Summary
This paper examines the requirements that a radio data transmission network needs to meet to serve as the train-to-wayside radio bearer for a Communications-Based Train Control (CBTC) system. Those requirements are first considered through a data traffic model, and then mapped against the capabilities of a Long Term Evolution (LTE) radio network, in order to identify the necessary configuration parameters and the network architecture.

The examination of the resulting parameters and architecture characteristics lead the author to conclude that public mobile telephony LTE networks may not be suitable to support CBTC systems, although private LTE networks can be configured to fulfil that mission.

1. Introduction
The last couple of years have seen a quiet revolution starting to unfold in the Communications-Based Train Control (CBTC) arena. A groundswell of change is clearly building up, and the moment is ripe for the greatest technology swap in this space in over a decade. But what will be involved in that change?

Since 2003, free-space propagation data radio transmission has been the norm in most CBTC projects around the world, as the possibility of using continuous radio communications allowed CBTC systems to overcome some of the issues presented by track-bound induction loop and waveguide technologies.

At the time, the most cost-effective off-the-shelf radio technology that could provide sufficient bandwidth for the CBTC application was, undoubtedly, the IEEE 802.11 standard family – commercially known as “Wi-Fi”. In a very short period of time, all CBTC suppliers in the world developed systems that made use of Wi-Fi-based radio solutions. Currently, dozens of Wi-Fi-based CBTC solutions are in full commercial operation in four continents, and a large number of CBTC deployment projects are currently in different stages of development all over the world.

Things, however, have changed since 2003. CBTC is expanding outside its original environment of underground, inner-city, relatively short dedicated mass transit lines. Newer projects are deploying CBTC over longer sections, on lines that go into the suburbs, becoming overground as they do so, and sometimes even encountering mixed traffic situations. This leaves CBTC systems more exposed to external radio interference than they had ever been in the past.

On the radio front, things have been changing even more. Wi-Fi technology has become so successful that it is now at the core of data consumption growth in the mobile telephony market, with smartphones being capable of connecting to Wi-Fi Access Points (AP) and being able to operate in a tethering mode, acting as a Wi-Fi AP itself.

At the same time, the “Internet of Things” is exponentially increasing the number of devices that are connecting via Wi-Fi networks to other devices. The unlicensed radio frequency spectrum bands where Wi-Fi operates are getting busier and busier with each passing day.

Recognising these challenges, the industry is taking the necessary steps to replace Wi-Fi-based radio systems in CBTC applications. In all cases thus far, the selected technology seems to be Long Term Evolution – as defined by the 3GPP family of standards [1]. A number of trials are underway, and commercial applications should not be more than a few years away, at most.

Given that radio communications lies at the core of CBTC system architecture, this change begs a number of key questions. What changes, if any, need to be made to existing CBTC applications in order to use LTE as a data radio bearer? And how does an LTE network need to be configured and optimised in order to support a CBTC application? Corollaries of great significance stem from these highly technical questions, such as whether CBTC could be implemented over a public mobile telephony LTE network, or how much spectrum bandwidth needs to be reserved for CBTC systems.

This technical paper will delve into the technical interface between CBTC applications and LTE radio networks. It will explore the requirements imposed by CBTC applications on their current radio bearers, and we will try to map those requirements against the data bearer services that LTE networks can provide. We will explore the implications of optimising LTE networks to meet those requirements, and what other applications could still make good use of an LTE network at different priority levels.

2. Data Traffic Model and Radio Interface Requirements
Firstly, we will address the way in which CBTC uses radio resources, in order to identify the requirements that the CBTC application imposes over any radio bearer used for train-to-wayside data transmission. In order to do this, we will have a closer look at the architecture of a CBTC system, both on the wayside and on board. We will then examine a series of
operational scenarios to map how the different components of a CBTC system interact with each other using the radio communications subsystem, thus building a data traffic model for a typical CBTC application that will allow us to identify the requirements that a CBTC application imposes over its radio subsystem.

2.1 CBTC System Architecture

This section will describe the architecture of a generic CBTC system, maintaining a vendor agnostic terminology based on the IEEE 1474.1 standard [2]. Figure 1 below shows the different components of an IEEE 1474 CBTC system.

The blue-shaded square corresponds to the Automatic Train Supervision (ATS) system. ATS monitors trains, adjusts individual train performance to maintain schedules and adjusts service patterns to minimise the effect of traffic perturbations. It also implements route setting, both manual and automatic. All changes to train behaviour instructed by the ATS subsystem are actually jointly implemented by ZC and OBC, and changes to trackside systems are implemented by IXL and OC.

Finally, the green-shaded areas in the centre of the diagram stand for the Data Communications Network (DCN). The DCN includes a Fixed Transmission Network (FTN) that acts as the glue between all the trackside elements – including the trackside components of the radio network. It also includes a radio element that implements train-to-wayside data transmission.

Currently, the radio network mentioned above is often implemented through a series of IEEE 802.11 (Wi-Fi) Access Points. In the near future, however, the architecture that is starting to replace 802.11-based radio networks will be composed of an Onboard Data Radio (ODR), an LTE Radio Access Network (RAN) – with a series of individual radio base stations called eNodeBs – and an Evolved Packet Core (EPC).

2.2 CBTC On Board Components

A lot of the details of the architecture of on board CBTC components will be dependent on the specific CBTC solution being implemented, but will change from train set to train set – since the OBC will need to interface the trains braking system, for instance, and be uniquely configured for each train set. Particulars about balise or beacon readers, tachometers, radar detectors to deal with slips and slides, etc… may all be different.

However, the radio communications interface presents certain trends that seem to be almost universal in the sector.

The pink-shaded squares correspond to the Automatic Train Protection (ATP) and Automatic Train Operation (ATO) functions.

The ATP subsystem provides safety by maintaining train separation, enforcing maximum speed restrictions and safely interlocking trackside equipment. Train separation across specific areas is maintained by the Zone Controller (ZC), which knows the location of all the trains within a given section of track, and which maintains communication with the computer-based Interlocking (IXL) regarding the status of different trackside Object Controllers (OC).

The ZC sends instructions regarding train movement to each individual train. Those instructions are received and acted upon by the Onboard Controller (OBC).

The ATO subsystem provides speed regulation, programmed stopping, door control and other train operator functions. These functions are implemented by the ZC and the OBC, as in the ATP subsystem.

Thus, Figure 2 above presents what is the most common solution for OBC-ODR architecture on board CBTC fitted trains. A single train set (two, three or more railcars) is usually fitted with two OBCs, one at each end of the train. Each one of the OBCs is
connected to an independent ODR, which is in turn connected to two rooftop antennas. We will assume an architecture such as the one presented in Figure 2 to model our generic CBTC radio interface.

2.3 Operational Scenarios

Based on the architectures presented in the sections above, the traffic model has been divided into five different operational scenarios:

1. Network Registration
2. Entry into CBTC Operation
3. Open Line CBTC Operation
4. Handover between Radio Cells
5. Handover between Zone Controllers

2.3.1 Network Registration

During the start-up process of CBTC onboard equipment, while a train is potentially still in a stabling siding or in a depot workshop, the Onboard Data Radio (ODR) will power up together with the rest of the on board equipment.

Upon powering up, the ODR will attempt to register onto the radio network. A network registration message exchange sequence will take place between the ODR and the wayside DCN infrastructure.

In the case of an IEEE 802.11 network, this traffic exchange will merely involve the nearest Wi-Fi Access Points (AP), therefore needing a configuration update of all the CBTC ODRs operating in the network whenever a new AP unit is introduced.

In the case of an LTE network, this registration process will take place on the Control Plane between the ODR, the LTE radio base station (eNodeB) in which the ODR is camping at the time, and the Mobility Management Entity (MME), the Serving Gateway (SGW) and the Home Subscriber Server (HSS) that form part of the Evolved Packet Core (EPC). See Figure 3 below for a brief schematic of LTE network architecture.

Once registration on an LTE network has been completed, the ODR will be ready to accept a dedicated data bearer with the Quality of Service (QoS) Class Indicator (QCI) profile that will correspond to the CBTC application – as we will discuss in greater detail further on.

The requirement from CBTC suppliers is that the network attachment process should not unduly delay the operational readiness of the train. With this in mind, a valid assumption for our data model would be that radio power up and network attachment process – from ODR turn on until the ODR is ready to receive instructions from the ZC – should not take longer than 45 seconds.

2.3.2 Entry into CBTC Operation

Once the radio is operational, the OBC will first try to establish contact with the local Zone Controller (ZC) in order to start exchanging information and to prepare for entry into full CBTC territory in fitted mode.

The trigger of this initial connection can be automatically included in the loading process of the OBC – if the address of the ZC is known to the OBC – or the establishment of that connection may be triggered by a balise or beacon located on the four-foot that instructs the OBC to contact a specific ZC.

Upon being instructed by the OBC to request a dedicated CBTC bearer and to establish contact with the appropriate ZC, and based on feedback from different CBTC suppliers, our model will assume that the ODR will be capable of establishing a connection with the relevant ZC within 5 seconds of the request being triggered, as required by CBTC suppliers.

2.3.3 Open Line CBTC Operation

Once a data link between the OBC and the ZC has been set up, the OBC will be capable of exchanging messages with the ZC. The nature of these messages – again, for a typical, IEEE 1474 compliant CBTC system, bearing in mind the proprietary nature of the different solutions offered by the supplier industry – is assumed to be as follows.

Typically, the OBC will send messages to the ZC at regular intervals. These messages – collectively called Position Updates (PU) – will in most cases contain three types of information:

- Train location updates, based on the location information obtained from the latest balise or beacon, updated by onboard instrumentation (tachometer, inertial navigation systems) and adding a safety margin as moving block margins.
Train speed, measured through rotary speed wheel sensors and Doppler radar systems (for slip-slide compensation).

Train health status information.

A specific proprietary OBC solution generates, on average and for each ODR, 1 message of 5 kilobits every 150 ms, corresponding to a total uplink (OBCs to ZC) data transfer rate of 13.33 kb/s.

A different CBTC supplier may propose a solution where both OBCs generate, on average, 1 message of 3.2 kilobits every 312.5 ms, generating a total uplink throughput 10.240 kb/s per train.

A comparison between the OBC-ZC data throughput requirements from different CBTC suppliers indicates that a large majority of them would require an average rate around 50 kb/s, with peaks at a maximum rate of 100 kb/s.

This data throughput would, in a Wi-Fi network, be dynamically shared between the two ODRs at either end of the train. In an LTE network, the same messages are more likely to be sent by one of the two ODRs, with the second one remaining in hot standby for redundancy purposes. In either case, the total OBC-ZC data throughput remains the same.

At the same time, the ZC and the ATS sub-systems will also send messages to each OBC in the trains within the ZC’s control area – the ATS instructions will be channelled through the ZC, which is the only device that interacts directly with the OBC through the radio interface.

The ZC will send Movement Authority (MA) messages, which state how far a given train can move down the track based on the location and speed updates from all the trains in the area and on the status of trackside Object Controllers, obtained from the area’s Interlocking.

The OBC will use information contained in the MA to apply the train’s braking system and/or to act upon the train’s traction system.

Through the ZC, the ATS system will regulate traffic between several trains – a process called Automatic Train Regulation (ATR) - in order to help railway operations to recover from previous disruptions in traffic or to optimise traction power energy consumption, by cascading train acceleration and deceleration – particularly if regenerative braking is in use.

This variety of messages can be modelled for the first CBTC solution mentioned above as 4 messages of 2 kilobits every 200 ms, corresponding to a Downlink (ZC to both OBCs) data transfer rate of 40 kb/s.

The second supplier taken as an example would generate a Downlink traffic of 1 message of 3.2 kilobits every 312.5 ms, generating a total uplink throughput 10.240 kb/s per train; that is, the same as the Uplink traffic.

Based on a value comparison between CBTC suppliers, a ZC-OBC bit rate per train of 100 kb/s would cover the requirements from most suppliers.

As for latency requirements, and based on information provided by CBTC suppliers, all supplier responses would be accommodated by a maximum end-to-end packet delay of 30 ms both in the uplink (OBC-ZC) and in the downlink (ZC-OBC).

2.3.4 Handover between Radio Cells

Inter-cell handover is one aspect where the two radio technologies – current Wi-Fi based solutions and future LTE networks – behave in a radically different way, to the point where changes may be experienced at the CBTC application level.

Upon completion of the registration sequence in a Wi-Fi network, the ODR will be registered onto the nearest Wi-Fi Access Point. But once the train starts to move, the ODR will very soon leave the range of the first Wi-Fi AP. Table 1 below shows the typical maximum range values available to different IEEE 802.11 standards in conventional configuration:

<table>
<thead>
<tr>
<th>Standard</th>
<th>Frequency</th>
<th>Maximum Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11a</td>
<td>5 GHz</td>
<td>120m</td>
</tr>
<tr>
<td>802.11b</td>
<td>2.4 GHz</td>
<td>140m</td>
</tr>
<tr>
<td>802.11g</td>
<td>2.4 GHz</td>
<td>140m</td>
</tr>
<tr>
<td>802.11n</td>
<td>2.4 / 5 GHz</td>
<td>250 m / 140 m</td>
</tr>
<tr>
<td>802.11ac</td>
<td>5 GHz</td>
<td>250 m (amplified)</td>
</tr>
</tbody>
</table>

Once an ODR moves out of the range of the AP to which it was connected, it will need to connect to a new AP to maintain the OBC-ZC connection.
This process may be eased through the use of Wi-Fi Mobility Controllers, but very often CBTC systems rely on having one ODR registered and transmitting with a given AP, while the ODR at the other end registers with the next AP down the line – that is, mobility is partly handled by the CBTC application itself.

An LTE network, however, will behave in a very different way. Inter-cell mobility is handled by the Mobility Management Entity (MME) and by negotiation between the eNodeBs involved (see Figure 3 above). It is not necessary to use two ODRs simultaneously to maintain OBC-ZC communication – a single ODR can transition between cells practically seamlessly.

This difference has an immediate implication on the overall availability of the system. With the same amount of on board equipment, the LTE based solution will have a higher availability than the Wi-Fi based solution, since it would be more tolerant to the failure of one ODR – it doesn’t need both ODRs to be transmitting at all times.

In either case, though, inter-cell handover requirements will be similar from the point of view of the CBTC application. A comparison between the requirements provided by different CBTC suppliers can lead to expect an average value of 1% packet loss during handover and a handover time below 200 ms for a 99% of handovers.

2.3.5 Handover between Zone Controllers

Many CBTC implementations do not require handovers between ZCs, often because they consist of completely separate lines where a single ZC controls the line end-to-end.

In the cases where trains can move from the area controlled by one ZC into the area controlled by a second ZC, the radio infrastructure will play a role in the process.

ZC-ZC transition may be triggered by a balise or beacon located in the four-foot, or each OBC may be have been programmed to trigger the transition upon reaching a certain location. In either case, the transition will be handled at the application layer, without intervention from the radio network.

In order to be able to communicate with both ZCs at the same time, however, an ODR may need to request a second dedicated data flow to the receiving ZC (this will depend on the details of how the CBTC application handles ZC-ZC handover). If this were the case, it is assumed that the allocation of the second bearer will also comply with the requirements listed above for OBC-ZC links, meaning twice as much data will come from a single train as in the open line scenario.

3. Dedicated Bearer Configuration

Once we have identified a data traffic model and a set of requirements, it is the moment to explore how the future technology of choice (LTE) will be able to meet those requirements.

An LTE network will effectively treat CBTC as a user application sitting on top of the LTE protocol stack. The LTE network will handle CBTC traffic by establishing a tunnel from the ODR, through the eNodeB located on the trackside, through the backhaul transmission network and the user plane of the EPC and onto the ZC connected to the EPC as an IP Service. LTE will use the GPRS Tunnelling Protocol (GTP) to establish data tunnels through the LTE network [3][4].

In an LTE network, user plane traffic (such as CBTC OBC-ZC data) is carried within virtual containers called “bearers”, with each bearer having a certain QoS profile.

When an ODR registers onto a network, it will use the GTP protocol to establish initial communication with the LTE core through a default bearer. This default bearer is used to transmit control plane information back and forth between the EPC and the ODR, establishing the identity of the ODR and its credentials to use the network, its current location and requirements, and so on and forth. This control traffic, which is in Communications parlance confusingly referred to as “signalling”, is maintained throughout the period when the ODR is connected to the LTE network.

Once the ODR has been authenticated on the LTE network – in a manner in all similar to that followed by any other User Equipment (UE) registered in the network – the QoS profile configured on the EPC to support the CBTC application will provide the parameters for the GTP layer to set up a second data bearer for the ODR.

This second data bearer – called a “dedicated” bearer – will be the actual carrier for the user plane traffic of the CBTC application; i.e., this second dedicated bearer will be the one to really carry CBTC traffic, encapsulating CBTC packets as user payload. So it is the configuration of the CBTC dedicated bearer that is critical to understand how an LTE network could support CBTC traffic on the OBC-ZC interface.
The key configuration parameters associated with an LTE dedicated bearer are the following – assuming that the CBTC bearer will be set up as a Guaranteed Bit Rate service:

- Guaranteed Bit Rate (GBR)
- Maximum Bit Rate (GBR)
- Allocation Retention Priority (ARP)
- Packet Delay Budget (PDB)
- Packet Error Loss Rate (PELR)

In conventional LTE networks, QoS parameters are usually grouped under specific QoS Class Identifiers (QCI). LTE specifications propose "typical" QCI profiles for certain generic services, such as conversational voice or video, real-time gaming or buffered video streaming, but they do not contemplate an application such as CBTC.

It is not the intention of this paper to propose a single bearer configuration that may satisfy all future CBTC deployments. It will be the responsibility of each specific CBTC deployment project to define the most adequate QCI profile for its CBTC application, depending on proprietary supplier requirements and on the other applications that may be using the same LTE network as a radio bearer. But we can venture a proposal of CBTC dedicated bearer configuration that would meet the requirements presented in previous sections. This parameter configuration is presented in Table 2 below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GBR/UL</td>
<td>50 kb/s</td>
<td>ARP</td>
<td>0.8</td>
</tr>
<tr>
<td>GBR/DL</td>
<td>100 kb/s</td>
<td>PDB</td>
<td>30 ms</td>
</tr>
<tr>
<td>MBR/UL</td>
<td>100 kb/s</td>
<td>PELR</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>MBR/DL</td>
<td>100 kb/s</td>
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</table>

Given the typical requirements expected from mission-critical push-to-talk voice (in the order of 10s of kb/s per UE), it is highly unlikely that an LTE cell will reach the levels of congestion necessary for CBTC dedicated bearers to start being pre-empted.

PELR have been chosen to match similar low-latency, low-bandwidth LTE services. Given that CBTC applications present their own mechanisms to handle message corruption, this value should be sufficient without presenting an overly taxing requirement on the radio network.

### 4. Availability and Network Architecture

There is one additional requirement we have not covered so far. The reason for that is that this requirement does not actually stem from the CBTC application itself or from the CBTC component suppliers, but rather from the expectations that a railway operator may set for the end-to-end operation of the CBTC system. We are talking about availability.

An indicative availability figure for the radio interface that supports OBC-ZC data transmission could be an availability of 99.999%, equivalent to a downtime of 5 minutes and 15.6 seconds per year during train operations – with planned maintenance activities and downtime not necessarily being counted against the total.

This would be an extremely demanding availability requirement for any radio network. And the key to meet such a requirement is the architecture of the LTE network itself.

A first approach to an architecture that could meet such a high availability figure would entail minimising single points of failure. This could be achieved by deploying:

- Redundant cores in separate physical locations with dual homing eNodeBs, so that traffic load is dynamically shared – rather than having one of the cores in cold/warm/hot standby.
- Overlapping coverage from adjacent radio cells.
- Dual fed radio sites.
- Duplicated power supplies.
- Secondary backhaul paths.

The specific network architecture for each site will depend on the topology of the CBTC system itself, and may include some or all of the suggestions above.
5. Conclusion
The previous sections have explored the requirements imposed by CBTC applications over the train-to-wayside radio interface.

When trying to map those requirements against the capabilities of LTE networks, we have seen that the network will need to be configured on a specific way in order to meet those requirements. Even more; the availability requirements of such a mission-critical application will impose rather onerous network architectures.

The most immediate corollary to these findings is that it may be very difficult to deliver CBTC over a conventional, carrier-grade LTE network. Public land mobile operators have optimised their LTE networks to serve the requirements of what constitutes their core business and their main source of revenue – consumer market data applications.

It would not be easy to reconfigure a carrier LTE core so that it can serve a CBTC application – changes may need to be made to such critical elements as the radio resource scheduling algorithms in order to meet CBTC’s very demanding latency and availability requirements. It would be even more complex to modify a carrier’s network architecture along the lines indicated above. And, most importantly, there would be very little economic incentives for public mobile telephony changes to enact these drastic changes in their networks in order to meet the requirements of an application from a client base that does not constitute a significant revenue stream.

It is therefore clear that, at least for the foreseeable future, CBTC applications will be limited to railway dedicated LTE networks that can be optimised to guarantee the operation of such a mission-critical application. This seems, in any case, to be the trend that the railway sector is following.

As for the amount of spectrum bandwidth necessary for CBTC, the application does not present very onerous data throughput requirements. Total bandwidth requirements will however vary between specific implementations, depending on the maximum number of CBTC fitted trains to be found in a single cell, but also – and foremost – on the expectation to support additional applications through the same LTE network. LTE’s priority and pre-emption mechanisms make the option of sharing a single radio network amongst several applications – such as mission critical voice, CCTV live streaming or on board equipment monitoring – a very real possibility.

All added up, the analysis of CBTC traffic presented in this paper, coupled with the joint field trials currently being conducted by CBTC and LTE suppliers prove that CBTC is a viable replacement for the current IEEE 802.11 (Wi-Fi) CBTC radio bearer. Bringing into consideration the drivers behind the push for an LTE-based replacement of CBTC’s Wi-Fi radio layer [6], it seems that the step from field trials into operational CBTC over LTE systems in coming years will be inevitable.

6. References
[4] 3GPP TS 29.274 v12.9.0 Tunnelling Protocol Control Plane (GTPv2-C)
7. Acronyms and Definitions

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
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<tr>
<td>AP</td>
<td>Access Point</td>
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<td>ATO</td>
<td>Automatic Train Operation</td>
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<tr>
<td>ATP</td>
<td>Automatic Train Protection</td>
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<tr>
<td>ATS</td>
<td>Automatic Train Supervision</td>
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<tr>
<td>CBTC</td>
<td>Communications-Based Train Control</td>
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<tr>
<td>DCN</td>
<td>Data Communications Network</td>
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<tr>
<td>eNodeB</td>
<td>LTE radio base station</td>
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<tr>
<td>EPC</td>
<td>Evolved Packet Core</td>
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<tr>
<td>FTN</td>
<td>Fixed Telecommunications Network</td>
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<tr>
<td>GBR</td>
<td>Guaranteed Bit Rate</td>
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<tr>
<td>HSS</td>
<td>Home Subscriber Server</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<td>IP</td>
<td>Internet Protocol</td>
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<tr>
<td>IXL</td>
<td>Interlocking</td>
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<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
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<tr>
<td>MBR</td>
<td>Maximum Bit Rate</td>
</tr>
<tr>
<td>MME</td>
<td>Mobility Management Entity</td>
</tr>
<tr>
<td>OBC</td>
<td>On Board Controller</td>
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<tr>
<td>OC</td>
<td>Object Controller</td>
</tr>
<tr>
<td>ODR</td>
<td>Onboard Data Radio</td>
</tr>
<tr>
<td>PCRF</td>
<td>Policy and Charging Rules Function</td>
</tr>
<tr>
<td>PDL</td>
<td>Packet Delay Budget</td>
</tr>
<tr>
<td>PELR</td>
<td>Packet Error Loss Rate</td>
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<tr>
<td>P-GW</td>
<td>Packed Data Network Gateway</td>
</tr>
<tr>
<td>S-GW</td>
<td>Serving Gateway</td>
</tr>
<tr>
<td>RAN</td>
<td>Radio Access Network</td>
</tr>
<tr>
<td>ZC</td>
<td>Zone Controller</td>
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8. About the Author

Mr Rodrigo Álvarez

Rodrigo has been involved in railway communications in the UK, Europe and Australia for over twelve years. His experience is especially centred in the integration of advanced railway signalling systems and telecommunications technologies. Past projects include Network Rail’s Cambrian ERTMS Deployment and Crossrail Programme in London, as well as GSM-R deployment in ADIF’s High Speed Network (Spain). He has also worked on railway research and development projects for the European Commission. Since February 2013, Rodrigo has been working for the Public Transport Authority of Western Australia in the planning phases of the Radio Systems Replacement and Automatic Train Control Projects. Rodrigo’s technical background includes the design of GSM-R networks, as well as SDH and Carrier Ethernet networks. On the signalling side, Rodrigo has a wealth of experience in ERTMS systems, and he is well acquainted with the transmission requirements of axle counters, modern Computer Based Interlocking, SISS and DOO systems. In the last three years, Rodrigo has had a very significant exposure to LTE, Wi-Fi and CBTC technologies.