Wireless Communication Infrastructures Used to Increase Safety in Railway Networks

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ABSTRACT
Railway management and communication systems can be used to enhance the railway signaling and control systems in order to increase the railway safety and efficiency. Several railway management and communication systems have been defined, some of them using both wired and wireless communication. This paper focuses on the most deployed and promising wireless communication and control systems, and compares these by using a certain number of requirements defined in this paper. This paper concludes that ERTMS appears to meet all the derived requirements and that it can become the most worldwide deployed wireless railway communication infrastructure.

Keywords
RCAS, railway, safety, ERTMS, CBTC.

1. INTRODUCTION
In 2008, the International Union of Railways (UIC) registered 2263 significant train accidents, 200 of them serious, with more than 1200 fatalities as a result [30]. Safety is important enough for it to be one of the core activities of the United States’ Federal Railroad Administration and the European Railway Agency [4]. In order to increase railway safety while train traffic increases, new communication and dissemination solutions are needed.

Railway infrastructures have been developing very rapidly in the last two decades, including their communication systems. In the past, the signaling and data communications in the railway industry were using wired communication systems. These wired communications systems were used to monitor the safe operation of the train including indicators such as vibrations, smoke, tilt ambient temperature, and humidity in wagons.

Recently the wired communication systems are being replaced by wireless communication systems (see Figure 1), which are also able to enhance safety by disseminating information among wagons and trains in order to keep a safe distance between trains and to safeguard rail personnel.

In particular, considering safety, many signaling strategies for railway management and communication systems have been developed over the years. Railway Management & Communication systems can be divided into Signaling & Control Systems, and Communication & Control Systems [27].

The signaling and control systems are mainly used to provide safety and efficiency of the train operations [1]. The main features provided by these systems are:

- Identification, where the system identifies the numbers of the locomotives, the engineer operating each locomotive and also any other mobile railway unit that is occupying a main railway track.
- Location determination, where the system locates quite accurately the geographic position of locomotives, trains, tracks and track forces.
- Detection, where the system detects railway switches, defective equipment, status of a railway/highway crossing.
- Monitoring, where the system provides self-diagnostics of different vital parameters in order to ensure that they are properly functioning. Such parameters are: (1) speed of the train, (2) acceleration and deceleration rate, (3) throttle position, (4) dynamic brake setting, (5) brake pipe pressure, (6) emergency brake application, (7) wheel slip, (8) locomotive health monitoring. This monitored information can be displayed on the same locomotive, on the equipment or transmitted to central location for maintenance or other purposes.
- Control and reliability, where the following capabilities are supported: (1) control of switches and their alignment for proper movement, (2) control of signals and route block interlocking, (3) speed control and enforcement of movement authorities through automatic brake applications to stop the train when they are in violation, (4) railway crossing at grade, where the train is protected from movement caused by another train.

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Currently, the most widely used wired signaling and control system is the IEEE-1473 [15]. Two versions of IEEE-1473 are deployed, IEEE-1473-T, also known as TCN (Train Communication Network), and IEEE-1473-L. IEEE-1473-T is used in both vehicle (wagon, or locomotive) and train-level communication. In particular, the train-level technology is called the WTB (Wire Train Bus) that uses shielded twisted-pair cables and interconnects vehicles over hand-plug jumper cables or automatic couplers. For the data transmission in WTB, Manchester encoding with inherent synchronization is used. Reliability is supported within WTB via two fully redundant physical networks, having one network active and the other standing standby. The vehicle level technology is called Multifunction Vehicle Bus (MVB) that connects the equipment within one vehicle. MVB can operate at 1.5 Mbps and it can use e.g. the fiber optic transmission medium, transformer coupled twisted pair. The IEEE-1473-L version is the most widely used signaling and control railway system. It is able to provide different services and is able to support communication with other devices within the network. In addition it provides end-to-end acknowledgement and authentication of messages and also priority delivery of real-time performance.

Several wireless signaling and control systems are also defined and operational. The most deployed ones are the CBTC (Communication-Based Train Control) [16], the ATCS (Advanced Train Control System) [22], ITSC (Incremental Train Control System) [23], PTC, and European Train Control System (ETCS) [9]. The CBTC provides a two-way continuous communications, safety control, speed and other railway signaling and control functions. CBTC has been standardized by ETSI. The ATCS system is mainly used to ensure seamless operation and interoperability between different railway systems. ATCS improves safety by ensuring train separation, and by the use of computer systems, it verifies the safety and integrity of all movement authorities issued to maintenance crews and trains and monitoring wayside equipment status and health. The development of the ATCS has been mainly accomplished within a joint project of the Railway Association of Canada (RAC) and the AAR (American Association of Railroads). The PTC system uses off-the-shelf equipment built to ATCS specifications. The main objective of the PTC is the elimination of wayside block signal systems, the management of train movements, enforcement of limits of authority, protection of work vehicles and maintenance-of-way employees. The ITCS provides enforcement of signal indicators, speed limits, temporary speed restrictions and advanced start or crossing signals. This system is developed by the Hamon Industry for Amtrak in Michigan, USA. ETCS is a train control system that has been developed in a project funded by the European Commission and its main goal is the capability of functioning in combination with all the existing tracks and wayside equipment and train protection and train control. More information on this system can be found in Section 3.

Most of the defined communication & control systems are wireless. The most deployed ones are the European Rail Traffic Management System (ERTMS) [12] and the Railway Collision Avoidance System (RCAS) [28]. More details on these systems are given in Section 3.

An efficient railway wireless communication & control system enables:

- Support of the main signaling and control system features.
- Interaction between signalers and drivers at any time from any point of the station.
- Communication between all drivers in a certain area using a common broadcast channel and be informed about any potential safety problem or hazard.
- Exchanging of information between train’s driver with signalers and the control station during an emergency situation.
- Reducing the number of incidents relating to signaling faults and failures.
- Timely and accurate dissemination of information to passengers regarding train schedules.
- Informing the train’s driver about the internal conditions of wagon attached to the locomotive.
- Providing high reliability and security in communications.

This paper identifies a number of wireless infrastructures and verifies whether these infrastructures can be used to support safety in railway networks.

The main research question in this paper is:

Which wireless communication infrastructures are able to increase the safety in railway networks?

In order to answer this question, the following sub-questions are applied:

- Which requirements have to be met by wireless communication infrastructures in order to support safety in railway networks?
- Which wireless communication infrastructure solutions can be used to support safety in railway networks?
- In what way do these infrastructures satisfy the requirements needed to support safety in railway networks?

The research is based on literature study and qualitative comparison of different wireless communication infrastructures. Section 2 describes the requirements that these wireless communication infrastructures will have to meet. Three wireless communication infrastructures that can be used to support safety and efficiency in railway networks are described in Section 3. A comparison of these wireless communication infrastructures based on the requirements described in Section 2 is given in Section 4. Section 5 concludes and gives recommendations for future activities.

2. REQUIREMENTS

Any system intended to enhance safety will have several requirements to meet, ranging from efficiency and scalability to security demands and meeting of international standards so it can easily be implemented.

2.1 Efficiency

The European Union has classified High Speed lines as track upgraded to allow speeds of 200 km/h, or track specially built to allow speeds of 250 km/h or higher [2]. In order for a communication system to be usable for collision avoidance at these speeds, the system will need to allow long-range
communication in addition to high transmission frequency in order to minimize the risks of belated braking as a result of transmission losses when near the end of the communication range. The range of communication should be at least 5 km for braking at a 200 km/h speed without endangering passengers [21], and 10 km at a 300 km/h speed.

2.2 Scalability
Scalability falls into two categories: vehicle-to-vehicle (V2V) communication scalability and vehicle-to-infrastructure (V2I) communication scalability.

Regarding V2V communication scalability, the communication system will need to function properly in shunting yards, which can be quite large: Maschen, in Germany, has a shunting yard where more than 300 freight trains, with more than 4,000 cars, are handled daily – a number that may double in the next 5 years [11]. In such a situation, a collision avoidance system will need a very high transmission frequency, while at the same time, transmissions will need to be short enough for all vehicles to be able to communicate without an excess of transmission collisions.

If a system works with V2I communication, it is possible for the system to connect to a central server. This may be helpful in areas where wireless communication itself does not function properly, leaving a need to connect to a central server through satellite connections. In such cases, the size of the area the server can disseminate and process information correctly from/to a certain amount of trains, within a certain designated “safe” timeframe. If a country has multiple servers, the trains will need to know when to send information to which server. Moreover, switching from one server to another includes a risk of communication mishaps if overlaps are not used.

2.3 Security requirements
Security demands are slightly different for train vehicles than for road vehicles: with a road vehicle, protecting the privacy of the drivers and passengers is important [24]. However, railway vehicles should only broadcast information about trains and wagons, meaning privacy plays a less significant role. Protection against false information, however, is very important. If a train receives false information about being on a collision course, this would result in an unnecessary reduction of speed and probably complete stop of the train. This situation would be affecting not only the movement of one train, but could also lead to a situation where the movement of several other trains would be affected as well. A security support system will be necessary, which will need to fulfill at least two major requirements: Confidentiality and Integrity.

2.3.1 Confidentiality
Confidentiality means that information should not be disclosed to unauthorized individuals or systems. However, due to the high transmission frequency, short transmission time and data-processing time required for safe collision avoidance, encrypting data may prove to be a risk when it comes to disseminating information in time.

2.3.2 Integrity
Integrity can mean many different things, but for this paper, only two of them matter: on the one hand, that data cannot be modified without authorization (data integrity), and on the other hand, that a train can verify if a received message is the same as the originally sent message. Regarding data integrity, it is best if the information that the train broadcasts cannot be altered by unauthorized personnel. However, if the system has an error and ends up transmitting wrong information, it may prove necessary to correct the mistake, run diagnostics, reset the system, or even shut it down. Regarding message integrity, a message can be intercepted and re-broadcast with changes made to it, or the signal can become distorted due to interference, so a detection mechanism for this should be supported.

2.4 Quality of Service support
Since a safety-enhancing system is more important for train traffic than, say, internet for passengers, priorities are necessary. This can be implemented in many ways. However, the system can use a different wireless channel for different services, use different queues for different service types, or even use a higher Quality of Service standard for critical information than for non-critical information, like specified in IEEE 802.11e-2005 [17]. No matter which approach is used, the supported QoS solutions should ensure non-critical services don’t end up hindering critical services.

2.5 Standards
In order for a safety-enhancing system to become widespread easily, it is helpful if it is standardized. For example, if a safety-enhancing system is intended for use in Europe, it will be more easily deployed if it is combined with or if it complements the ERTMS system [6].

3. EXISTING INFRASTRUCTURES
This section describes several infrastructures for railway network safety currently in production, or still in development or testing phase.

3.1 ERTMS
In the European Union, more than 20 different train control systems are supported. These systems are non-interoperable, meaning extensive measures must be taken for trains to be able to run across borders. An example is the Thalys, which requires 7 different train control systems to run from Amsterdam to Paris. In order to remedy this, the European Rail Traffic Management System (ERTMS) [12], a single unique European train control system, is being developed in cooperation with the European Commission [6].

3.1.1 How it Works
ERTMS combines the GSM (Global System for Mobile communications) standard for Railway operations, called GSM-R [29], for internal voice and data communication in the railway environment and the European Train Control System (ETCS) [6], a system intended to standardize the areas of signaling and train control systems in Europe. It is important to note that ERTMS can only efficiently operate by letting the vehicles (wagons and trains) communicate with and via fixed railway equipment that can be located either on the railway side and/or on a centralized train controlling entity.

The key features supported by ERTMS are:

- Use of train control-command to ensure safety operation of the trains in the network.
- Standardized signaling interfaces to allow trains to operate across country borders with a single system, creating a free market.
GSM-R is a special version of the GSM standard, defined through EIRENE (European Integrated Railway radio Enhanced Network) - MORANE (Mobile Radio for Railways Networks in Europe) specifications, and is able to guarantee performance at speeds up to 500 km/h (310 mph), without any communication loss.

GSM-R can be considered to be a secure platform for voice and data communication between shunting team members, train engineers, railway operational staff, including drivers, dispatchers, and station controllers. It delivers features such as group calls (VGCS), voice broadcast (VBS), location-based connections, and call pre-emption in case of an emergency. This will support applications such as cargo tracking, video surveillance in trains and at stations, and passenger information services. This technology is typically implemented using dedicated GSM-R base stations located close to the railways.

In order to provide a high degree of availability and reliability, the base stations are located at a distance of 7-15 km between each other. Furthermore, the train maintains a circuit switched digital modern connection to the train control centre at all times. This communication link, intended to support safety and the most important functionality of ERTMS, operates with higher priority than normal communications, using the Multi-Level Precedence and Pre-emption Service (eMLPP). The eMLPP supports priority levels ranging from 0 (highest) to 4 (lowest). In particular, control-command (safety) is priority level 1 and can only be superseded by a railway emergency. It is important to emphasize that if the GSM-R connection is lost, the train will automatically stop.

The physical layer of GSM-R is based on GSM, but only uses the 876-880 MHz frequency band for data transmission, and the 921-925 MHz band for data reception [25]. It uses the Time Division Multiple Access (TDMA) method for channel access, and is solely used for railway communication. GSM-R networks are being deployed all over Europe – over 100 000 kilometers of line have already been or are being equipped [5].

ETCS is a signaling and train control system, which introduces a uniform signaling system that is usable worldwide, and supports a rich functionality to railways allowing the efficient supervision of rail track equipment [6]. ETCS is intended to replace the various European train control systems, in order to protect international train traffic.

ETCS supports three functionality levels. On level 1, which simply builds on existing signaling systems, railway track sends information to the train allowing it to calculate its maximum permitted speed, while beacons along the track also forward information about trackside signaling. On level 2, a radio block centre (RBC) monitors the trains, and provides the trains with relevant information through GSM-R – at this point, most trackside signaling is rendered unnecessary. On level 3 (shown in Figure 2), trains determine their own position and send their position and direction to the RBC, allowing for the elimination of fixed intervals, and minimizing the needed headway between trains. Figure 3 shows how these different ETCS levels are supported within the Netherlands.

ETCS conversion has been much slower, although almost 17 000 km have been equipped or are being equipped, in the EU27 (the 27 EU member countries) and Switzerland. In addition, more than 16 000 km outside of Europe have also been equipped or are being equipped with ERTMS.

ERTMS supports a strong security for the disseminated information, using the available authentication, confidentiality and integrity mechanisms provided by GSM-R and ETCS [8].

Prices for renovating lines vary between €30,000 and €300,000 per kilometer of track. The European Commission and representatives of the European Railway sector have signed a Memorandum of Understanding to guarantee the success of ERTMS – the larger the scale on which the system is implemented, the more costs will drop. Currently ETSI has formed two technical committees that work on standardizing ETCS and GSM-R.

3.2 ITS ISO CALM
The Communications access for land mobiles (CALM, previously known as Communications, Air-interface, Long and Medium range) architecture is being standardized by the ISO (International Organization for Standardization) TC (Technical Commission) 204 [18]. The CALM architecture and protocol suite is mainly driven by the automotive industry. However, it could be applied in any other types of vehicles, e.g. trains if railway signaling and control applications are defined that could be supported by the CALM protocol suite. It is important to emphasize that this protocol suite has not yet been finalized. However, it is known that the protocol can be applied in vehicle to vehicle and vehicle to infrastructure scenarios and that it can be used by, amongst others, traffic safety applications. Moreover, it is agreed upon that CALM should be able to support QoS, reliability and security, CALM considers infrared communications, as well as radio systems that are following
different standards and communication technologies, such as GSM (Global System for Mobile Communications), UMTS (Universal Mobile Telecommunication System), DAB (Digital Audio Broadcasting), IEEE 802.11p, microwave millimeter wave. The CALM architecture has been specified by ISO [19] and is shown in Figure 4.

The CALM protocol stack is shown in Figure 5. The first layer represents the physical and link layer, which corresponds to the OSI layers 1 and 2, respectively. The second layer represents the network and transport layer, which corresponds to the OSI layers 3 and 4, respectively. The third layer represents the CALM services and applications layer, which corresponds to the session, presentation and application OSI layers 5 through 7. The left part of the figure shows the CALM management functions, which are residing outside the communication protocol suite. The purpose of these functionalities is to set-up and release of connections between media and services. Finally, the top layer is not a part of the CALM protocol suite, but is shown here to emphasize that user services and applications can use the CALM protocol suite via the Application Programming Interfaces (APIs).

3.3 RCAS

As mentioned before, ETCS is intended to replace the various European train control systems, in order to protect international train traffic. However, based on estimations of the German railway company "Deutsche Bahn" (DB), it is possible that this could take up to 20 years and cost up to 8 billion Euros to introduce ETCS across all of Europe [26]. Moreover, using ETCS, a locomotive driver can only be warned of a hypothetical hazardous situation if the operation center decides to do so, due to the fact that information that has to be disseminated usually has to pass through the centralized operational center.

Therefore, the German Aerospace Center (DLR) [3] is developing a new system that will mainly be used to support communication between vehicles (wagons, trains) without having to rely on components in the infrastructure. This system is denoted as Railway Collision Avoidance System (RCAS) [28]. The main goal of the system is to gather train control information by calculating the own position and movement vector as well as other train control information, and to broadcast this information. In particular, the received information is analyzed, and by using the own position and movement vector and an electronic track map, possible collisions can be detected. This will generate an alert signal, advising the driver about the danger and about the most convenient strategy to follow in order to avoid the danger. In addition to this, the system can also take into account different danger sources, like advancing trains or road vehicles or obstacles, and classify them according to a specific risk scale.

3.3.1 How it Works

Each rail vehicle will have an RCAS unit (see Figure 6), which has several sensors (including a Global Navigation Satellite System receiver), intended to provide the vehicle with accurate information about its status, including location and speed. This information is broadcasted in 150 bits, as shown in Figure 7, through an antenna on top of the train. Warnings about threats on or near the track are also broadcasted. Received data is analyzed together with a unit’s own status, in order to identify collision threats, and warn drivers or even give them braking commands.

As the system is intended to be used in regional networks, where installing special infrastructure equipment is often considered too expensive, it does not require an infrastructure, relying on vehicle-to-vehicle communication only. However, as shown in Figure 6, it is compatible and capable of cooperating with systems like ETCS and the German electronic timetable EbuLa. Since line of sight cannot be assumed, the system is
intended to use frequencies in the lower UHF band (around 460 MHz), for likely wave guiding effects.

A special MAC layer protocol has been designed for RCAS, named COMB (Cell-based Orientation-aware MANET Broadcast) [10], which divides the communication coverage map into hexagonal cells. COMB is based on localization-aware cross-layer dimensioned CDMA (Code Division Multiple Access) cells, and uses the SOTDMA (Self-Organized Time Division Multiple Access) [20] MAC protocol as intra cell scheme, while the inter cell scheme relies on direction and speed awareness. The COMB MAC protocol is able to solve both the hidden terminal problem, and the contention slot problem, that occurs when multiple nodes contend for the same slot. The hidden terminal problem can be explained using Figure 8. Nodes A and C, while both in node B’s range, are out of each other’s range, and therefore do not know of each other’s existence, and try to broadcast on the same timeslot, leading to a message collision.

![Figure 8. Hidden terminal problem, taken from [12].](image)

COMB works as follows: the communication coverage map is divided into hexagonal cells smaller than the range of a train, but with at least three cells between cells with the same CDMA code (to ensure a train will not receive messages from two different cells with the same code). A cell’s CDMA code is used to codify messages sent from within the cell. Inside the cell, the SOTDMA protocol is used. If a node is about to cross a cell border, it reserves a free slot in the new cell, following the priority of its current cell (with the cell directly north of the new cell having priority 1, then going clockwise with priority 2-6).

Because of this, COMB is able to differentiate the transmission of data depending to the cell priority. However, the author of this paper could not find an RCAS solution describing how other QoS and security solutions are used by the RCAS system.

### 4. USEFULNESS AND COMPARISON

All three described systems have to meet several requirements in order to reliably increase railway safety. However, since ISO CALM is still very much a work in progress, not much can be concluded about it, aside from that it is intended to support both QoS and security.

#### 4.1 Efficiency

As described before, GSM-R guarantees performance at speeds up to 500 km/h. Furthermore, in ERTMS, base stations are placed close enough to each other for transmission losses, that could be caused by long communication ranges, to be reduced.

The RCAS system is designed for a maximum speed of 200 km/h. The RCAS designers consider the safety level on higher speed lines to be high enough already, due to existing control mechanisms and equipment [21]. RCAS is intended to have a guaranteed communication range of 5 km, stated before as the minimal guaranteed range to allow for safe braking with trains moving with a speed of 200 km/h. Moving trains generate and transmit messages at a rate of 1 Hz, while static trains do this at a rate of 0.2 Hz.

#### 4.2 Scalability

RCAS only uses vehicle-to-vehicle communication, so no server is required. ERTMS uses mainly V2I, which requires a centralized controlling server, making RCAS a more scalable solution than ERTMS. Moreover, according to COMB simulations, a message collision rate of slightly more than 10% can be observed at a system load corresponding to train density in the Maschen shunting yard. This message collision rate could be further decreased by slightly changing the COMB protocol [21].

#### 4.3 Security Requirements

The author of this paper could not find an RCAS solution that describes how security is provided by the RCAS system. Therefore, only a description of how ERTMS supports security can be given.

##### 4.3.1 Confidentiality

In ERTMS, messages exchanged between trains and RBCs are encrypted, providing a measure of confidentiality.

##### 4.3.2 Integrity

ERTMS uses ETCS that supports data integrity [14]. Regarding, GSM-R the author of this paper could not find any indication as to if GSM-R supports data integrity. However, since GSM-R is based on GSM, this does seem likely.

#### 4.4 Quality of Service Support

ERTMS supports a strong level of QoS. In particular, one of GSM-R’s features is Multi-Level Precedence and Pre-emption Service (eMLPP), used to provide QoS differentiation to guarantee QoS for safety communication [33]. However, the GSM-R network showed a lack of capacity in busy commuter areas in 2003, assuming due to signal interference [7].

The only QoS related feature supported by RCAS is associated with the COMB feature that uses cell priority in order to minimize data collisions between radio coverage cells. The author of this paper could not find any other document that describes if and how other QoS features are supported by RCAS.

#### 4.5 Standards

ERTMS is backed by the European Commission, since many projects associated with ERTMS were funded by the European Commission. It uses the GSM-R standard that is currently being adopted by the ETSI standardization body. Moreover, ERTMS is deployed within Europe and is being adopted and deployed by various other countries, due to its qualities. CALM is currently a work in progress that is being standardized by the ISO. RCAS however, while being developed by the German Aerospace Center, is currently not being standardized by any international standardization body.

### 5. CONCLUSIONS AND FUTURE WORK

Several requirements for safety-enhancing wireless communication infrastructures in railway networks were stated. Three systems were then described, followed by an analysis of the degree in which they currently meet the requirements.
ERTMS enjoys strong support and international popularity, and appears to meet all the requirements stated. However, converting railway tracks to ETCS is expensive and slow.

RCAS is very much bare bones, not suitable for new high-speed lines, and does not appear to have any security. However, it is flexible and cheap, and can therefore be used – especially if the system is enhanced to support security – as a reliable stopgap for regional lines until ERTMS is deployed on them. Although CALM is being standardized by the ISO, which means it has a high potential, many of its qualities are still unknown. In addition, since it is mainly driven by the automotive industry, it may not be truly suited for railway safety applications, aside from applications used for safety support on road highway to rail intersections.

It can be concluded that: (1) ERTMS is highly promising and it can become “the” wireless railway communication infrastructure, (2) RCAS shows a high potential as being a complementing technology, although it still needs to be improved and tested before it can be deployed, (3) ISO CALM, on the other hand, is probably more suitable for automotive traffic safety applications than for railway traffic applications.

6. REFERENCES