Wireless Communications in Railway Systems

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***Abstract*—Railway management systems are based on a centralized structure where the Central Post centrally manages all the components, trains and railways, with the aim to guarantee the safety of the service and the efficiency of the network capacity. This architecture requires an extended exchange of information between management units, monitoring systems and actuators. In general, the communication is based on wired links that ensure required performance, but present also some drawbacks. For instance, copper cable-based links are affected by cables thefts or can limit the type and the amount of information that can be sent due to the capacity of involved technologies. In all these scenarios, the introduction of a wireless link can improve the safety, the performance and the flexibility of the communications. In this paper, the use of wireless communications as backup or extension of the pre-existent wired links is deepened. Trackside and on-board communications, as well as European Rail Traffic Management System and EURORADIO protocol are studied analyzing the issues related to wired links and illustrating how the use of wireless communications can face off their drawbacks.**

***Keywords*—Railway systems; wireless communications; trackside systems; on-board systems; signalling; ERTMS; EURORADIO; RadioInfill; MRP.**

I. Introduction

Railways are complex systems composed by infrastructure, vehicles, and all the elements required to make these components work together efficiently and safely. Vehicles for freight and passengers transit on the railways that are a complicated network of connections where they have to be synchronized in order to avoid accidents. Furthermore, the transport system has to be managed efficiently in order to increase the system capacity in terms of number of convoys travelling on the network. Both these requirements, safety and efficiency, require and required along the time to monitor and manage the trains transit and the railways. This is the motivation of the complex and highly populated system composed by trackside and on-board equipments used by the signalling system to monitor the state of infrastructures and convoys, to dispatch and actuate command. In particular, a huge variety of devices performing important functions are distributed along a railway. Examples are railway switches boxes that command switches, equipment that monitor the trains status (bush temperature detector) and the trains transit (axle counter, track circuit), light signals used to communicate with the train drivers, components that allow the communication between the ground management system (Computer-Based Interlocking) to the on-board management system (Lineside Electronic Equipment and Encoder), etc. Furthermore, both on-board and trackside devices communicate with the centralized management units through some intermediate management and information points. Indeed, the trains management has a centralized structure where a central unit, the Central Post, has the task of manage the network infrastructure and the trains. This unit distributes its commands by means of intermediate points, the Peripheral Posts, in general corresponding to the trains stations. At their turn the Peripheral Posts dispatch and elaborate the command received by the Central Posts to the trackside and on-board equipments by means of the *Computer-Based Interlocking* (CBI) system. Moreover Peripheral Posts and CBI receive and elaborate the information collected by trackside and on-board equipments and send the derived information to the Central Posts in order to update the management system. This centralized architecture allows to organically and safely manage the complex railways system reaching all the devices distributed along the railways.

Reflecting and following the historical evolution of the railway systems dragged by the modifications of the involved technologies, most of these equipments are evolved starting from simple mechanical devices, to electromechanical, to electric-digital components, see for instance the first CBI, where the logic where implemented by a mechanical leverage, or old railway switches that were manually operated. Furthermore, these components are not isolated entities but they communicate together in order to exploit their functions. Until now, most of the communications are based on wired links, where the information derived by the monitoring systems are dispatched to the central management unit and the commands set by the last one are sent to the actuators spread on-board of trains or trackside. In dependency of the type of message and of the involved devices these communications are based on different protocols. However, as previously said, wired links based, for instance, on copper cables, or optical fibers, are used. Through the right choice of transmission technology and protocols and thanks to the appropriate setting of transmission parameters, wired links ensure required performance but present also some drawbacks. For instance, copper cable-based links are affected by cables thefts due to the high monetary value of copper [1]. This is a severe damage, especially in the case of links used for critical communications since their interruption can seriously jeopardize safety trains transit. Furthermore, in some cases, such as on-board communications, wired links limit the type of information that can be sent due to the capacity of involved technologies. In all these scenarios the introduction of a wireless link can improve the safety, the performance and the flexibility of the communications. In this paper, the use of wireless communications as backup or extension of the pre-existent wired links, in dependency of the application, is deepened. Both trackside and on-board communications are studied analyzing the issues related to wired links and illustrating how the use of wireless communications can face off their drawbacks. Some meaningful case studies will be provided in order to corroborate the proposal along with the highlight of some open issues related to the introduction of wireless links.

The rest of the paper is composed by the mentioned study that is exposed in Section II, whereas in Section III some conclusions are drawn.

II. Introducing wireless communications in railway systems

The railway management deals with a capillary structure where railway lines are populated by a huge amount of devices suitable to monitor the transit and the status of the train and by actuators used to manage railway lines. They communicate with the Central Post, responsible to centrally manage the whole infrastructure, through the Peripheral Posts. Furthermore, on board of convoys monitoring and actuators collect the information about the state of the train and execute the received commands. In general, the communication is based on wired links that, in dependency of the applications, can result not sufficient to support new functionalities, for instance video surveillance or on-board entertainment, or are subject to critical damages or copper cable thefts that seriously jeopardize the critical management applications. Thus the evolution of railway systems has to consider new solutions suitable to face off these challenges. A possible solution is the adoption of wireless communications both as a backup of the wired one, for instance to ensure the service until the system is recovered, or as integration to the wired one in order to allow new services or to improve the pre-existent ones.

In the following, some use cases about the introduction of wireless communications in the railway domain are illustrated in order to highlight the potentialities of this approach.

A. Communications between wayside equipment and Peripheral Post

Copper or fiber optic cables typically support communications between trackside devices and accidental or intentional damage of copper cables can cause unavailability of the corresponding link. Wireless communication can be introduced as a backup of the wired link. This require to analyze the communication requirements in terms of bandwidth, delay, packets loss strictly related to the particular application. To overcome the problem of possible interference, a Spread Spectrum technology can be Zang2005Zang2005chosen as possible alternative to narrowband technologies [2]. Indeed, thanks to its robustness against noise and intrusion, this technology is suitable to provide the required reliable communication level. Beyond the precise design and setting of the wireless link that has to be apt to provide the required Quality of Service, further investigations require analyzing the compatibility of legacy communication interfaces of the involved railway devices, often based on proprietary connectors, with the proposed wireless devices that in general have standardized interfaces. In this case, either a re-engineering of the devices is required, either an interface adapter has to be designed for this connection.

A considered use case is the link between Eurobalise and Lineside Electronic Unit (LEU). Switched Eurobalise communicates with the corresponding LEU through the C interface, which is continuously powered by the LEU and it is connected to the physical wired link for the exchange of telegrams, powering and other information about the train transit. In order to use wireless links for their communications, an interface adapter is required to be connected to the C interface on one side and to the Ethernet interface of the wireless device on the other side, as illustrated in Figure 1. The same apply on the corresponding interface of the LEU.

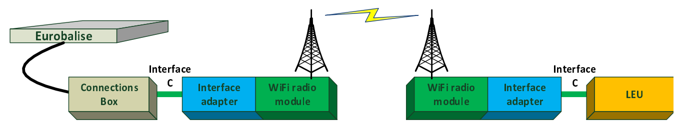

Figure 1. Eurobalise - LEU case of study.

The adapter mechanically interconnects the proprietary input-output connector of the C interface to the standard interface of the Wi-Fi module. It adapts electrical features of the cable signals to the corresponding ones of the serial or Ethernet standard and preserves timing requirements. Creating wireless link requires a careful design in order to connect in a point-to-point topology the two Wi-Fi devices for the wireless transmission between Eurobalise and LEU that implies to consider different aspects. Since Eurobalise and LEU are placed in fixed locations, the position of the directional antenna of each Wi-Fi device has to be chosen carefully. Each antenna has to be placed far not more than few meters from the corresponding Wi-Fi equipment to minimize signal losses through the cable and should be placed in Line of Sight of trackside poles where the antennas are mounted, at a height compatible with other railways elements eventually present. In case of obstacles and, in general, in presence of Non Line of Sight, it is necessary to insert one or more bridge-repeaters that turn around the obstacle. Obviously, the radio link has to meet the requirements about bandwidth, frame loss and delay, preserving the connection between Eurobalise and LEU. In particular, the link budget, i.e., the algebraic sum of all gains and losses of each component of the radio system has to be taken into account since it allows to decide if it is necessary to act on transmission power or antenna gains to obtain the desired performance. Experimental results shown that the wireless link can meet the mentioned requirements providing a backup connection suitable in case of hard damage of the wired one due to accidental or intentional

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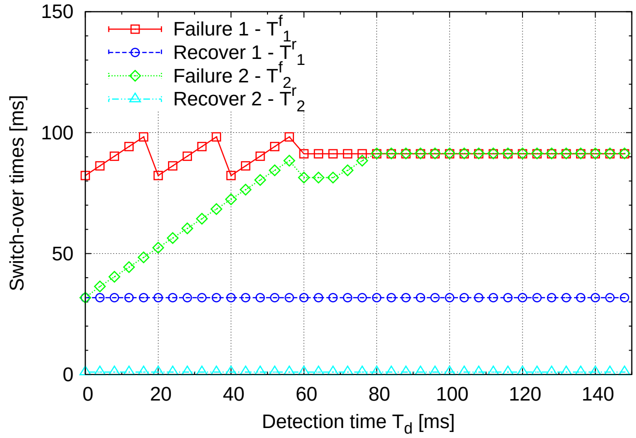

Figure 2. Switch-over time of MRP. vs detection time

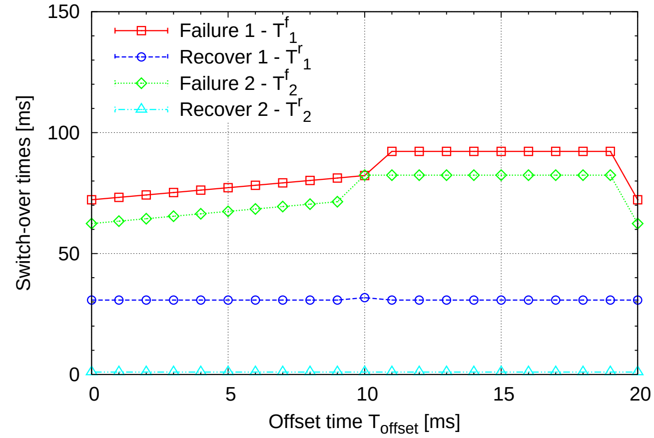

Figure 3. Switch-over time of MRP. vs offset time

damage (theft or physical cut), improving the system fault tolerance.

The completely reduction/elimination of copper cables implies further open issues, related to the presence of power cables. In this case the approach is completely different with respect to communication cables, since the requirements involve the continuous power provisioning. For instance, solution based on energy harvesting could overcome this challenge [3].

B. Railway control networks and communications between Peripheral Post and Central Post

Ethernet is penetrating railway communication networks mainly for its simplicity and cost effectiveness but also thanks to several emerging Industrial Ethernet solutions that improve the Ethernet standard. Specifically, Industrial Ethernet solutions often include proprietary redundancy management protocols for the automatic handling of failures on ring topologies. The *International Electrotechnical Commission* (IEC) has published IEC 62439 in 2010 [4] including the specification of a standard redundancy management protocol, i.e., the *Media Redundancy Protocol* (MRP), that attracted the attention of most network equipment vendors. With the settings specified in IEC 62439, MRP guarantees a worst case recovery time of 30 ms in rings composed of up to 50 switches, and can support multi-ring topologies guaranteeing similar performance. MRP is currently used in various network segments of RFI railway communication serving the control of high-speed high-capacity train. In [5], two factors are identified (i.e., offset time and the physical detection time) that jointly affect the MRP performance. Their impact on the recovery time has been consistently evaluated with an analytical approach, with simulations (see Figure 2 and Figure 3), and by means of experimental measurements. Obtained results confirmed that, in all the considered scenarios, the switch-over is performed within the target time declared in IEC 62439.

In this scope, wireless communications can be used as a backup of PVS wired communications between Peripheral Post and Central Post, in most of the system performed by EURORADIO standard protocol or by proprietary national protocols, such as Italian *Protocollo Vitale Standard* (PVS). This intervention could have a huge impact involving important communications, whereas the adoption of wireless communications, for instance based on IEEE 802.11ac protocol, can easily provide the required levels of Quality of Service in terms of bit data rate and security.

C. On-board LAN

Another important challenge is the introduction of wireless communications on the Local Area Network on the train (i.e., on-board LAN). Typically on-board LANs on the trains are implemented using commercial layer 2 switches interconnected by means of copper cables traversing the several carriages. This solution is able to provide adequate bandwidth (e.g., 100 Mbps or 1 Gbps) on the LAN, but introduces some rigidity in the dynamic re-combination of carriages. The utilization of a wireless bridge among adjacent carriages could facilitate dynamic re-arrangement of trains carriages while guaranteeing adequate network performance. The main problems to be addressed are the maximum supported bitrate, and the required integration of the wireless devices in the failure recovery mechanisms typically supported by the on-board LAN. Regarding the supported bit rate traffic bandwidth of up to 200 Mbps can be supported with very cheap hardware (e.g., about hundred dollars each wireless bridge). Regarding the integration of the recovery techniques, properly designed scripts should be implemented and deployed on the wireless devices so that failures of the local interfaces can be announced to the rest of the on-board LAN to properly recover the affected traffic flows.

D. ERTMS

European Rail Traffic Management System (ERTMS) [6], [7] is the European reference management system suitable to homogeneously manage different national trains when they cross national boundaries. It aims to overcome the limits of the diverse national management systems, each one based

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on different communication protocols, system architectures, trackside and on-board components. This heterogeneity implies that when a train travels across different countries the on-board equipment has to be able to interface to different signaling systems. This problem is generally overcame by substituting the locomotive, where the on board system is placed, or equipping the locomotive with all the different equipment corresponding to the different crossed nations. Obviously, this approach is not flexible and efficient, impacting on travel time and railway capacity. In this context ERTMS aims to homogenize the signaling systems by the introduction of a unique management system. Furthermore, its goal is to improve the railway efficiency by a progressive substitution of wired communications with wireless ones. This will allow a reduction of trackside devices and the introduction of further and improved functionalities, as will be described in the following. The introduction of ERTMS theoretically follows three different steps, starting from Level 1, compatible with pre-existent systems based on exclusively wired communications, to Level 2, see Figure 4, where wireless communications are side by side to the wired ones, to the Level 3, where only wireless links are used.

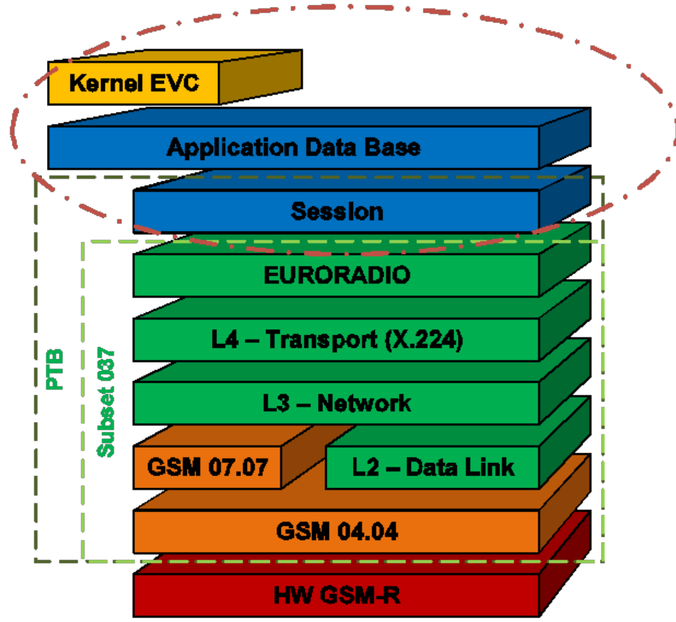

Figure 5. EURORADIO protocol.

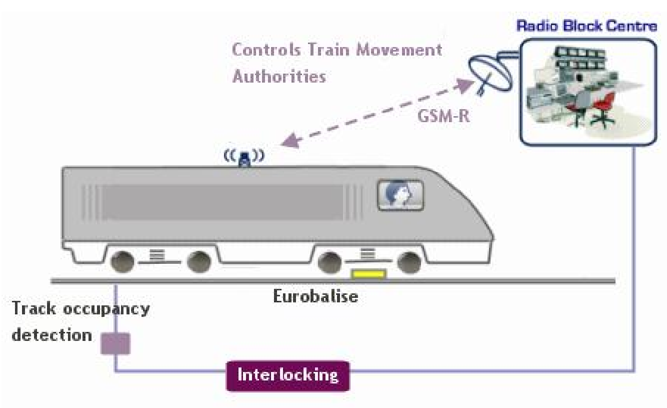

Figure 4. ERTMS Level 2

1) EURORADIO: ERTMS defines as secure communication protocol EURORADIO [8] based on an open communication network such as *Global System for Mobile Communications âĂŞ Railway* (GSM-R). It is based on a layered architecture and all the layers are executed onboard of the train to enable the communication. In particular, a *Safety Functional Module* (SFM) and a *Communication Functional Module* (CFM) respectively deal with safety transmission functionalities and communication system functionalities.

In [2], an implementation of EURORADIO is presented, developed with open-source tools for better portability. It is based on software stack of different layers that form a hierarchy of functionalities starting from the physical hardware components (Modem GSM-R) to the user interfaces at the software application level (Radio-Infill Application), see Figure 5.

EURORADIO layers communicate together by means of API. Each layer receives information from the layer above, processes and transfers that to the layer below, adding its own encapsulation information (header).

EURORADIO is the basis for ERTMS Level 2 and Level 3 but it allows to improve the behavior also of ERTMS Level 1, where the trackside-traiborne communication (communication between the ground subsystem SST and the onboard subsystem SSB) is through Eurobalises based on a duplication of information. This communication is discontinuous being Eurobalises placed in fixed and meaningful positions along the railways lines. Furthermore, the train driver can modify the train speed only after these information points. This makes the speed curve not optimal, due to discontinuous accelerations and decelerations, and the trains circulation not efficient. However, the introduction of the RadioInfill function is suitable to provide a compromise between the use of ERTMS Level 1 and the continuous communications.

2) RadioInfill: RadioInfill function supported by EURORADIO in ERTMS Level 1 at the application layer faces off the lack of responsiveness typical of discontinuous ATP systems. In ERTMS Level 1 the signaling information delivered to the train driver is based on information points, for instance light signals used to deliver stop and go information to the train driver. A scheme based on duplicated information is used for safety reasons. Double information points convey a single type information: one notice point as an advice, and one protection point as a confirmation. RadioInfill allows an early release of the running restriction before the next information point, as shown in Figure 6. The early release function is used when routes conditions are further exchanged and a train deceleration is no more necessary and to manage deceleration in proximity of stations. Some implementation of RadioInfill are based on pre-existent signaling system sending coded electric signals through the track circuit or on dedicated

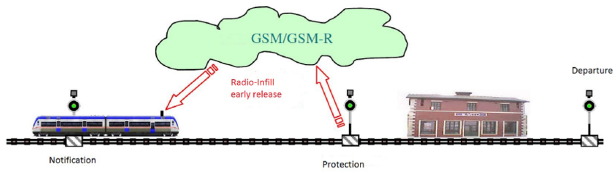

Figure 6. The early release of RadioInfill function.

trackside components (Euroloop). In [2], an implementation of EURORADIO protocol and of RadioInfill is described. The experimentation shown as this function can reduce the travel time and improve the power saving reducing the number of braking.

3) ERTMS Level 3: As mentioned, the distinctive element of ERTMS Level 3 is the exclusive use of wireless communications for the exchange of information between train and ground system, see Figure 7.

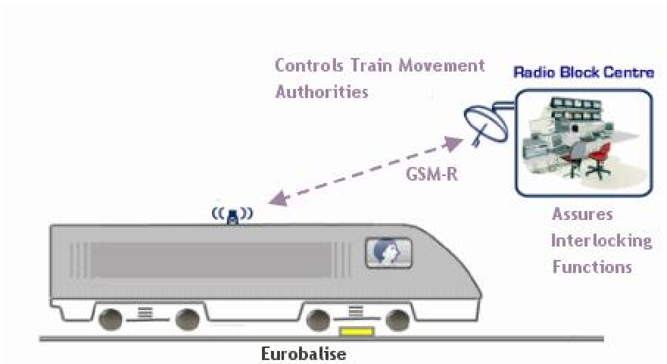

Figure 7. ERTMS Level 3

This allows the reduction of trackside signaling devices with a consequent reduction in costs and maintenance load. Furthermore, the speed curve is continuous improving energy consumption efficiency and passenger travel comfort. At the present time there are no implementations of ERTMS Level 3 but railway operators and European national authorities are actively considering the evolution of their systems in order to implement its functionalities, see Norway or Finland, and some nations of the East of Europe are evaluating to update their national management systems directly to ERTMS Level 3, pushing forward the evolution and avoiding the huge implementation of the consecutive different levels, starting from Level 1.

4) Moving Blocks: The goal is to improve the efficiency of rail traffic management and the quality of service offered by increasing the capacity of the line. For this purpose, ERTMS Level 3 is based on the use of the Moving Block concept to manage trains on the same line [9]. *Moving Block Signaling* (MBS) is an intelligent control system where safety zones around the train are defined that can not be crossed by adjacent trains. Specifically, MBS exceeds the Fixed Block limits where the line is divided into fixed length blocks determined based on the braking capacity of the train in worst case conditions, taking into account the speed allowed in the line, and delimited by signals. According to this system, a train can access a block only if its next one is free, so the distance between two trains on the same line is more than one block [10] [11]. This results in an accumulation of braking times and excessive spacing between the trains, affecting the density of trains on the line. To increase the capacity of the line, i.e., the number of trains on it, MBS introduces "mobile" blocks that are no longer delimited by long distance signals and whose length is not fixed but determined by the safety distance needed to completely stop the train.

According to this method, the moving block is determined by the position of the train and the safety distance from it, and no other signaling equipment is needed being managed by the ERTMS control system. Particularly in Moving Block, the train is modeled with a safe-envelope consisting of the sum of its length, a rear safety margin that takes into account the distance of rollback, uncertainty in determining the position of the train and spacing with the next train, and a frontal security margin which, in turn, takes into account the uncertainty in determining the train head and the distance traveled during the maximum permissible time interval in which ground-to-earth communication can be interrupted [12]. Thus, the minimum distance of a train from the preceding one, the *Limit of Movement Authority* (LMA), is dependent on the position of the train ahead and its specific braking and speed properties. This interdiction space moves along the line to proceed to the next train. This reduces the length of the moving blocks and, consequently, the distance between the trains, allowing to increase the capacity of the line.

III. Conclusion and Future Work

In this paper, some use cases about the introduction of wireless communications as backup or integration to the wired ones in the railway domain are illustrated. Trackside and on-board communications, as well as ERTMS systems and EURORADIO protocol are studied analyzing the issues related to wired links and illustrating how the use of wireless communications can face off their drawbacks.

Despite the use of wireless communications in most cases is a challenge especially considering the strict safety and service requirements but, from the other hand it opens new field of application and feeds the evolution of the railway systems.

Future works will be focused on the management of the train integrity. Until now, this function is guaranteed by the train inauguration process and by the monitoring of the train and of its queue in particular by means of the *Train Communication Network* (TCN). Furthermore, it can be integrated by the use of wireless communications, for instance, monitoring the round trip time between the head and the queue of the train.

Further application of wireless communication that deserves to be deepened is the "cloudification" of railway management and services which can be based on wireless links as backup connections.

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