Quick analysis on the use of Long-Term Evolution (LTE) and 5G on the future of the European Railway Traffic Management System (ERTMS) and European Train Control System (ETCS)

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***Abstract*—With the rise in rail travel in Europe and environmental concerns of the European Union's member states, there ~~has~~ have been talks to unite the rail system of these countries together. However, differences in railway gauges, signaling, and rail control systems complicate this effort. The European Union Agency for Railways introduced the European Railway Traffic Management System (ERTMS) and the European Train Control System (ETCS) as the first step towards this process. This paper discusses the current state of European rail control systems, how the ERTMS and ETCS helps to alleviate these issues and giving an outlook into the future of ETCS with the usgae of mobile connection standards.**

***Index Terms*—ETCS, ERTMS, train control, mobile network, LTE, 5G, FRMCS**

1. Introduction

European rail travel has become popular in the last decade, in some countries reaching passenger-kilometer (pkm) numbers higher than ever in the last 5 years (Eurostat, 2024) and in very specific cases, having banned or is planning to ban short-haul inland aviation travel like France or Spain. However, travelling between different countries may be a challenge, as each country has ~~their~~ its own electrical systems, different railway gauges and the main focus of this paper, rail control systems. On 11 May 2016, with Directive Number 2016/797, and most recently as of the time of writing, with European Regulation 2024/1679, the European Parliament and European Council have set out a list of guidelines to help with unifying the European rail system, including the usage of the European Railway Traffic Management System (ERTMS) and its train ~~controlling~~ control standard, the European Train Control System (ETCS). Even though these directives aim to help in the process, there are still concerns with how these systems are being implemented at the moment. This paper discusses the current disarray of standards in rail control systems in Europe and security concerns with them, how the ERTMS in general, the ETCS standard in particular, address these issues and the future forward for the ETCS standard with the use of mobile connection standards adapted for use for railway systems, in regard to how signaling from and to a train station can be improved with these new standards.

There has been proposed models that utilize mobile network standards as a means of real-time communication, including one from Zimmermann et al. [1] using the GSM-R standard for their implementation in 2005. However, during this time, there has also been newer standards developed based on the 4G/long-term evolution (LTE-R) and the currently used 5G networks, considering the offset of GSM based networks in many countries and its official end-of-life set to 2030. In our paper, we would like to give a short description of an implementation using these current technologies as a baseline for an imaginary rail control network, how it can be implemented and addressing any security concerns with them.

In the next section, we will go through the current background of European rail control systems by examining 4 different rail systems in Europe in some of its different regions, and examining how these systems might be flawed in their implementations. Section 3 will consider how ETCS would be an attempt at solving the aforementioned issues with current implementations, while also considering mobile network usage instead of the transmission methods currently being implemented in today's landscape.

2. Background Information

To understand the reasons behind rail unification in terms of rail control systems, we would like to first take a look at the current implementations that are being used in several different European countries.

2.1. Germany

2.1.1. The Punktförmige Zugbeeinflussung (PZB) Standard. The Punktförmige Zugbeeinflussung (PZB) is a train protection system, or as literally translated from the German word "Zugbeeinflussung", a train influencing system. It is currently used in the German-speaking region of Europe and a few other European countries as the main system for controlling trains in their regional or lower-speed rail networks.

The implementation can be divided into two sections: the trackside equipment and the trainside equipment. For the trackside equipment, it consists of a tuned inductor in the form of an RLC circuit, which is tuned to one of three different frequencies: 500 Hz, 1000 Hz and 2000 Hz.

These different inductors are placed at a distance close to the track, as opposed to direct installation on the track themselves, and each inductor frequency relates to a different type of signal for the driver, including caution corresponds signals, speed limits and other motion-related warnings. The driver has to follow certain speed limits set out in the different frequencies, with an acknowledgement from the driver necessary for the train to move forward.

The trainside equipment consists of a magnetic field detector and a display or a light panel with the corresponding buttons for the PZB system. An example of how this display is implemented can be found in a specifications file from the Austrian Federal Railways (Österreichische Bundesbahnen, or ÖBB/OEBB) [2], where both an analogue solution and a digital adaptation for the warning display are described. These warning displays are accompanied by audible warnings in the driver's cabin, where different tones signal indicates different types of signals that the detector has picked up and interpreted.

One advantage of the PZB is the ease of installation compared to other standards, including the ETCS, due to the minimal installation equipment, both trackside and trainside. However, due to the limitations regarding the technical details of this standard, the regulated speed limit for a PZB-only rail system is set at 160 km h^{-1}.

2.1.2. The Linienzugbeeinflussung/Linienförmige Zugbeeinflussung (LZB) Standard. The LZB standard was introduced in the 1960s to help overcome the speed limitations of the PZB. In Germany, it is required for lines travelling faster than 160 km h^{-1}, and in Spain, the minimum speed requirement is increased to 220 km h^{-1}. However, the ETCS will deprecate and replace this standard by 2030, especially on high-speed train lines.

Unlike the PZB, where the equipment is placed on the side of the rail track, LZB control signals are transmitted through cable loops installed on the rail segments themselves, and all signals are controlled through a central control centre, which is made out of a 2-of-3 computer system, similar to autopilot technology on commercial aeroplanes. To find a train's position, there are crossed cabling every 100 m, which have a phase difference of 180°, which the train will pass through, and this can be transmitted back to the control centre. To prevent signal degradation through the lines, repeaters are installed every 300 m of wiring ~~installed~~.

The trainside equipment here, however, is especially more complicated than the PZB. The train requires computers, sensors, receivers, pulse generators, and transmitters installed in the driver's cabin for the system to function. Keeping our comparison to the PZB, the trains, in this case, can be more automated, letting the driver focus better on observing their surroundings and complying with the signals. Despite this technology, signalling through the different components of the train, including the throttling and brakes, is controlled through a serial interface, showing a great limitation in sending multiple commands to multiple systems onboard.

2.2. France

2.2.1. Trackside signaling in France. Signaling equipment in France is placed differently depending on the region the train is being operated, which can mean that regions close to each other can have rail signaling placed on different sides. Overall, the general signal system consists of a color light and signage telling the driver the type of signal. There are three types of signals in the system: non-permissive (Non-franchissable/Nf), which the drivers cannot pass unless given notice; permissive signals (Franchissable/F or Permissivité restreinte/PR), where the driver can pass when certain conditions are met; and distant signals (e.g. Avertissement/A), which mostly consist of warnings from afar. This signage is accompanied by colored lights, illuminated according to the Verlant code (see [3] for a detailed explanation in French).

The Verlant code used the three basic colors of red, yellow and green, with each light signal containing four lightbulbs to assist signaling of different specifics. Alongside the light signal are other types of signals, including hand signals, signal boards or acoustic signals.

Rail lines in France are separated with the block system, where minimum distances are enforced and are divided into three types: non-interlocked manual blocks, interlocked manual blocks (only used on single tracks) and automatic block signaling, which is only used in areas with lower traffic.

Once speeds have gotten too fast however, drivers are unable to catch the light signals, and therefore, cab signaling has to be used, and the Transmission Voie-Machine (TVM) standard is created.

2.2.2. Transmission Voie-Machine (TVM). The development of this track-to-train system is connected with the development of the well known French high-speed train: the Train à Grande Vitesse, better known by its acronym: TGV. It was developed to be used on high-speed railway lines, specifically for their Lignes à Grandes Vitesses (LGV) system of rail tracks with higher speed limits (250 km h^{-1} to 320 km h^{-1}).

There are two versions of the standard: *TVM-430* and *TVM-300*, the former being the newer standard and has extensions made for either only automatic train control or full autonomous train driving. The track is divided into certain blocks of different lengths, ranging from 1500 m for the newer *TVM-430* to 2100 m for the older *TVM-300*. However, this also comes with a range of speed limit between 270 km h^{-1} for the latter, and 360 km h^{-1} for the former. The trackside equipment consists of trackside boxes, which control 15 km stretches of track, and connected to a traffic control centre, each with its own track circuit. The signals sent to the train are transmitted through these boxes and encoded as AC electrical signals. There are 4 different signal carrier frequencies for a TVM signal, ranging from 1700 Hz to 2600 Hz, alongside another 18 to 27 modulated audio frequencies. When a receiver at the end of a block cannot receive track circuit signal, it will be interpreted as the existence evidence of an occupied block of track, and according to the permissive signalling system, the train can proceed with a speed limit of 30 km h^{-1}. If the speed exceeds 35 km h^{-1}, the train will be stopped.

The trainside equipment consists of a lit square indicator board, which can have 2 or 3 rows, and these squares are colour-coded, displaying different target speeds are displayed to the driver. The speedometer is placed below this display, which shows the target speed and the current speed to the driver. Target speeds are transmitted to the driver multiple blocks ahead, and relay-based sensors are used to determine the train's position. The standard is built with redundancy in mind, though full control of the train cannot be taken over by just the *TVM* signaling alone.

2.3. Finland

The Finnish signaling system is also based on colored lighting, just like most other countries, however, instead of using one singular type of light like most other countries would, e.g. France, there are multiple shapes of lights placed at different positions along the track, which help the driver know what to look out for later on in their trip. The signals used on the mainline network, which is operated mostly by VR, Finland's national rail company. Alongside this signaling system is the automatic train control system known as Junakulunvalvonta (JKV), designated as ATP-VR/RHK, which is derived from Alstom's EBICab 900 technology.
Like many other standards, there are balises mounted on the track to help with the communication to the train. These balises transfer signals at a carrier frequency of 4.5 MHz, with packet size of 255 bit, in which 180 bit are vital information [3], including signals, speed restrictions, distances, and other information. Special locations on the track, denoted as information Locations, contain two balises that are activated when the train passes through them, since these balises are **passive**, just like the PZB. There are antennas mounted underneath the train's body that take in this magnetic signal, and transmit them to a display on the driver cab. These standards, even with redundancy built in mind, can all have failures with the hardware, which leave them unavailable and requires manual intervention. In addition, however, there can be concerns with manual hardware intervention, where malicious data or corrupted data can be sent through these balises. Additionally, the difference in both the trackside and trainside equipment has created the need to create a standard that can let all the trains of every European country to be able to communicate with the host country's signaling and safety features.

3. ERTMS and ETCS

The European Railway Traffic Management System (ERTMS) is an Automatic Train Protection (ATP) standard for use in the European Union, divided into different types and modes of operation, depending on the type of protection offered by the implementation. The European Train Control System (ETCS) is the standard used for the signaling and control section of the ERTMS.

3.1. Current Technical Standards of the ETCS

There were originally three main levels of ETCS operation, ranging from Level 1 to Level 3; however, Levels 2 and 3 have been merged into one another, creating an extended version of ETCS Level 2 during a meeting of the European Union Agency for Railways (ERA) in June 2023 [4]. There exists a definition for level 0, where ETCS-fitted rolling stock is being used on tracks without ETCS equipment installed on the track side.
Level 1 is when the cab signaling system of ETCS with the newer Eurobalises is used on top of the currently existing signaling, track-release and control systems in place. The train's movement however, is still monitored by on-board computers, in regard to maximum speeds and braking curves. The balises are powered by a magnetic field transmitted from the Eurocab system installed in the rolling stock itself, which is modulated to a frequency of 27 MHz. They are numbered to indicate the direction the train has to go, and these are spaced 3 m apart, giving an average uplink data transfer rate of 564.48 $\mathrm{kbit\,s^{-1}}$ for a train moving at a speed of 500 $\mathrm{km\,h^{-1}}$. In some cases, there can be signals emitted from the track-side equipment, and where there is less equipment, it can be considered an implementation of ETCS Level 1 Limited Supervision, letting the individual countries tailor the equipment to their own specific needs.

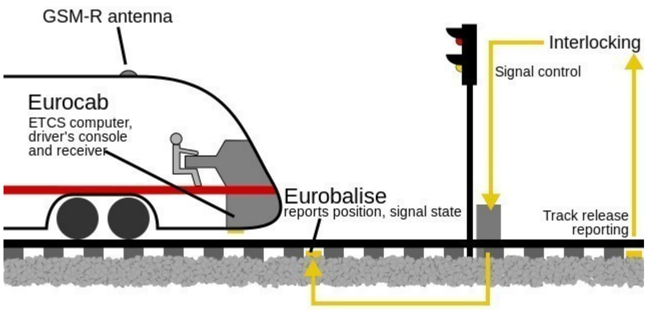

Figure 1: ETCS Level 1 signal transmission

ETCS Level 2 and 3 is what our paper is of concern, as in this case, the communication is now radio-based, and where track-side signaling can be eliminated. In this situation, the Eurobalises installed on the track are only responsible for giving the location of the train, communication is now sustained continuously through the use of GSM-Railway, which is based on 2G networks. In Europe, whereas there can be GSM signals within the range of either 900MHz or, in some cases, 1800MHz, GSM-R exclusively operates on the 900MHz band, with specific uplink frequences between 876 MHz and 915 MHz, and downlink frequencies between 921 MHz and 960 MHz. This would usually ensure that there would be less noise on the communications system, while keeping long-range communications possible.
What used to differentiate Level 2 and Level 3 operation modes of ETCS is the use of full radio-based train spacing, which means that the trains transmit positioning signals to a radio block centre, which can be considered as a rack system that is specifically made to process these signals. A derivative of the former Level 3 standard is ERTMS Regional, where the equipment was simplified to reduce equipment and operating costs.

3.2. LTE-R and FRMCS, and potential central control through mobile networks

3.2.1. LTE-R and FRMCS. Long Term Evolution (LTE) has been a standard for mobile communication networks

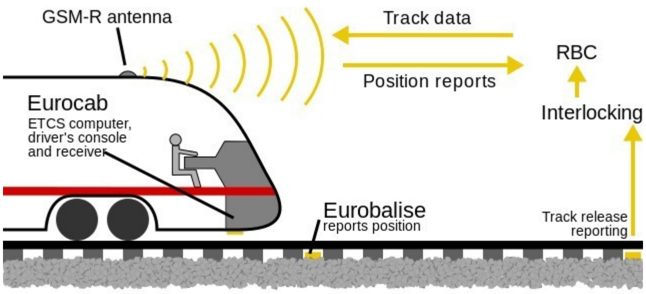

Figure 2: ETCS Level 2 signal transmission

TABLE 1: Call setup times by the International Union of Railways

Call type	Setup time	Network processing time
Railway emergency call	< 4 s	< 2.5 s
High priority calls	< 5 s	< 3 s

for the last decade, with the first deployment dating back to 2009 in Oslo and Stockholm by the company now known as Telia. In recent years, discussions of using LTE and the more recent 5G networks for train communications has come up, as more mobile carriers have decided to shut down their GSM networks, which is currently being used in many areas for train traffic management. In this section, we would like to discuss several aspects of LTE and the Future Railway Mobile Communication System (FRMCS) that can make them more suitable for railway communications than GSM-R.

with higher frequencies LTE and 5G allow for more channel bandwidths

One advantage of these two standards over GSM-R is the available bandwidth for rail communication systems. Instead of only using one fixed channel bandwidth of 200 kHz, by using LTE and 5G, there can be more channel bandwidths with higher frequencies, which can help achieve higher theoretical data transfer speeds, in some cases, up to the hundreds of megabits per second, despite using the same frequency bands as the currently used GSM-R technology.

With the use of newer technologies comes the integration of technologies that can be used in multiple fields at the same time. For example, Voice over LTE (VoLTE), which is a standard feature of LTE networks, can be used for the use of setting up calls in the train network. From the EIRENE System Requirements Specification (SRS) Version 16.0.0 [5] and the Functional Requirements Specification (FRS) Version 8.0.0 [6], we can generate Table 1 with the technical call setup times, with a focus on the network processing time in our third column.

These technologies also bring with them higher reliability and lower latencies, helping not only setting shorter communication delays, but also help train systems and drivers react faster to any emergencies that are reported over the network. Instead of delays in the hundreds of miliseconds range like GSM, latency of sub-10 ms range or even sub-millisecond can be achievable with LTE-R and 5G. Additionally, as explored by S. Dwivedi, R. Shreevastav and F. Munier, et al. [7], real-time positioning with 5G, including velocity, acceleration, and displacement is possible, which can help simplify the equipment required for the trackside sections, and letting control stations get positional information more accurately and quickly.

3.2.2. Possibility of Central and Real-time Control of Rail Systems. As we have specified earlier, the use of LTE and 5G in rail communication networks come with the possibility of real-time and centralized control of a rail network. We would like to propose a model specifying how this can be achieved, taking Hamburg Central Train Station (Hamburg Hauptbahnhof/Hbf) as our example. A map of the surrounding area is provided in Figure 3.

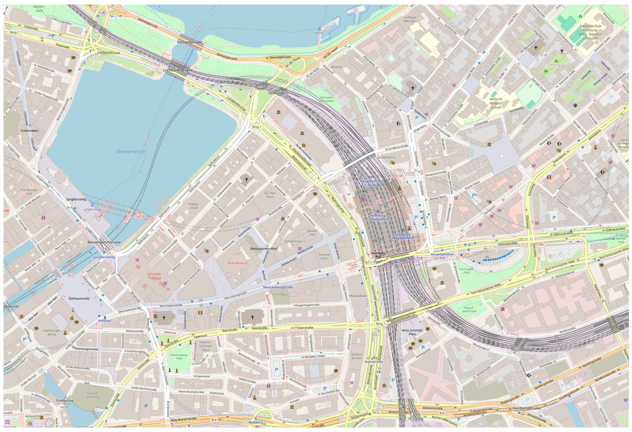

Figure 3: Map of area around Hamburg Central Station

Taking inspiration from air traffic control systems, we can create control booths of communication between train stations and train drivers in the station themselves, with the usage of both dedicated and existing LTE and 5G infrastructure. However, we must consider the use of sub-6 GHz 5G networks, since the mmWave standard has a shorter range and is more susceptible to interference from physical infrastructure, which we can prove using the equation $\lambda = c \cdot f$, where λ is the wavelength of our signal, c is the speed at which the signals travel and f is our signal frequency. The higher the frequency, The control center can have an overview of the positioning of different trains using this same network, and with certain jurisdiction around a certain space around the station, in some cases, neighboring stations, and in Hamburg's case, its other major stations in Hamburg Dammtor, Hamburg Altona and Hamburg Harburg, same as how most air traffic control systems are implemented. However, the main difference here for this type of train control system is that alongside this radar, the operator can have direct control over the train, if the driver has not acknowledged any messages from the control center. For example, emergency stop signals can be directly transmitted to the train through the use of transponders from the station and receivers on the trains, which can process the signals quickly such that the trains can automatically stop themselves. This can be a possible option, since for most implementations of ETCS, the removal of trackside signaling means that there can be issues for drivers to know what exactly is happening in front of them.

While this type of implementation can come with the aforementioned adavantages, there can be major cyber-security issues with this system. The use of technologies

such as IPsec and signal encryption overall can help mitigate issues regarding signal interception. Another issue that may come up is latency, however, this is an inherent issue with the usage of wireless networking, and therefore, the only way to overcome this is with the use of dedicated signal wiring, which can complicate the installation of equipment for communications.
Despite that, with the use of LTE-R and FRMCS, this operation model can be made possible, and it will take time before members of the European Union would consider the different aspects of communication, such that it can function between multiple countries at once, not just in a local scale.

4. Conclusion

The move away from GSM-R towards FRMCS can be the most influential change to the European rail unification process, since the usage of real-time communication and control can help alleviate not only delays, but also improve safety and security of the continent's rail system. Even though there are issues within the companies to be addressed, such as different ticketing systems, the benefits of these technologies can help make rail travel in Europe easier, faster, more convenient and less cost-consuming for travellers.

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