as an uniform random variable in $[0, \beta A]$, where $\beta < 1$.

The outage probability is calculated as the time percentage the received power is under the receiver sensitivity with respect to the total time requested by the train to go through the line. The scenario depicted in Fig. 5 has been considered for 2 MNOs with 7 BSs along the line. The following parameters
Figure 5. Main parameters of the synthetic scenario

are assumed: $R=5 \text{ km}$, $\beta = 3 \cdot \alpha$.

In Fig. 6 $P_{\text{out}}$ is shown as a function of the cell radius $R$, for variable $\alpha$ and $A$. As expected, for a fixed $R$ value, the outage probability increases when both $\alpha$ and $A$ increase. In...

Figure 6. Outage probability vs cell radius for different $A$ and $\alpha$

Fig. 7, the calculation of the minimum cell radius $R$ requested to obtain a target $P_{\text{out}}$ is shown as a function of $A$, for some $\alpha$. For fixed $A$, the requested $R$ increases when $\alpha$ increases or when the outage probability target value is decreased. In

Figure 7. Minimum cell radius needed to obtain the outage probability target

Fig. 8, the $P_{\text{out}}$ is shown as a function of $A$, for one and two MNOs. As expected, the possibility of having two (or more) MNOs covering the line turns out in better performance of $P_{\text{out}}$.

Figure 8. $P_{\text{out}}$ vs cell radius for different number of MNOs ($\alpha=0.1$)

VII. CONCLUSIONS

PLMN networks and satellites can be used for railway traffic management in low traffic and regional lines. We proposed a methodology for performance and cost assessment to integrate PLMNs and satellites in the message exchange between train and control center (i.e., EVC and RBC) based on the Euroradio protocol. In particular it has been presented an extended CFM architecture to support multi operator and multi technology approach improving system performances. Results show that outage probability can be reduced according to requirements by reducing the inter-site distance or increasing the cell radius. Moreover performance can be improved by considering more than one operator or more than one single technology.

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REFERENCES