CAPSTONE PROJECT REPORT

MINT PROGRAM

Study of Rail Transit System Communication Network (BCN/TCN) and Related Sub-Systems

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1.0 Introduction

The signaling and train control system is like lifeblood for any rail transit system. The train control system requires continuous information on the location of the trains on the track and based on this information use signaling to control the movement of the train. This requires a reliable communication system to transfer information related to train location and signaling between train, wayside controls, and signaling system. The system needs to transfer information between various equipment without delay and to keep its integrity intact. The communication network deployed for train control system plays a key role in the safe and secure operation of the train system.

1.1 Background

The development of the steam engine led to the expansion of railways worldwide. The 19th century saw the rapid development of railways all over the world including Canada, and it virtually brought a revolution in the transportation industry (Marsh, 2009). The invention of diesel and electric locomotives which could pull much large load enhanced the efficiency and capacity of the network many folds. The railways played a major role in industrialization, development of new markets and integrating them to create a demand for resources and technology. However, the railway's infrastructure required major investments, land requirements and right of way. This requirement of funds was met by massive public expenditures in various forms, but the results were a substantial contribution to the employment, business development and general economic growth of the far-flung regions.

With the rapid expansion of the railroad system for transportation of human resources, the railroad system became complex infrastructure requiring special techniques and technologies to manage it. Railroad-Based transportation has become a lifeline for metro cities to carry a large number of people from their home to workplaces without the hassle of getting into traffic jams. With the introduction of the electric locomotive, it is a most environmentally friendly system for mass movement of men and material across the nation. The railroad system has come under pressure to increase its capacity and speed to ease pressure from busy roads and everyday traffic snarls.

The complexities of the system have led to many disasters due to technical problems as well as human errors. February 26th, 2012, saw a major VIA train derailment at Burlington in Canada when a Via train ran at 56 MPH over 15 MPH crossover killing three crew in the engine and injuring 46 persons (Wightman, 2018).

Managing complex railroad infrastructure requires timely information on rail stock using an automated, reliable and failsafe system for train management. Train Communication Network (TCN) is an effort in this direction. The train signaling and communication system plays a key role to meet increased demand and safety (F. R. Yu, 2018).

1.2 Evolution of Train Control/ train signaling Systems

Rails provide low friction path for the trains, but this feature leaves the train system with poor braking capabilities. In the beginning, only one train used to ply over the rail track. The increase in rail traffic demanded the use of the same track for multiple trains operating close to each other. The signaling system is used for basically avoiding collision and derailment of trains plying on the same track (Morar, 2012). This required stringent traffic control and led to the development of a block system where rail track was divided into blocks or sections, and only one train was allowed to be in the block to avoid a collision. Each block was protected by a mechanical signal placed at the beginning of the block to provide information to the driver of the train about the availability of the block or section as shown in Figure 1 (Railway Technical, 2019). The signal shows green when the block is unoccupied and red when the block is occupied.

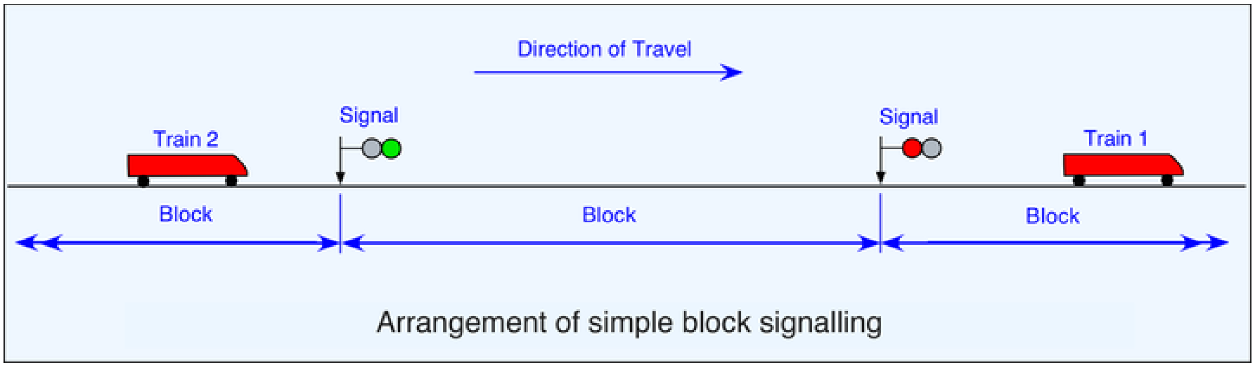


Figure 1. Schematic of signal block section (Railway Technical, 2019)

The train signaling and control systems were developed with the basic objective to prevent collisions of two trains traveling on the same track. This requires a control system to have the knowledge of the location of the train on the track. (F. R. Yu, 2018)

The first signaling control system using Track Circuit was developed in late 1800 by William Robinson (Mansour, 2017). The track circuit was used to detect the train's presence or absence on the track and provided tracks status on trackside signals to provide information about track condition ahead to the drivers. The track circuit consists of a low voltage generator that energizes a relay though rails and activates the go signal as shown in Figure 2 (Railway Technical, 2019).

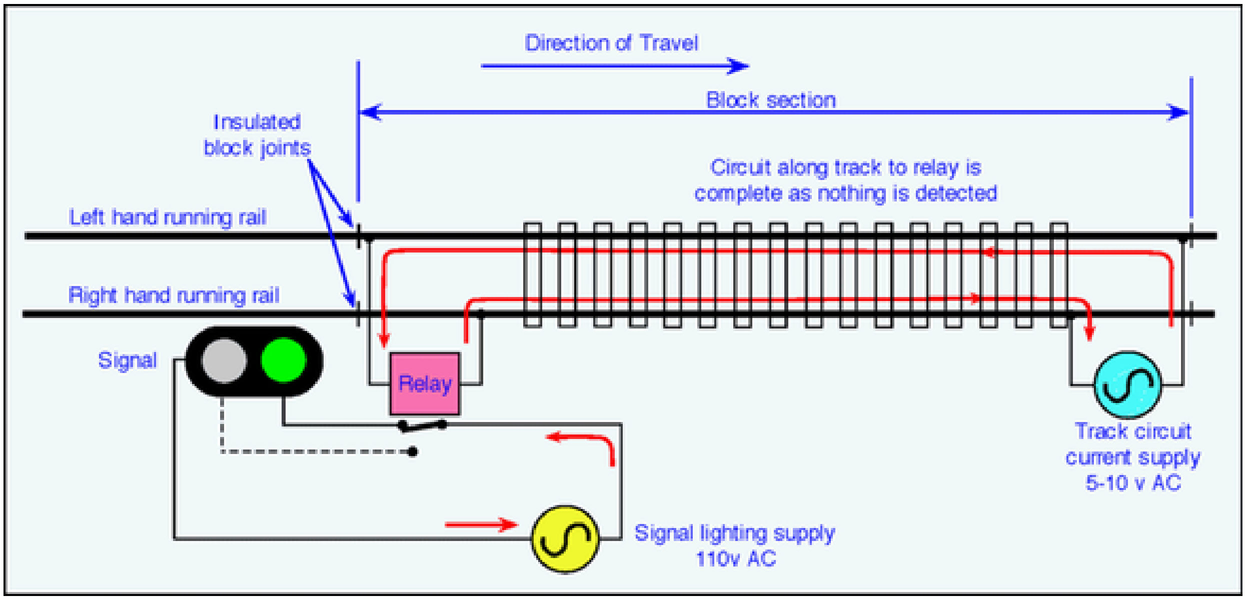

Direction of Travel
Block section
Insulated block joints
Circuit along track to relay is complete as nothing is detected
Left hand running rail
Right hand running rail
Signal
Relay
Track circuit current supply 5-10 v AC
Signal lighting supply 110v AC

Figure 2 Track Circuit - Block Unoccupied (Railway Technical, 2019)

When the train is there on the track, the presence of wheels interrupts the current flow through the relay to de-energize the relay and activate the stop signal as shown in Figure 3. This system provided "fail-safe" operation as any problem in the circuit will lead to relay getting de-energized and put as stop signal to avoid any mishap.

The simple Track circuit based signaling allowed limited train operational flexibility and throughput constrained by the block length and wayside signal aspects. The next improvement in signaling came with the replacement of a wayside signal by in-cab signal. The system used coded circuits that transmitted the speed codes from wayside over the rails. The speed codes were picked up by the equipment in the train, and this provided continuous information about the track condition to the driver on the train. The system allowed automatic operations but again was limited by the layout of the track circuit and number of speed codes used. This technology was used in the latter half of the 20th century by many railroad systems including Washington (WMATA), Victoria line of London underground, lines in Hongkong and many more (F. R. Yu, 2018).

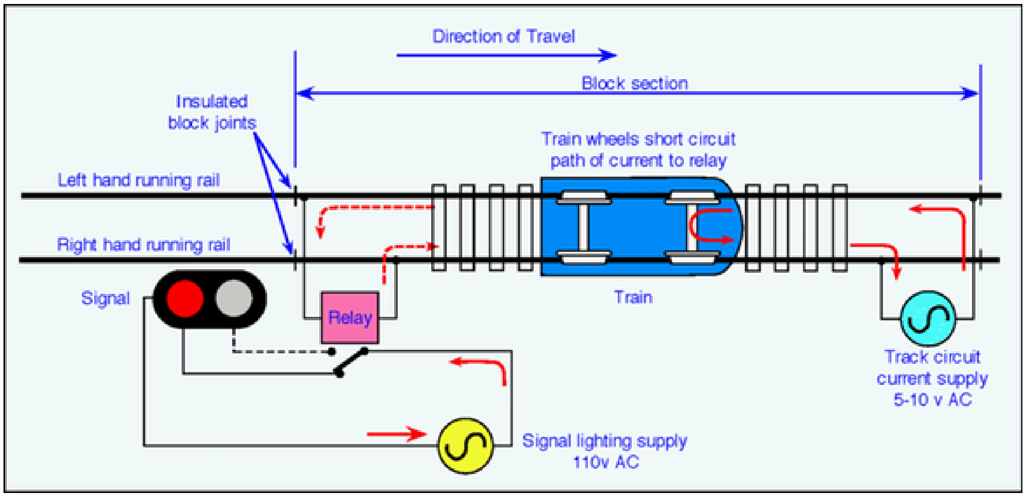


Figure 3. Track Circuit - Block Occupied. (Railway Technical, 2019)

The further improvement in signaling system came with the introduction of distance-to-go technology shown in Figure 4.

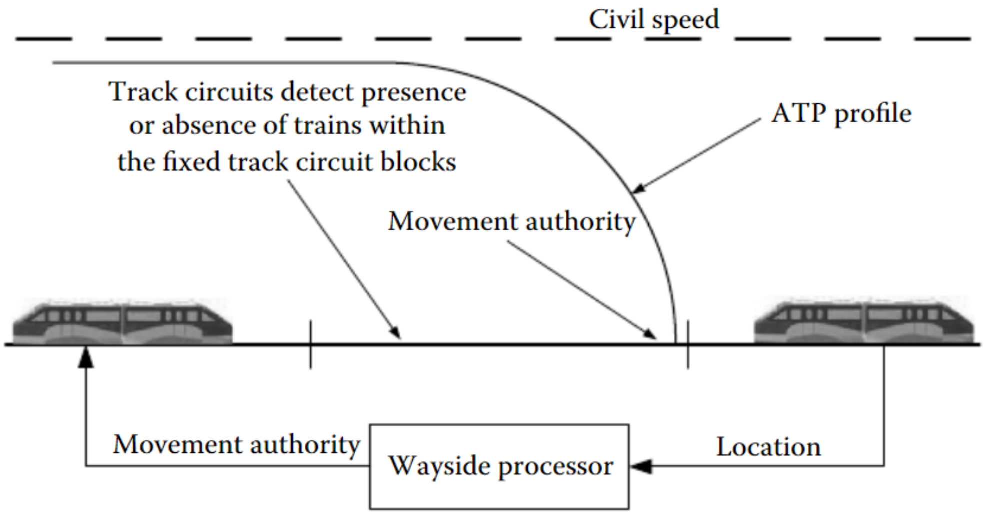

Civil speed
Track circuits detect presence
or absence of trains within
the fixed track circuit blocks
ATP profile
Movement authority
Movement authority
Wayside processor
Location

Figure 4. A profile-based train control system (F. R. Yu, 2018)

The system uses a track circuit for train detection. A wayside processor picks up the track signal and generates a coded message containing the target speed of the train, permitted line speed, and the distance to go (at the target speed). This allows the train's in-cabin equipment to calculate the speed profile that the train needs to follow. The in-cab equipment also has a database of the track map including station location, curvature, grade, and speed limit. The ID of cab signaling allows the train to know the track circuit it is on. The track database is then used to calculate an accurate speed distance profile. (F. R. Yu, 2018)

The next generation of train control system evolved with the introduction of Communications-based train control (CBTC) that provides the exact location of the train. The system does away with traditional track circuits and reduces the wayside and trackside equipment. The CBTC system is not constrained by boundaries delineated by physical track circuit layout and is dynamically established using train location reports that provide "moving block" or "virtual block" based control. In the CBTC system, the main train control logic is located in equipment on board the train and a data communication network between the train and the wayside provides to and from information flow for train control. The CBTC system provides much better operational flexibility and throughput as compared to track circuit based systems. (Yu, 2018; Farooq & Soler, 2017; Morar, 2012; Nakamura, 2016)

The signaling system based old technologies using track circuits and axle counters was inefficient, suffered from low throughput, and led to delays in the system. Due to these reasons, it is being replaced by newer technologies such as CBTC system. Countries such as Denmark have embarked upon a program to replace the old signaling systems with CBTC based system (Banedanmark, 2010).

The CBTC system will be discussed in detail in the forthcoming section.

1.3 Communication Network

The modern train control system depends heavily on the communication network for critical data transfer from devices within train to train control system onboard, an onboard system to wayside facilities, from wayside facility to central/regional control centers, and links to the corporate network. The communication network includes wired as well as wireless networks. With the vast type of communication requirement, rail system uses many communication technologies for the transfer of information. The communication system plays a critical role in the safe and secure operation of the train system. (Craven, 2004)

The use of electronics and IT system has revolutionized the way we work and do business. The industrial sector including railways has benefited from the use of technology to run operations of the railway system efficiently and safely. The use of IT has increased many folds in the last decade. However, the IT and communication network has brought with them the associated risk. These vulnerabilities have caused large scale damages with an attacker taking advantage of the same to disrupt the system. The SCADA (supervisory control and data acquisition) system used by industry including railways has also been targeted (Shaw, 2004). The SCADA system is based on IT and communication technologies. This requires that security aspects of IT and communication network used for train control system should be taken seriously and necessary steps are taken to mitigate the associated risks. (Vane, 2010) (Craven, 2004)(Chen et al., 2014)

The rest of the report is organized as follows. The second section looks into the train control systems used around the world. The third section discusses the CBTC system in details along with its various components. The fourth section reviews the communication technologies used in rail communication including Ethernet, Wi-Fi, GSM-R, Tetra, LTE-R, etc. and SCADA system for train control. The fifth section looks into the security aspect of communication in the train control system including security aspects of SCADA and communication system used. The sixth section list the main train control system manufacturers followed by conclusion and bibliography.

2.0 Train Control Systems Around the World

A large number of accidents due to train collisions and derailment has led to the loss of many lives and money. This prompted rail organizations around the world to adopt a train control network for its safe and secure operation. This section describes the two key train control systems Positive train control and European Train Control system adopted by major railway setups around the world.

2.1 Positive Train Control systems

The U.S. brought legislation and adopted Positive train control (PTC) after the collision of a Union Pacific freight train and a Metrolink Commuter train in California on September 12, 2008. In the accident, 25 persons died, and 135 passengers were injured. The accident occurred when the red signal was ignored by the train driver while texting on his mobile. The existing Automatic Train Stop (ATS) and Automatic Train Control (ATC) operating at that time in many U.S. rail network were reactive in nature and could not have prevented the accident due to the driver not acknowledging the signal. It prompted enacting of Rail Safety Improvement Act (RSIA) law mandating the use of a PTC system in time bound manner. PTC system provides “functional requirements for monitoring and controlling train movements as an attempt to provide increased safety” (Wightman, 2018).

The federal law defines PTC system as a “system designed to prevent train-to-train collisions, over speed derailments, incursions into established work zone limits, and the movement of a train through a switch left in the wrong position” (Peters, 2018).

In the U.S. all Class I railroad systems are mandated to install a PTC system positively by 2020. By the end of 2018, PTC was made operational in 83% or 44,695 miles (AAR, 2019).

As per The American Railway Engineering and Maintenance-of-Way Association (AREMA), the main characteristics of PTC are (Lanham, 2009):

- Avoidance of train to train collisions
- Enforcement of line speed to prevent derailments due to excessive speed

- Safety of wayside rail workers, by preventing intrusions into the working zone
- Prevention of movement due to a switch accidentally left in the wrong position.

In addition to the above, the system must be interoperable so that the train can also operate on any track using existing signaling and control systems.

2.1.1 PTC System

The PTC is an upgraded version of the Automatic Train Stop and Automatic Train Control system that used track circuits and fixed block system earlier. The federal law did not specify any technical requirements for PTC. The PTC uses predictive technology based on upcoming conditions and assumes control of the train in case the train operator fails to respond within the defined time. The PTC System technical Architecture is shown in Figure 5 and has four main components as given below (Hartong, Goel, & Wijesekera, 2007):

- **Onboard Locomotive System or mobile units**: The system on board the locomotive monitors trains speed and position and applies brakes in case of speed restriction violation and any unauthorized movement of the train to undesired sections.
- **Wayside System**: It monitors various signals along the track, switches, interlocks and communicate authorization for movement (MA) to the locomotive.
- **Back Office Server or dispatch/control unit:** It stores all information related to the train network in its operational control. It provides the authorization for train movement to new sections of the track. It consists of a PTC server and computer-based dispatching system. The database in the PTC server stores all the information related to trains, tracks and restriction need to be enforced for the safe operation of the rail system.
- **Maintenance of Way**: It is a handheld terminal with maintenance personnel and vehicles. They use this terminal to provide feedback to the PTC server on the maintenance status of the system. The PTC server based on the maintenance status of the tracks or wayside system advises the driver on train operation.

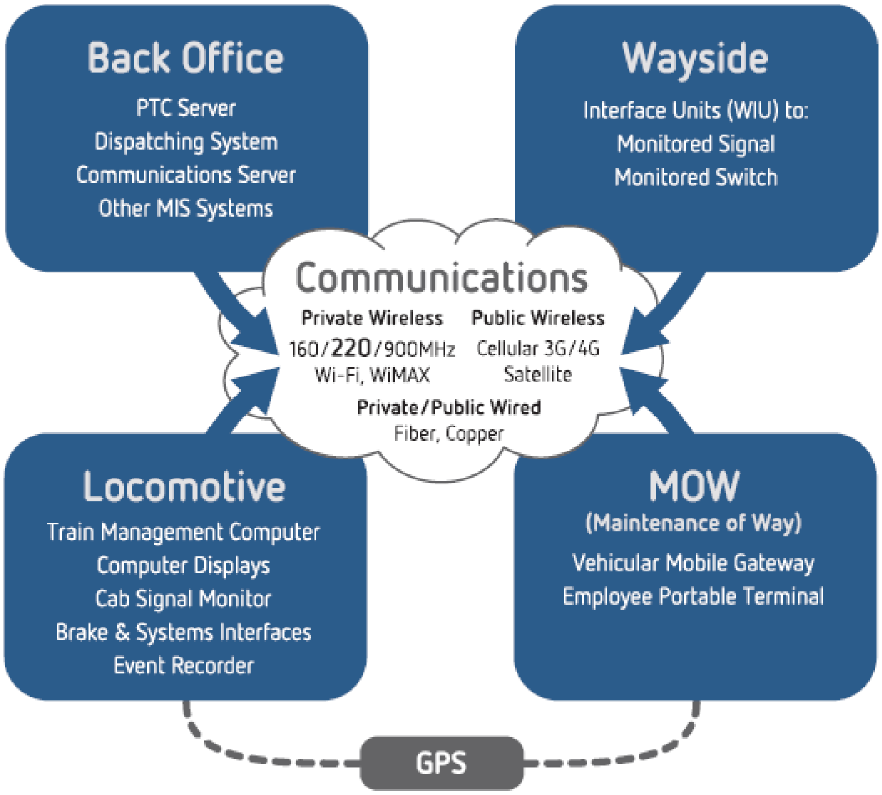


Figure 5. technical architecture of PTC (Baker, 2012)

2.1.1.1 PTC System Operation

The operation of the PTC system is depicted in Figure 6. The use of augmented GPS system for train position improves the accuracy of traditional track circuit-based system for train location. The use of GPS can also do away the cost of balises deployment throughout the railroad system. The use of reliable wireless communication for data transmission is key to the successful implementation of the PTC system. (Baker, 2012)

Use of 220 MHz VHF radio system was selected for PTC operation in the U.S. due to the following reasons (Baker, 2012):

- The existing 160 MHz system developed by BNSF for its Advanced Railroad Electronic System was too congested to take additional load.
- 900 MHz channel used by earlier railroad system for the Advanced Train Control System was not capable of handling the data load required for the PTC system.

- The 220 MHz provide longer range due to its propagation characteristics and the bandwidth required was available for allocation for PTC.

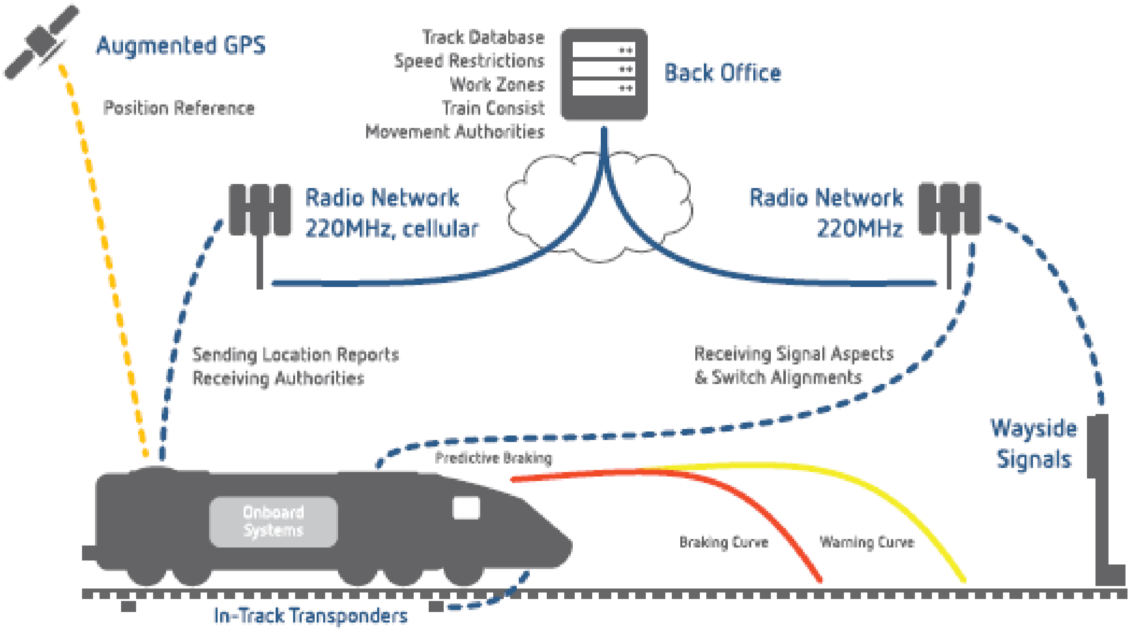


Figure 6 PTC System operation (Baker, 2012)

2.1.1.2 PTC high-level architecture

Typical high-level architecture of an end-to-end PTC solution is shown in Figure 7. The system consists of four main architectural components; back office equipment, onboard system, wayside equipment, and bi-directional communication transport comprising of Wi-Fi and GSM system (CISCO, 2013).

The back-office system consists of the back-office server for processing and storage of information received from other subsystems including onboard system, wayside servers, and the operational staff. The back-office server maintains a database of trains, tracks, speed restrictions, and work zone. The back office server issues movement authorities and other information to the locomotives. (CISCO, 2013)

The onboard computer gets motion authorities from the back office server and notifies the driver of the parameters to be used for train control such as speed limits, track availability, etc. The driver upon getting information from back office server and wayside servers take action as required for safe driving the train. The train driver is given 15 sec to respond else the onboard train computer applies the brake to stop the train. In case of loss of connectivity, the train is stopped from going to the next block for safety reason. (CISCO, 2013)

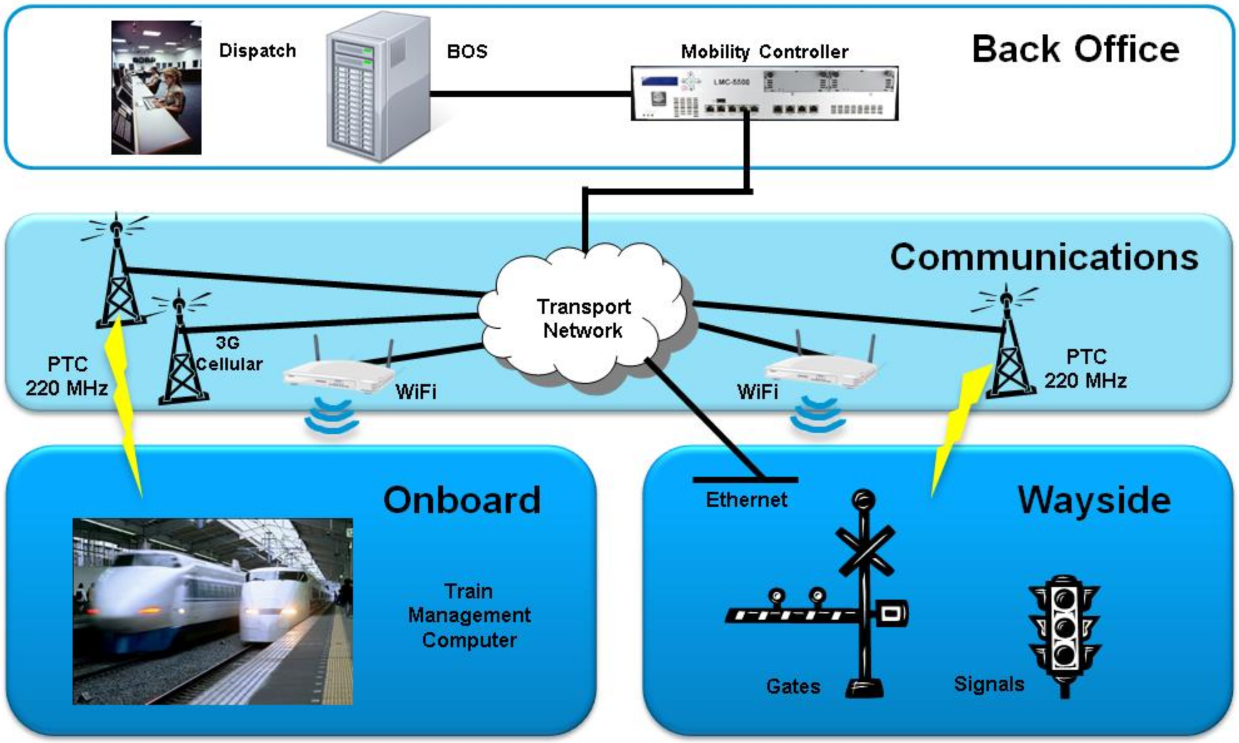


Figure 7 The High-Level Architecture of an End-to-End PTC Infrastructure (CISCO, 2013)

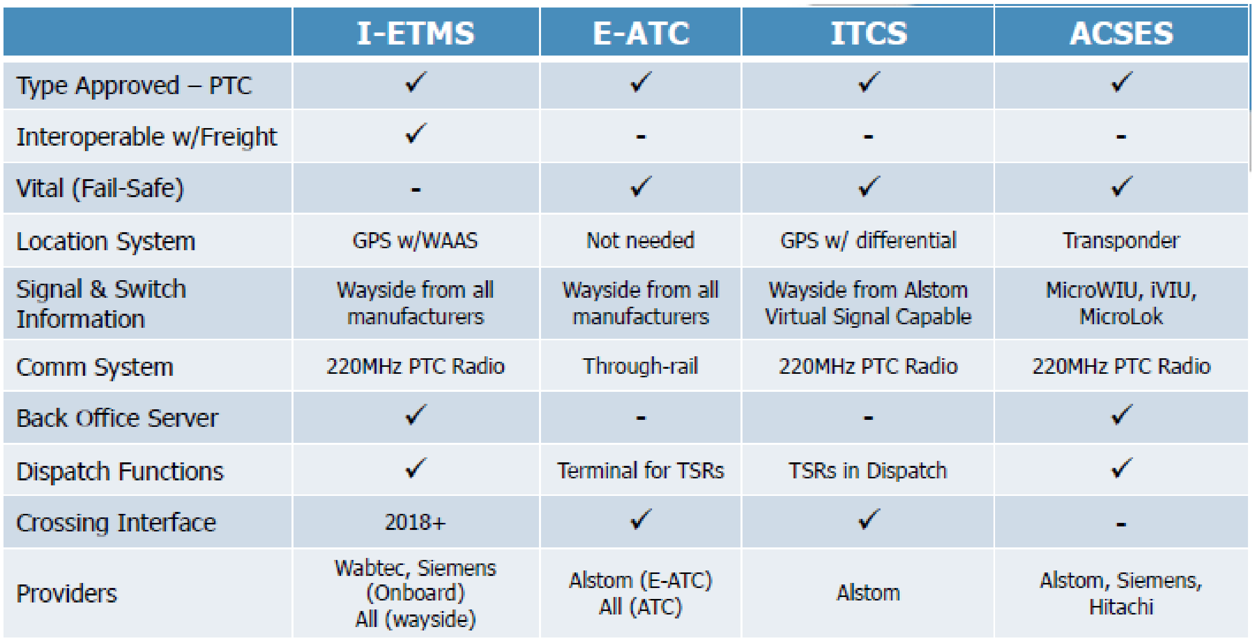
The wayside equipment contains signaling equipment, switches, track circuits, gates, etc. These devices connect to the wayside server via the Wayside Interface Unit. The wayside server then sends the information to the back-office server for further processing and send processed information to the locomotive to take necessary action for safe train movement.

The bidirectional and redundant communication system is used between train, wayside and back office. Four types of wireless interface can be used in the PTC system. These are Wi-Fi, Ethernet, GSM 2G/3G and 220 MHz radios. The locomotive uses GSM or 220 MHz radios to ensure mobility. The 220 MHz has been standardized for railway due to its longer range of 20-30 miles. Thus primary communication by locomotive may be

220 MHz with a backup using 3G, and in the yard or at the station it may use Wi-Fi. (CISCO, 2013)

The transport network provides a resilient communication path between back-office systems and field devices. It consists of industrial Ethernet switches at the edge and a multipath backbone system. (CISCO, 2013)

Number of PTC approved systems have been produced, and a brief list of these with main features is given in Figure 8.



	I-ETMS	E-ATC	ITCS	ACSES
Type Approved – PTC	✓	✓	✓	✓
Interoperable w/Freight	✓	-	-	-
Vital (Fail-Safe)	-	✓	✓	✓
Location System	GPS w/WAAS	Not needed	GPS w/ differential	Transponder
Signal & Switch Information	Wayside from all manufacturers	Wayside from all manufacturers	Wayside from Alstom Virtual Signal Capable	MicroWIU, iVIU, MicroLok
Comm System	220MHz PTC Radio	Through-rail	220MHz PTC Radio	220MHz PTC Radio
Back Office Server	✓	-	-	✓
Dispatch Functions	✓	Terminal for TSRs	TSRs in Dispatch	✓
Crossing Interface	2018+	✓	✓	-
Providers	Wabtec, Siemens (Onboard) All (wayside)	Alstom (E-ATC) All (ATC)	Alstom	Alstom, Siemens, Hitachi

Figure 8. Approved PTC Systems (Burkhardt, 2015)

2.1.1.3 IEEE 802.15 Positive Train Control Group

IEEE in 2011, constituted a group called IEEE 802.15 Positive Train Control group to develop standards for worldwide implementation of a wireless system for PTC. The group focused on the development of RF/PHY/MAC part of a communication system for PTC based on existing IEEE 802.15.4 standard.

IEEE-SA Standards Board on March 27, 2014, approved 802.15.4p Rail Communications and Control (RRC) standards. As per Lilee systems “The IEEE 802.15.4p RRC Task Group, founded and chaired by Lilee Systems' Vice President of Strategic Development Jon Adams, developed the baseline for wireless links between trains or locomotives and track infrastructure, creating the framework for locomotive and transit communication standards” (Lilee Systems, 2014). It extends the IEEE 802.15.4p to “include a sensor, control, and information transfer applications for rail transit entities” (Lilee Systems, 2014).

2.2 Enhanced Train Control (ETC)

The Enhanced Train Control system is similar in goals to U.S. PTC but tailored for Canadian rail environment. The Canadian Rail Research Laboratory (CaRRL) has taken the initiative to suggest and evaluate the efficacy of the ETC system to prevent incidents related to the Canadian rail system (Leaton, 2016). ETC system defines a four-level hierarchical framework to minimize system complexity while maximizing the safety. The ETC level 1 is a monitoring system that is locomotive-centric and assisted by the crew, with no wayside assistance or system as shown in Figure 9 (Scanlan, Macciotta, & Hendry, 2018). The system issues audio-visual warnings to the train driver about situations on the track ahead.

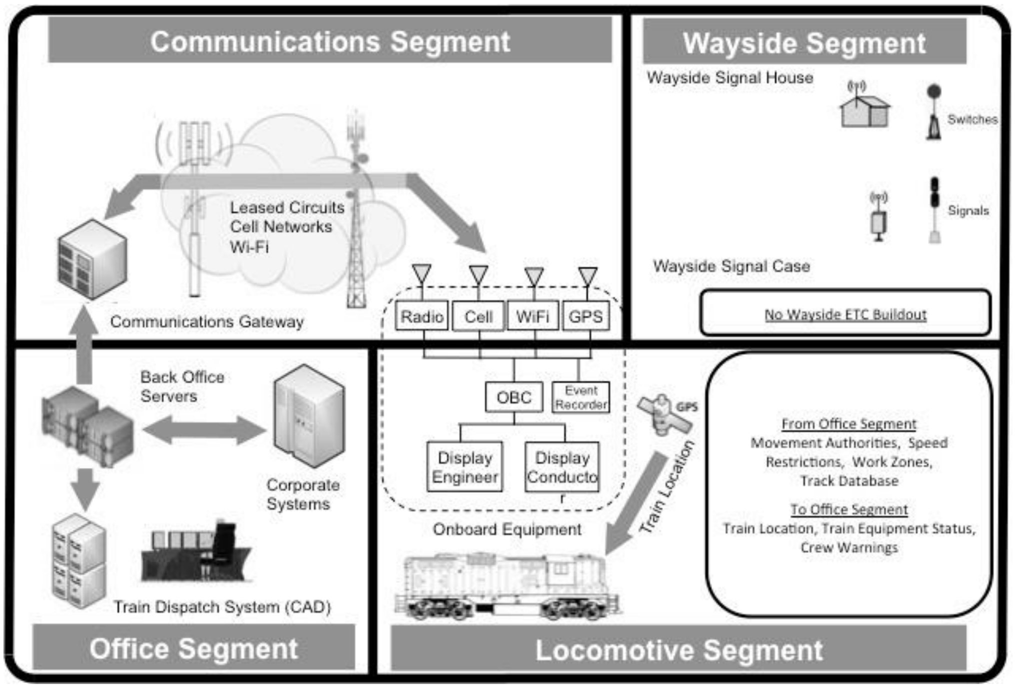


Figure 9 Diagram of the proposed ETC Level 1 system (Scanlan et al., 2018)

The ETC level 2 has selected wayside monitoring of switches as well. This limits the cost at the same time and protects key switch locations. The ETC Level 2 system is linked to the train brakes, and this allows automatic braking of the train in case the driver does not respond to the warning messages. In the level 3 system, all switches are monitored and signaling part taken care of to protect even unauthorized reverse movement of train and enforcement of other restrictions required for the safety of the system. The system resembles closely to U.S. PTC system. The system is implemented as an overlay onto the control infrastructure existing on the ground. The ETC level 3 system is depicted in Figure 10 (Scanlan et al., 2018).

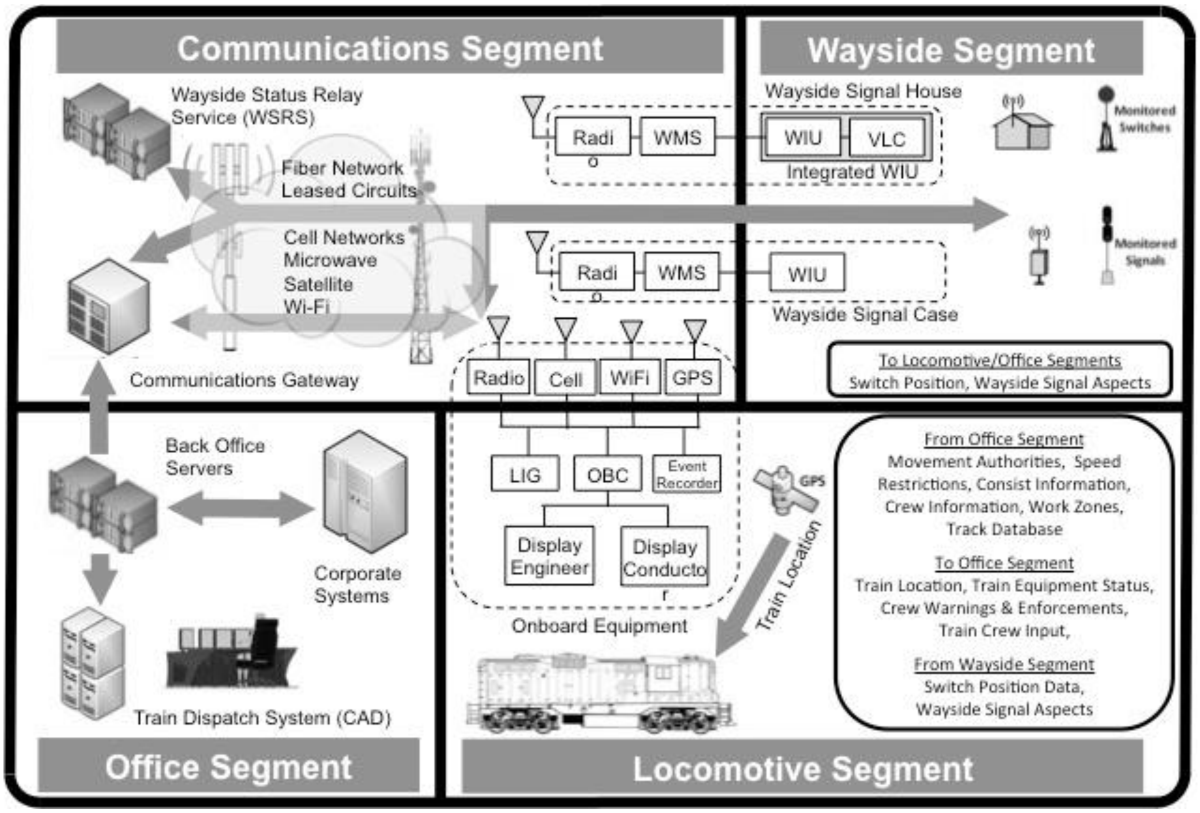


Figure 10 ETC Level 3 system with a full buildout into the wayside segment (Scanlan et al., 2018)

The ETC Level 4 system is for new or replacement of existing system with the latest train communication-based control system based on new design. The system is intended to replace old wayside devices and verbal transmission of commands for train control.

The results on theoretical implementation of various ETC Level based on the last ten years database named Canadian Railway Occurrence Database System (RODS) of rail-related incidents were examined, and the result showed that majority of the incident preventable would have prevented just with the implementation of basic ETC 1 level system. As per the report, “The results of the ETC preventability analysis demonstrated that between 3.55 and 5.96% of the 14,036 incidents would have been preventable at ETC Levels 1 through 4 (leaving at a minimum, 94.04% of incidents non-ETC preventable)” (Scanlan et al., 2018). The report provides the way forward to take a decision on the implementation of Level of ETC system taking into account various considerations.

2.3 European Train Control System (ETCS)

The European Train Control System is an automatic train protection system designed for the protection of rail systems around Europe. ETCS is the signaling and control part of the European Rail Traffic Management System (ERTMS) which handles the total train operation and control of the rail system. The ETCS technology can be implemented in four levels of signaling depending on the train traffic. The ETCS L0 (LS) is for trains on non-ETCS route. The ETCS L1 (FS) can be overlaid on an existing system to enable trains to move to cross border areas where the ETCS system supplied by other operators are in use. The ETCS L2 is the most advanced version using a digital wireless system for the exact location of the train and providing movement authority directly to the train driver using an onboard computer. It is also designed to reduce the overall maintenance cost, provide better safety, operational flexibility, and reliability. ETCS is intended to replace incompatible safety systems used in the European rail system.

The ETCS system consists of two parts; onboard equipment and trackside equipment.

2.3.1 ETCS Trackside Equipment

The ETCS trackside equipment includes balises, Euroloops, Radio Block Centers (RBC), and Radio In-fill Units. The balise is a configurable transponder which is mounted in four ft. Area. It does not require any external power supply as it gets energized by a train passing over it. Once activated by passing train, it sends the telegram or data back to the train as per its configuration. The balise is used in a group of 8 balises with each balise in the group having a unique identity. Each group also has a unique identity. The balise group provides direction of train movement as well as redundancy when one balise in the group fails. (RSSB, 2010)

The Radio Block Centre (RBC) communicates with onboard ETCS equipment and is located with other signaling and controlling equipment in the system. The transmission uses GSM-R (Global System for Mobile Communications – Railway) radio. The data packets have the same structure as that of balise. The Radio Block Centre is used for monitoring interlocking and generating movement authority messages. The Radio Block Centre messages contain restrictions and route speed. The Radio Block Centre also provides an interface to another signaling system regarding train location etc. (RSSB, 2010)

The Euroloop is a track mounted loop, used only in ETCS L1 system, to transfer electronic messages to the train. The Radio In-fill Unit has the same function as Euroloop but uses GSM-R radio for data transmission (RSSB, 2010). The ETCS L1 basic system using radio in-fill unit is shown in Figure 11. The ETCS system is overlaid on top of the existing signaling system. The in-fill balise groups are located at some distance on the approach to the signal to which it applies. It is also connected electrically to the signal. This enables the early update to the train system. (RSSB, 2010)

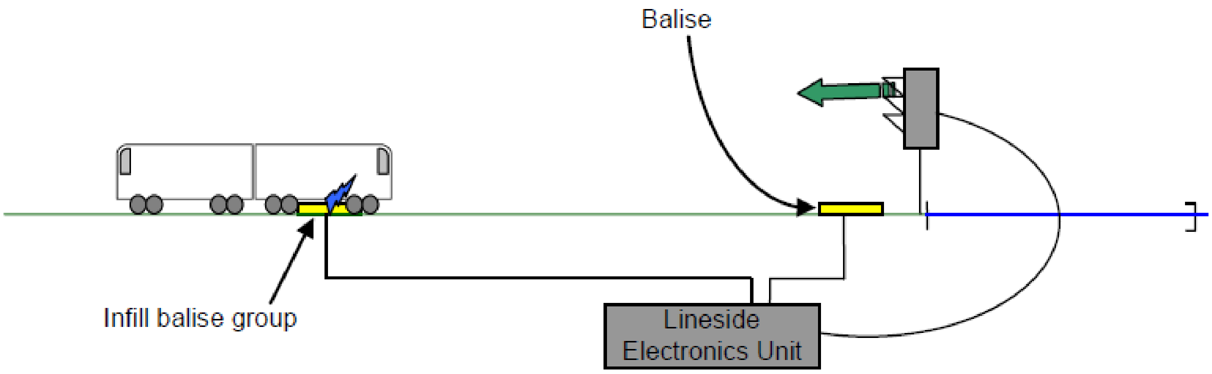


Figure 11 Level 1 (with infill balise group) (RSSB, 2010)

The architecture of the ETCS L2 system without lineside signals architecture is shown in Figure 12. The ETCS L2 system allows advance shortening of train route without the requirement of timers for this work. This allows faster time for revoking route of any train.

The ETCS level 3 architecture is like L2 without lineside signals and trackside detection equipment. The ETCS onboard equipment takes care of train detection and also reports it to the ETCS trackside. (RSSB, 2010)

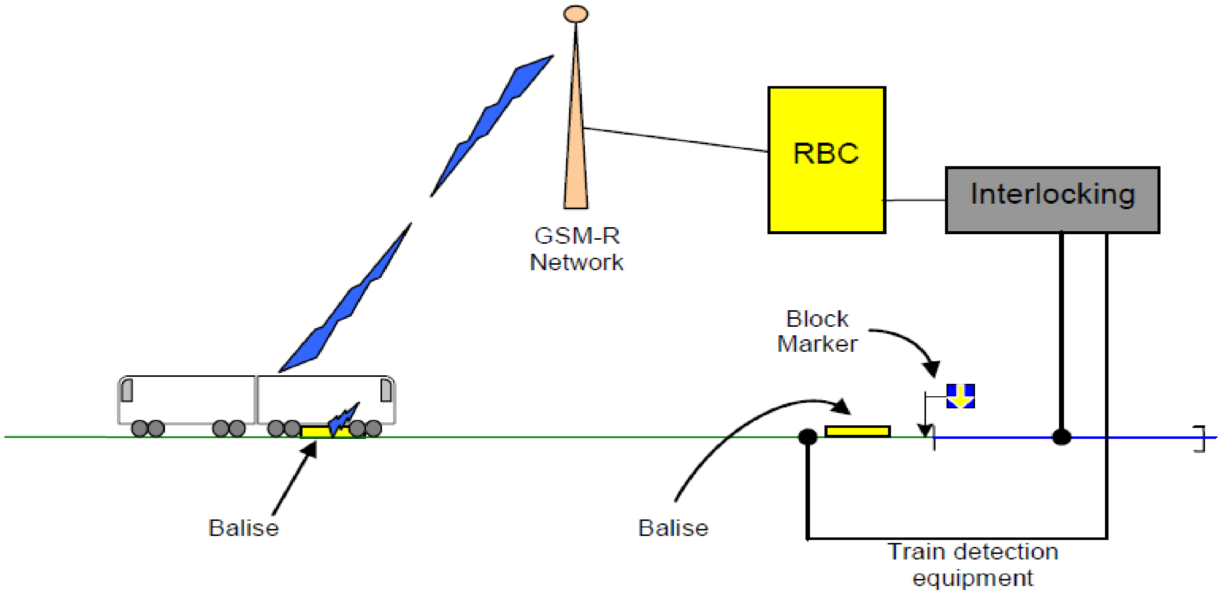


Figure 12 Level 2 without lineside signals (RSSB, 2010)

2.3.2 ETCS Onboard Equipment

The basic architecture of the ETCS onboard equipment is depicted in Figure 13. The main control system uses a computer termed as European Vital Computer (EVC). European Vital Computer provides supervisory and control system for train operation. EVC system interacts with the train driver using in-cab display system or visual graphical interface. The EVC controls the train function using Train Interface Unit (TIU) which provides an interface to other functions. The train function systems include the train braking system, train control, engine control, and cab status information. A balise reader energizes balise and picks up data transmitted by balise and transmits it to the EVC using Balise transmission module. The driver machine interface provides communication between the EVC and the driver. The driver gets information such as distance permitted, the maximum permissible speed of the train and the point when the driver must apply brakes to avoid activation of the automatic brake system. The Juridical Recorder Unit is onboard data recorder like flight data recorder in the aircraft and enables reconstruction of events in case of an accident. It records all the important parameters used for train operation and control along with various actions taken by the driver. The odometry system provides information on train speed and distance covered. The brake interface via TIU allows automatic brakes to be applied in case of any safety violations (RSSB, 2010)

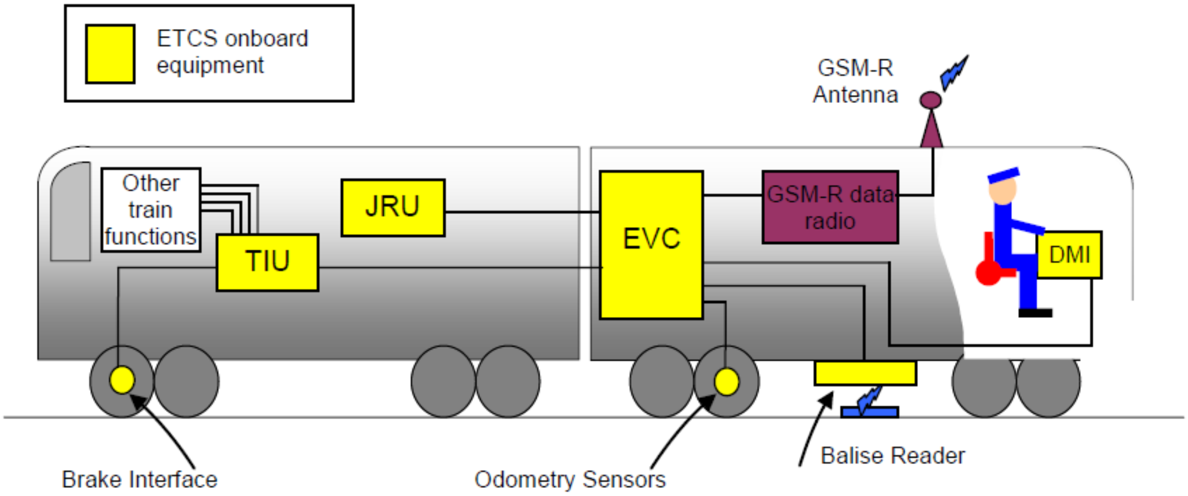


Figure 13 ETCS onboard equipment (RSSB, 2010)

2.4 Chinese Train Control System (CTCS)

Chinese Train Control System defines the signaling system for the Chinese railway network. Like the ETCS system in Europe, it is intended to provide safe operation of mainline railways in China. CTCS will provide interoperable systems as locally manufactured, and imported systems will conform to its specifications. The CTCS standard takes care of signaling interface standards between various systems, data transmission, and migration of existing systems to the new system, easy maintenance, and broad availability in the market. (Ning, Tang, Qiu, Gao, & Wang, 2010)

Chinese Train Control System is similar to the ETCS system and is divided into five levels which are corresponding to Level 1 to level 3 of the ETCS system. CTCS level 0 is for trains having speed up to 120 km/h using the existing signaling system. The CTCS level 1 trains with speed between 120 km/s to 160 km/h. The train operation in this mode uses the onboard system without using block signals and requires the installation of transponders on track for train location detection. Level 2 system can be radio-based or transponder based. CTCS level 2, a points and continuous system, is continuous control for the train with speeds of more than 200km/h but less than 250 km/h that require automatic protection circuits on board the train. CTCS level 3 uses GSM-R for communication and is compatible with Level 2 with the downgrade and is intended for trains with speed between 300-350 km/h. The last level CTCS level 4 is next generation system using long-term evolution for railway (LTE-R) for communication, train interval control using moving block function, and train positioning system using global navigation satellite systems (GNSSs). The Level 4 system reduces the maintenance cost as the use of wayside is minimized. The system also allows for flexible train density on the same line. (Junting, Jianwu, & Yongzhi, 2016)(Ning et al., 2010)

Golmud–Lhasa line in China has an incremental train control system (ITCS) based on PTC. The ITCS is a fail-safe system developed by GE originally for Amtrack’s Detroit and Chicago in 1995. It is a cost-effective system that can be used as an overlay or standalone system (Hann, 2010). The ITCS system for Qinghai–Tibet railway used GSM-R for communication. The onboard computer at Tibet ITCS gets signaling status and status of wayside equipment ahead of the train. It provides automatic train protection and man-machine interface to the train driver. The ITCS system diagram is shown in Figure 14 (Hann, 2010)

The ITCS system has also been implemented in the U.S., Australia, and Columbia apart from China.

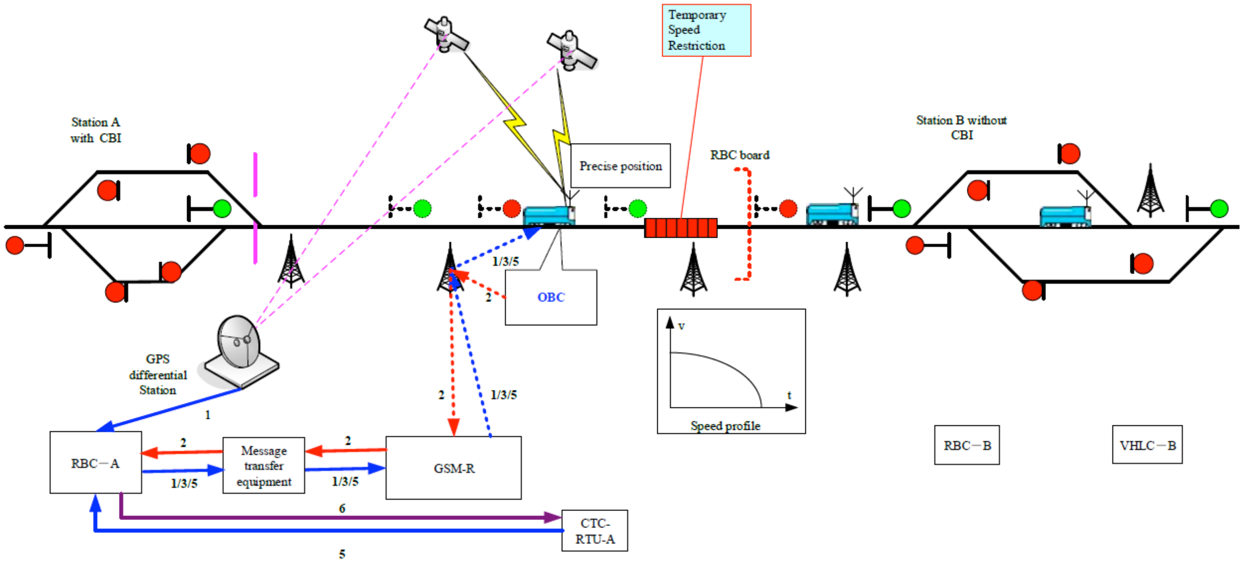


Figure 14. The system structure of ITCS based on GSM-R (Hann, 2010)

3.0 Communications Based Train Control (CBTC)

Communications Based Train Control is considered as a direction of a next-generation rail control system in the world. The system can be used in all types of railway systems including, metro, light rail and main rail systems (Bin, Tao, Min, & Hai, 2006).

The use of a CBTC system allows trains with much closer headways than the traditional track circuit-based systems. The ability of the CBTC system to determine the exact location and direction of movement of trains allows safe and secure operation of the rail system. (Pochet, Sandou, & Baro, 2017)

3.1 Fixed block vs. moving block

The signaling in the conventional rail system works by dividing the track into fixed blocks with each block protected using a signal. The length of the block depends on maximum speed allowed, braking capability of train, sighting, occupancy of the track, etc. The exact location of the train inside the block cannot be determined, and therefore when the train is inside the block it is declared as occupied, and no other train is allowed to enter in the block. This operation is termed as fixed block operation. In contrast, the CBTC provides moving block operation as in CBTC the real location of the train is known. This is made feasible using communication between wayside and the train. With the real location of the train known, the exact headway between trains can be calculated. The constant communication between the trains near to each other allows them to adjust their speed and distance to meet safety requirements. The block changes as the train moves and no fixed location of the block are defined. This makes the train run closure at the same time keeping sufficient distance to brake safely as shown in Figure 15. Thus, the CBTC system allows an increase in train density for each track. The communication between the train and the computerized dispatching systems is direct thereby removing the requirement of wayside equipment and reducing maintenance.

ATO functions include automatic station stopping, alignment, speed regulation, train and platform door control, and routing. ATP function is protection against over speed, collision, and avoiding other dangerous conditions. The ATS monitors and controls the movements of trains for the entire system. (Ali, 2017)

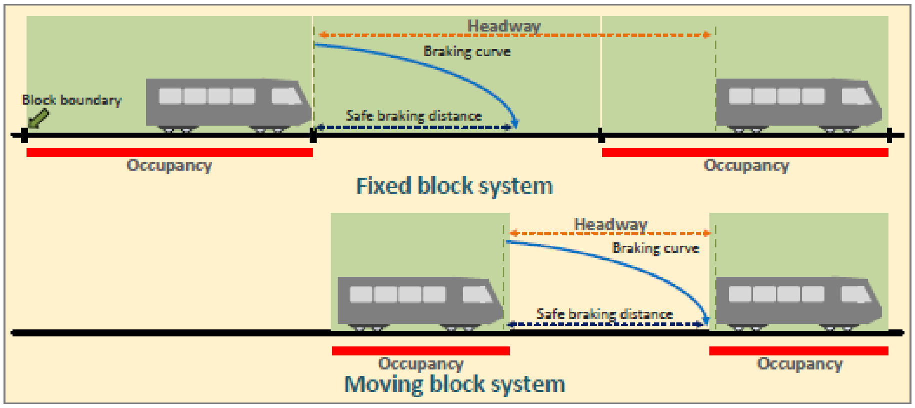


Figure 15 Fixed vs. moving block (Farooq & Soler, 2017)

The CBTC system can provide various levels of automation termed as Grades of Automation (GOA), and these grades are defined in IEC 62290-1. The grades of operation are (F. R. Yu, 2018):

- GOA1: Manual protected operation
- GOA2: Semi-automated operation
- GOA3: Driverless operation
- GOA4: Fully automated operation

3.2 Characteristics of CBTC System

The main characteristics of the CBTC system are:

1. CBTC system can determine the position of a train, and it does not depend on track circuits for that instead it uses the transponder tags or beacons which are installed along the track. As we can see in the following figure, the Course position of the train is provided by the tags, and the fine position is calculated by tachometers which are installed on the axles. (Ali, 2015)

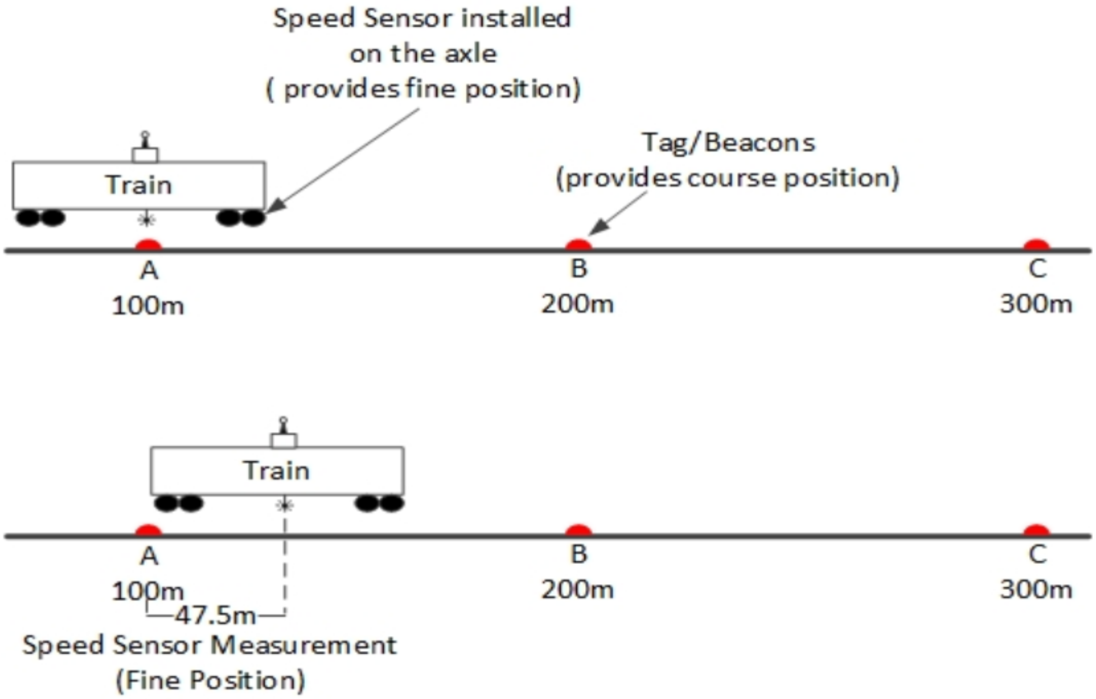


Figure 16 Positioning Basics in CBTC (Ali, 2015)

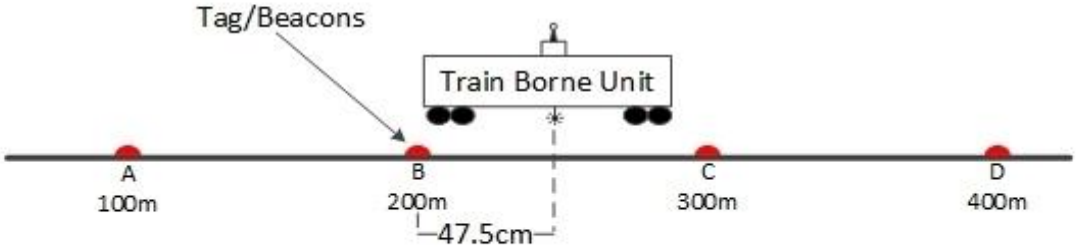


Figure 17 CBTC Positioning Characteristics

(Ali, 2015)

In the above figure, when the train traverse through tag B, it becomes aware that it is at the mark of 200 m. When the train goes further, then tachometer will tell the train borne unit how far the train has traveled from the coarse position. Combining both coarse and fine position, train borne unit will have the location of the train from the zero-reference spot which is 247.5 m. (Ali, 2015)

2. When the location of the train is verified, the data must be transmitted to the wayside system. There are many ways to do this, but Radio is a de facto standard of the industry. Access points are installed along the track. The train-borne unit connects to the new access point whenever it comes in its range, and the protocols for the communication used in this channel are UDP/IP or TCP/IP. (Ali, 2015)

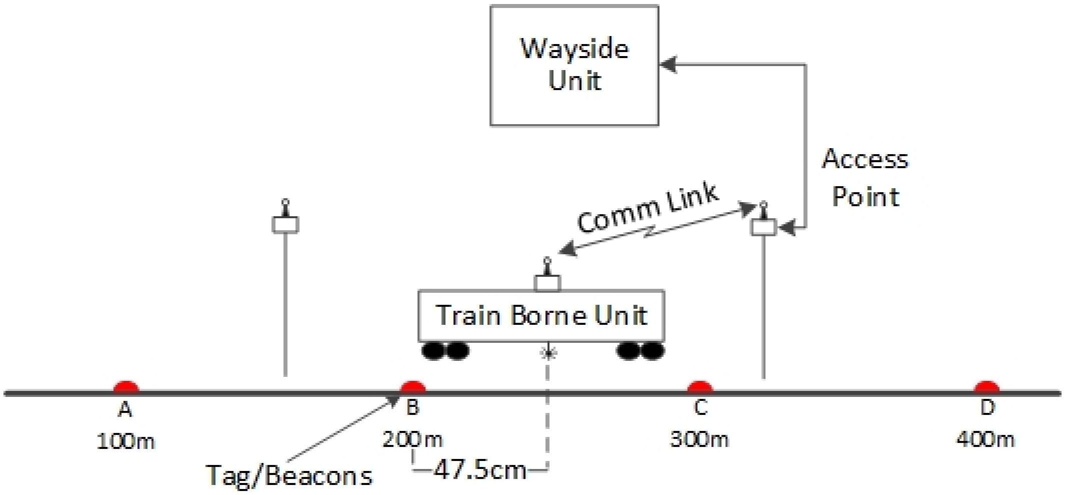


Figure 18 CBTC Positioning Characteristics (Ali, 2015)

Through this channel, all data goes through, but this link is not considered vital. So, to keep the data safe and ensure data integrity, many mechanisms are used (CRC and sequence numbers, etc.).

3. Apart from determining the position of a train, a CBTC system has to perform other vital functions which can be grouped into three categories:

Collision Avoidance

CBTC's ability to keep trains protected from any accident and avoid any crash with the obstacles along the rail tracks.

Excessive Speed Protection

CBTC's ability to determine and manage the speed of the train and restrain it in limits.

Other Protections

It is important for CBTC to access all the subsystems present in whole CBTC architecture to execute its functions properly. So, network consistency and data accessibility must be established. All the processors and subsystems in CBTC are tightly integrated.

3.3 CBTC System Architecture

Typical Communication-based train control system is shown in Figure 19.

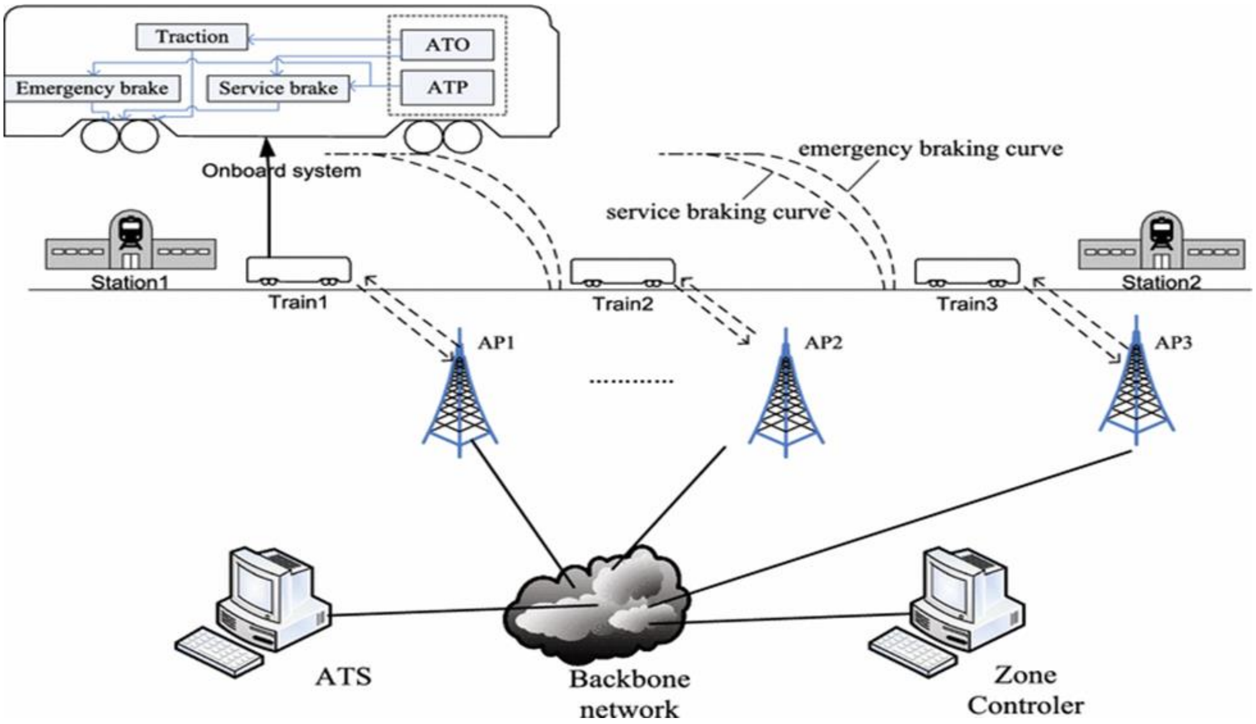


Figure 19. Communication-based train control (CBTC) system (L. Zhu, Yu, Ning, & Tang, 2014)

A CBTC system consists of following major subsystems and their equipment as shown in Figure 20:

- Train-borne
- Wayside
- ATS
- Data Communication System

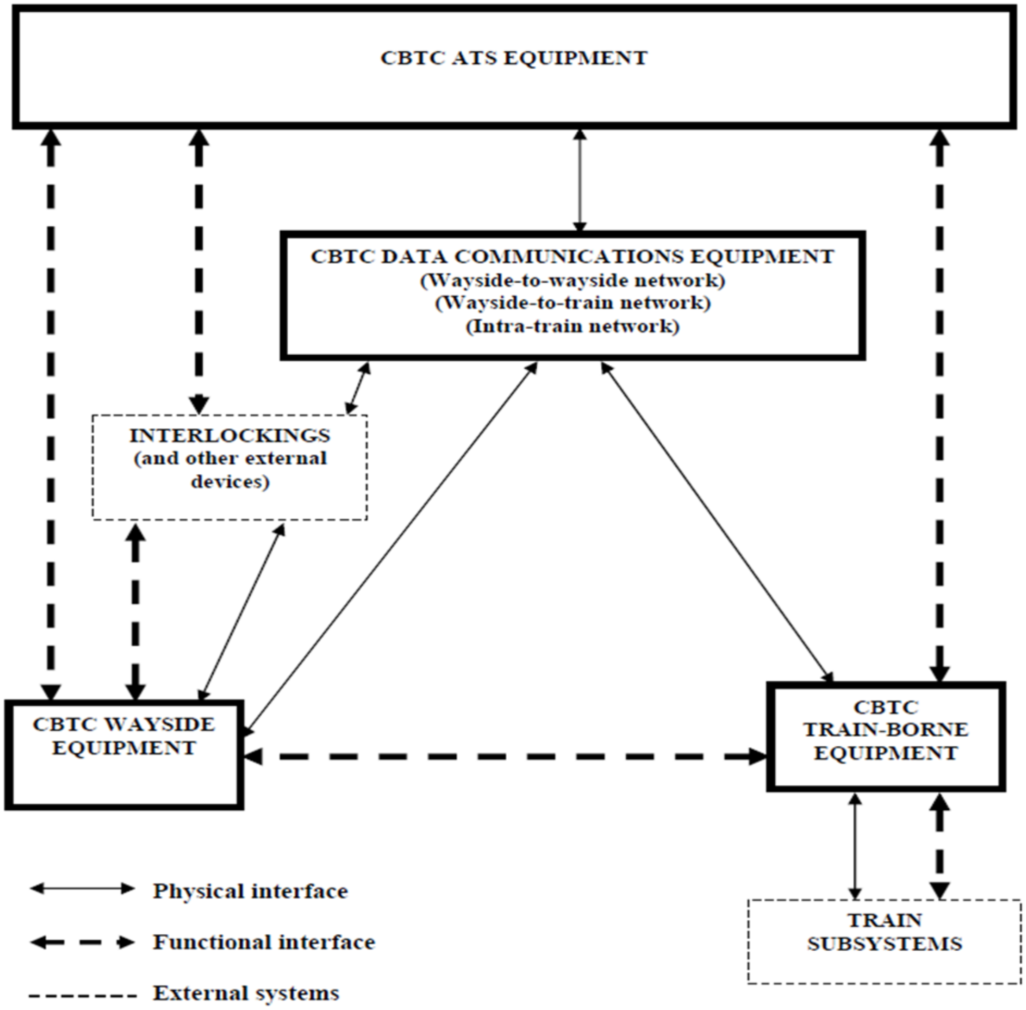


Figure 20 Major CBTC Subsystems (IEEE Std 1474.3-2008)

3.4 CBTC subsystems

3.4.1 Components and Networks

CBTC equipment and components are placed in the control center, equipment rooms for wayside stations, at trackside and on the train. Control center equipment is linked to ATS functionality including the central HMI (Human Machine Interface) of the CBTC. Wayside equipment rooms have Ethernet switches, Zone Controllers (Movement Authority Controllers and computer-based interlocking system are combined to form a ZC). Trackside equipment (Also considered part of wayside equipment) consists of transponder tags, RF transceivers, and railroad switches. Onboard train equipment has processor-based units and its peripherals. (Lam, 2017)

3.4.2 Vehicle Onboard components

The onboard apparatus consists of Onboard Control Unit (OBCU). This system transmits train control info to the wayside system. On-board ATP and ATO subsystems are segments of aboard ATC functionalities. The ATO subsystem provides the functionality of automation in the train operation. These operations include starting, accelerating, braking and stopping the train. ATP system supervises the speed and takes control in case of any failure or mistake by the driver.

Data Communication System components (DCS) are also present. It consists of both hardware and software. Radios and antennas are part of this. Communication between wayside and train system is dependent on this subsystem. It will be discussed in detail in the Data communication section.

3.4.2.1 Onboard Control Unit (OBCU)

OBCU is a critical ATC element of CBTC onboard system. It detects the tags located on tracks, extracts the data from tags and checks that against the data in the database. The database on the OBCU has all related information which includes speed limits, station stops, and locations for switch and signals. (Farooq & Soler, 2017)

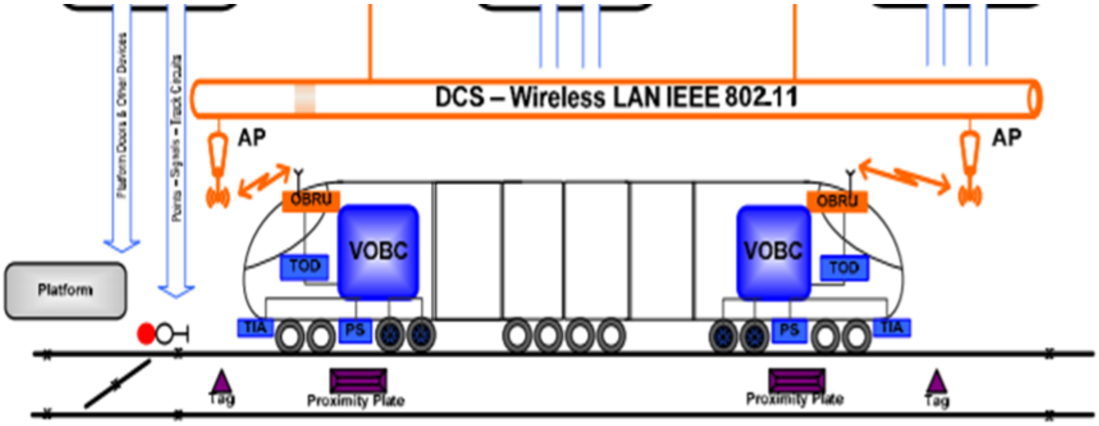

Platform Doors & Other Devices
Points – Signals – Track Circuits
DCS – Wireless LAN IEEE 802.11
AP
AP
OBRU
OBRU
VOBC
VOBC
TOD
TOD
Platform
TIA
PS
PS
TIA
Tag
Proximity Plate
Proximity Plate
Tag

Figure 21 System Architecture of Onboard components (Lam, 2017)

In every three-car multiple unit (MU) train, OBCU has one Main Processor and one Peripheral Processor. Trains usually operate as six-car formations having 2 MUs and therefore having OBCU (also called VOBC) at each end. Having redundant VOBCs provide high availability. (Lam, 2017)

3.4.3 Wayside components

Figure 22 shows typical wayside elements of CBTC system. Zone Controller (ZC) is a critical part of the wayside system. A zone controller controls a specific area in rail networks. The Zone controller divides the track into multiple zones where each zone has an independent zone controller. ZC is the receiver for all location information sent from the trains in its area. The main operation of the zone controller is to set route by commands delivered from the Central control system. So, ZC maintains safe separation of the train. Wayside ATO and ATP subsystems are also typically present in ZC. ATP is the subsystem which determines the movement of Authority of the train. Computer-based interlocking (CI) system is responsible for interlocking functions such as route setting, point movement, locking and releasing. Mostly, CI is embedded in the ATP subsystem. (Farooq & Soler, 2017)

As we can see in the above figure, trackside has many Wi-Fi access points (APs). Each unit has 1 AP. Trains communicate with the APs via a radio connection. APs are then able to connect with the wayside system. Movement Authority Controller is located at Control center office and wayside stations. It is a computer-based controller, and it performs the following functions (Keevill, 2013)::

- Movement Authority Controller monitors the data collected by the Interlocking systems like route setting and locking and switch point.
- Check the location of all the train operating in its control area.
- Send Movement Authority Limit on the basis of the above information to all the trains in its area.

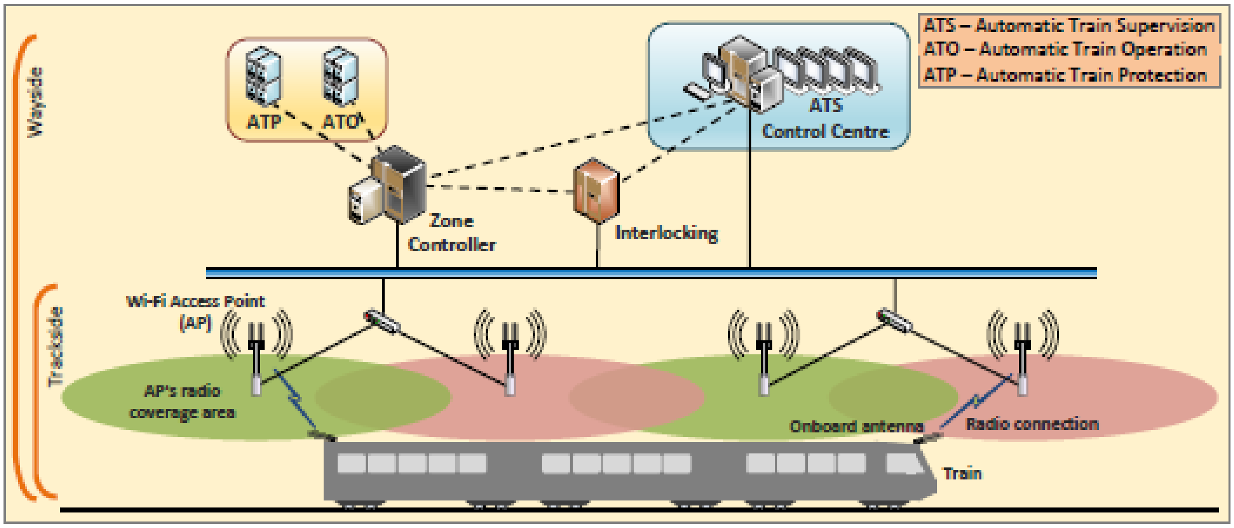


Figure 22 CBTC wayside components (Farooq & Soler, 2017)

3.4.4 Automatic Train Supervision

Main Equipment in ATS include:

- Central ATS data-loggers and servers
- ATS Operator and timetable compiler Workstations
- ATS DCS backbone

Central ATS servers are located in OCC (Operational Control Center). These servers communicate with local ATS servers located in every zone. The DCS system is the one which integrates all the systems, and it provides the network infrastructure for communication among ATS, ZC, OBCU or VOCB, trackside radio network and all external components and interfaces which convey control commands and instructions. (Lam, 2017)

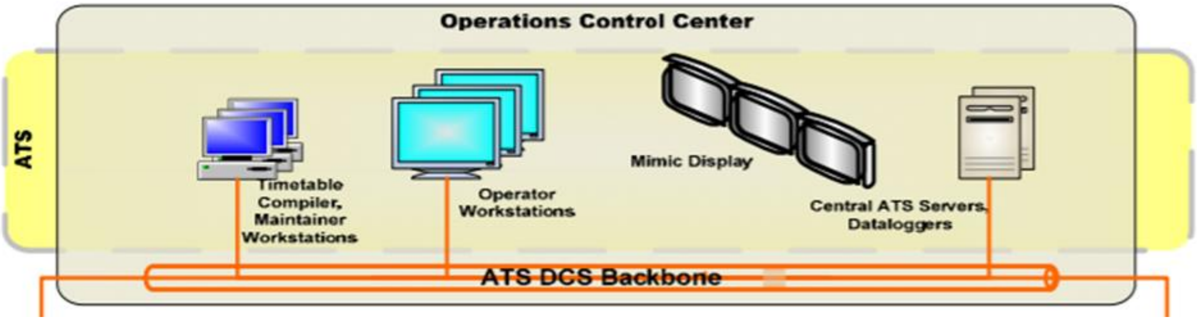

Operations Control Center
ATS
Timetable Compiler, Maintainer Workstations
Operator Workstations
Mimic Display
Central ATS Servers, Dataloggers
ATS DCS Backbone

Figure 23 System Architecture of Operational Control Center (Lam, 2017)

3.4.4.1 Data Communication System

The DCS system is the communication infrastructure which integrates OCC, the wayside and On-board systems. The communication can be via wired media (between the control center and wayside units), or it can be wireless (between wayside units and trains).

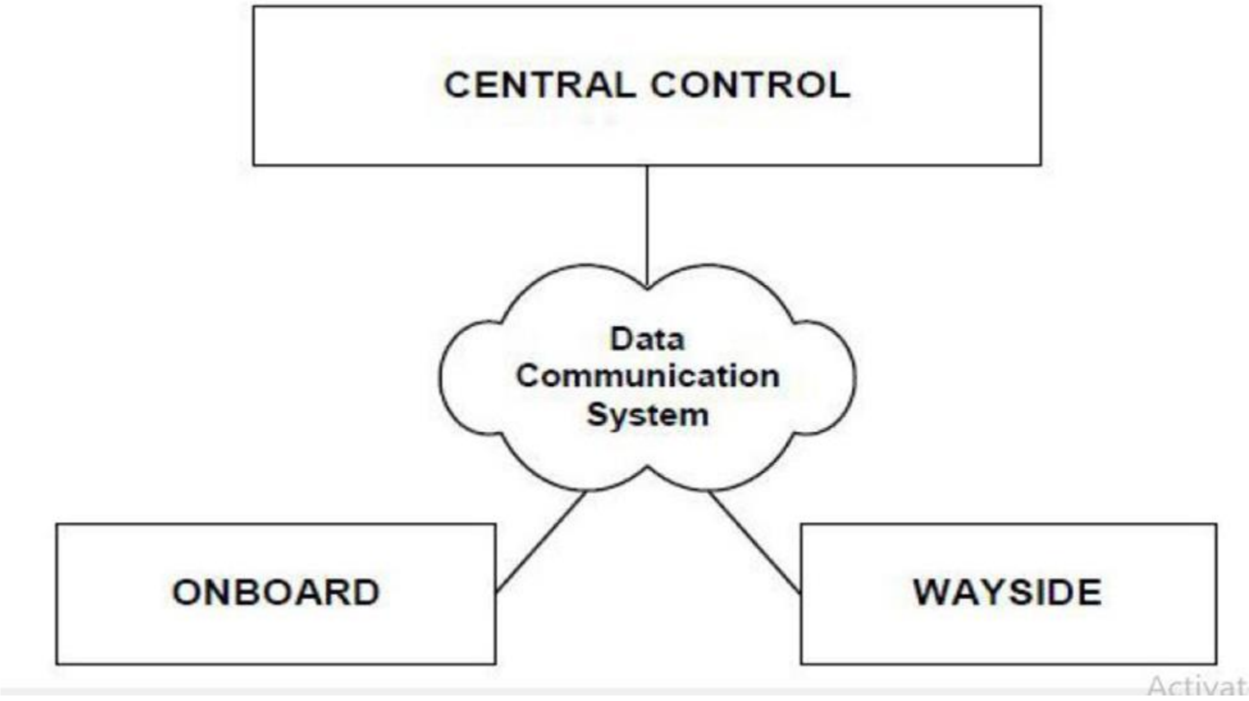


Figure 24 DCS SYSTEM (CBTC Overview Wayside Equipment, 2019)

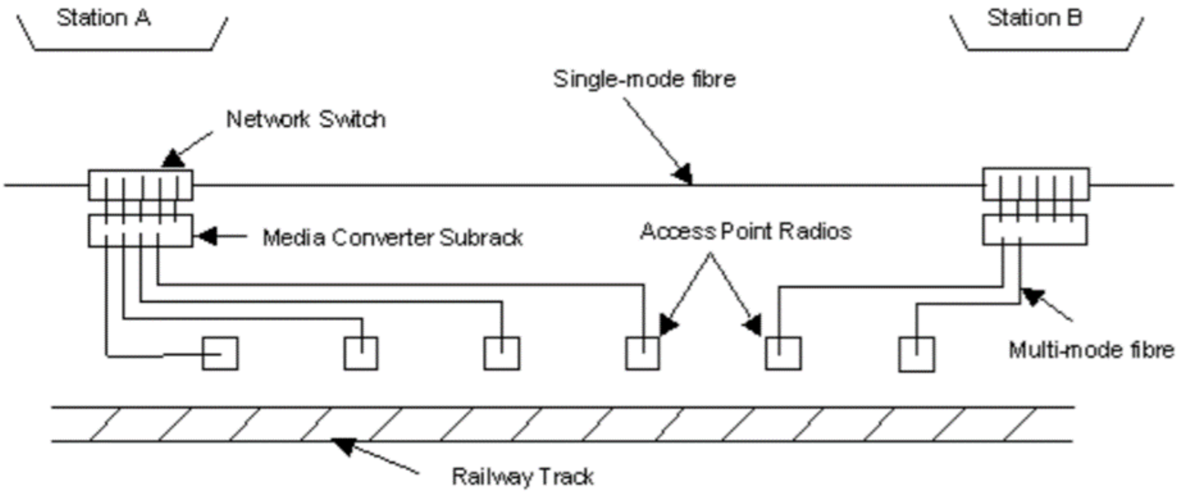


Figure 25 Wired Network (Kuun & Canada, n.d.)

DCS is an integrated Ethernet-IP network which consists of both wired and wireless components. DCS is a complex blend of network equipment and RF wireless components protected by a strong security system based on IPSec protocol. Ethernet switches, routers and fiber optic cabling in combine form the wired portion of DCS. Ethernet switches which are located in the station equipment rooms connect wayside controllers (ZC) with various APs. The interconnection of Ethernet switches via fiber optics form a high-speed Ethernet backbone. Ground radio connectivity is established when various Access points are linked together via network switches, and fiber optics are used for the connection between APs and Ethernet backbone. (Tianhua, Tang, Chunhai, & Cai Baigen, 2009)

Sending and receiving control data between ZC and trains is one of the core operations of DCS, and this data includes direction, location, speed, and Train ID code. Zone controller generates a movement authority (MA) on the basis of received data and sends MA to the train. The train cannot commute outside the next secure position until it receives the MA. When designing a DCS, the procedure to decide the installation and deployment of APs usually depends on the gathered on-site engineering information. When a train is commuting towards the edge of adjacent Access Point coverage, a handoff process occurs, and it is quite a frequent process that keeps happening during the movement of the train. Let's take an example of rail transit which we assume have a thirty Kilometer rail track and this infrastructure has 200 APs installed which means 200 times handoffs occur. These handoffs can affect the quality of communication. Also, the interference problem in APs and propagation path-loss issue. All these issues should be taken into account meticulously when deploying the Infrastructure of the DCS system. (Wen, Constantinou, Chen, Tian, & Roberts, 2018)

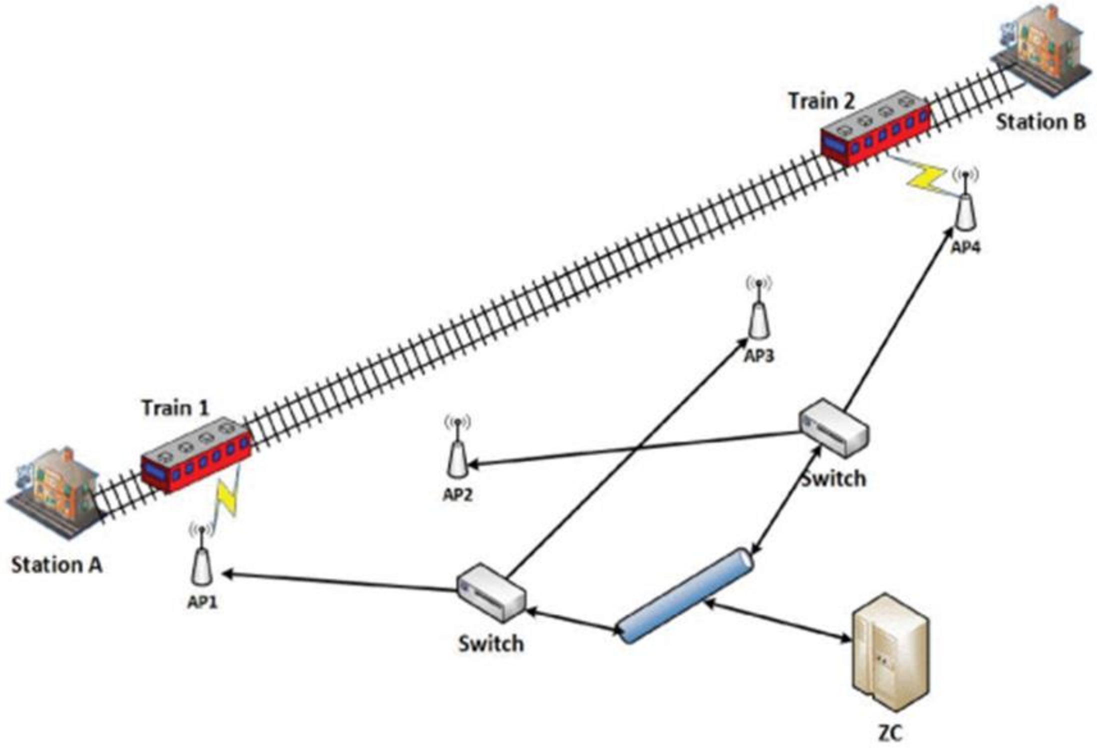
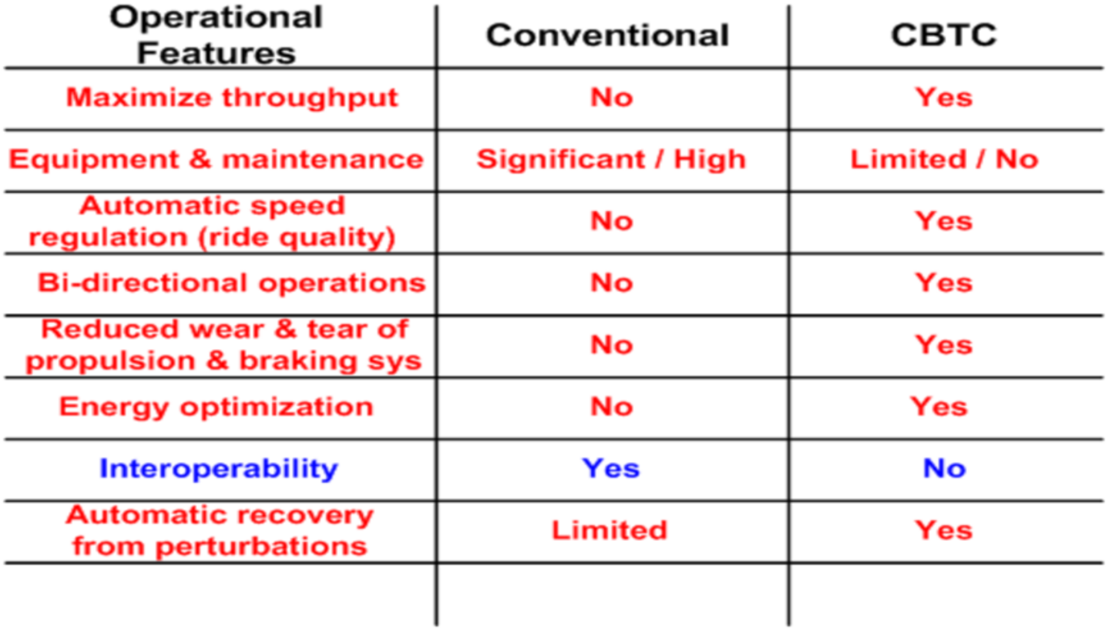


Figure 26 Simplified CBTC Architecture (Wen et al., 2018)

3.5 The Evolution of Communication Technologies for Railway Signaling

It all started with conventional signaling. These systems used AC track circuits to determine the location. The low capacity of communication resulted in achieving less precise train position information. Conventional signaling cannot match the operational benefits and services of CBTC. Throughput is the basic reason why CBTC is attractive for transit authorities. Its capability of reducing headways cannot be achieved in conventional signaling. Apart from the capacity, the bidirectional operations of CBTC both in train movement and communication enhance the flexibility of the rail infrastructure to deal with traffic problems. Trains in CBTC are in uninterrupted communication with Control center because of the continuous data link.

If we see at the hardware differences between CBTC and Conventional signaling at track level, CBTC is much more viable and sustainable. Equipment and devices for communication and networking can be placed in equipment rooms, and trackside equipment only contains transponders, a switch mechanism, and wayside radios. The maintenance of the hardware at the track level in conventional signaling is far expensive than in CBTC. Everything is computerized and programmed in CBTC. The level of automation in CBTC provide automatic speed regulation and automatic recovery in case of any perturbations. (Ali, 2016)



Operational Features	Conventional	CBTC
Maximize throughput	No	Yes
Equipment & maintenance	Significant / High	Limited / No
Automatic speed regulation (ride quality)	No	Yes
Bi-directional operations	No	Yes
Reduced wear & tear of propulsion & braking sys	No	Yes
Energy optimization	No	Yes
Interoperability	Yes	No
Automatic recovery from perturbations	Limited	Yes

Figure 27 Conventional signaling systems vs. CBTC (Ali, 2016)

3.5.1 Early CBTC systems

Inductive loop technology was used for early CBTC systems. The first time, this technology was used in Toronto in 1985. The basic concept in these systems was mounted inductive loop cables on the tracks, and these loops worked as a metal detector which measures and verify the train location. These systems worked in the kHz frequency range as compared to GHz range in CBTC. This technology was in use for railways for almost three decades, but the difficulty in establishing such infrastructure and its vulnerability with regards to security were some of the many drawbacks because of which there was a need to switch to more efficient technology.

3.5.2 Radio-based CBTC:

Bombardier was the first supplier for CBTC system. They implemented it in Francisco Airport in 2003. Radio-based CBTC systems can be split into two groups. Those which are based on older technology, i.e., leaky waveguide and those which are based on COTS technologies.

3.5.2.1 Custom and Commercial-off-the-shelf (COTS) radio:

Early CBTC systems were custom solutions and developed for specific requirements for a particular project. One problem with CBTC systems is that they are weak in interoperability. Once a supplier is selected, then the transit agency depends completely on the supplier. Later on, no other controller can be used. Although, this trend is now changing gradually as transit agencies are making the suppliers follow the IEEE, APTA, AREMA and other defined standards. An early CBTC example is Model 2400 solution which was developed and installed by Bombardier. It was leaky waveguide based. It was one hundred times expensive than Wi-Fi-based solution. Later on, Bombardier switched to spread-spectrum technology, but it was still ten times costly than Wi-Fi solution. (Farooq & Soler, 2017)

3.5.2.2 Leaky waveguide

The leaky waveguide is also called leaky cable or feeder. Leaky coaxial cables are used as a continuous radiating structure, and it allows radio signals to leak in or out. It has been used and deployed in the past for decades. It offers certain benefits. In Leaky waveguide, open-air communication is quite limited because it occurs between a small distance around 0.3-0.6 m and the equipment include aboard receiver antenna and leaky cable. Therefore, less interference and less propagation loss. Some rail transits have applied it in combination with radio communication. At such rail transits, the leaky waveguide is applied where there are chances of more interference like in open air and radio communication in tunnels. Combining the two technologies and switching between them is a big task. The drawback of leaky cable technology is that it is expensive and its deployment and maintenance is quite difficult. Moreover, the leaky waveguide is susceptible to environmental factors like snow and signal degradation can occur. For these issues, it has not been very reasonable for the CBTC. (Farooq & Soler, 2017)

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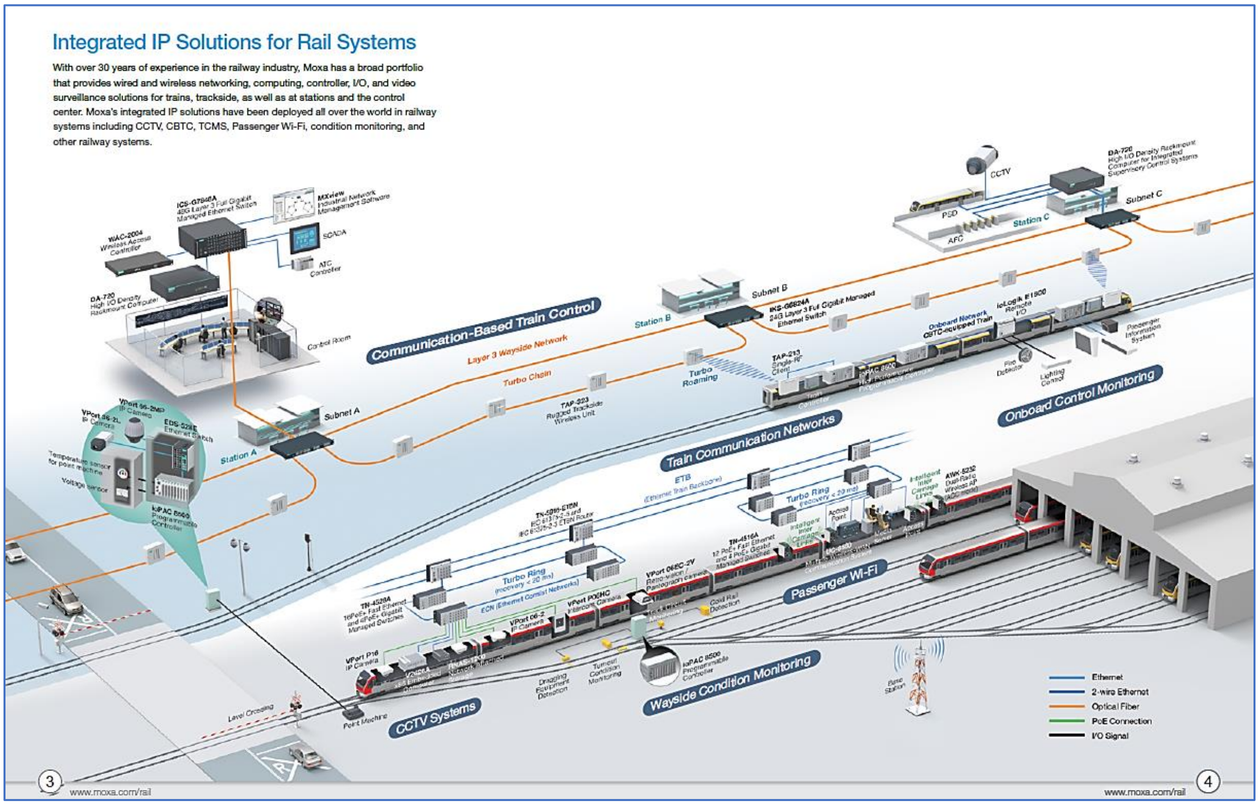
Rail transit system communication network (BCN/TCN)

4.0 Rail Communication Network and Technologies

The rail communication has varied requirement of communication. These include data communication for various equipment inside the train, communication requirement between the train and wayside equipment, and interlinking of all wayside equipment to the central control room for monitoring and supervision of rail system from a central location. The data communication within the train is normally wired communication and is called Train Communication Network. The train to wayside communication is wireless communication. The wayside to control system connectivity is normally using fiber optic cables. The overall train monitoring and control system is a highly sophisticated system involving almost all the telecommunication technologies for safe and secure operation of the system. A typical modern representative train monitoring, control, and supervision system based on the latest technologies are shown in Figure 28 (Moxa, 2019).



Integrated IP Solutions for Rail Systems

With over 30 years of experience in the railway industry, Moxa has a broad portfolio that provides wired and wireless networking, computing, controller, I/O, and video surveillance solutions for trains, trackside, as well as at stations and the control center. Moxa's integrated IP solutions have been deployed all over the world in railway systems including CCTV, CBTC, TCMS, Passenger Wi-Fi, condition monitoring, and other railway systems.

Figure 28 Train monitoring, control, and supervision system (Moxa, 2019)

The modern train system requires broadband access for passengers to view videos, TV, latest news and Internet access. This requires large bandwidth as well as high data speed which is a challenge especially the high-speed trains moving at speeds greater than 350 Kmph. (Masson & Berbineau, 2017a)

This section will look into the various technologies used for TCN and wireless communication.

4.1 General Requirements

Reliable voice and data communication are prerequisites to the safe operation of the train system. The data communication needs to be error-free and delivered on time else the automated brakes mechanism brings automotive to halt for safety.

This requires low latency and error-free performance from wireless system deployed (Cortes Alcala, Lin, He, & Briso-Rodriguez, 2011). Also, the system needs to facilitate Video transmission, Emergency group communications and security (Masson & Berbineau, 2017b). To provide reliable and low latency communication over wireless system mandates the use of a dedicated frequency band for rail communication. Europe, Asia, Australia, and North Africa all use GSM-R (Global System for Mobile Communications – Railway) frequencies in 900 MHz band. U.S uses 220 MHz for its PTC system. (DIGI, 2018)

The basic requirements of a rail communication system for TCN are (DIGI, 2018):

- Network Performance and Resilience: The cellular system with dedicated frequency band can provide this.
- Rugged Devices – Trains and rail wayside are challenging environments for deployment of communications systems. This requires ruggedized housing and the system that can withstand extremes of vibration, shock, temperature, and humidity.
- Long Life: The equipment in the rail environment are distributed over a large area and therefore repairing them is a costly affair, and this requires reliable operation and long life with minimum failures from the equipment side.

- Security – The rails communication system is a mission-critical application, and this requires the system to ensure error-free delivery with data integrity and privacy. The system must provide sufficient safeguards by using encryption, authentication, etc. to ensure that data is delivered securely and safely without delay.

Apart from the technical requirement, the main functional requirement specific to rail system are given below:

4.1.1 Train Control

The wireless communication system for train communication carries essential information and need to have high availability. The QoS parameters for GSM-R for ETCS are provided in Table 1. Thus, transmission error probability should be less than 1% /h, and 99% of data should have less than 0.5s latency. (Choi, Song, & Kim, 2013)

Table 1 QoS parameters for GSM-R (ETCS) (Choi, Song, & Kim, 2013)

QoS parameters	Demand value
Call setup time	≤ 10s (100%)
Connection establish failure probability	< 1% (100%)
Data transmission delay	≤ 0.5s (99%)
Error rate	< 1%/h (100%)
Duration of transmission failures	< 1s (99%)

4.1.2 Redundancy of network and coverage

The redundancy of wired as well as the wireless network is required to provide higher availability. This requires all critical components in the system to have a hot standby configuration, and the communication network too should have redundancy.

4.1.3 Video surveillance

The safe train operation of modern railroad requires video surveillance of passenger cabin. The real-time video of key locations such as tunnels, crossing points needs to be made available to the train driver for safe operation. However, this requires high bandwidth which is not supported by current railway communication standards such as GSM-R. (Choi et al., 2013)

4.1.4 Exclusive voice call function for railway

This facility is required in emergencies such as train failure or accident when the driver is required to respond immediately to the situation. This requires not only special call processing but also low call setup time. The rail system also requires Priority and Preemption to override the regular calls in case of an emergency.

“The exclusive voice call function includes the voice call between a train driver and the control center, emergency call in case of emergency, group call between users in a certain area or specific users, broadcasting for the railway workers within a certain area” (Choi, Song, & Kim, 2013). The adequate call quality requires delay time of less than 200 ms between two voice codecs.

The voice call processing functions exclusive railway are Functional Addressing Railway, Emergency Call, and Location Dependent Addressing. In functional addressing, the call is made using train operational number rather than using the unique subscriber number. In Location Dependent Addressing one button pressing is used by the supervisor to make an urgent call to the train in his area. Railway Emergency Call allows the supervisor to make an immediate group call to all the drivers in the train in his command area by pressing a single button. Figure 29 shows the three voice call processing functions specific to railways. (Choi et al., 2013)

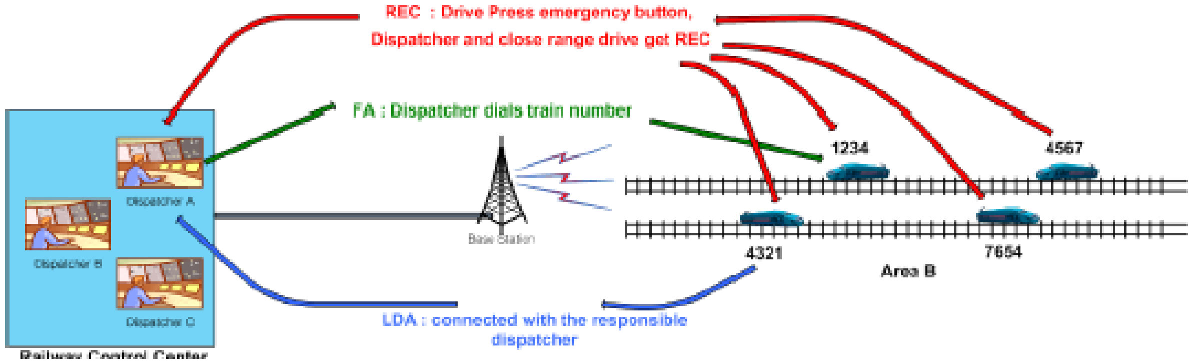

REC : Drive Press emergency button,
Dispatcher and close range drive get REC
FA : Dispatcher dials train number
Dispatcher A
Dispatcher B
Dispatcher C
Railway Control Center
Base Station
1234
4567
4321
7654
Area B
LDA : connected with the responsible dispatcher

Figure 29 Railway specific call processing features (Choi et al., 2013)

4.2 Train Communication Network (TCN)

The Train Communication Network consists of a system to connect various electronic devices on board the trains and communicating the data collected to Train Control and Management System (TCMS). When the first electronic monitoring and control systems were introduced for train monitoring and control, the individual system was hardwired directly to the control system using dedicated wiring (Neil, 2012). As the number of systems increased the cost of wiring went up, and the approach was not scalable. The serial communication provided a solution to the problem by reducing the number of wires and allowing all the systems to transmit data on a single bus which led to a reduction in the cost and complexity of cabling in rail communication. (Holmberg, 2016)

However, the use of proprietary serial technologies did not allow equipment interoperability and to sort out this issue standardization was undertaken by International Electrical Commission (IEC). The standard for Train Communication Network (IEC 61375-1) was published by the IEC in collaboration with the International Railway Union(UIC) along with UIC CODE 556 leaflet (Information transmission in the train) (Schafers & Hans, 2000). Train Communication Network standard IEC 61375-1 specifies the standard for exchange of data between various systems in the network with the aim of interoperability between various equipment (Park & Lee, 1998). As per Schafers & Hans (2000) “UIC 556 and the accompanying UIC codes define the operator's view on the train, the framework for the coordination of the different applications and the operational handling to ensure interoperability between vehicles from different manufacture” (Schafers & Hans, 2000).

The IEC 61375-1 TCN standard provides hardware specifications, MAC and Link layer protocols and defines a protocol for inter-link communication. The standard also provides higher level real-time protocols for a node to node data exchange. Thus TCN provides a methodology of data exchange between equipment and control systems for Train Control and Management. (Holmberg, 2016)

TCN standard (IEC 61375-1) specifies two network buses, Wired Train Bus (WTB) (IEC 61375-2-1:2012, 2012a) and a Multi-function Vehicle Bus (MVB) (IEC 61375-2-1:2012, 2012b) to take care of dynamic configuration of the train. WTB is for inter-vehicle communication and MVB is for intra-vehicle communication as shown in Figure 30 (Holmberg, 2015).

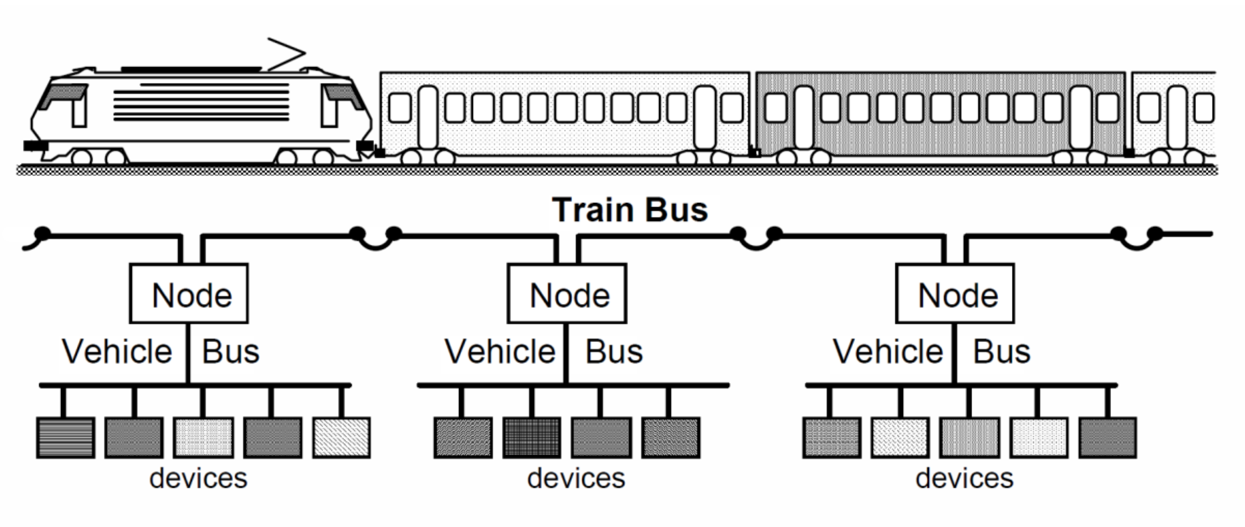


Figure 30 Train Communication Network. IEC 61375-1 (Holmberg, 2015)

A vehicle bus may span single or multiple vehicles as in the case of mass-transit train-sets which operate as a single vehicle and do not get separated during operation. Figure 31 shows various scenarios with Fig a showing connected train set, Fig b showing closed train set and Fig c showing nonstandard bus that can be integrated as vehicle bus (Hubert Kirrmann & Pierre A. Zuber, 2001). TCN uses logical addressing to take care of different types of coaches and equipment. Each node in the system supports a number of applications which can be accessed by a unique function number. (Schafers & Hans, 2000)

4.2.1 Multi-function Vehicle Bus

MVB provides high-speed communication between devices including motors, brakes, batteries and other control systems in one vehicle of the train to provide real-time information. MVB also provides communication in one train set used in Metro rail sets. The MVB uses the following three media types for communication at the data transmission speed of 1.5 Mbps (Schafers & Hans, 2000):

- RS-485 for short distance up to 20 m.

- Twisted pair wire with transformer coupling for up to 200 m
- Optical fibers for distance up to 200 m. These are also used in harsh EMC environment

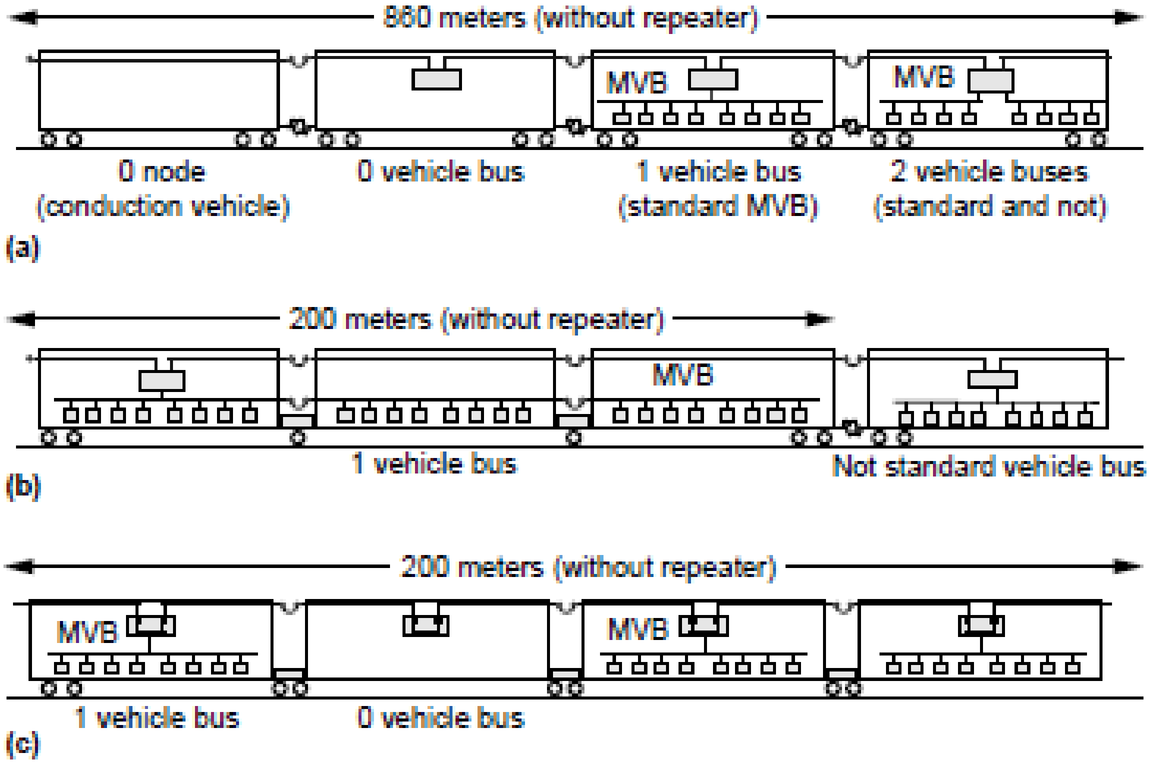


Figure 31 Open train with the Multifunction Vehicle Bus as vehicle bus (in some vehicles) and the Wire Train Bus as train bus (Hubert Kirrmann & Pierre A. Zuber, 2001)

A dedicated bus master controls MVB. It may be used redundantly to increase reliability. An integrated bus controller allows the connection of devices without a processor. The MVB uses Manchester encoding for data integrity (Schafers & Hans, 2000)

4.2.2 Wired Train Bus

WTB provide interconnection and interoperability for a smooth connection between various vehicle units in the train. The interconnection between vehicles is done using automatic couplers or hand plug jumper cables as shown in Figure 32. Shielded twisted pair cable is used for communication. The standard allows maximum cable distance of 860m without any repeater with a connection up to 32 nodes. The WTB uses inauguration procedure to auto number the nodes in sequential order and also allows a node to recognize their location with respect to the train, i.e., left or right side of the train. The inauguration procedure gets executed each time composition of the train changes. The numbering of the train bus is done sequentially. The topology of the WTB is informed to all vehicles after the end of the inauguration. This information includes TCN address, nodes orientation, the position of a node with respect to the master, and number and position of other nodes in the train. Every node can become a master in case of failure of the bus master. Normally the mastership is transferred to a neighboring node automatically in case of failure of the working master. The data transfer rate of WTB is 1 Mbps.

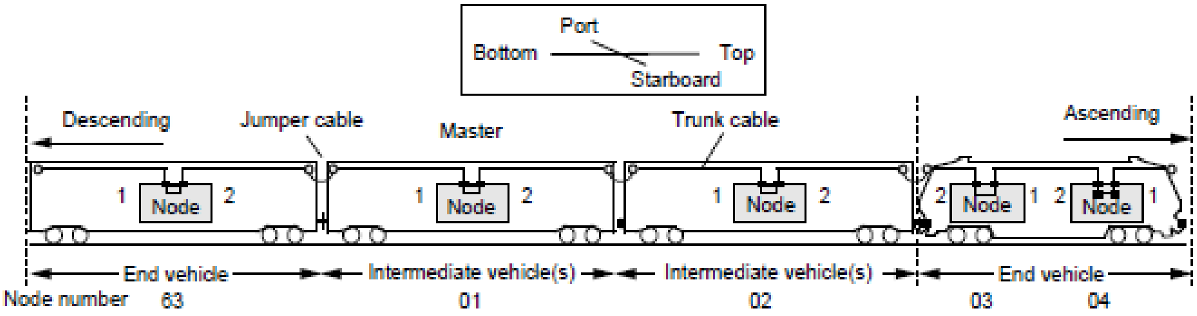


Figure 32 Wire Train Bus (Hubert Kirrmann & Pierre A. Zuber, 2001)

4.2.3 Common Real-time Protocols (RTP)

MVB and WTB both use the same higher layer protocol called the Real-Time Protocol though, the physical and link layer protocols used are different. TCN provides automatic online configuration.

Two types of data traffic are defined in the TCN protocol stack. The real-time process related data and messages which are not real time. Process data in TCN provides train parameters such as its speed, motor current, and commands which must be transmitted in a short time. TCN standard provides maximum process data latency of 100 ms for inter-vehicle and 50 ms for intra-vehicle communication. The process data is transmitted periodically in predefined time to achieve the latency required. The messages which are not real-time are sent as per the demand. The process data takes a fixed time slot of traffic on the bus, and the transmission during this phase is done by master polling devices in sequence allowing polled devices to broadcast its process information. A real-time scheduling algorithm is used to schedule the period and size of process data. The sporadic data is transmitted between the two periodic phases using a contention resolving algorithm as shown in Figure 33. (Park & Lee, 1998)

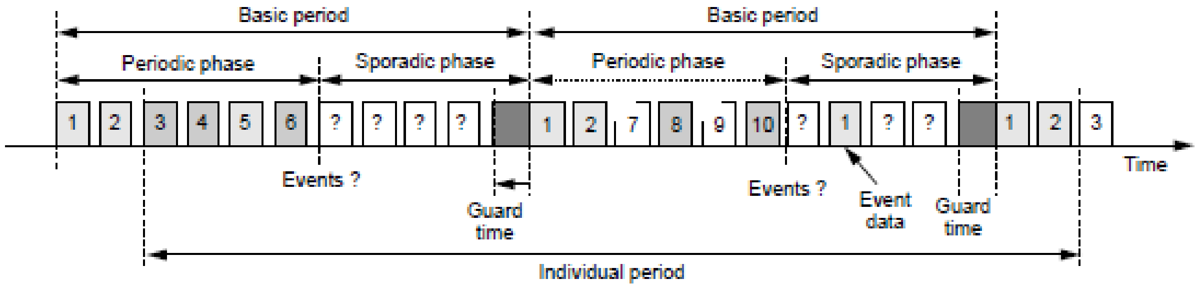


Figure 33 Alternating periodic and sporadic data transmissions (Hubert Kirrmann & Pierre A. Zuber, 2001)

4.2.4 TCN Gateway

The TCN gateway is used for connecting MVBs with the WTB using a special application termed as the Process Data Marshalling (PDM). The routing is done based on the internal structure of the vehicle preconfigured at the time of inauguration and stored in the function directory table. (Schafers & Hans, 2000).

4.2.5 UIC Communication

TCN defines communication mechanism between MVB and WTB but does not provide application specific profile such contents of messages and process data frames, process period, etc. UIC realized that that TCN in this form is not enough to ensure interoperability between vehicles produced by different manufacturers and came out with definitions. (Schafers & Hans, 2000).

UIC code 558 defines the cabling. The profile for communication is defined in UIC code 556. The UIC code for process and message data application are provided as per details below (Schafers & Hans, 2000).:

- UIC code 557: for diagnosis
- UIC code 647: remote traction control

- UIC code 560/660: door control
- Code 54x: a brake control

The definitions defined by UIC are for train bus communication only and treats vehicle like a black box. R(regular)-telegrams are used for transmission of process data and E(vent)-telegram are for TCN messages. The R-telegrams are broadcasted to each vehicle, but E-telegrams are sent on point to point basis or point to multipoint basis as required. The UIC addresses the vehicles by numbers starting from 1 onward. The addressing is fixed at the time of UIC inauguration process like TCN inauguration. The UIC inauguration builds a Node Address and attribute Directory (NADI) consisting of a description of the complete train, and at the end of the process, every node has the same copy of NADI. The UIC Mapping Server (UMS) as part of the gateway performs UIC inauguration and builds NADI. (Schafers & Hans, 2000)

4.2.6 ERRI test train

The UIC sponsored full-scale TCN implementation through European Railways Research Institute (ERRI) was carried out from May 1994 to September 1995. The testing was carried out in the lab as well as existing track using equipment from different vendors. The test validated the interoperability and completeness of standards. After testing and updating of documents to incorporate quality requirement, the TCN was adopted by IEEE Rail Transit Vehicle Interface Standards Committee as IEEE Std. 1473 for onboard data communication. (Hubert Kirrmann & Pierre A. Zuber, 2001)

4.2.7 Ethernet Train Backbone

The original WTB specifications (IEC 61375-2-1) defines bus using RS- 485 with a data transmission rate of 1 MBPS. The requirement of video surveillance, interactive entertainment system, broadband access for passengers, remote monitoring and software update capabilities in the newer train system needed larger bandwidth than provided by the original TCN system. To take care of new requirement, Ethernet Train Backbone (ETB) was defined by the IEC 61375-2-5 standard to replace the old system as shown in Figure 34 (IEC, 2014) (CENELEC, 2015). The ETB provides bus bandwidth of 100 Mbps with a maximum of 63 nodes and distance of 100 m between the nodes (EKE-Electronics, 2019).

The ETB has an architecture similar to original TCN. The ETB backbone runs along the full length of the train. The gateway function is done by Ethernet Train Backbone Nodes (ETBN). It routes packets between ETB and ECN (Ethernet Consist of Networks). ECN handles communication within the vehicle. ETB uses the same real-time protocol as the original TCN leaving application interface unchanged. The Ethernet is attractive technology as its use can use bandwidth up to 10 Gbps and enables seamless interface and communication with many end devices. The real-time data in ETB is sent using IP for network transfer and UDP/TCP for transport. The equipment is provided with IP addresses during inauguration phase controlled by the Train Topology Discovery Protocol. In this system, ETBN continuously checks for the presence of new nodes and on detection of any change new inauguration process is initiated. During inauguration phase, a device in each ECN sends information about all the devices connected to the ECD using CSTINFO telegram. The information combined from all CSTINFOs is used for the construction of the Train Topology Database (TTDB). The TTTB consists of complete information on train including IP address and domain names for each End Device. The end devices connected to ECN use two methods of communication like in TCN. However, unlike old TCN, here multiple process packets can be sent from each End Device (ED). ED can send multiple packets corresponding to functions of the node.

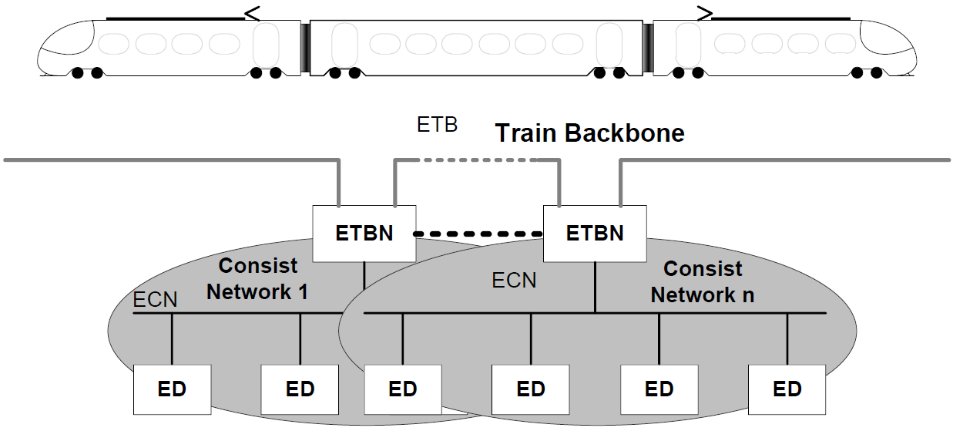


Figure 34. Ethernet Train Backbone. (Holmberg, 2015)

Unlike the use of bus master to control data transmission in the original TCN, the process data sent by ED is routed using the IGMP and UDP protocols. The use of Ethernet in TCN provide higher bandwidth, more flexible network, and access to broader markets. (Holmberg, 2016)

4.2.7.1 Redundancy in Ethernet for TCN

The railway environment is a harsh environment, and industrial Ethernet products with specialized connectors provide a good solution for the environment. Redundancy is one of the key requirements of TCN. In the case of Ethernet-based network, the redundancy can be provided using suitable protocols for the topology used. In the case of TCN, the key requirement for redundancy will be switchover time which is required to be less than 1.4ms (Heine & Kleineberg, 2012). Two protocols Redundancy Protocol (PRP) and High Availability Seamless Redundancy (HSR), defined by IEC 62439-3 standard for industrial Ethernet. The PRP and HSR both provide almost zero switchover time, and these can be most suitable in the TCN environment (Aitzol Zuloaga, Armando Astarloa, J. Jiménez, & Jesús Lázaro, 2013).

For implementing redundancy in PRP two separate Ethernet network is used and each device is connected to these two networks using the independent connection. The transmission is done on both the LANs. The nodes on LAN use first received frame and discard the duplicate frame received later. Thus, in case of faults in one LAN the nodes will receive the data over working LAN. This methodology requires no switchover time. (Aitzol Zuloaga et al., 2013)

In the case of HSR, like in PRP case, two LANs in ring configuration are used. The data is sent via both the LAN in both directions in the ring network as shown in Figure 35. However, the use of HSR requires each node or devices to have two Ethernet ports supporting HSR. Another solution to use conventional devices for HSR operation is to use Redundancy Box device. (Aitzol Zuloaga et al., 2013)

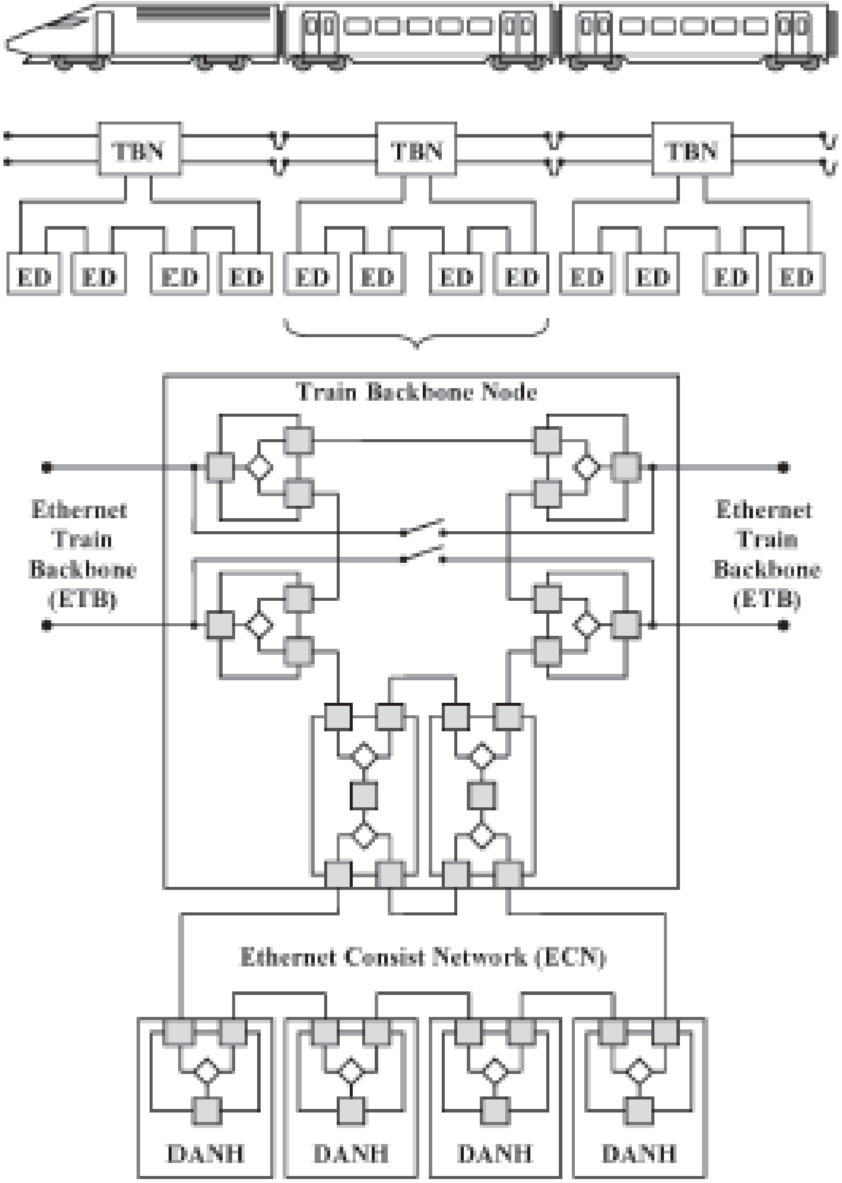

TBN
TBN
TBN
ED
Train Backbone Node
Ethernet Train Backbone (ETB)
Ethernet Train Backbone (ETB)
Ethernet Consist Network (ECN)
DANH
DANH
DANH
DANH

Figure 35 HSR based TCN (Aitzol Zuloaga et al., 2013)

4.2.7.2 TCN using Switched Ethernet

Switched Ethernet has gain popularity of late in all type of applications including that in communication, defense, aerospace and industrial control due to the high bandwidth and availability of low-cost switches. Avionics full duplex switched Ethernet (AFDX) is a data bus being used for avionics applications. It has been modified to transfer real-time data and reliability as per the requirement of aviation systems. It is now used by large aircraft manufacturers for their large commercial aircraft. The main advantage of AFDX is its uses of commercial off-the-shelf systems with proven reliability. It also reduces channel jams, provides improved data transmission rate, and limits transmission delay. (Ma, Zhong, Cao, Xing, & Zhang, 2014)

Ma et al. (2014) proposed switched Ethernet-based system using a system similar to Avionics full duplex switched Ethernet for use in TCN. The use of switched Ethernet can remove the problem of Ethernet uncertainty. The topology of the proposed system is shown in Figure 36. The scheme uses a 3-layer structure for TCN based on switched Ethernet. The first layer corresponds to the WTB of TCN and is the backbone of the system. The Ethernet switch in each vehicle is connected in cascade to realize train level control. The first and last vehicle is connected directly to form the ring network. The information is sent in each direction of the ring. The system uses the redundant double line for circuit connection to improve reliability. (Ma et al., 2014)

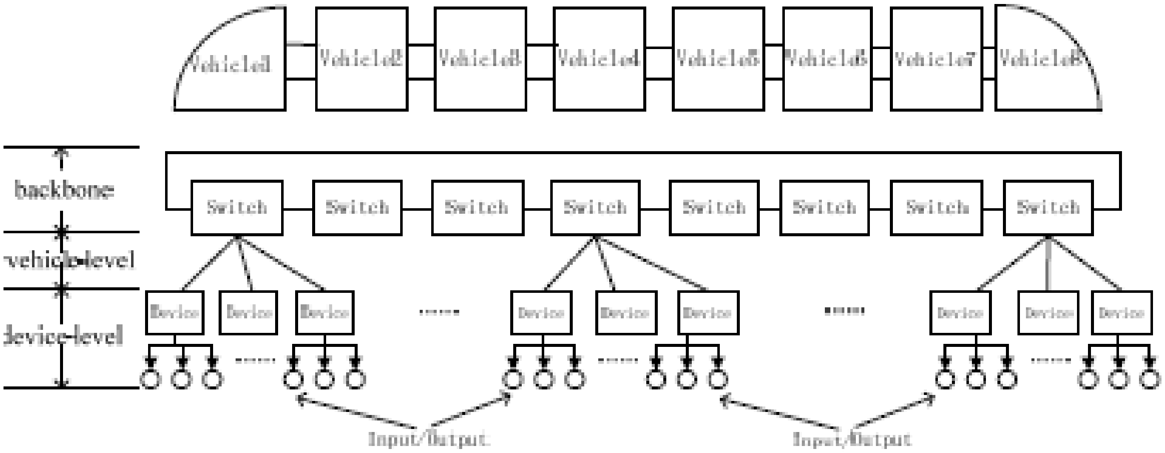


Figure 36 The TCN topology structure based on switched Ethernet (Ma et al., 2014)

The second layer called vehicle level layer uses redundant twisted shielded pair cable for connection. It uses start topology instead of the bus in case of TCN, and each terminal equipment is connected to Ethernet switch. This methodology avoids the collision domain and reduces data transmission delay. (Ma et al., 2014)

The third layer is a device layer and has devices that are connected to switches in the vehicle layer.

The TCN protocol stack used for Switched Ethernet has three main improvements over traditional TCN protocol as shown in Figure 37. The task is categorized into real-time and non-real-time tasks. Then an RTP and a virtual RTP layer are set up. The transport layer uses TCP and UDP protocol whereas the network layer is IP and switched Ethernet. Real-time protocol for switched Ethernet is compatible with traditional RTP protocol. The virtual real-time layer provides upper layer RTP with the data and conforms to RTP requirement and also provide shied to RTP from the bottom. (Ma et al., 2014)

The simulation studies show that switched Ethernet TCN can replace TCN without any problem and provide a substantial improvement in time delay and bandwidth availability.

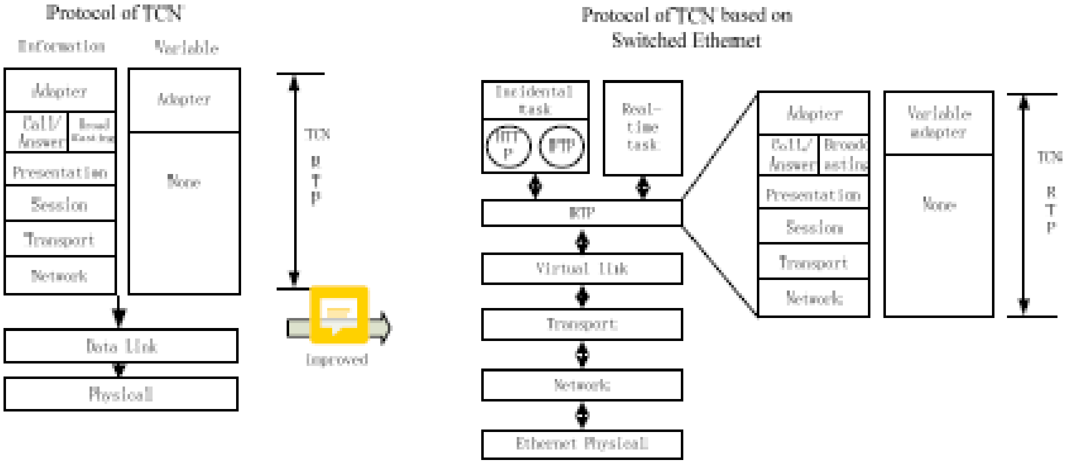


Figure 37 Improvement of the communication protocol stack. (Ma et al., 2014)

Figure 38 shows Ethernet-based train control and supervision system by Moxa, a provider of ruggedized Industrial Ethernet products for railways. The onboard Ethernet switch in each cab connects the local system such as IP Camera, train controller. The information exchange between train and wayside network is using two top-mounted wireless clients. The wayside infrastructure is Ethernet-based using fiber optic as a medium of communication.

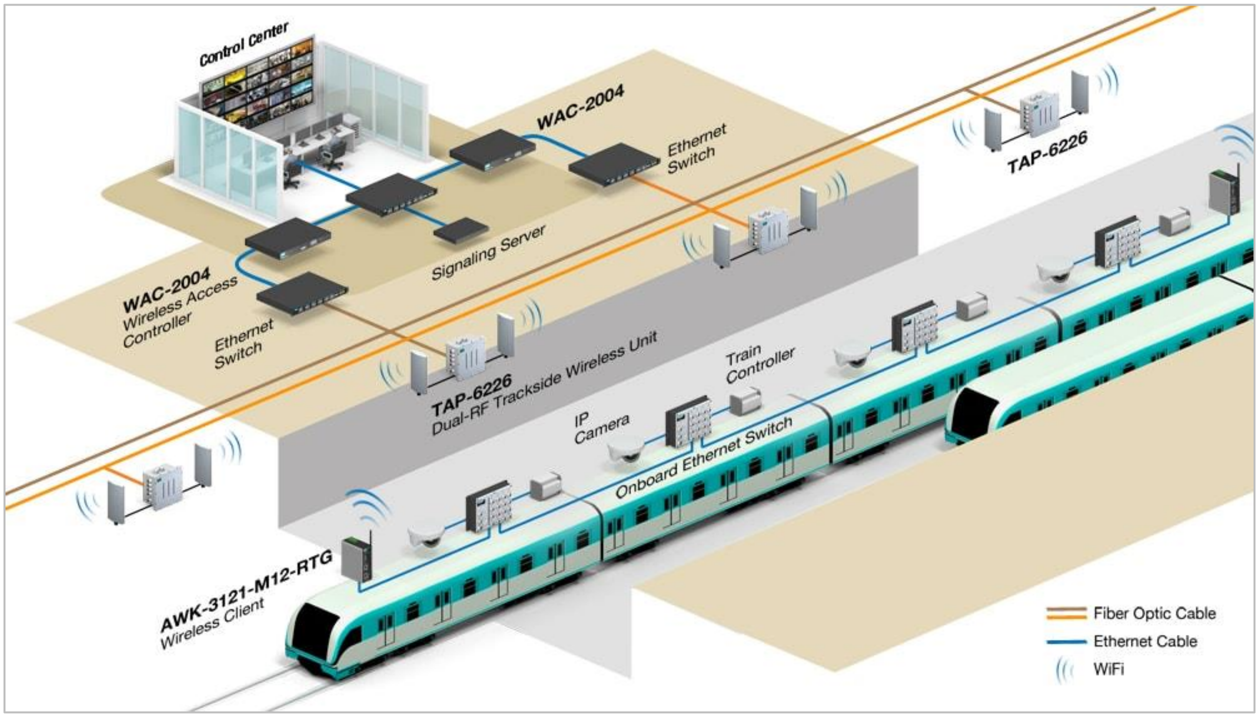


Figure 38 Ethernet based train control and supervision system (Moxa, 2019)

4.3 Wireless Technologies for rail communication.

The very nature of mobile to wayside communication in rail communication requires intensive use of the wireless system for communication requirements for signaling, operation, and maintenance of the system. The use of wireless communication can optimize infrastructure requirements and reduce operational and maintenance costs. (Cesar Briso & J.I. Alonso, 2007)

The area of application of wireless communication in the railway system are:

- Train control
- Operation and maintenance
- Information dissemination.

Each of these applications has its demands from the communication system. Of these, train control is most important to run operations efficiently and safely.

This section will evaluate three main wireless technologies namely TETRA, Wi-Fi and GSM-R for railway data communication requirements.

Wireless communication is considered unreliable, and the rail system needs to be reliable. Therefore, designing a communication system for reliable and safe train system is a challenging task. The conventional signaling system can tolerate some error in communication as the distance between trains following each other is large. In CBTC headways being short can lead to train not receiving the information in time in case of communication failure. This may lead to train applying emergency brakes and bring it in manual mode. In an automatic system, it may cause a chain reaction with many trains coming to a halt leading to loss of track capacity (Bu, Yu, & Tang, 2014). Thus a railway communication network must provide low transmission delay and high QoS (Cortes Alcala et al., 2011).

In the CBTC system, the onus of providing train location information to the wayside equipment is of the train, and it depends on the communication system to deliver it securely and reliably (Pascoe & Eichorn, 2009). This, in turn, makes the failure of communication very critical for proper functioning of the CBTC system.

To overcome the communication unreliability, additional protection margin is kept in the safe breaking distance calculations in CBTC systems (IEEE Std 1474.1-2004, 2005). The conventional train detection method may also be used as fall back, and it also takes care of non-CTBC systems operating on the same tracks (Pascoe & Eichorn, 2009).

The CBTC typical control message size is of around 400-500 bytes and requires a message transmission time of less than 100 ms. These messages are sent with frequency ranging from 100-600 ms; the data capacity of the CGTC system comes to around 20-40 kbps and not exceeding 100 kbps (Bu et al., 2014).

4.3.1 WLAN System for Rail Communication

WLAN or Wi-Fi is the most popular technology used in a data communication system between the train and wayside equipment. The WLAN system used is based on the IEEE 802.11 family of standards and uses 2.4 GHz and 5 MHz industrial, scientific and medical (ISM) band. The IEEE ratified first 802.11 standard WLAN in the year 1997 and specified 1 Mbps and 2 Mbps data rates. The 802.11 standards define, the physical layer and link layer, the bottom two levels the ISO model. (IEEE 802.11, 2019)

4.3.1.1.1 IEEE 802.11 Architecture

Each wireless node is referred to as a station in 802.11. The portable station can be mobile or move from point to point but is only used at a fixed point. Mobile stations can access the WLAN during movement. The two or more stations can come together to communicate with each other, and in this situation, they form a Basic Service Set (BSS). 802.11. WLANs use the BSS as the standard building block. (Crow, Widjaja, Kim, & Sakai, 1997)

IEEE 802.11 Data Link Layer

The 802.11 divides the data link layer into two sublayers: Logical Link Control (LLC) and Media Access Control (MAC). 802.11 uses the same Logical Link Control layer and 48-bit addressing as wired 802 LANs. The common LLC allows for simple bridging between wireless and wired networks. (Crow et al., 1997)

The wireless medium is a shared medium, and the 802.11 MAC is designed to support multiple users in the wireless medium by making the sender senses the medium before transmission. 802.11 uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) or the Distributed Coordination Function (DCF) for accessing the shared medium. Explicit packet acknowledgment (ACK) is used in CSMA/CA to prevent collisions. In this method, the receiving station confirms the proper receipt of the packet to the sender before next transmission by the sender. In case of non-receipt of ACK message the transmission station assumes collision and it retransmits the packet after a random amount of time. This method of avoiding collision leads to the lower performance of WLAN as compared to the wired LAN. The data integrity of the packet is maintained by using CRC checksum. (Pathak, 2017)

IEEE 802.11 Physical Layer

The original 802.11 standard specified two types of physical layers one radio operating in the 2.4 – 2.4835 GHz band and the other in the infrared band. The power output is limited to 1 watt. The radio uses two spread spectrum techniques; Frequency Hopping Spread Spectrum and Direct Sequence Spread Spectrum. With the publication of more standards number of physical layer, supplements have been introduced as depicted in Figure 39.

4.3.1.2 WLAN Standards

The 802.11 series of standards offer a number of standards developed over a period using various technologies and frequency bands (IEEE 802.11, 2019). The standards applicable for railway network shall be discussed below.

IEEE802.11a: It was ratified in September 1997 using 5 GHz band. It uses Orthogonal Frequency Division Multiplexing (OFDM) with support to speed up to 54 Mbps. Due to its higher frequency band, 802.11a is not compatible with 802.11b, the most popular system in 2.4 GHz band. In OFDM the data carrier is divided into a number of low-speed carriers which are located apart at precise frequencies that are orthogonal to each other. These frequencies are then transmitted simultaneously on a single transmission path. The precise spacing of frequencies allows the demodulators to see their own frequencies only. The use of frequencies close to each other provides OFDM with high spectral efficiency, resiliency to RF interference, and lower multi-path distortion.

IEEE802.11b

The IEEE802.11b standard was ratified in 1999. It supports the data rate up to 11 Mbps and uses ISM Band from 2.402 GHz – 2.479 GHz. It uses Direct Sequence Spread Spectrum and bandwidth of each channel is 22 MHz. (Pathak, 2017)

In the direct sequence spread spectrum, the signal to be transmitted is spread over a full band by modulating it by a random binary string (called the spreading code). The data bits get mapped to into a pattern of "chips" and these chips are mapped back into a bit at the destination. This requires the transmitter and the receiver to be synchronized using the same spreading code.

The range of operation is 30 meters indoor and 100 meters outdoor. The data rate achieved goes down as the distance of communication increases. The data rate is dynamically adjusted depending on the quality of the link. As the standard shares the same band as for Bluetooth, cordless mobile and other gadgets it is prone to interference. (Abdelrahman, Mustafa, & Osman, 2015)

IEEE802.11g

The IEEE802.11g, ratified in 2003, uses 2.4 GHz ISM band for communication. It uses Orthogonal Frequency Division Multiplexing and supports bandwidth up to 54 Mbps. It is backward compatible with 802.11b and in this mode, it uses DSSS modulation. However, like 802.11b it is also prone to interference from other devices using the ISM band. It provides a higher range as compared to 802.11b. (Abdelrahman et al., 2015)

IEEE802.11n

The 802.11n standard, ratified in 2009, uses Orthogonal Frequency Division Multiplexing. It uses multiple antennas for data transmission and reception. It also uses Multiple Input, Multiple Output (MIMO) for increasing the range and throughput. The maximum bandwidth supported by the standard is 300 Mbps. The outdoor range of IEEE802.11n is 250 meters, and the indoor range is 75 meters. The MIMO technology also called smart antenna systems divides the original signal into multiple streams, and each steam is then transmitted using a separate antenna simultaneously on the same channel. At the receiver end, the signals are received by multiple antennas and combined to provide an output signal. The use of multiple antennae provides path diversity which is an important point in an urban environment where lots of reflections take place due to the topology of the urban environment. This process allows the use of the spectrum efficiently and provides better reliability.

IEEE802.11ac

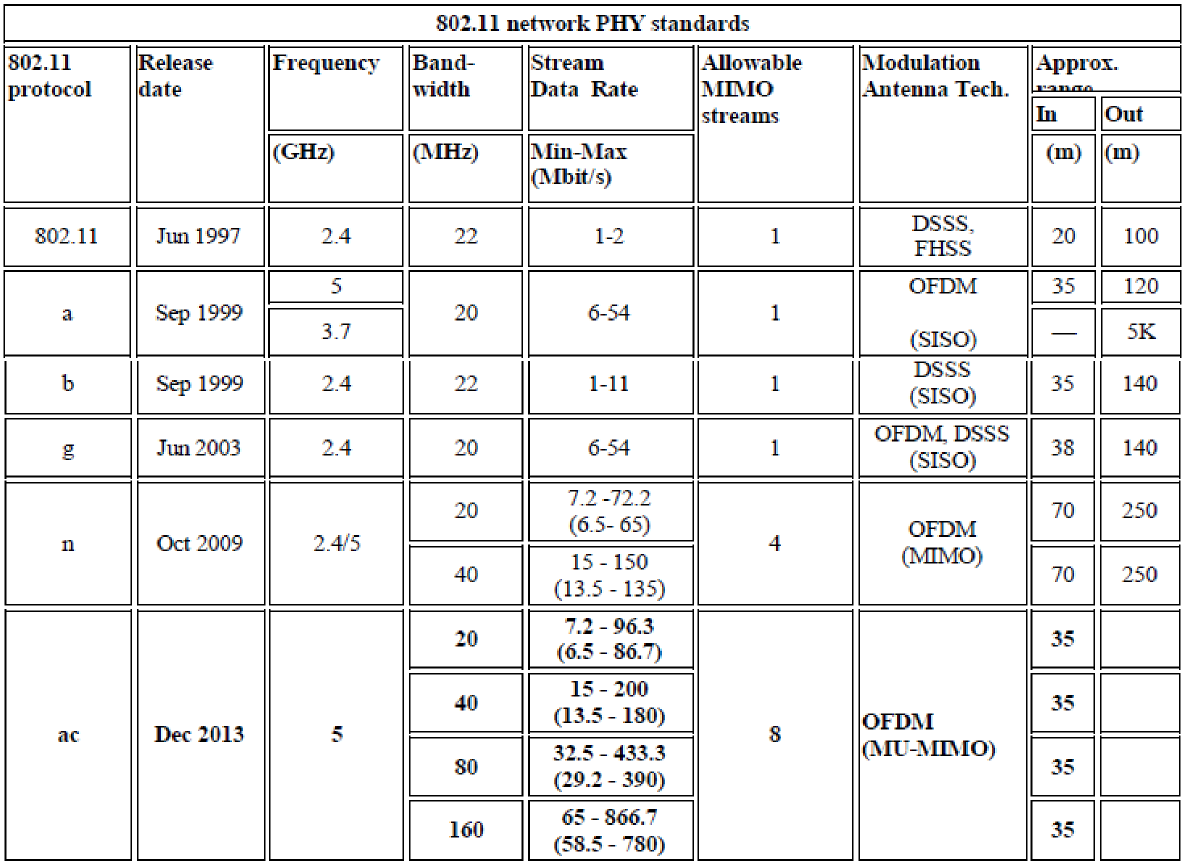
The IEEE802.11ac, released in December 2013, uses 5 GHz band for operation. The data rates depend on the bandwidth used and are as follows (Abdelrahman et al., 2015):

- 7.2 - 96.3Mbps for 20MHz,
- 15 – 200Mbps for 40MHz
- 32.5 - 433.3Mbps for 80MHz

- 65 - 866.7Mbps for 160MHz.

The IEEE802.11ac use MIMO and larger bandwidth to provide higher data rates. The standard also specifies the use of beamforming technique to increase data rate and coverage. Due to beamforming, it can use up to 256 QAM (Quadrature amplitude modulation) as against 64 QAM in 802.11n. (Pathak, 2017)

A comparison of various 802.11 series standards is shown in Figure 39.



802.11 network PHY standards

802.11 protocol	Release date	Frequency	Band-width	Stream Data Rate	Allowable MIMO streams	Modulation Antenna Tech.	Approx. range	
							In	Out
		(GHz)	(MHz)	Min-Max (Mbit/s)			(m)	(m)
802.11	Jun 1997	2.4	22	1-2	1	DSSS, FHSS	20	100
a	Sep 1999	5	20	6-54	1	OFDM	35	120
		3.7				(SISO)	—	5K
b	Sep 1999	2.4	22	1-11	1	DSSS (SISO)	35	140
g	Jun 2003	2.4	20	6-54	1	OFDM, DSSS (SISO)	38	140
n	Oct 2009	2.4/5	20	7.2 -72.2 (6.5- 65)	4	OFDM (MIMO)	70	250
			40	15 - 150 (13.5 - 135)			70	250
ac	Dec 2013	5	20	7.2 - 96.3 (6.5 - 86.7)	8	OFDM (MU-MIMO)	35	
			40	15 - 200 (13.5 - 180)			35	
			80	32.5 - 433.3 (29.2 - 390)			35	
			160	65 - 866.7 (58.5 - 780)			35	

Figure 39 Comparison Between IEEE 802.11a,b,g,n and ac (Abdelrahman et al., 2015)

4.3.1.3 Wireless LAN Topology/Configurations

The IEEE 802.11 defines the following two modes of operation:

- Ad-Hoc Mode

- Infrastructure mode

4.3.1.3.1 Ad-Hoc Mode

The Ad-Hoc mode is also called an Independent Basic Service Set (IBSS) or peer-to-peer mode. In the Ad-Hoc mode of operation, the nodes directly communicate with each other as shown in Figure 40. The topology allows quick setting up of wireless network anywhere without any infrastructure requirement. (Dhanalakshmi & Sathiya, 2015)

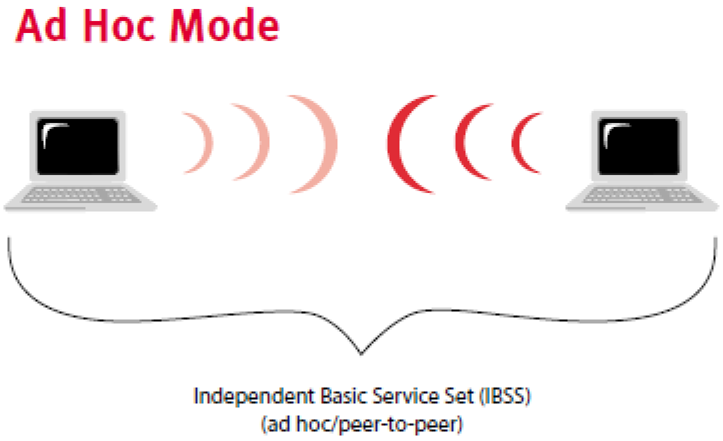


Figure 40 Ad hoc mode(Dhanalakshmi & Sathiya, 2015)

4.3.1.3.2 Infrastructure mode

The infrastructure mode wireless system consists of at least one access point (AP) to which a number of stations connect. The access point also encrypts the data for security. The access point may be connected to wired LAN at the back end and connect the mobile station via AP to the wired LAN. The operation of a wireless system with a single access point is called a Basic Service Set (BSS). The Extended Service Set (ESS) is formed when two or more BSSs forming a single subnetwork as shown in Figure 41. The movement of the mobile station between the BSSs is taken care of by forwarding the traffic from one BSS to another BSS. (Dhanalakshmi & Sathiya, 2015)

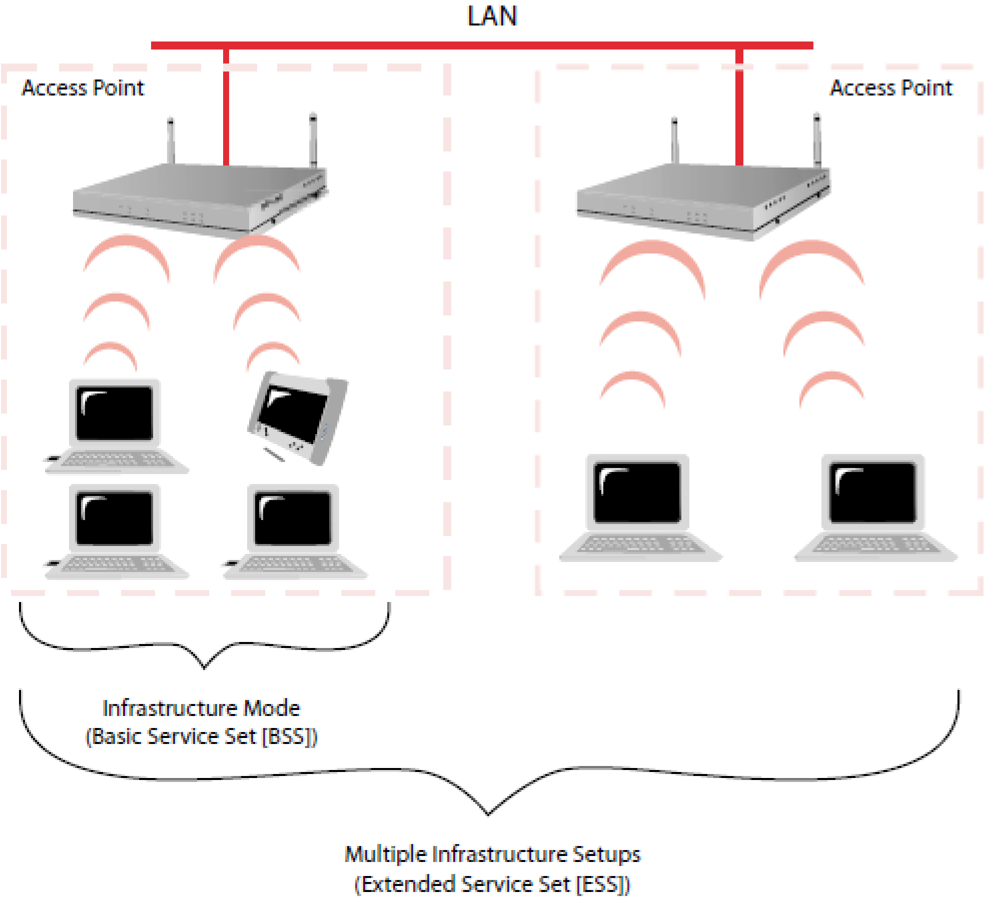

LAN
Access Point
Access Point
Infrastructure Mode
(Basic Service Set [BSS])
Multiple Infrastructure Setups
(Extended Service Set [ESS])

Figure 41 Basic Service Set (BSS) and Extended Service Set (ESS) (Dhanalakshmi & Sathiya, 2015)

4.3.1.4 WLAN Performance

The performance of an 802.11 WLAN depends on many environmental factors as well as the product. The access point automatically negotiates the signaling rate based on environmental conditions such as (US Robotics, 2019):

- The distance between the access point and mobile
- AP power output
- Obstructions in the transmission path
- RF interference from other gadgets
- Signal propagation conditions
- Type of antenna and its location.

Thus, the mobile node data access speed changes depending on the environmental conditions prevailing

4.3.1.5 Advantages of Wi-Fi

The WLAN systems are very popular as these are low cost, do not require licensing; these are easy to deploy, maintain, and shift. (Cesar Briso & J.I. Alonso, 2007)

From the point of view of rail communication, the advantages of using WLAN are (Farooq & Soler, 2017):

- They provide High data throughput
- WLANs are easy to deploy and maintain
- WLANs use reduces the requirement of trackside equipment
- These are Cost-effective
- Provide Redundancy
- They use open standard Protocols
- WLANs have large Industry support and market

Modern applications or systems in CBTC such as CCTV, PIDs, Aboard Internet, remote analysis and broadcast redundancy require high data rates. Wi-Fi supports the infrastructure to meet this requirement. Wi-fi equipment for COTS is cheaper.

The biggest advantage of using Wi-Fi is the non-requirement of taking permission from regulatory authorities for frequency use and licensing.

4.3.1.6 Wi-Fi Drawbacks

The Wi-Fi system has some inherent drawbacks such as (Farooq & Soler, 2017):

- Prone to interference
- The requirement of strict security measures
- No support for mobility
- Limited range
- Network congestion

Susceptibility of Wi-Fi system from interference is known issue due to the shared nature of frequency band used by it. The failure of CTBC systems has also been reported due to interference in the Wi-Fi system. A case in point is the Shenzhen Metro where interference was due to Wi-Fi user in the surrounding area (Huifeng, 2012). However, an environment such as an underground railway system, the probability of interference becomes much less (Alvarez & Roman, 2013). The interference can be mitigated to a certain extent during deployment by using measures such as using alternating frequency channels.

4.3.1.7 Improvements Proposed in WLAN for CBTC system

The frequent handoff in wayside communication in train system along with packet loss and delays in communication requires optimization of performance. Sun, Yu, Tang, & Bu (2016) modeled a networked control system (NCS) consisting of a multi-train CBTC system and proposed a new train control scheme to improve the QoS of CBTC systems. The energy consumption was minimized using MAC layer retry limit and the trip time track errors were mitigated using guidance trajectory update. The simulation of this system showed substantial improvement in energy consumption and a reduction in trip time errors. (Sun, Yu, Tang, & Bu, 2016)

Another train performance approach based on deep reinforcement learning was proposed. The approach uses linear quadratic as the metrics for performance control. The optimal train control policy and handoff policy is obtained by optimizing the train control action and handoff decision. The optimization minimizes the energy consumption and travels profile tracking error which in turn control train safety and control accuracy. For this purpose, the proposal models the dynamic transition characteristics and the time-varying channel using the finite state Markov channel (FSMC) model. The simulation results showed that the optimization method could improve train control performance of the CBTC system at the same time system safety requires some sacrifice in performance. (Cesar Briso & J.I. Alonso, 2007)

4.3.1.8 Handling roaming in Wi-Fi

The Wi-Fi network in CTBC is built by locating the Wireless access points (APs) closely together along the railway track in such a way that their coverage areas overlap. However, this requires the moving train to look for suitable AP continuously and connect to it as the train moves along. This requires smooth switching over of communication from AP to another within an acceptable delay. The high speed of trains requires a rapid change of channels as the train moves and the handover algorithms used in stationary Wi-Fi environments are not suitable in railroad system (Jiang, Zhao, & Zhao, 2011).

The packet loss in the rail system due to handover is more than due to radio wave propagation (Jiang et al., 2011). A study showed that the packet loss of 10% was observed at a train speed of 200 km/h, overlap area of 20 meters and a maximum handover time of 180 ms. The typical handover time in CBTC is 70-120 ms and a maximum of 1 sec. If the handover time is less than a control message interval in CBTC, the loss will not matter much (Bu et al., 2014).

To have a smooth transition, two radios, one at each end is installed in the train so that at least one of the two radio is all the time connected to an AP. As handover mechanism is not specified in IEEE 802.11 standard, the CBTC system manufacturers develop their own roaming algorithm.

A proposal to use cooperative relaying cognitive CBTC system was given enhancing the wireless system reliability (Li, Yu, Zhu, Tang, & Ning, 2015). The proposed system is shown in Figure 42. In the normal system the access system is placed at both ends of the train, but in case of the proposed system, the end communication point in the train can also work as relay nodes for other trains. This is called cooperative relaying as shown in Figure 42. The use of cooperative relaying enhances communication between the access point and the train. The packet collision is avoided by using request-to-send (RTS)/clear-to-send (CTS) message exchange between the receiver and sender (Bletsas, Lippman, & Reed, 2005). This message exchange also enables the sender and receiver to estimate the current state of the channel. In case of failure of an AP the communication gets disrupted, but with the use of the direct train to train communication the front rail can provide information about train position directly to the train behind it. In the rail environment, there is dynamic variation in received Signal to Noise Ratio (SNR) and in case of deep fading this can disrupt communication. Studies have shown that cooperative relaying can only provide better performance than direct communication only on certain channel conditions (Woradit et al., 2009). In the case of the CBTC system, the handover is quite frequent, and this requires the proper design of handover policy so that CBTC performance does not get affected. (Li et al., 2015).

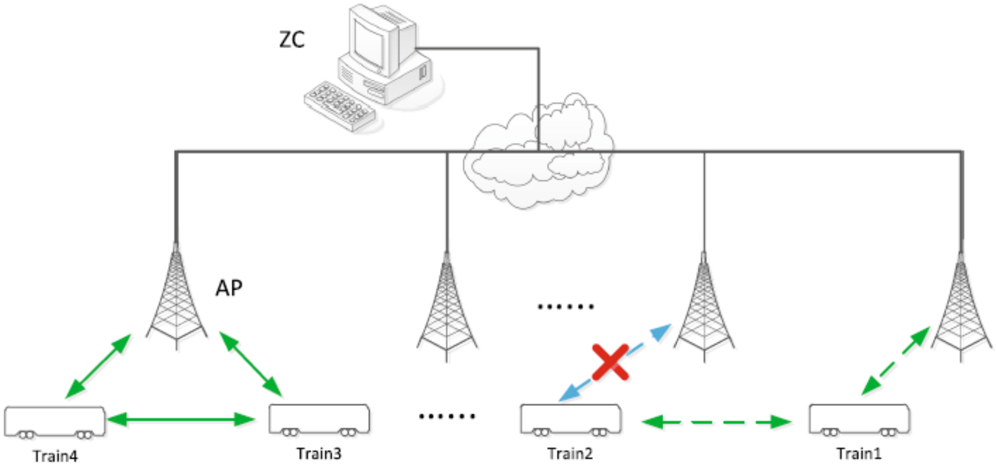


Figure 42 The proposed cooperative and cognitive CBTC system (Li et al., 2015)

In the CBTC system, the acceleration and deceleration decision is taken by the train based on the information about the train in front of every communication cycle. This requires the train to have precise information about train ahead, and this information is used by the cognitive control system to make a decision. However, the communication latency in train to AP communication, the train may not get updated information about the train in front for a certain period. In such a case, the train will use old information available with it. This gap in front train information is taken as an information gap to be used for the cognitive control system. In the proposed system this information gap is used by the cognitive controller to decide on acceleration or deceleration so that this information gap is reduced. The simulation results showed that the proposed cooperative and cognitive CBTC system could bring substantial improvement in the system performance (Li et al., 2015).

4.3.1.9 DCS RF Coverage

CBTC systems are used all around the world. DCS of all these systems is based on radio frequency to transport data between wayside components and commuting trains. Even though the DCSs of these different CBTC systems are not the same, but they have similar functions and characteristics.

The very rudimentary requirement for DCS is to give RF coverage to make sure that the communication between wayside components and CBTC onboard train goes uninterrupted on any place or location on the track even in storage areas. Proper RF coverage is usually attained by using antennas which are attached to the apparatus normally known as Wayside radio unit (WRU) located in the wayside infrastructure. The number of WRUs and distance between them depends on many considerations like the existence or absence of portals or tunnels and propagation losses at the current radio frequency. A very important factor as we said is to provide communication without interruption between Train and wayside equipment. This is done when the Radio units are installed in the train on both front and back side. So, the train connects with WRUs from both front and back of the train as it commutes. When the train comes close to WRU, communication occurs through the front radio unit of the train and rear radio unit keeps searching for the other WRUs. As the train passes the first WRU and is about to lose the communication, the back radio has already found another WRU and connect to it to avoid any interruption in the communication with wayside. This is possible because of the overall arrangement of WRUs. If the WRUs are placed closely then such arrangement will improve the reliability. (Fitzmaurice, 2013)

A very crucial part in RF coverage is the frequency of the DCS operation. Mostly CBTC systems operate at 900 MHz or 2.4 GHz or 5.8 GHz. Most of the CBTC systems which we can see in the above figure work at 2.4 GHz frequency. The choice of the frequency band in CBTC can be decided on the basis of low-cost and verified equipment. In case of such hardware, mostly 2.4 GHz is chosen because of the large industry support and the market for Wi-Fi compatibility. CBTC vendors usually use already in market COTS radios instead of developing their own. The selection of the frequency of DCS also depends on RF interference. The decision of operating frequency does not depend on one factor, but it decided in consideration with CBTC system overall.

There are two kinds of antennas used for wayside:

- Continuous antenna
- Discrete antenna

Continuous antennas are leaky coaxial cables having holes in their outer walls used as a continuous radiating structure, and it allows radio signals to leak in or out. Discrete antennas are usually lightweight and cheaper in installation and maintenance. Other than fulfilling the data transfer requirements of CBTC, this type of antenna can carry signals from CCTV cameras on trains. The RF interference is an issue in every DCS which should be considered carefully. There could be many reasons for RF interference. Therefore, many mitigation strategies can be applied to overcome the issue. A crucial characteristic that every DCS should have is to warn the system if there is any excessive RF interference so that the suitable measure can be taken before Excessive RF interference affects the operation of DCS.

4.3.2 Terrestrial Trunked Radio (TETRA) System for Rail Communication

TETRA is a digital Trunked Radio system standardized by ETSI (ETSI EN 300 392-2 - V3.7.2, 2016). It has been extensively used by public utilities such as police, medical services, sports, commercial organization, emergency communication, etc. The ETSI standard defines network interfaces, air interfaces, service, and facilities so that infrastructure and products developed by different manufacturers are fully interoperable with each other. The railways across Europe, Asia, and Latin America use TETRA system in mass rapid transit, metros and railways. The TETRA service generally operates in 300-400 MHz band. (Tsogtbayar, Kang, Lee, & Boldbaatar, 2016a)

4.3.2.1 TETRA systems technical characteristics

TETRA provides a number of services which are characterized as bearer service and teleservices. The bearer services are the same as general networks. The teleservices are similar to mobile communication included bearer services. The TETRA is a private mobile radio (PMR) where the dispatcher distributes calls according to a priority list. (Cesar Briso & J.I. Alonso, 2007)

TETRA uses encrypted data communication for providing (Tsogtbayar, Kang, Lee, & Boldbaatar, 2016b):

- Point to point voice communication
- Group voice call
- Acknowledged voice group call
- Broadcast voice call

TETRA allows data communication at the speeds of less than 10 Kbps. The call setup time in TETRA is less than 1 sec which meets the requirement of emergency services. The group calling facility of TETRA is suitable for its use in risk situations where the speed of communication is important. (Esteban & Solanas, 2016)

TETRA uses Time Division Multiple Access (TDMA) with a carrier spacing of 25 kHz. It uses 4 TDMA timeslots and π/4 QPSK modulation. The data rate per time slot is 7.2kb/s per time slot, and the aggregate data rate is 28.8Kbps. The mobile radios in TETRA can communicate using direct-mode operation (DMO) as well as using trunked-mode operation (TMO). This facility is availed using switching and management infrastructure in TETRA base stations. The system allows direct communication if network coverage is not available and this mode is called DMO mode. DMO can also use one of more TETRA terminals in series for establishing communication, and this method is called DMO gateway or repeater as per the usage. This facility can be used for direct communications in underground or bad coverage areas. (ITU-R M.2418-0, 2017)

The TETRA system provides a number of types of data communication. It provides short data services and status messages using the main control channel of the TETRA system. The specifically assigned channels are used for circuit-switched data or packet-switched data communication. End to end encryption allows protection against eavesdropping. The terminals are authenticated using infrastructure. Using a single button user can make a call to a predefined group of mobiles. The studies show that the performance of TETRA even at higher speed (up to 500 Km/h) is not much different than at lower speed due to forward error correction. (ITU-R M.2418-0, 2017)

4.3.2.2 TETRA Network Architecture

A typical TETRA network architecture diagram is shown in Figure 43 (Donner, Saleemi, & Mulero Chaves, 2014). The TETRA system consists of mobile stations, line stations or control centers, and management and switching system/infrastructure (SwMI).

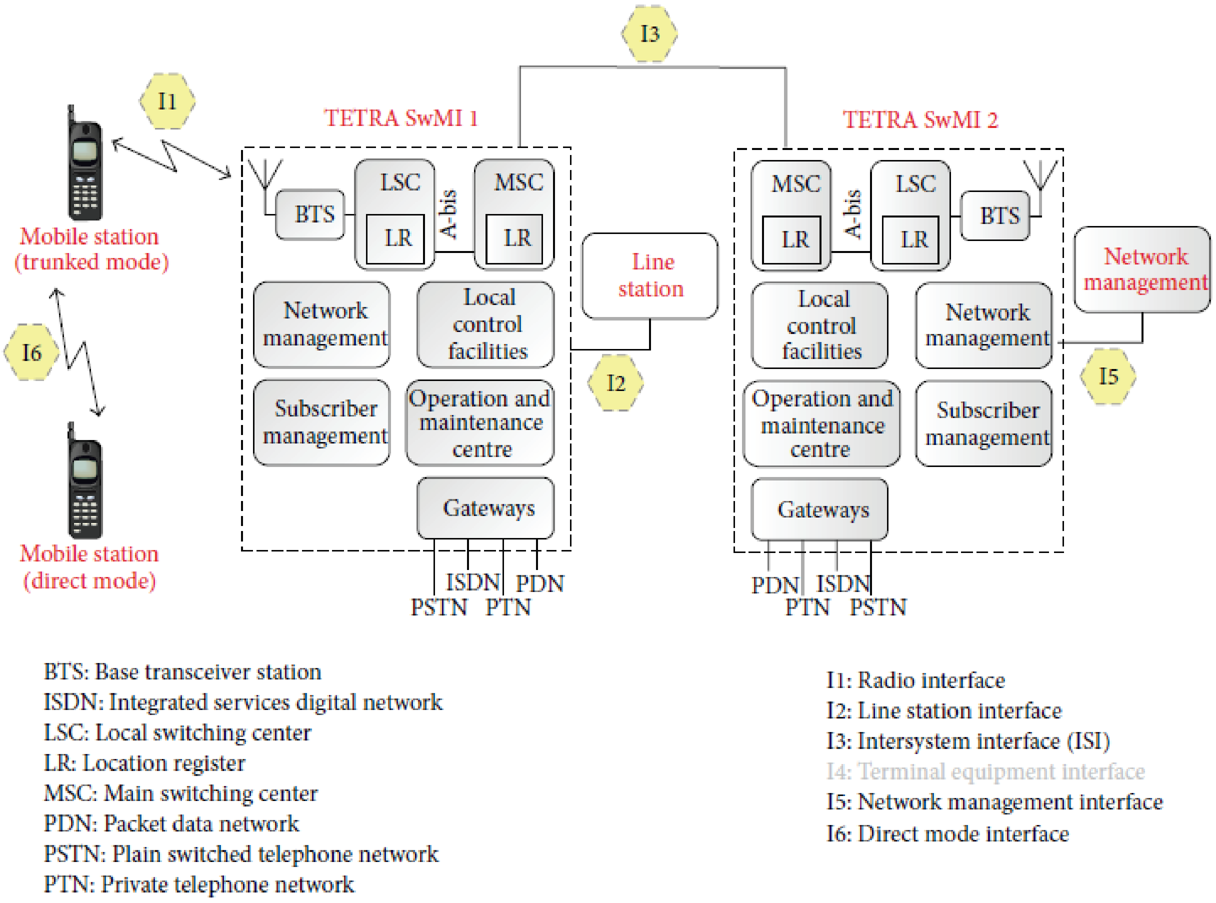

I3
I1
TETRA SwMI 1
TETRA SwMI 2
Mobile station
(trunked mode)
BTS
LSC
LR
A-bis
MSC
LR
Network management
Local control facilities
Subscriber management
Operation and maintenance centre
Gateways
Line station
I2
I6
Mobile station
(direct mode)
ISDN PDN
PSTN PTN
MSC
LR
A-bis
LSC
LR
BTS
Local control facilities
Network management
Operation and maintenance centre
Subscriber management
Gateways
PDN ISDN
PTN PSTN
Network management
I5
BTS: Base transceiver station
ISDN: Integrated services digital network
LSC: Local switching center
LR: Location register
MSC: Main switching center
PDN: Packet data network
PSTN: Plain switched telephone network
PTN: Private telephone network
I1: Radio interface
I2: Line station interface
I3: Intersystem interface (ISI)
I4: Terminal equipment interface
I5: Network management interface
I6: Direct mode interface

Figure 43 TETRA network architecture diagram (Donner et al., 2014)

The base transceiver stations (BTSs) in SwMI provide air interface to mobile stations. SwMI also provides call switching with the help of home and visitor location and provide key management functions. When the wireless connectivity between BTS and MSC is not there, a fallback mode of communication is used in which a local switching center (LSC) establishes the local call. The LSC is part of every BTS. The gateways provide an interface to voice and data network of other systems such as PSTN, PDN, GSM, etc. (Donner et al., 2014)

Intersystem interface (ISI) is used for connecting two different TETRA systems. The systems may be from the same operator or another operator.

4.3.3 Cellular Technology for Rail Communications

Cellular technology has emerged as the main technology for voice and data communications for safe and efficient rail operations. With the adoption of GSM-R standard, many incompatible analog systems used in Europe were replaced by systems based on GSM-R. The use of GSM-R provides much-needed interoperability among various systems.

4.3.3.1 GSM-R Standard

Secure and safe operation of rail system needed a reliable, proven, and off the shelf communication system. Studies were undertaken, and discussion resulted in the acceptance of GSM as the main system which could be used with minimum modifications. It required the addition of Advanced Speech Call Items (ASCI) features to the existing GSM system. After discussions, European Conference of Postal and Telecommunications Administrations (CEPT) was approached to add 4 MHz to the GSM band and provide it for the exclusive use of railways. In 1992 International Union of Railways or Union Internationale des Chemins de Fer (UIC) along with railways and EC formed a group called EIRENE (European Integrated Radio Enhanced Network) to work out functional specifications that will fulfill the needs of railways and provide interoperability across borders. After finalization of specifications by EIRENE, another project named MORANE (MObile radio for RAilway Networks in Europe) was set up by the consortium of GSM suppliers, railways and laboratories. The equipment developed under MORANE were installed and tested at three pilot line at (ETSI, 2019):

- Florence - Arezzo
- Stuttgart - Mannheim
- Paris

After the completion of pilot project and preparation of a final report incorporating the field trail details, UIC and railways signed Memorandum of Understanding for implementation of GSM-R for its communication requirements in 1997. Within Europe, 32 railways are signatories of the MOU (UIC, 2019).

GSM-R is based on the GSM standard with some enhancement for railways. The enhancements include (ETSI, 2019) :

- Dedicated frequency bands in Europe: 873-880 MHz (Uplink) and 918-925 MHz (Down Link). Germany allocated its earlier trunked radio mobile band 873–876 MHz and 918–921 MHz for GSM-R use ("Frequenznutzungsplan [Frequency Use Plan] (PDF) (in German)," 2008).
- Functional addressing for call handling
- Private Mobile Radio (PMR) features including "Voice Broadcast Service," "Voice Group Call Service, and Priority and Pre-emption
- Location dependent addressing

The GSM-R frequency band allocation in various countries is as follows (GSMR-Info, 2009):

In China and South Africa the band allocated for GSM-R is:

- 885–889 MHz (Uplink)
- 930–934 MHz (Downlink)

In Australia, the band allocated for GSM-R is in DCS band (Railway Safety Regulator, 2012)

- 1,727.5–1,732.5 MHz and 1,772.5–1,785 MHz (Uplink)
- 1,822.5–1,827.5 MHz and 1,867.5–1,880 MHz (Downlink)

In India, the band allocated uses P-GSM band with 1.6 MHz range

- 907.8–909.4 MHz (Uplink)
- 952.8–954.4 MHz (Downlink)

The GSM-R uses GMSK modulation. GSM-R like GSM is a Time Division Multiple Access (TDMA) system, with each frame, has 8-time slots or logical channels and carry 148-bit data. The data is transmitted in frames of 4.615 ms. (GSMR-Info, 2009)

ETSI Technical Committee "Railway Telecommunications" (TC RT) is responsible for maintenance and further development of the GSM-R system. TC RT is also collaborating with railways world over to take care of railways evolving requirements including provision for global roaming in GSM-R environment. All changes request for GSM-R are submitted by TC RT as Change Requests to the 3GPP (3rd Generation Partnership Project). (ETSI, 2019)

A new project called ERTMS/GSM-R was started by UIC to complement work done by EIRENE and MORANE. The ERTMS/GSM-R project combines the knowledge from various groups and trails for enhancement of the system. (UIC, 2019)

The three permanent GSM-R working groups are (UIC, 2019):

- European Radio Implementers Group (ERIG)
- Functional Group (FG)
- Operators Group (OG)

ERIG group consists of railway members who have signed the MoU and the AoI. This group exchanges information about lessons learned from projects already implemented, gaps in specifications, and other reports related to implementation. The group acts as a dissemination platform for all information related to GSM-R. (UIC, 2019)

Functional Group maintains the FRS and reviews the implementation reports related to functional requirements and create change request based on the reviews. The group in collaboration with other groups such as OG and the GSM-R industry Group (IG) works out requirement and solutions. IG is a group of GSM-R suppliers that works for the promotion of GSM-R worldwide and also interfaces with railway groups FG and OG. (UIC, 2019)

UIC works with ETSI Technical Committee on Rail Telecommunications for protection of feature specific to railways and improvement of GSM standard. GSM-R improves on the call setup time over the normal GSM to meet low call setup time required for railway operations.

A study of communication failures dues to the stochastic nature of GSM-R was carried out to assess the capacity reduction with ETCS level 3. It was found that the framework of ETCS is good enough to take care of errors in GSM-R that are more than the traditional system. (Jansen, Klabes, & Wendler, 2010)

4.3.3.1.1 Railway Specific Function in GSM-R

The functions specific to GSM-R are as follows (He et al., 2016):

Voice group call service (VGCS): VGCS provides establishing group calls between drivers, wayside workers, railway staff or any other groups.

Voice broadcast service (VBS): VBS is used for a broadcasting message to a group. It is one-way facilities where group member can only listen. It can also be used for broadcasting recorded messages for announcements as well.

Enhanced multilevel precedence and preemption (MLPP): eMLPP defines a multilevel priority for users and is used for making emergency group calls.

Shunting mode: Shunting mode is for communication with shunting personnel, and it provides group communication facility.

Functional addressing: In this mode, the call is made by a number that identifies the function rather than the permanent subscriber number.

Location-dependent addressing: This enables making calls from the train to numbers allocated for certain functions based on the train’s location.

4.3.3.2 GSM-R Architecture

GSM-R network consists of a trunk transmission circuit and GSM-R digital mobile communication system. The four parts of the GSM-R system are:

- Network subsystem (NSS): includes mobile switching subsystem (SSS), mobile intelligent network (IN) subsystem, and GPRS subsystem
- base station subsystem (BSS),

- operation and support subsystem (OSS)
- Terminal device.

GSM-R system structure and main interfaces are shown in Figure 44.

4.3.3.2.1 Mobile Switching Subsystem

Mobile Switching Subsystem or depicted as SSS in Figure 44 consists of many subsystems such as MSC, HLR, and VLR. The functions of SSS are user call switching, mobility management, user database, and security management. The signaling system for communication is No.7 signaling protocol. The functions of various subsystems are as follows (Z.-D. Zhong et al., 2018):

Mobile Service Switching Center (MSC)

Mobile Service Switching Center is the core of the network and provides call control and mobility management. Gateway MSC provides an interface between GSM-R and other communication networks.

Visitor Location Register (VLR)

VLR is a dynamic database and stores all information related to mobile users which are in its control area. It along with HLR provides facilitates mobile roaming. At the time of mobile station (MS) goes to a new area Home location register (HLR) registers it with VLR obtains data about MS form VLR. When the user moves out of roaming area, the data is deleted.

Home Location Register (HLR)

HLR is a database for mobile user management and stores the mobile user data in its area. The information includes the location information, the identification sign, etc. HLR updated location information in its database when MS goes roaming and also provides call routing information for the user.

Authentication Center (AuC)

AuC stores user authentication information and encryption key entities. AuC provides authentication and encryption information to MSC, VLR, and SGSN to ensure safety and security of communication.

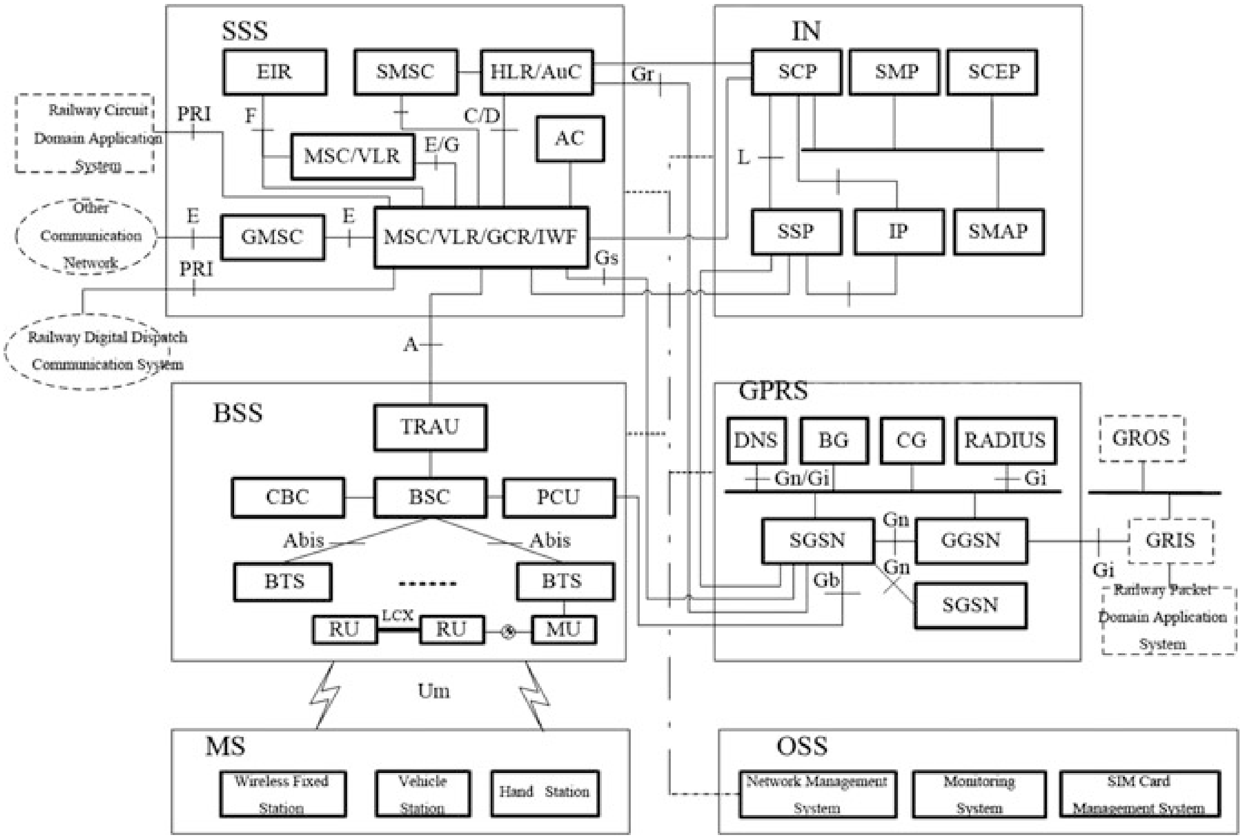


Figure 44 GSM-R system structure (Z.-D. Zhong et al., 2018)

Interworking Functional Unit (IWF)

IWF provides necessary conversion for the exchange of information between fixed-network data terminals and GSM-R network

Group Call Register (GCR)

GCR stores the group ID of mobile users and facilitates initiation of group call service (VGCS) and voice broadcast service (VBS).

Short Message Service Center (SMSC)

SMSC facilitate transmission of SMS to MSC.

Acknowledge Center (AC)

Acknowledge Center records information about railway emergency calls.

Equipment Identity Register (EIR)

EIR stores the mobile International Mobile Equipment Identity (IMEI) database. Based on the category of IMEI list the system decides about the service to be provided.

4.3.3.2.2 Mobile Intelligent Network Subsystem

IN subsystem provides intelligent control of the call by separating the network switching function and the service control function. GSM-R intelligent network consists of GSM many subsystems described below (Z.-D. Zhong et al., 2018).

- GSM Service Switching Point (gsmSSP) acts as an interface between SCP and MSC. It detects the service request and communicates with the SCP for processing the call.
- GPRS Service Switching Point (gprsSSP) acts as an interface between SCP and SGSN. It detects the service request and communicates with the SCP for processing the call.
- Service Control Point (SCP) provides service logic of IN and in collaboration with SSP controls the intelligent service connection and charging.
- Intelligent Peripheral (IP) along with SCP provides resources such as receiving DTMF, generating signals, recording of notices, etc.
- Service Management Point (SMP) manages SCP and user service data.
- Service Management Access Point (SMAP) manages access to the services provided by SMP and manages users data related to services.
- Service Context Entering Point (SCEP) is responsible for IN service development, testing, and verification.

4.3.3.2.3 General Packet Radio Service (GPRS) Subsystem

GPRS provides packet-based data communication for mobile users. It includes a core layer and a wireless access layer.

The core layer consists of several units such as Service GPRS Support Node (SGSN), Gateway GPRS Support Node (GGSN), DNS(Domain Name Server), RADIUS Service, etc. as per details below (Z.-D. Zhong et al., 2018).

- Service GPRS Support Node (SGSN) provides mobility management and route searching.
- Gateway GPRS Support Node (GGSN) acts as a gateway between the GPRS network and external data network and provides necessary protocols etc. required data exchange.
- Domain Name Server (DNS) provides domain name resolution for SGSN, GGSN, and other network nodes.
- RADIUS Service stores user identity information, and provides user authentication services.

The wireless access layer consists of a Packet Control Unit, base station, and terminal (Z.-D. Zhong et al., 2018).

- Packet Control Unit (PCU) manages packet transmission including channel management, error detection, and automatic data retransmission.
- Border Gateway (BG) provides an interface between different GPRS networks including security, routing protocol, etc.
- Charge Gateway (CG) takes care of billing by managing the ticket record of all GPRS support nodes and transferring the information to the charge center.
- GPRS Network Interface Equipment consists of GPRS home server (GROS), GSM-R terminal, and GPRS interface server (GRIS). GRIS provides protocol conversion for data exchange between a railway application system and GPRS terminal.

4.3.3.2.4 Base Station Subsystem

The mobile station connects with the base station over a wireless interface. BSS provides radio resource management, and transfers call data including signaling information between mobile and MSC for call connection. The brief on various subsystems is given below (Z.-D. Zhong et al., 2018):

- BSS consists of a base station controller, the transcoder/rate adaptor unit (TRAU), the cell broadcast center, the base transceiver station, etc.
- Base Station Controller (BSC) manages all interfaces, wireless parameters, radio resources, channel assignment, and signal processing for call establishment.
- Transcoder/Rate Adaptor Unit (TRAU) provides voice coding and rate adaptation between BSC and MSC.
- Cell Broadcast Center (CBC) manages the cell broadcasting message service.
- Base Transceiver Station (BTS) is an interface between the mobile station at one end and BSC at another end. BTS provides functions such as air interface, channel coding/decoding, and modulation/demodulation.
- Relay Transmission Equipment is used to extend wireless coverage of GSM-R in the weak signal are using repeater station and associated equipment.

4.3.3.2.5 Operation and Support Subsystem (OSS)

Operation and Support Subsystem provides user management and network management. (Z.-D. Zhong et al., 2018)

Network Management System

The network management system monitors configure and control all the network devices. It provides network reports and helps in the planning and maintenance of the system.

Monitoring system

An interface monitoring system monitors various network interfaces, analyses network subsystems, data processing equipment, server, and other systems.

SIM Card Management System

SIM Card Management System manages user accounting and operating functions.

4.3.3.2.6 Terminal

The terminal is the devices with the user that interface with the system. It can be a fixed station or mobile station. The terminal consists of a mobile or stationary device and a SIM card. The mobile station can be a handheld device, train rail information transmission device, train control data transmission equipment, vehicle safety detection information transmission terminal, and disaster prevention detection information transmission. Z.-D. Zhong et al., 2018).

4.3.3.3 GSM-R Network Hierarchical Structure

The typical GSM-R network structure of the complete railway system is shown in Figure 45. The overall network consists of tandem mobile switching centers located strategically (TMSC), and these are connected to each other using trunk line as well as MSC in their area. For redundancy, Each Y+TMSC can control MSCs of other areas as well. The long-distance traffic originating from MSCs are transmitted via TMSCs. (Z.-D. Zhong et al., 2018).

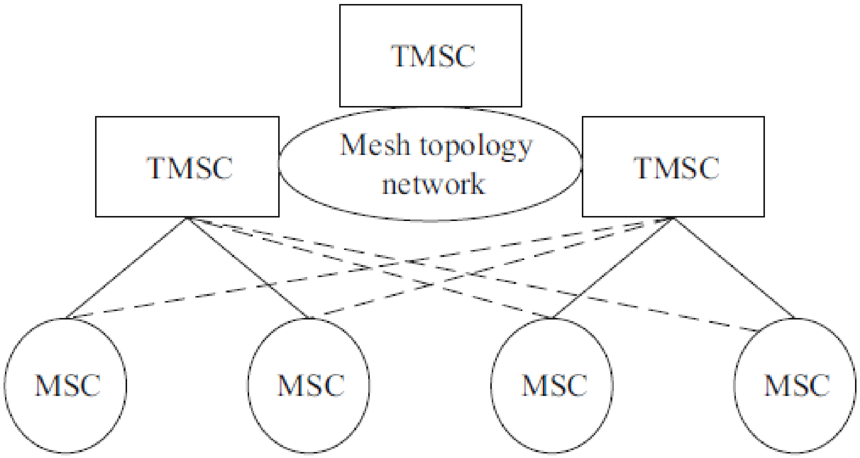


Figure 45 The GSM-R network structure of the whole railway (Z.-D. Zhong et al., 2018)

GSM-R intelligent network is shown in Figure 46. It is based on the ITU-T/3GPP intelligent network, and for providing railway specific services, CAMEL3 protocol standard is used. GSM-R intelligent network consists of SSP, SCP, SCEP, SMP, SMAP, and, intelligent peripherals along with the link connecting these nodes. (Z.-D. Zhong et al., 2018).

The GPRS backbone network is used for transfer of the message from one system to another. The routers in the backbone system forward the data from one local area to another local area and are connected to form a mesh network for redundancy of routes. The edge routers perform the transfer of data between the local nodes. (Z.-D. Zhong et al., 2018).

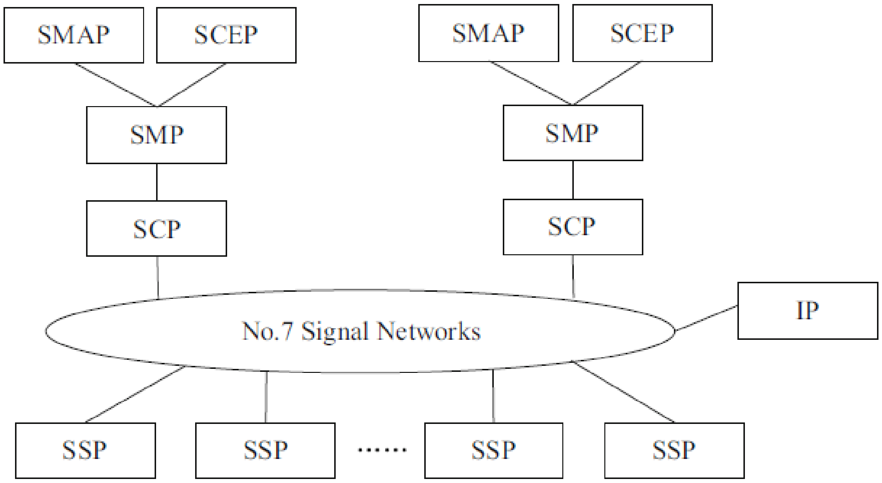


Figure 46 The GSM-R intelligent network structure (Z.-D. Zhong et al., 2018)

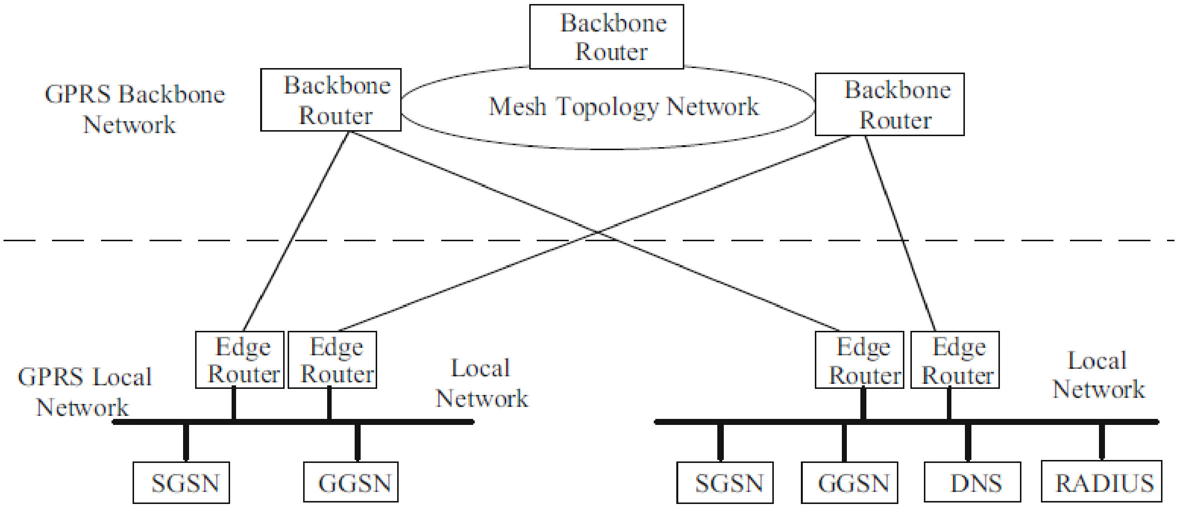


Figure 47 GSM-R GPRS backbone Network (Z.-D. Zhong et al., 2018)

4.3.4 A Comparison of TETRA Vs. GSM-R

TETRA has four times better spectrum usage than GSM. TETRA uses four channels in 25 kHz as compared to eight channels in 200 kHz, making TETRA support a higher number of channels for higher traffic. This will allows additional capacity for future applications without requiring additional equipment. (Sepura, n.d.)

The operating frequency range of 300 MHz and above whereas GSM-R operates in 900 MHz band. The lower frequency allows better coverage than GSM-R and reduces the number of repeaters required. Due to this TETRA has typical cell size of 10 to 25 km radius as against GSM-R's 5 to 10 Kms depending on terrain. The reduction in a number of stations reduces the cost of equipment and on land infrastructure such as buildings, towers, power equipment, etc.(Sepura, n.d.)

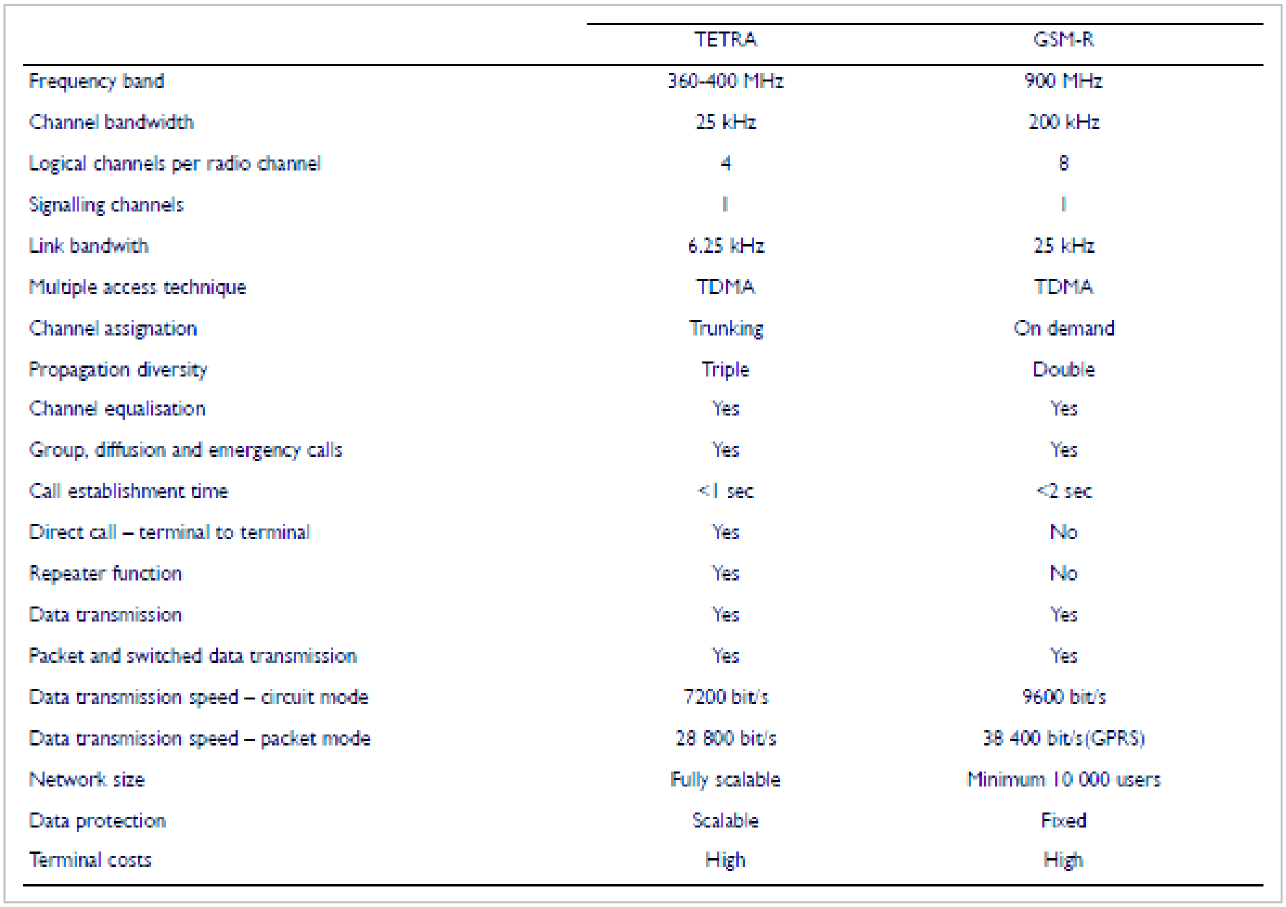
TETRA and GSM-R are similar in many respects. Both are designed primarily for voice communication but also provide low-speed data communication. Tetra system provides much better call setup time than GSM-R. The call setup time for TETRA is less than 1 sec as compared to less than 5 sec for GSM-R. Unlike the GSM-R, the TETRA system's voice codec is designed to provide good quality in a noisy environment.(Cesar Briso & J.I. Alonso, 2007)

TETRA system can work in circuit switched mode as well as packet mode. Single-use can dynamically use all four TDMMA time slots for data transmission providing a maximum speed of up to 28 Kbps. In contrast, GSM-R provides data communication at up to 9.6 Kbps in circuit-switched mode and up to 38.4 Kbps using GPRS mode. However, GPRS cannot be used for functionalities such as group calling, diffusion, and emergency calls. This limits the use of GPRS for ATP applications. TETRA supports text message of up to 256 characters as against 160 characters in GSM SMS service. (Cesar Briso & J.I. Alonso, 2007)

The train control system requires data communication in circuit switched mode so that permanent connection with the bi-directional link is available continuously and operation and availability can be guaranteed. Another important feature of TETRA is to make calls and send data in direct mode and this mode is not available in GSM-R. (Cesar Briso & J.I. Alonso, 2007)

Tetra offers more levels of call coding to meet security requirements as compared to GSM-R. The TETRA system has fully scalable architecture starting from low capacity single location to national coverage. The large database of GSM provides GSM-R with lower cost advantage and future support. The GSM-R is more suitable for highly dynamic applications of railway system than TETRA which has lower bandwidth and has more sensitivity to multipath fading and Doppler Effect. (Cesar Briso & J.I. Alonso, 2007)

A comparison of TETRA and GSM-R specifications is shown in Figure 48 (Cesar Briso & J.I. Alonso, 2007).



	TETRA	GSM-R
Frequency band	360-400 MHz	900 MHz
Channel bandwidth	25 kHz	200 kHz
Logical channels per radio channel	4	8
Signalling channels	1	1
Link bandwith	6.25 kHz	25 kHz
Multiple access technique	TDMA	TDMA
Channel assignation	Trunking	On demand
Propagation diversity	Triple	Double
Channel equalisation	Yes	Yes
Group, diffusion and emergency calls	Yes	Yes
Call establishment time	<1 sec	<2 sec
Direct call – terminal to terminal	Yes	No
Repeater function	Yes	No
Data transmission	Yes	Yes
Packet and switched data transmission	Yes	Yes
Data transmission speed – circuit mode	7200 bit/s	9600 bit/s
Data transmission speed – packet mode	28 800 bit/s	38 400 bit/s(GPRS)
Network size	Fully scalable	Minimum 10 000 users
Data protection	Scalable	Fixed
Terminal costs	High	High

Figure 48 Comparison of TDMA digital communications systems (Cesar Briso & J.I. Alonso, 2007)

4.3.5 Long term Evolution-Railway (LTE-R)

The Long term Evolution (LTE) is the successor of GSM G3 technology. The LTE needs to be tailored for railway requirement and is termed as LTE-R on lines of GSM-R. First LTE-R based system was claimed to have been implemented by Samsung and KT for Wonju-Gangneung high-speed railway line. The line has a maximum speed of 250 km/h and key railway specific features include availability Mission-Critical Push-to-talk (MCPTT) button as per specifications are given in 3GPP standards Release 13. To be compatible with the high-speed line the LTE-R based system must be able to operate at speeds up to 500 km/r to match the speed of high-speed trains (Netmanias, 2017)

4.3.5.1 LTE-R Architecture

3GPP via its Rel8 specifications ratified new technology called Long Term Evolution (LTE) or Evolved UTRAN (E-UTRAN). It uses Evolved Packet System (EPS) which in turn uses Evolved Packet Core (EPC). EPC is based on a flat IP structure and uses Orthogonal Frequency Division Multiplexing for downlink. The uplink uses Synchronization Channel-Frequency Division Multiple Access (SC-FDMA) using carrier bandwidth from 1.4 MHz up to 20 MHz. It can use frequency division duplexing as well as time division duplexing. The interference using co-ordination techniques are avoided by using SC-FDMA's Inter-Cell Interference Coordination (ICIC) function. The base station of GSM or Node B of UMTS is termed as evolved-Node B (eNode-B) in LTE. eNode-B does radio resource management. The LTE supports peak theoretical data rate of up to 150 Mbps on the downlink (using two x2 MIMO and 20 MHz BW) and 75 Mbps for uplink using 10 MHz BW. (4G Americas, 2012)

Figure 49 shows the projected architecture for LTE-R (He et al., 2016). The LTE-R inherits main features of LTE and additional radio access system is provided to communicate with onboard units as per requirement of high-speed rail (HSR). The difference between LTE and LTE-R include network layout services, system parameters, architecture, and QoS. The LTE-R network similar to LTE uses evolved packet core (EPC) as a core network and Evolved Universal Terrestrial Radio Access Network (E-UTRAN) as a radio access network. The EPC is based on Internet protocol

(IP) provides seamless voice and data handovers as mobile moves from one cell area to another cell area. (He et al., 2016)

The eNodeBs are deployed along the train for communication with onboard train system. The eNodeB is connected to EPC using wire or optical fiber links and provide connectivity to train control centers. The vehicle unit is normally located in the ceiling on top of the train to avoid train carriage losses. (Z. Zhong, Ai, Zhu, Wu, & Xiong, 2018)

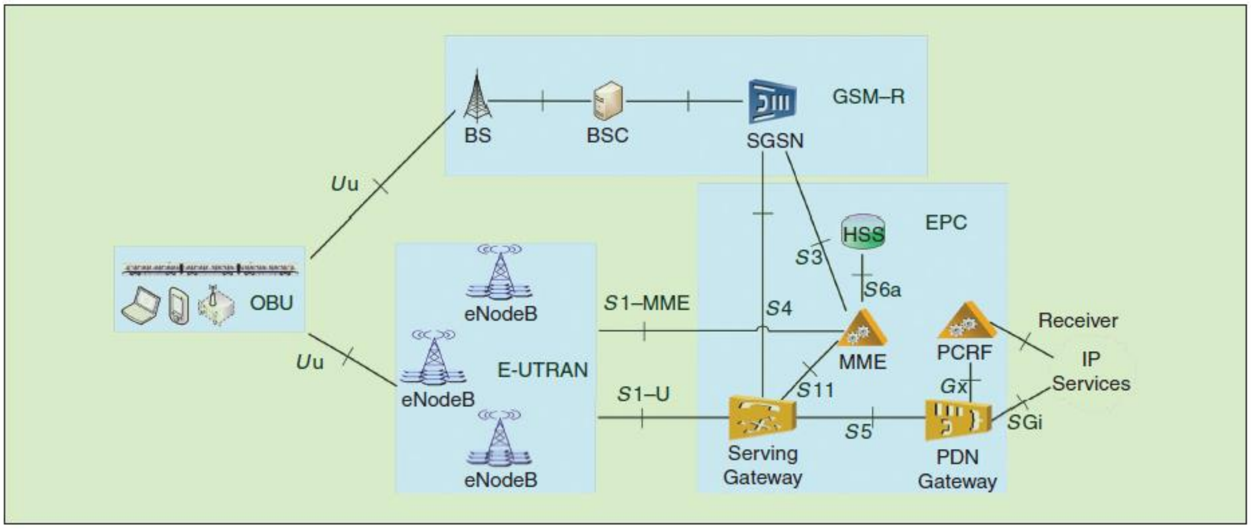


Figure 49 The LTE -R architecture for HSR communication (He et al., 2016)

4.3.5.1.1 The Core Network

The Evolved Packet Core controls OBU and the establishment of the bearers. PC consists of the following subsystems (Z. Zhong et al., 2018):

- Mobile Management Entity (MME)
- Home Subscriber Server (HSS),
- Serving Gateway (S-GW)
- Packet Gateway (P-GW)
- Policy Control and Charging Rules Function (PCRF)
- Multimedia Broadcast Multicast Service Gateway (MBMS-GW)
- Broadcast Multicast Service Center (BM-SC),
- Multicell/multicast Coordination Entity (MCE) routers

The trunking communication system required by railway is based on proposed technology given in 3GPP LTE R13. The push to talk requirement of the railway was also taken care of in 3GPP R13 standard by the use of Mission-Critical Push To Talk (MCPTT) server network element. (5G Americas, 2016)

Mobile Management Entity (MME): MME processes the signaling between the user node and the core network. It uses Non-Access Stratum (NAS) protocols for the message exchange. MME provides support for user mobility and session management. The function of MME in detail are given below (Z. Zhong et al., 2018):

MME provides authentication and authorization of users. The authentication is done using identities such as International Mobile Subscriber Identification Number (IMSI), Globally Unique Temporary UE Identity (GUTI), and other unique identities. GUTI is used for protection of IMSI and to this MME assigns user GUTI after first user attachment.

The MME mobility management updates timer of the registered user periodically. After the expiry of the timer, periodic tracking of the user is done and if the users are not in coverage of E-UTRAN, the update is done when users get back to the coverage area. When users are not found or in case of expiry of subscription, the HSS is informed of the same. The mobility restriction is enforced depending on the user’s subscription. MME also provides the user with multiple PDN connections using the packet gateway.

The session management takes care of call establishment and release. The user subscription information is used for selecting P-GW for the PDN connection and available S-GW connection. The MME selection is done during the handover process based on the network topology.

Home Subscriber Server (HSS). The HSS database stores user subscription information, subscribed QoS profile, restrictions for roaming, location information, and user authentication. The information on the address of PDN to which a user can connect is also held inside HSS. HSS provides MME all the information required for the authentication of users. HSS does the user's current location registration and it updates current service MME address. Depending on the user’s status, HSS initiates the request for deleting original MME.

Packet Gateway *(P-GW):* Packet Gateway allocates IP address for the user, QoS enforcement and charging as per data flow as per rules in PCRF. P-GW filters downlink user IP packets into bearers based on QoS requirement using Traffic Flow Templates. QoS based enforcement include guaranteed bit rate bearers. It also plays a role in interworking with technologies other than 3GPP based.

Serving Gateway (S-GW): S-GW takes care of connecting the eNodeB and switching of eNBs when a user moves from one eNodeB to another eNodeB. The information on idles state of SER is stored by S-GW and also buffers the data in the downlink for the duration of re-establishment of calls. The S-GW provides an administrative function such as session management, Mobility Management, Routing, and data forwarding, QoS control, charging information collection, etc. It acts as a gateway for connecting to other technologies such as GPRS.

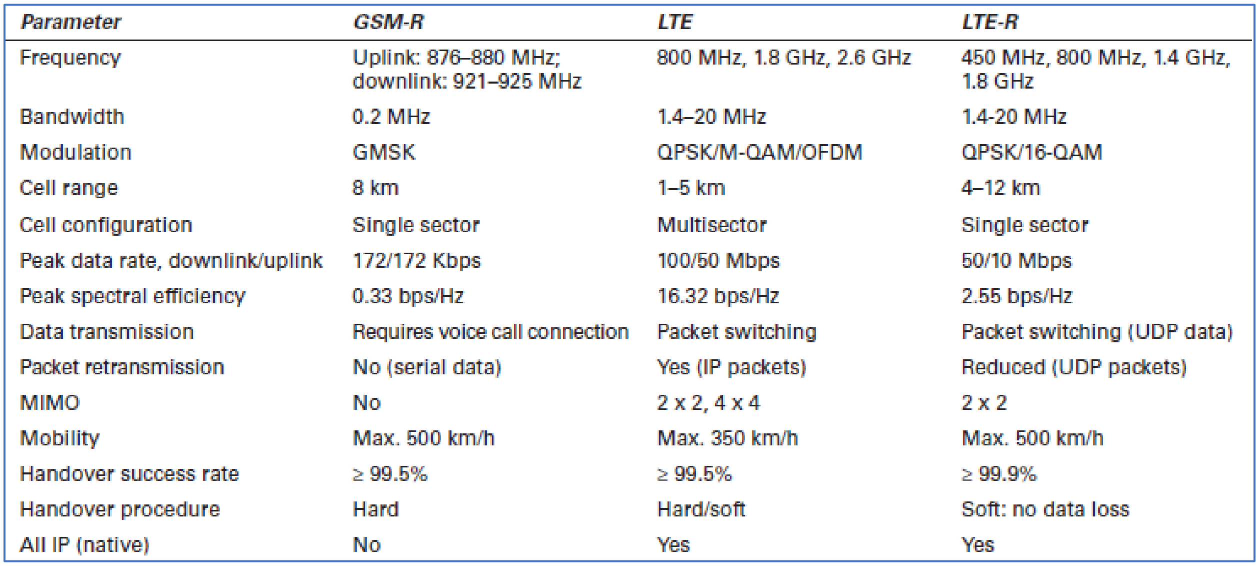
Policy Control and Charging Rules Function: The data flow in the system is governed by the policy available in PCRF that resides in P-GW. It ensures that the data flow is as per the user’s subscription profile.

Multimedia Broadcast Multicast Service Gateway (MBMS-GW): It is used for delivering multimedia services using IP-multicasting to a group of users.

Broadcast Multicast Service Center (BM-SC): BM-SC is part of the core network and provides point to multipoint or group broadcast services required for railway applications. It also plays a role in scheduling and transmission of content, service announcements, billing, content synchronization, and security.

Multicell/multicast Coordination Entity (MCE) routers: It administers the radio resources required for multimedia broadcast Multicast services at eNodeB, and it is part of eNodeB.

The various system parameters for GSM-R, LTE, and LTE-R are summarized in Figure 50.



Parameter	*GSM-R*	*LTE*	*LTE-R*
Frequency	Uplink: 876–880 MHz; downlink: 921–925 MHz	800 MHz, 1.8 GHz, 2.6 GHz	450 MHz, 800 MHz, 1.4 GHz, 1.8 GHz
Bandwidth	0.2 MHz	1.4–20 MHz	1.4-20 MHz
Modulation	GMSK	QPSK/M-QAM/OFDM	QPSK/16-QAM
Cell range	8 km	1–5 km	4–12 km
Cell configuration	Single sector	Multisector	Single sector
Peak data rate, downlink/uplink	172/172 Kbps	100/50 Mbps	50/10 Mbps
Peak spectral efficiency	0.33 bps/Hz	16.32 bps/Hz	2.55 bps/Hz
Data transmission	Requires voice call connection	Packet switching	Packet switching (UDP data)
Packet retransmission	No (serial data)	Yes (IP packets)	Reduced (UDP packets)
MIMO	No	2 x 2, 4 x 4	2 x 2
Mobility	Max. 500 km/h	Max. 350 km/h	Max. 500 km/h
Handover success rate	≥ 99.5%	≥ 99.5%	≥ 99.9%
Handover procedure	Hard	Hard/soft	Soft: no data loss
All IP (native)	No	Yes	Yes

Figure 50. System parameters of GSM-R, LTE, and LTE-R (He et al., 2016)

4.3.5.2 *Railway specific functions in LTE-R*

3GPP Rel-13 defines the following functions specific to railways:

4.3.5.2.1 Mission Critical Push-To-Talk Over LTE (MCPTT)

3GPP Rel-13 specifications are for the push to talk system for mission-critical voice over LTE (VoLTE). The specifications are designed to enable interworking of LTE based systems with existing land mobile radio systems such as TETRA and P25. The idea is to allow a smooth transition from the existing system to LTE based system. As per report “An aspect of MCPTT is the use of 3GPP Proximity Services (ProSe) to allow two public safety devices to communicate directly with each other both in and out of regular LTE network coverage. The MCPTT capabilities, based on the requirements in 3GPP TS 22.179, will include group calls, person-to-person calls, prioritization of calls and of individuals, group management, user management, configuration management, security, operation in relay-to-network mode, operation in off-network mode and a number of other related features”(5G Americas, 2016).

4.3.5.2.2 Group-Based Enhancement (GROUPE)

Group-based messaging specifications allow broadcasting of a message to group members located in a particular geographical area. A service capability server gets a request and provides the group call service. Group-based addressing and identifiers are used for identifying the members and delivery of messages. The messaging architecture of group-based services is shown in Figure 51.

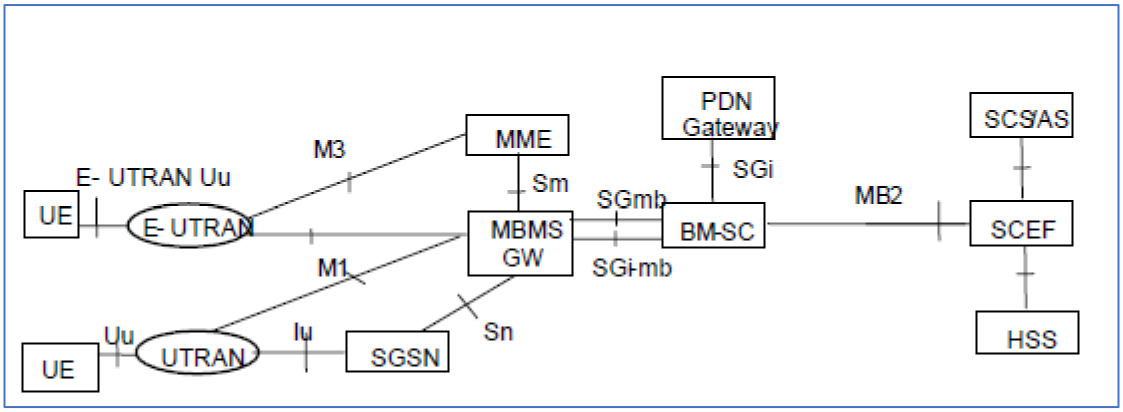


Figure 51 MBMS Based Group Messaging Architecture (5G Americas, 2016)

4.3.5.2.3 Other Services

An e-train project of UIC suggests the following services to improve, efficiency, QoS, and security (He et al., 2016).

Information transmission of control systems: For real-time information, the LTE-R system provides a delay of less than 50 ms, which is in line with the requirements of ETCS-3 and Chinese Train Control System Level 4. The train location information will be detected by equipment on the board the train. LTE-R also can be used for automatic train operation.

Real-time monitoring: LTE-R technology to provide video monitoring of cabin, car connector, track conditions, sensitive locations, cross track, etc. to enable monitoring of conditions of the system. This is especially useful in harsh climatic conditions. The information can be shared with less than 300 ms delay.

Train multimedia dispatching: LTE-R can provide complete dispatching data including video to train drivers, and yard. The system will provide functionalities of group calls, short messaging, voice trucking, multimedia messaging, etc.

Railway emergency communications: LTE-R to provide voice, data, and image transmissions in case of emergencies such as accidents, natural disasters, or any other emergency requirements.

Railway Internet of Things (IoT): LTE-R to provide the railway-specific IoT services such as goods or train tracks, real-time queries, to provide additional services. The railway IoT can be used for improving safety by monitoring various subsystem using remote monitoring of devices and systems involved in the operation of the system.

Figure 52 depicts the services that can be provided using LTE-R. These services are based on technical reports published by the UIC, ERA and China railway.

4.3.5.2.4 Wireless communication at high speed:

In the LTE standard, the mobility is supported up to speeds of 350 km/h. The data loss at the speed of 350 km/h is 40% at the signal to noise ratio of 20 dB as shown in Figure 53. For trains having the speed to more than 350 km/h, the data loss needs to be verified for a maximum speed of operation and system must be designed taking into account the results.

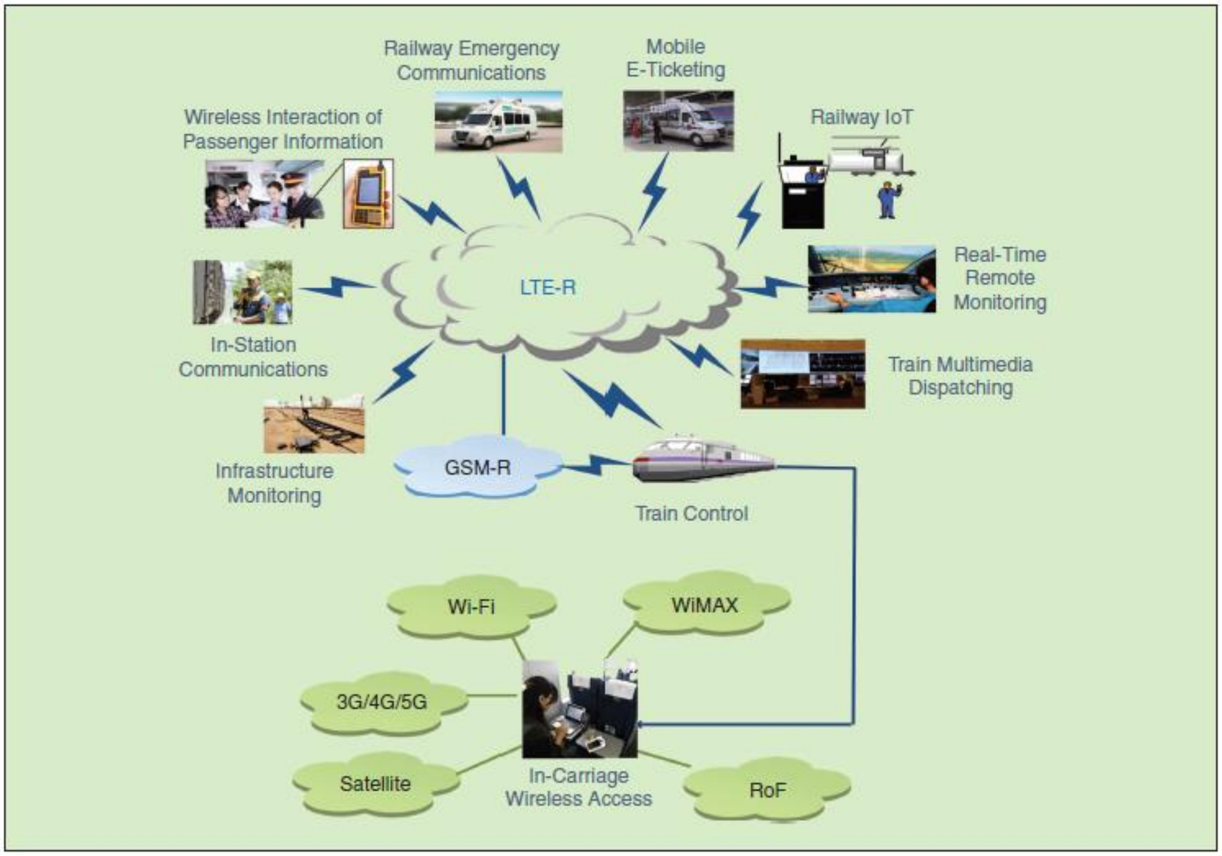
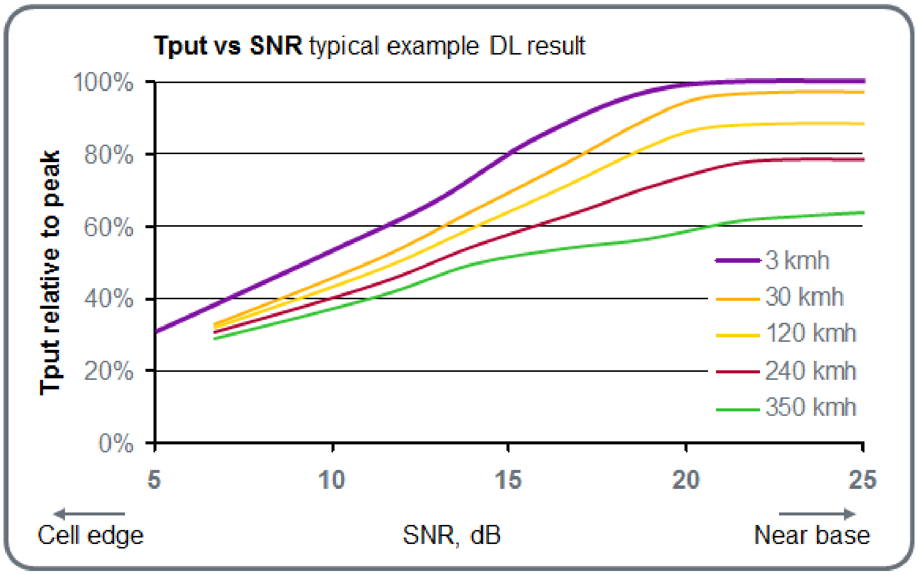

Railway Emergency Communications
Mobile E-Ticketing
Wireless Interaction of Passenger Information
Railway IoT
Real-Time Remote Monitoring
LTE-R
In-Station Communications
Train Multimedia Dispatching
Infrastructure Monitoring
GSM-R
Train Control
Wi-Fi
WiMAX
3G/4G/5G
Satellite
In-Carriage Wireless Access
RoF

Figure 52 LTE-R services (He et al., 2016)



Example results shown similar behavior observed for SM MIMO, SIMO and SFBC and UL SIMO

Source: LSTI, February 2009

Figure 53 LTE throughput performance versus train speed (Choi et al., 2013)

4.3.6 Future Railway Mobile Communication System

The GSM-R is predicted to be obsolete by 2030, and no support for GSM-R based systems will be available after that. Long life expectancy of European Train Control System and future communication requirement of railways require the development of a new system that can be the successor to the GSM-R system with life expectancy equivalent to the train control system. The International Union of Railways has come out with specifications for Future Railway Mobile Communications System (FRMCS). (FRMCS, 2019)

The scope of the FRMCS is shown in Figure 54. The key user-centric features defined in FRMCS document are (FRMCS, 2019):

- "…satisfy the communication needs of the railway operation
- …support the applications independently of the used FRMCS networks and radio access technologies by any of the users.
- …Transition of a user to or from other FRMCS networks or radio access technologies shall not lead to interruption of the usage of the applications
- …human being at the center of the design

- …support the application of the harmonized operational rules and principles where available
- …support the exchange of information and performance of actions without the manual assistance of humans (machine to machine communication) both for operational and maintenance purposes
- ..mitigate the risk of miscommunication.
- ..cost effective
- ..provide precautionary measures to prevent unauthorized access” (FRMCS, 2019).

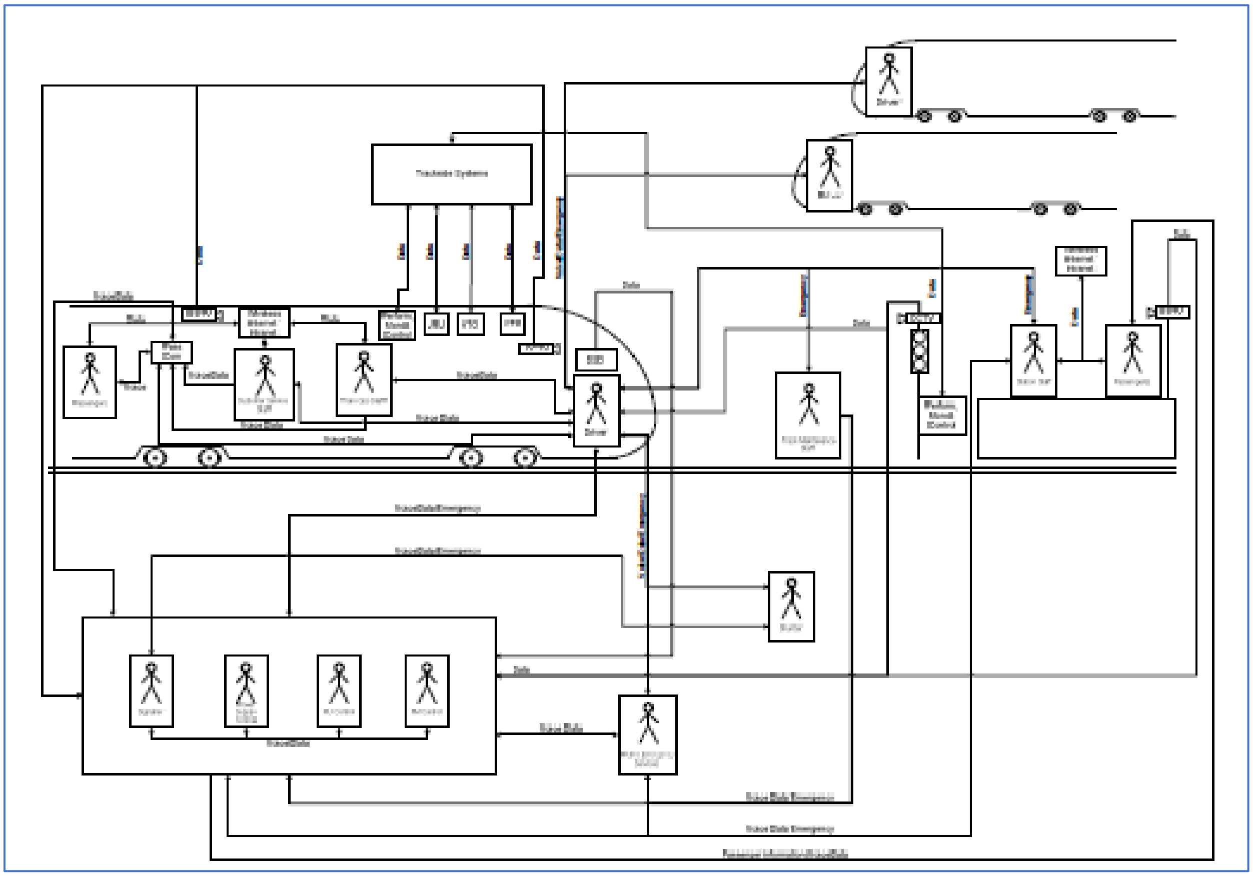


Figure 54 Application Layer Relationship Diagram (FRMCS, 2019)

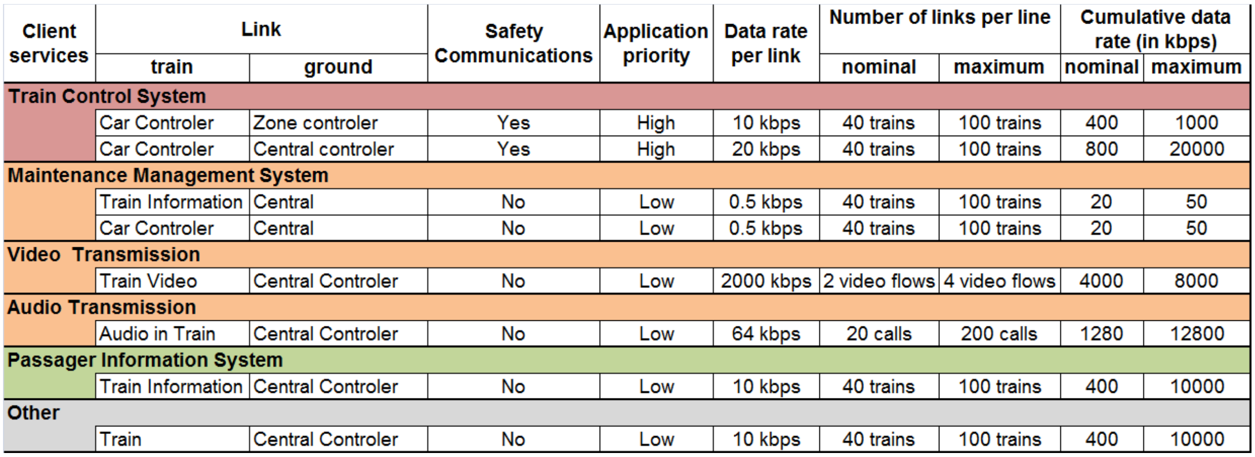
The Technical Study Group (TSG) SA1of 3GPP is looking into the gaps between existing 3GPP system functionalities and the requirements put forward in FRMCS User Requirements Specification document. The trials for FRMCS based system are planned from 2020 onward and deployment by 2022 (DIGI, 2018).

Railways and member state supporting FRMCS are still uncertain on technology to be used for the new system. The natural choice is the use of 4G Long Term Evolution (LTE) which is being implemented in the telecom sector. However, trials of next-generation 5G technology are expected to begin by the end of the decade, and this makes 5G more logical choice for a new system so that the new system has extended life. As such the 4G LTE systems life is expectancy is till 2030 only, and this makes 5G as a better choice (Smith, 2017).

4.3.6.1 The use of FRMCS based on 5G

A number of issues are still to be sorted out in finalization of technology for the new system. One of the main issues is spectrum allocation for the new system. The new system and existing systems are likely to coexist at least until all old systems are replaced with the new system. This requires the sharing of the existing spectrum if no additional spectrum is available for the new system. It is felt that the existing spectrum if used for both GSM-R and FRMCS, can lead to degradation in services of old as well as the new system. To sort out spectrum-related issues for railways, the Electronics Communications Committee wing of CEPT has formed a new project team named FM56, to identify solutions. (Smith, 2017)

As per ETSI report on Spectrum requirements for Urban Rail Systems in the 5, 9 GHz range, the radio access dimensioning is done as in Figure 55. (ETSI TR 103 111 - V1.1.1, 2014).



Client services	Link		Safety Communications	Application priority	Data rate per link	Number of links per line		Cumulative data rate (in kbps)	
	train	ground				nominal	maximum	nominal	maximum
Train Control System									
	Car Controler	Zone controler	Yes	High	10 kbps	40 trains	100 trains	400	1000
	Car Controler	Central controler	Yes	High	20 kbps	40 trains	100 trains	800	20000
Maintenance Management System									
	Train Information	Central	No	Low	0.5 kbps	40 trains	100 trains	20	50
	Car Controler	Central	No	Low	0.5 kbps	40 trains	100 trains	20	50
Video Transmission									
	Train Video	Central Controler	No	Low	2000 kbps	2 video flows	4 video flows	4000	8000
Audio Transmission									
	Audio in Train	Central Controler	No	Low	64 kbps	20 calls	200 calls	1280	12800
Passager Information System									
	Train Information	Central Controler	No	Low	10 kbps	40 trains	100 trains	400	10000
Other									
	Train	Central Controler	No	Low	10 kbps	40 trains	100 trains	400	10000

Figure 55 Urban rail requirements,(Mottier, 2016)

This shows that the railway system uses many applications with different bandwidth and speed requirements. The train control system is a high priority application but with low data rate requirement and high safety. All other requirement has low priority. The video transmission requires maximum bandwidth. This shows that the spectrum dedicated by UIC cannot handle FRMCS application. One way to solve this issue is the use of UIC spectrum for high priority applications and use the shared spectrum for low priority applications. (Mottier, 2016)

The modern train system now requires broadband access for the passenger for Internet access and video displays (Masson & Berbineau, 2017b). The graphical representation of next-generation smart mobile system requirement has been depicted in Figure 56.

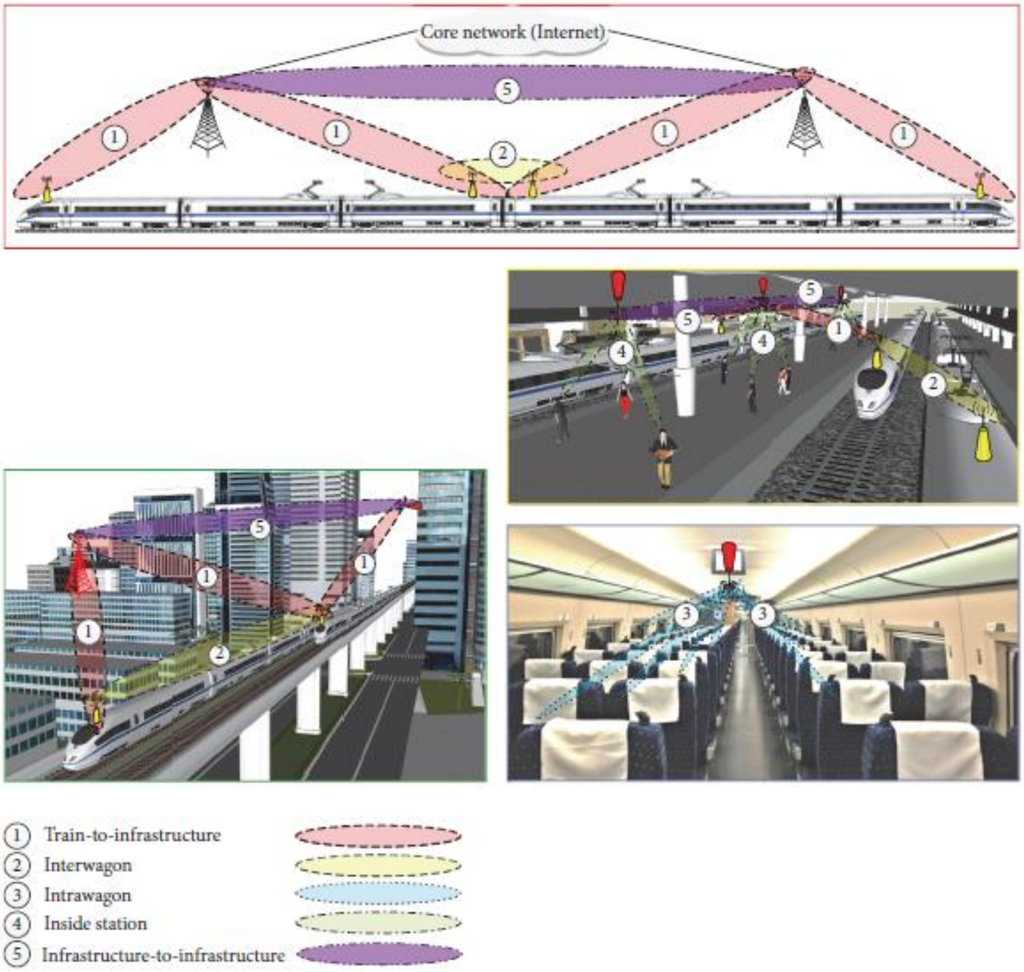


Figure 56 Five communication scenarios of smart rail transportation (Briso-Rodríguez, Guan, Xuefeng, & Kürner, 2017)

Figure 56 shows five scenarios or operation. The Train-to-infrastructure communication required HD video and critical real-time data for train operations. Interwagon communication is wireless communication between two trains for exchanging information. Intra-wagon is communication between passenger and access points on the train. Inside the station is the wireless communication between APs and user equipment at train stations. Infrastructure-to-infrastructure is communication, HD video and real-time, between wayside equipment and ail control room. This may be from a service provider or railways own system. These systems will require large bandwidth to the tune of several GHz to accommodate large data transfers as shown in Table 2. (Briso-Rodríguez et al., 2017)

Table 2 Requirements of a communication network for noncritical communications in HST (Briso-Rodríguez et al., 2017)

HST Communication Links	
Train-to-infrastructure (terrestrial)	1 Gbps
Train-to-infrastructure (satellite)	0.2 Gbps
Intra wagon	1Gbps
Inter wagon	10Gbps
Inside station (all commuters)	100 Gbps
Infrastructure-to-infrastructure	10Gbps

The authors of the report suggest the use of GSM-R for critical communication and the use of broadband for the rest of the requirement. This will solve the problem of backward compatibility and use time tested GSM-R for critical rail applications. (Briso-Rodríguez et al., 2017)

A suggested broadband network for the high-speed train (HST) is shown in Figure 57. The system will use a 5G service. The first and last car of the train shall be connected using the redundant terrestrial link. To reduce fixed infrastructure requirements and achieve reliable communication moving relay solution (Scott et al., 2013) may be used. The system may use a high capacity link based on 802.11ac/ad.

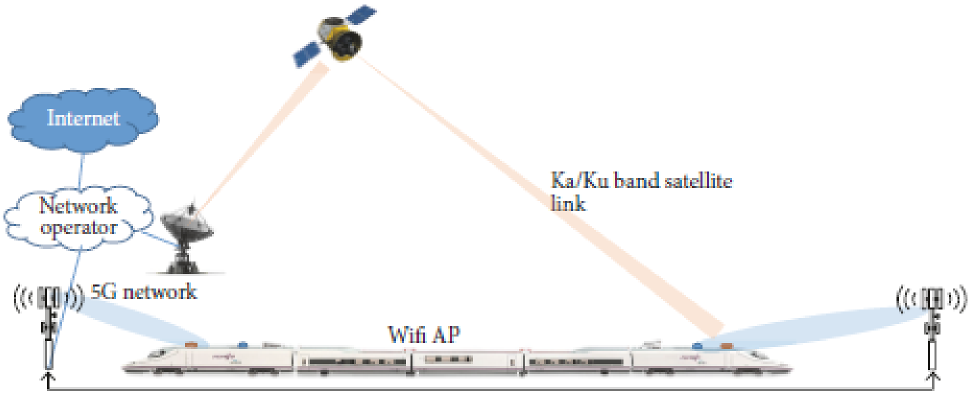
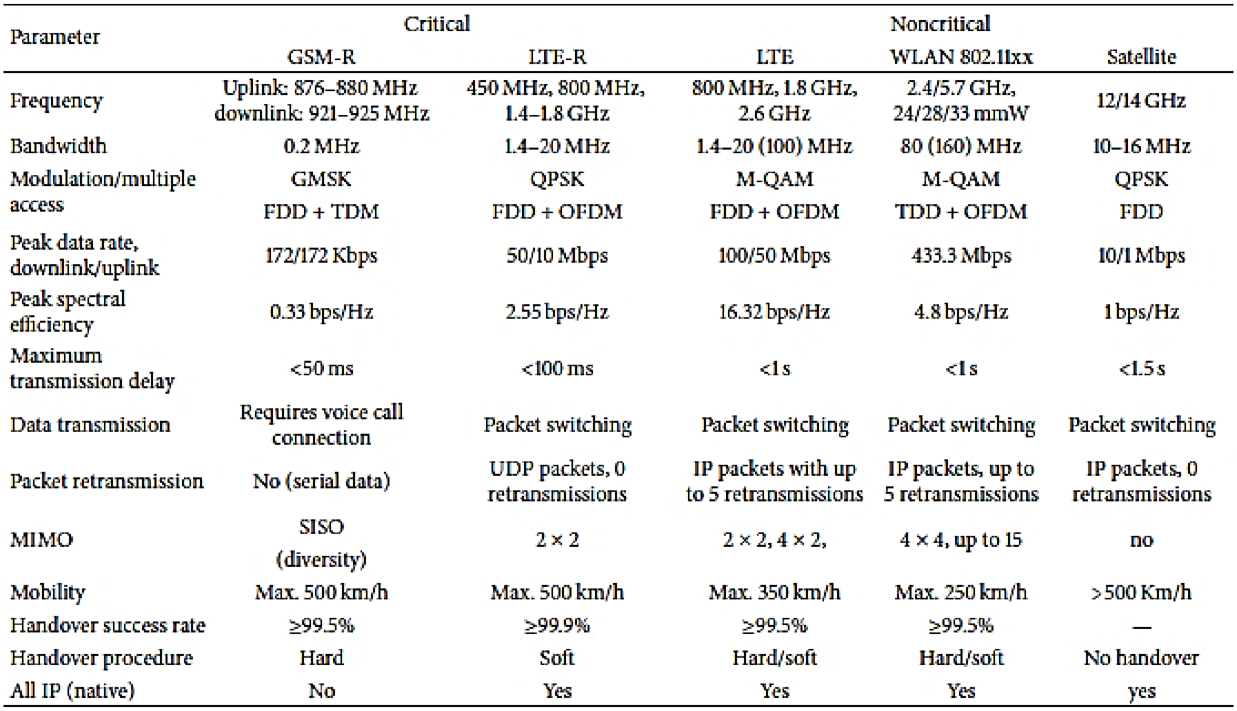


Figure 57 Broadband network for HST noncritical communications. (Briso-Rodríguez et al., 2017)

The satellite link will be used as a backup for the terrestrial link and will provide speed up to 100 Mbps using a top mounted antenna with azimuth control. The train shall use the 10Gb internal fiber-based network for multimedia applications including news, TV, advertising screens, video surveillance, etc. The details of technologies that can be used in railway applications for the critical and noncritical system is given in Figure 58 (Briso-Rodríguez et al., 2017)



Parameter	Critical			Noncritical	
	GSM-R	LTE-R	LTE	WLAN 802.11xx	Satellite
Frequency	Uplink: 876–880 MHz downlink: 921–925 MHz	450 MHz, 800 MHz, 1.4–1.8 GHz	800 MHz, 1.8 GHz, 2.6 GHz	2.4/5.7 GHz, 24/28/33 mmW	12/14 GHz
Bandwidth	0.2 MHz	1.4–20 MHz	1.4–20 (100) MHz	80 (160) MHz	10–16 MHz
Modulation/multiple access	GMSK FDD + TDM	QPSK FDD + OFDM	M-QAM FDD + OFDM	M-QAM TDD + OFDM	QPSK FDD
Peak data rate, downlink/uplink	172/172 Kbps	50/10 Mbps	100/50 Mbps	433.3 Mbps	10/1 Mbps
Peak spectral efficiency	0.33 bps/Hz	2.55 bps/Hz	16.32 bps/Hz	4.8 bps/Hz	1 bps/Hz
Maximum transmission delay	<50 ms	<100 ms	<1 s	<1 s	<1.5 s
Data transmission	Requires voice call connection	Packet switching	Packet switching	Packet switching	Packet switching
Packet retransmission	No (serial data)	UDP packets, 0 retransmissions	IP packets with up to 5 retransmissions	IP packets, up to 5 retransmissions	IP packets, 0 retransmissions
MIMO	SISO (diversity)	2 × 2	2 × 2, 4 × 2,	4 × 4, up to 15	no
Mobility	Max. 500 km/h	Max. 500 km/h	Max. 350 km/h	Max. 250 km/h	>500 Km/h
Handover success rate	≥99.5%	≥99.9%	≥99.5%	≥99.5%	—
Handover procedure	Hard	Soft	Hard/soft	Hard/soft	No handover
All IP (native)	No	Yes	Yes	Yes	yes

Figure 58 Example of different wireless communications systems customized for critical and noncritical communications (Briso-Rodríguez et al., 2017)

4.4 Supervisory/SCADA system for train control

As the railway grew, the operations of the railway system have become more sophisticated. The central monitoring and control of the system play a key role in the safe operations of the railway system. In general, for each railway system, there is an Operation and control center which is linked to smaller control centers at stations and wayside using high-speed links. Supervisory Control and Data Acquisition (SCADA) system are used for monitoring of various equipment and subsystems distributed over various locations along the rail tracks. The SCADA system collects the data from various remote sites and sends it to central monitoring and controls system to carry out necessary monitoring and control of the system. (Belmonte, Boulanger, Schön, & Berkani, 2006)

4.4.1 Typical SCADA System

A typical SCADA system integrated with the corporate enterprise network is shown in Figure 59. The three key functional units of SCADA system are the master terminal unit (MTU), the remote terminal unit (RTU), and communication system.

4.4.1.1 Remote Terminal Units

The remote terminal units are connected to the field sensors, switches, controls, etc. and collect data from these devices. The remote terminal units are installed at various locations for collecting the data to be monitored. SCADA system can use RTU or Programmable Logic Controller (PLC) as per the system configuration. PLCs are small industrial computers that can collect the data as well as perform complex processes for onsite data processing. PLCs, traditionally, have been used for process control systems in plants and manufacturing units. These automate many controllers and logic systems earlier used by the industry. PLC nowadays is also used in place of RTUs where local processing and control of the system is required. Due to their flexibility and lowering of cost, these have replaced RTUs in many systems. (Stouffer, Falco, & Kent, 2006)

4.4.1.1 Master Terminal Unit

The master terminal unit consists of servers running SCADA and other application software, engineering work stations, and Human-Machine Interface or Man Machine interface. The master terminal unit interacts with RTU periodically to collect data and send to SCADA system processor or server for processing it and display to the operator using man-machine interface of the visual display unit. (NCS, 2004)

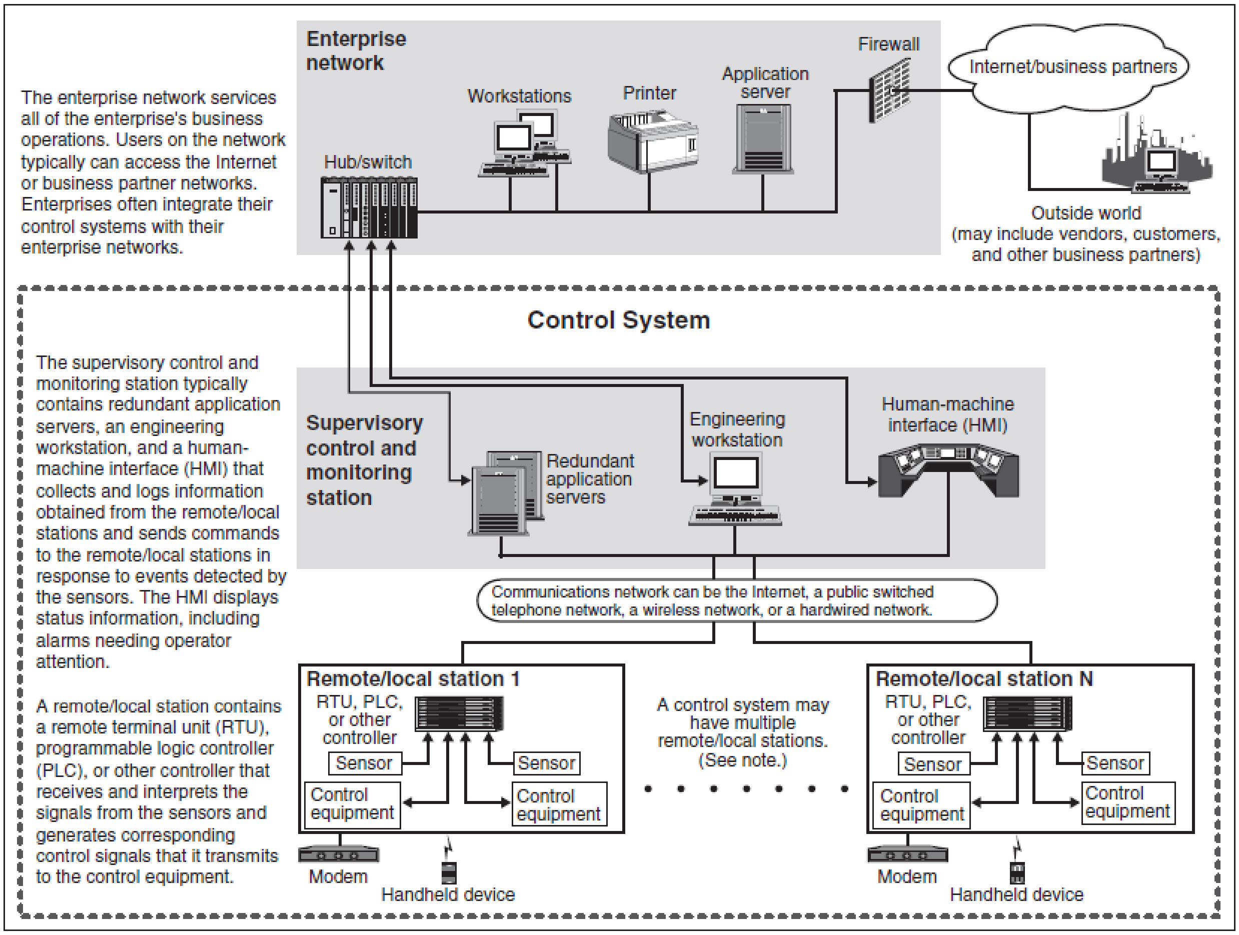

The enterprise network services all of the enterprise's business operations. Users on the network typically can access the Internet or business partner networks. Enterprises often integrate their control systems with their enterprise networks.
Enterprise network
Workstations
Printer
Application server
Firewall
Internet/business partners
Hub/switch
Outside world (may include vendors, customers, and other business partners)
Control System
The supervisory control and monitoring station typically contains redundant application servers, an engineering workstation, and a human-machine interface (HMI) that collects and logs information obtained from the remote/local stations and sends commands to the remote/local stations in response to events detected by the sensors. The HMI displays status information, including alarms needing operator attention.
Supervisory control and monitoring station
Redundant application servers
Engineering workstation
Human-machine interface (HMI)
Communications network can be the Internet, a public switched telephone network, a wireless network, or a hardwired network.
A remote/local station contains a remote terminal unit (RTU), programmable logic controller (PLC), or other controller that receives and interprets the signals from the sensors and generates corresponding control signals that it transmits to the control equipment.
Remote/local station 1
RTU, PLC, or other controller
Sensor
Sensor
Control equipment
Control equipment
Modem
Handheld device
A control system may have multiple remote/local stations. (See note.)
Remote/local station N
RTU, PLC, or other controller
Sensor
Sensor
Control equipment
Control equipment
Modem
Handheld device

Figure 59. Typical Components of a Control System (GAO-04-354, 2004)

The HMI is a combination of hardware and software that allow operators to monitor and control the system. The operator can change a system setting, configure the system, and put set point controls using HMI. Engineering work stations are used for system reconfiguration or updating. The HMI can also display operation status reports, alarms, equipment status, trends, historical information, etc. The HMI consists of a number of work stations and a large display to show the current status of the system along with critical parameters necessary for system monitoring. (Stouffer, Falco, & Kent, 2006)

4.4.1.2 Communications System

The communication system is used for data collection from sensors to the RTUs, transfer data from RTU's to the master control units. The communication network can be wired, wireless, Ethernet, satellite or combination of one or more of these technologies as required. The remote sites not accessible using wired systems use wireless systems to transfer data from RTU's. For difficult to access remote locations, the satellite terminals are used for collection of data from RTU (Stouffer, Falco, & Kent, 2006)

4.4.1.3 SCADA System in Train control

A typical example of train control and operations system using SCADA is shown in Figure 60. The system consists of a primary control center and three field stations/subsystems. The main control center is connected to the three centers using ring topology-based WAN. The field RTUs and PLCs collect data from wayside equipment and transmit it to the rail control center over the WAN. (Stouffer, Falco, & Kent, 2006)

The monitoring and control are done using Man/human-machine interface (MMI) or operator console and associated input devices such as keyboard and trackball for navigation. Large video displays are used or displaying the system status for monitoring the rail network. The system generates an audio-visual alarm in case of any problem to alert the operator.

Railway supervision can be divided into three hierarchical levels (Belmonte et al., 2006):

i. Route control: Include train control, route setting, ending commands, and protection functions

ii. Traffic flow control: Real-time monitoring of the system, conflict solving, etc.

iii. System management and planning

The key functions of the train supervisory system are:

- Displaying stations graphically, guideway, track switch, depot, transfer tables, etc. to provide a global view of the system.
- Displaying status and physical location of the trains
- Train Identification
- Status of track switch and transfer table
- Status of various equipment including signal systems
- Status of critical facilities for each station
- Status of power feeders and electrification system

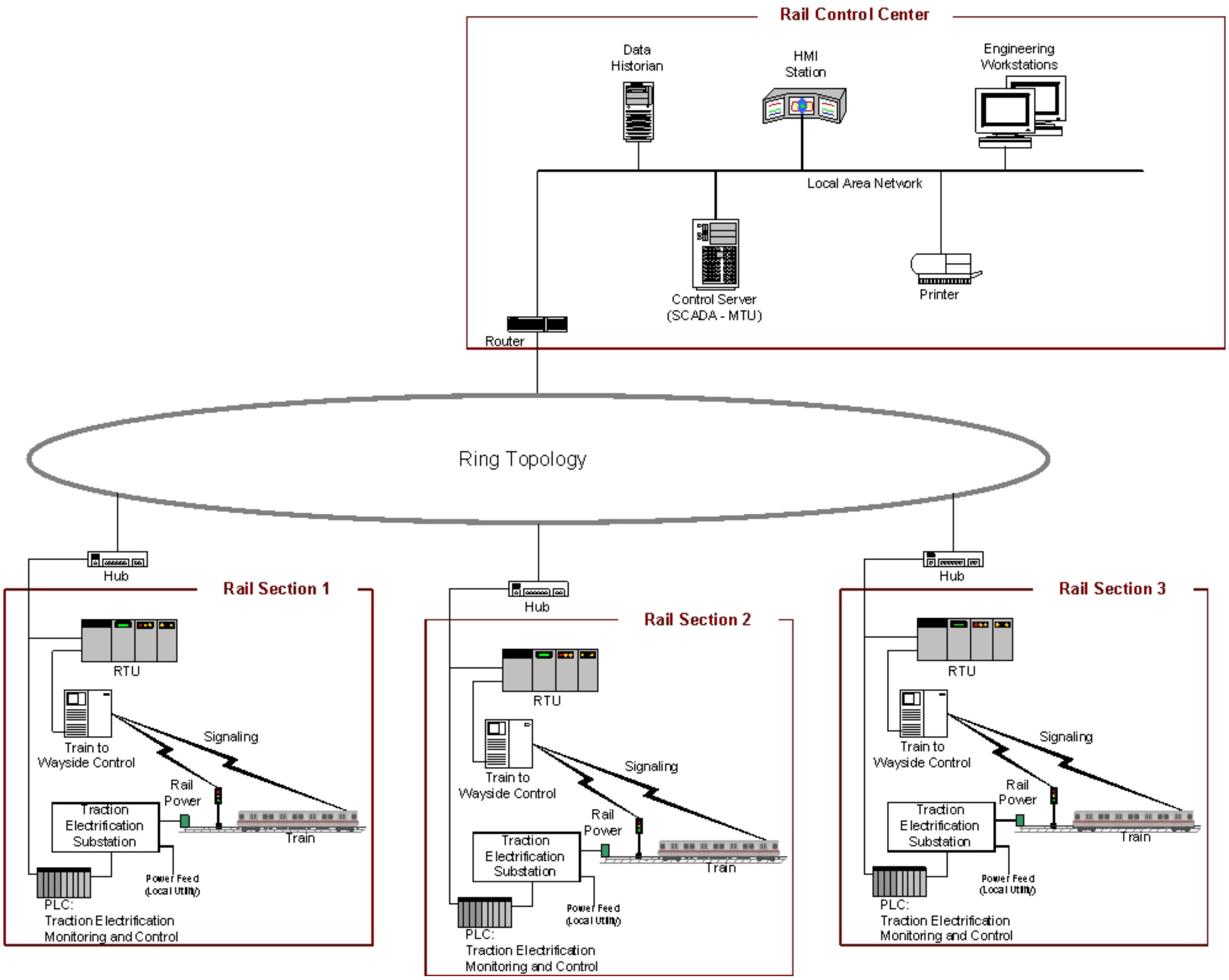

Rail Control Center
Data Historian
HMI Station
Engineering Workstations
Local Area Network
Control Server (SCADA - MTU)
Printer
Router
Ring Topology
Hub
Rail Section 1
RTU
Train to Wayside Control
Signaling
Rail Power
Traction Electrification Substation
Train
Power Feed (Local Utility)
PLC: Traction Electrification Monitoring and Control
Hub
Rail Section 2
RTU
Train to Wayside Control
Signaling
Rail Power
Traction Electrification Substation
Train
Power Feed (Local Utility)
PLC: Traction Electrification Monitoring and Control
Hub
Rail Section 3
RTU
Train to Wayside Control
Signaling
Rail Power
Traction Electrification Substation
Train
Power Feed (Local Utility)
PLC: Traction Electrification Monitoring and Control

Figure 60. SCADA System Implementation Example (Rail Monitoring and Control) (Stouffer, Falco, & Kent, 2006)

5.0 Security of Train Communication System

The rapid automation of railway system has brought many new technologies including internet for use in train control systems. Earlier, the use of proprietary hardware and software systems and protocols were difficult to understand and this made hacking into these systems difficult unless some insider with system knowledge was involved. With standardization and interoperability of equipment, the use of commercial off-the-shelf (COTS) especially IT related system has grown many folds and brought down the system costs and their maintenance substantially (GAO-04-354, 2004). The standardized technologies including operating systems, protocols are widely used and also have commonly known vulnerabilities such as virus, worms and other attacks. The availability sophisticated and of easy to use exploitation tools for these vulnerabilities allow exploitation of these simple resulting in substantial increase in attacks using the common vulnerabilities. The transit industry has also used these technologies and COTs extensively to lower the system cost, cost of training and maintenance over proprietary systems. This has led to many attacks on ICS and SCADA system by exploiting the known vulnerabilities. (Stouffer, Pillitteri, Lightman, Abrams, & Hahn, 2015) (APTA SS-CCS-RP-001-10, 2010)

The use of wireless technology to provide mobility and use of modern techniques in the train control system has opened the system to vulnerabilities of the wireless system. With the use of a wireless system, the network and trains no longer function as a closed system that leads to vulnerabilities and threats. (DHS, 2012) (Chen et al., 2014)

This section looks into the security aspect of the SCADA system and various communication technologies used in modern train control systems such as Wi-Fi, GSM, LTE, etc.

5.1 Attacks on ICS/SCADA Systems

A large number of attacks on rail systems, Industrial control system (ICS) and SCADA have been reported. (Sayegh, Chehab, Elhajj, & Kayssi, 2013) (APTA SS-CCS-RP-001-10, 2010)

NIST classifies the ICS/SCADA security-related incidents in three categories: intentionally targeted attacks, unintentional threats, and unintentional internal security consequences. The unintentional threats are damages due to worms, virus, system failure etc. The unintentional internal security consequences are related to the changes or configuration carried out without proper authorization. The intentionally targeted attacks are most damaging of the three as the attacker is normally a skilled person and has knowledge about the system. The threat agents to a control system include ex-employees, contractors, and other dissatisfied individuals working for the organization. (Stouffer et al., 2015)(Sayegh, Chehab, Elhajj, & Kayssi, 2013)(Shaw, 2004)

5.1.1 Intentional Attacks

- **Salt River Project:** In 1994**,** a breach in the computer system of the Salt River Project, supplying water and electricity to Phoenix, Arizona was detected. The attackers accessed the computer system by dialing into a backup computer using the modem. (GAO-04-354, 2004)
- **Worcester Air Traffic Communications:** The air traffic at the airport of Worcester, Massachusetts was disrupted for many hours when a teenager was able to disable part of the phone system. The attacker used a simple modem to get into the Bell Atlantic computer system. (Thomas, 1998)
- **Maroochy Shire Sewage Spill:** Vitek Boden, an Australian employed by the company who has installed the sewage control system, attacked the system leading spill of millions of liter of raw sewage into local parks at Maroochy Shire, Queensland. He did so after his application for employment in the company was turned down. (Thomas, 1998)
- The other incident occurred when a Polish teenager modified his TV remote and used it to hack into the tram system in the city of Lodz (Leyden, 2008). He used the remote to change the track point, and this led to the derailment of trams and spreading chaos. The device he used was able to maneuver the trams and the tracks.
- Siemen’s S-7 SCADA was attacked using a malware called Stuxnet in Iran in 2010. The system was infected using a USN drive, and the worm was installed

on a PLC to inject malware code into the system. The Stuxnet malware exploits Windows LNK-files security loopholes. The malware looks for certain specific information and then send it to the external servers. (McMillan, 2010)

5.1.2 Unintentional Consequences

- **CSX Train Signaling System:** The rail system has also been the victim of these attacks. The virus attack on CSX railway in 2003 and hacking of polish tram in 2007 have been well documented. A virus, called “Sobig,” infected CSX Corporation’s computers at their headquarter in Jacksonville, Fla and thus led to disruption in dispatching, signaling, and other systems (DAVID HANCOCK, 2003). This outage affected complete CSX system covering 23 states and led to delays and cancellation of many trains.
- **Northeast Power Blackout:** A failure of the alarm processor of the First Energy’s SCADA system led to tripping of 345 kV transmission lines in Northern Ohio as the operators could not get the information about alarms. This lead to the failure of the grid and tripping of 256 power plants. (Stouffer et al., 2006)

5.1.3 Unintentional Internal Security Consequences

- **Vulnerability Scanner Incidents:** This incident happened at Sandia National Laboratories a facility created for the U.S. Department of Energy’s National Nuclear Security Administration. During testing of 9 ft, robotic arm of SCADA system using ping sweep made the arm “active” and it swung 180 degree and damaged wafers worth $50,000. (Stouffer et al., 2006)
- **Bellingham, Washington Gasoline Pipeline Failure:** The SCADA system failure at Bellingham, Washington Gasoline Pipeline led to a leak of 237,000 gallons of gasoline in 1999. The pipeline later caught fire and led to the death of 3 persons, injuring eight and caused extensive damage to the property. (Stouffer et al., 2006)

The consequences of a security breach in the SCADA system are many and include physical, economic, and social impacts. The attacks can lead to loss of production, death, injuries, damage to equipment and property, damage to the environment, theft of materials, contamination of natural resources, loss of confidential data, loss of company's brand image in public and many more. (Stouffer et al., 2006)

5.2 SCADA System Vulnerabilities

The modern SCADA systems use communication technologies such as Ethernet, TCP/IP, and other Internet technologies for seamless networking and interconnection among the equipment from different vendors. The use of web-based technologies such as ActiveX, Java, etc. opens more possibilities of cyber-attacks (Hentea, 2008). This has resulted in vulnerabilities associated with these communication and networking technologies to get passed on to SCADA systems using these technologies. (NCS, 2004)

The General Accounting Office (GAO) report on Information Security Issues also validates above and indicates that the risk to industrial control systems have escalated due to the use of standard systems with known vulnerabilities, use of insecure remote connections, interconnection of SCADA system to other systems, and availability of network infrastructure and control system details in public domain. The GAO report also gave a typical diagram of a SCADA system depicting the interconnection to remote units and outside systems. The communication can be using wired or wireless connections. The connection to the outside world is using the Internet. (GAO-04-354, 2004)

Security of SCADA system can be compromised in many ways in the system, and the easiest place is from the control room or host level. The connection to the corporate network is another area where SCADA systems can be accessed. In case of the corporate network getting compromised the SCADA system also become vulnerable. (NCS, 2004)

From a security point of view, the linkages between different networks are the weak points in the network as an attacker can exploit these to get into the system. The SCADA system host is vulnerable to following attacks from the weak linkage (NCS, 2004):

- The launch of Denial of Service (DoS) attack to bring down the SCADA server and shutting down the server
- Deleting SCADA server system files
- Insert trojan into the system to take control of the system
- Steal username and password by logging operator’s keystrokes.
- Steal sensitive data about operations to get a competitive advantage
- Modifying data set points to deceive system and operators to make them shut down the system
- Hack remote database and modify the same
- Use the SCADA server to launch an attack on the corporate network.

The NCS report has detailed these vulnerabilities in a tabular form. An important observation in reports says “SCADA Administrators and Industrial Systems Analysts are often deceived into thinking that since their industrial networks are on separate systems from the corporate network, they are safe from outside attacks” (NCS, 2004)

Another report by American researchers found twenty fine zero-day vulnerabilities in SCADA software for critical infrastructure systems from 20 leading suppliers. The vulnerabilities were found in the communication equipment between servers and remote stations. These vulnerabilities are the cause of concern as in this area there is no firewall to protect the network. (Ashford, 2013)

5.2.1 Cyber Attacks on SCADA Systems

5.2.1.1 Attacks on Hardware

The attacks on hardware can happen due to unauthorized physical access to the system or remote access.

5.2.1.2 Attacks on Software

The software attacks include holes in the operating system used. The absence of any privilege of protection in embedded operating systems used. The buffer overflow can create a problem for servers, work stations, as well as field devices as these systems, run for a very long time without rebooting leading to accumulated memory fragmentation and program stalling. Many SCADA applications use SQL (Structured Query Language) for accessing the database. The SQL is susceptible to cyber-attack. In SQL injection attack the attacker manipulates web application data by inserting a number of unexpected SQL statements into a query. (B. Zhu, Joseph, & Sastry, 2011)

5.2.1.3 Attacks on Communication Stack

TCP/IP protocol is vulnerable to many attacks, and some of the attacks that can harm the SCADA system are given below (B. Zhu et al., 2011):

Network Layer attacks

Diagnostic Server Attacks through UDP port: The UDP port can be used by an attacker to get system details by using debugging tools used by the developers.

Idle Scan: It is used to blind a port scan so that attacks such as dumb "zombie" host or another attack cannot take place. The scanning functionality of two popular protocols MODBUS and DNP3 used by SCADA systems when used over TCP/IP is vulnerable to this attack.

Smurf: In this continuous stream of ICMP (Internet Control Message Protocol) is sent to the host to overload it with requests leading to crash. The PLC can crash or issue dangerous command if PLC acts on any modified message. (B. Zhu et al., 2011):

Address Resolution Protocol (ARP) Spoofing/Poisoning: ARP is used to port IP address to Ethernet MAC address for transfer of data over LAN. The ARP spoofing attack changes Ethernet MAC address to attacker's address and so that it gets associated with the IP address and all the traffic gets diverted to attacker's computer. In case of a SCADA system, this will make network devices send a packet to attackers or an unreachable host. (B. Zhu et al., 2011):

Transport Layer attacks

SYN flood attack host is flooded with TCP message more than it can process leading to a system crash.

Application Layer attacks

The SCADA protocol does not have any mechanism to find out the source of data, and hence anyone with access to the devices using these protocols can attack the system. DNS forgery is one such attack when fake DNS reply with matching attributes but the attacker's information inside is sent for processing by the client before a real DNS reply is received. (Hansman & Hunt, 2005)

Attacks on SCADA protocols

The MODBUS/TCP is an application layer protocol used by SCADA system access server from the client end. Since there is no encryption involved, the system is prone to attacks. DNP3 protocol is used for communication between master control stations and remote stations mainly in power and water companies. The DNP3 based remote stations can be reset or reconfigured by sending code 0x0D. The attacker can use this facility to manipulate or delay response from the remote station. (B. Zhu et al., 2011)

The Factory Intelligent Network Services (FINS) Protocol used by many PLCs does not use any encryption, and any eavesdropper can extract the password and hack into the system. The other attacks that can be launched using FINS are replay attack, fragmentation attacks, DoS attacks, etc. (Sayegh et al., 2013)

5.3 Security of Wireless Networks

The wireless network's vulnerabilities include those in traditional wired network plus the vulnerability due to the easy interception of wireless signals using appropriate device or equipment.

5.3.1 Vulnerabilities and Threats to Wireless Networks

The vulnerability of wireless networks can be due to the following (Lane, 2019):

5.3.1.1 Eavesdropping or Sniffing

The wireless signals can be easily intercepted even outside the premises using a proper receiver. In the case of the rail network, the access point is located by wayside making it easy anyone near to eavesdrop on the signals. The attacker after intercepting the data can modify or insert another data the network. A number of free wireless sniffing tools such as tcpdump and Ethereal are available for free on websites for capturing data. Tcpdump uses the text-based command to capture data while Ethereal provides a graphical interface for capturing and analyzing the data. AiroPeek from WildPackets and Sniffer Wireless from Network Associates are two of many commercial tools available for sniffing and analyzing the captured data. (Sankar, Sundaralingam, Balinsky, & Miller, 2004)

5.3.1.2 Physically insecure locations

The installation of wireless equipment in an insecure location can allow an attacker to access the system by using its administrative port. (Lane, 2019)

5.3.1.3 Rogue access points

The rogue access points are access point installed by an attacker to trick users into accessing their system so that they can sniff into the data and steal information. (Lane, 2019)

5.3.1.4 MAC address spoofing

Wireless access points can be configured to allow only devices whose MAC address has been registered with the WAP. However, an attacker may get around this by spoofing the MAC address, and therefore some additional mechanism is needed to restrict access.

5.3.1.5 Wardriving

The wardriving is normally used to check the coverage area of a mobile system. The vehicle with wardriving equipment goes around the places to check the access. However, this can be used by a hacker to map the system. A number of wardriving tools are available in the market such as Kismet, Network Stumbler, MacStumbler for MAC, bsd-airtools for FreeBSD OS and Wellenreiter for BSD and Linux. (Sankar et al., 2004)

5.3.1.6 Denial-Of-Service (DOS) attacks

The wireless system can be kept out of service by launching a signal of higher power than the normal signal. The radio-jamming system is used for this. The attacker can also disable the system by repeatedly transmitting a signal to keep the channel occupied thereby prohibiting other equipment to transmit. (Sankar et al., 2004)

5.3.1.7 Disassociation and De-authentication Attacks

In the original 802.11 protocol when a user tries to connect to an AP, authentication messages are exchanged between the user and the AP and is followed by an association message. The user is allowed to access the network once the association message is received. An attacker can send a bad association message to keep user disconnected from the network. Tools such as Mike Schiffman‘s Ometra, AirJac’s essid_jack, and ReykFloeter’s void11 allow sending fake association messages. (Sankar et al., 2004)

5.3.1.8 Exploiting security protocol loopholes

Exploitation of a security hole in the protocols used can be exploited by an attacker to get into the system. For example, wireless equivalent privacy (WEP) protocol proposed along with 802.11 standards has many security holes. (Sankar et al., 2004)

5.3.2 Security Mechanisms in IEEE 802.11 protocols

IEEE 802.11 based standard has built-in security provisions as part of the standard. However, weakness in the protocol has been reported. This part of the report will discuss vulnerabilities in various 802.11 standards.

5.3.2.1 Wired Equivalent Privacy

Wired Equivalent Privacy (WEP) was published as part of the 802.11 standard security mechanism. The idea of WEP was to provide security similar to the wired network. The WEP uses RC4 cipher, a symmetric secret-key stream cipher, for data encryption to provide security of data. The short secret key is taken by RC4 and expanded into pseudorandom keystream of length that of the message as shown in Figure 61. The pseudorandom keystream and the message are XORed to get ciphertext. (Gast, 2009)

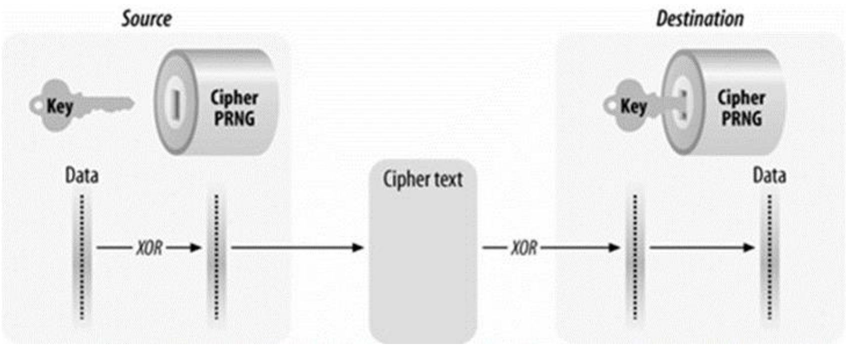


Figure 61 Keyed stream cipher operation (Gast, 2009)

The result of Cyclic redundancy check (CRC) of the frame to be transmitted generates a 32-bit value called an integrity check value (ICV). The ICV will be added as payload in the frame and allows the integrity check of the data received. The encryption of payload and ICV is done using C4 cipher using IV and a secret key of a 40, 64 bits as shown in Figure 62. The secret key was updated to 108 or 128-bit versions later. The IV is changed sequentially or randomly for each frame to keep keystream different for each frame. The resulting key and payload data are encrypted using RC4 cipher. The transmitted frame consists of an unencrypted header, IV, key number, and an encrypted payload. The system allows four types of keys, and the key number helps its recognition at the receiver. Thus, WEP adds 64 bits to the header. (Sankar et al., 2004) (Gast, 2009)

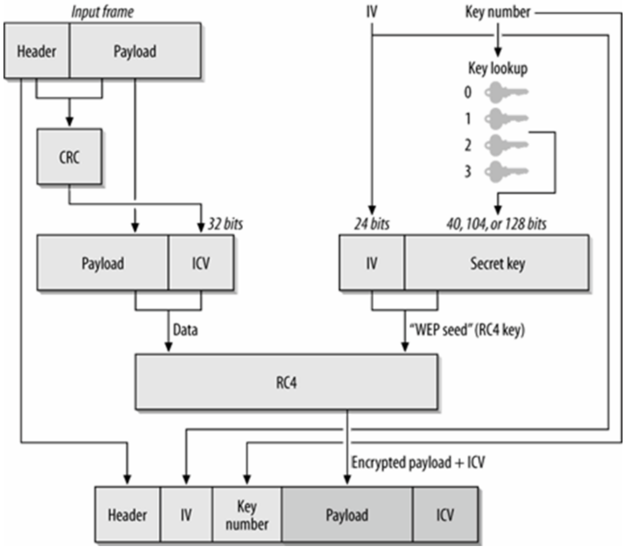


Figure 62 WEP operations (Gast, 2009)

5.3.2.2 WEP Weaknesses

The WEP provides reasonable security, but many flaws were found in it and are described below:

- **One set of keys for the entire network:** WEP uses a key pair which is shared among all users of the entire network. The key leakage by any user can compromise the whole network. The manual key distribution is also a big risk as any widely distributed item is likely to come in the public domain at some point. (Gast, 2009)
- **Key size:** The key size of 40 or 64 bit proposed by WEP is considered weak as minimum acceptable key size from a security point of view needs to be at least 128 bit long. However, it was extended to 108 and then to 128 bit later.
- **WEP deployment:** Fluhrer et al. (2001) showed that the deployment of WEP was found be errored, making RC4 used unsecured and used passive “ciphertext only” attack to show the discovery of secret key. The attack collects network packets over a period and then identifies the packet with a weak key structure. After sorting out these weak packets, the byte value with the highest number reveals the key. (Fluhrer, Mantin, & Shamir, 2001).
- **Initialization Vector:** Another weakness in WEP is the reuse of keystream in RC4 encryption. It was observed that the XORed value of two RC4 encrypted packets is the same as the XORed value of two plain text frames. The analysis of the difference between two streams can lead to the content of the frame. To overcome this IV was inserted to make keystream different in every frame. As IV is sent after encryption, the encryption of two packets with the same IV will have the same key. Due to the 24-bit length of IV, the number of available keys is limited and will get exhausted after some time, and then old IV shall be used again. The attacker can accumulate the packets with the same IV over a long period and then break the key to compromise security. Tools such as AirSnort which are commonly available can be used for breaking the key. (Borisov, Goldberg, & Wagner, 2001)

- **One-sided authentication:** WEP provides one-sided authentication where the only user gets authenticated by the AP, but the user has no way of knowing if AP is original or fake. This allows an attacker to install rogue AP with credential similar to original AP and deceive the user to use that. (Borisov et al., 2001)
- **CRC-32 checksum:** Researchers showed that CRC 32 checksum calculation scheme has lacunae in checking integrity and allows unintended authentication attacks. The attacker can put a rogue AP after knowing the key and then modify packet in transit. The attacker can use message inject attack to compromise on authentication and decrypt packets with detection. (Borisov et al., 2001)

5.3.2.3 Wireless Protected Access

To overcome WEP limitations, Wi-Fi- Alliance in 1993 suggested another protocol called Wireless Protected Access (WPA). The WAP provide mutual authentication and uses temporal key integrity protocol (TKIP) for encryption. (Wi-Fi Alliance, 2019)

5.3.2.3.1 Temporal key integrity protocol

TKIP uses a 64-bit message integrity check protocol called Michael. In Michael, an algorithm is used to derive an 8-byte message integrity code (MIC). The calculated MIC is put between the data and the 4-byte ICV in the 802.11 frame and protects the reassembled data unit as shown in Figure 63.

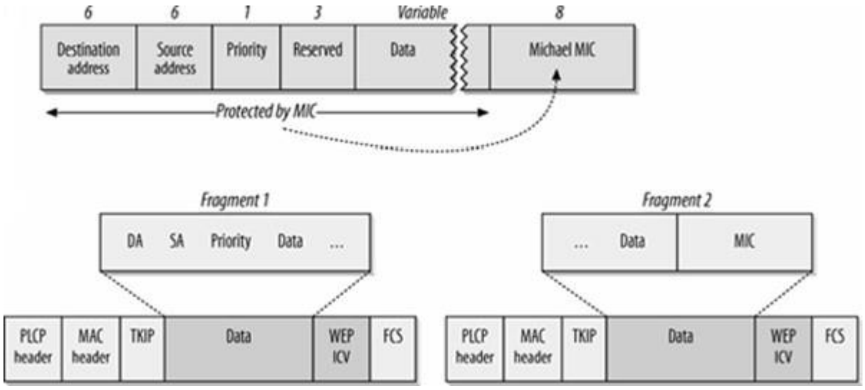


Figure 63 Protection by Michael (Gast, 2009)

TKIP derives a unique key for the encryption of each frame. The key is derived by mixing MAC address, temporal key, and 32 most significant bits of 48-bit sequence number first and then mixing the output with remaining 16 bits of sequence counter as shown in Figure 64. The temporal key is changed after transmitting 10,000 packets. The sequence counter is used by the receiver to mitigate replay attack. The WPA implementation requires no additional hardware. (Gast, 2009)

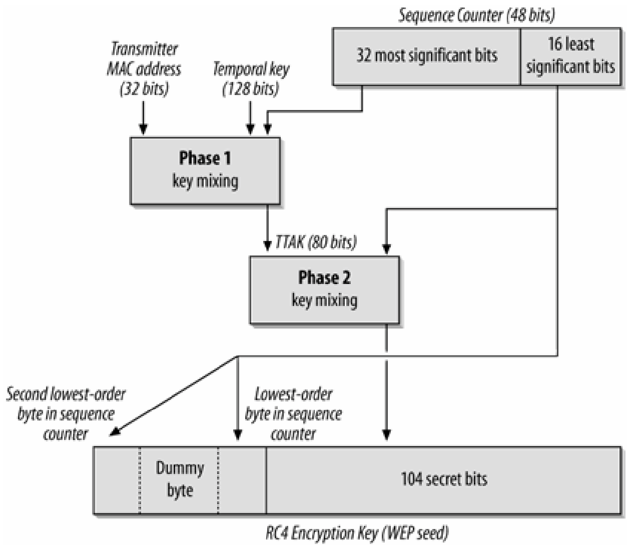

Sequence Counter (48 bits)
32 most significant bits
16 least significant bits
Transmitter MAC address (32 bits)
Temporal key (128 bits)
Phase 1 key mixing
TTAK (80 bits)
Phase 2 key mixing
Second lowest-order byte in sequence counter
Lowest-order byte in sequence counter
Dummy byte
104 secret bits
RC4 Encryption Key (WEP seed)

Figure 64 TKIP Key mixing (Gast, 2009)

The mutual authentication in WPA is provided using two schemes. The first scheme, less secure and intended for personal use, uses a pre-shared key (PSK) and the second scheme intended for corporate users uses IEEE 802.1X/Extensible Authentication Protocol (EAP). In EAP, authentication server processes all the access request and only after successful authentication network access is allowed. (Khasawneh, Kajman, Alkhudaidy, & Althubyani, 2014)

5.3.2.3.2 WPA Vulnerability

WPA vulnerability was demonstrated using chop-chop method by Tews & Beck (2008). However, it was shown that it could be avoided if the timing between keys is less than 120 sec. (Tews & Beck, 2009)

5.3.2.4 Wireless Protected Access 2 (WPA2)

Wi-Fi Alliance updated WPA to WPA2, and later it was made part of IEEE 802.11i wireless security standard. WPA 2 uses Advanced Encryption Standard (AES) instead of TKIP used by WPA. The encryption in AES is done using Counter-Mode (CCM)/CBC-MAC Protocol (CCMP). The AES supports the key length of 128-bit, 192-bit, and 256-bits. The WPA2 like WPA provides two modes of authentication using PSK for personal use and AES-CCMP for enterprise mode. (Khasawneh et al., 2014)

In CCM/CCMP single key is used for authentication and encryption. Here two modes of operation for encryption are used; a counter mode for encryption and Cipher Block Chaining Message Authentication Code for integrity. Frame processing in CCMP is s shown in Figure 65. The frame processing uses a temporal key for frame encryption and authentication, a packet number identifier, a key identifier, and the frame to be transmitted.

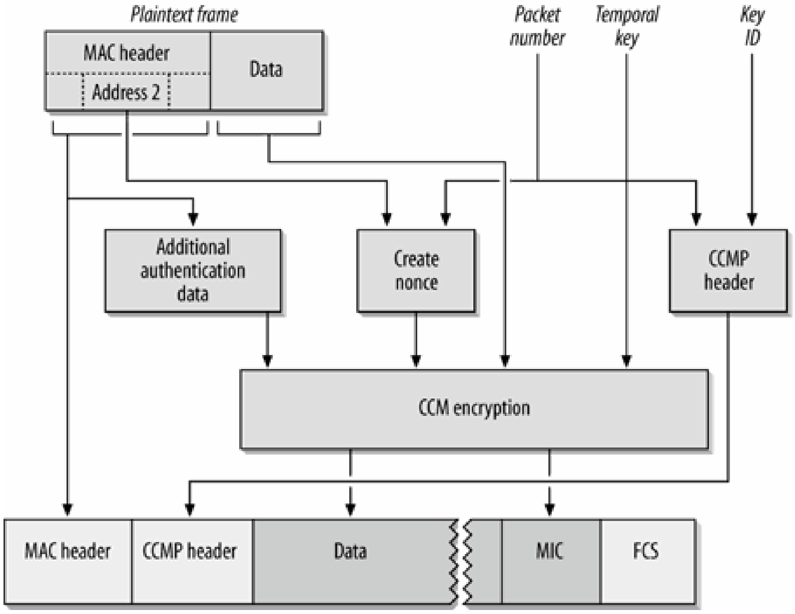


Figure 65 CCMP frame processing encryption (Gast, 2009)

5.3.2.1 IEEE 802.11i

The IEEE 802.11i encompasses WPA2 along with few additional features for message confidentiality and integrity. The standard defines two network types; Transition Security Network (TSN) and Robust Security Network (RSN). TSN allows the use of old WEP and RSN to work in network whereas in RSN only node capable of RSN requirement can work. Strong security associations are used by RSA for its APs and IEEE 802.1x protocol is used for authentication. (Aruba, 2018)

5.3.2.1.1 The vulnerability of WPA2/ IEEE 802.11i

Proper implementation of WPA2/ IEEE 802.11i provides good data confidentiality and integrity, but it does not provide any protection against DoS attacks.

Airtight Networks detected a Hole 196 vulnerability in WPA2 that exposes it to insider attacks. The WPA2 shares a group temporal key (GTK) that is used for broadcast data, among all authorized clients. The AP encrypts data broadcasted to the group using GTK and is decrypted by the client using GTK. A client can inject spoofed GTK and used it to sniff data from other users. However, this can be exploited by an insider with access to the network. (Wexler, 2010)

The main issue in WPA2 was susceptibility of PSK mode to dictionary attacks as it uses predefines a key and lightweight authentication handshake. The 802.1X/EAP mode of operation for enterprise required proper implementation due to complex configuration requirements. Moreover, it was too complex for small enterprises such as café who provide public Wi-Fi hot spots.

5.3.2.2 WPA 3

To address problems with WPA2, a new protocol called WPA3 was introduced to simplify the security. As per Wi-Fi Alliance, “WPA3 adds new features to simplify Wi-Fi security, enable more robust authentication, deliver increased cryptographic strength for highly sensitive data markets, and maintain resiliency of mission-critical networks” (Wi-Fi Alliance, 2019).

WPA3 Personal uses Simultaneous Authentication of Equals (SAE) instead of PSK in WPA2. It provides robust authentication using a password that may not be very complex. It protects from dictionary attacks. The system protects data even after the password is compromised. (Wi-Fi Alliance, 2019)

To secure an open public network, Opportunistic Wireless Encryption (OWE) was introduced (Harkins & Kumari, 2017). When the user gets associated with an AP, the

OWE performs an unauthenticated Diffie-Hellman resulting in a key that is known to only user and AP. This key is then used for encryption and management for the link. This methodology provides much better security than WPA2- PSK. (Aruba, 2018)

The key tools used in WPA3 are (Wi-Fi Alliance, 2019):

- **“Authenticated encryption:** 256-bit Galois/Counter Mode Protocol (GCMP-256)
- **Key derivation and confirmation**: 384-bit Hashed Message Authentication Mode (HMAC) with Secure Hash Algorithm (HMAC-SHA384)
- **Key establishment and authentication:** Elliptic Curve Diffie-Hellman (ECDH) exchange and Elliptic Curve Digital Signature Algorithm (ECDSA) using a 384-bit elliptic curve
- **Robust management frame protection:** 256-bit Broadcast/Multicast Integrity Protocol Galois Message Authentication Code (BIP-GMAC-256)” (Wi-Fi Alliance, 2019).

The use of CNSA (Commercial National Security Algorithms) for 802.1X/EAP configuration ensures that no misconfiguration is done and mix and match of the algorithm in an insecure manner cannot be done as in case of WAP2. (Aruba, 2018)

5.3.3 Security of Cellular Network

The security of cellular communication has kept pace with technology. The evolving security architecture from GSM to LTE is shown in Figure 66. The risk in earlier versions has been addressed in a later version to make the system more secure. However, as the communication mode shifted from voice-centric to data-centric and flatter architecture, the system is now more prone to attacks making it challenging work to maintain security in cellular networks.

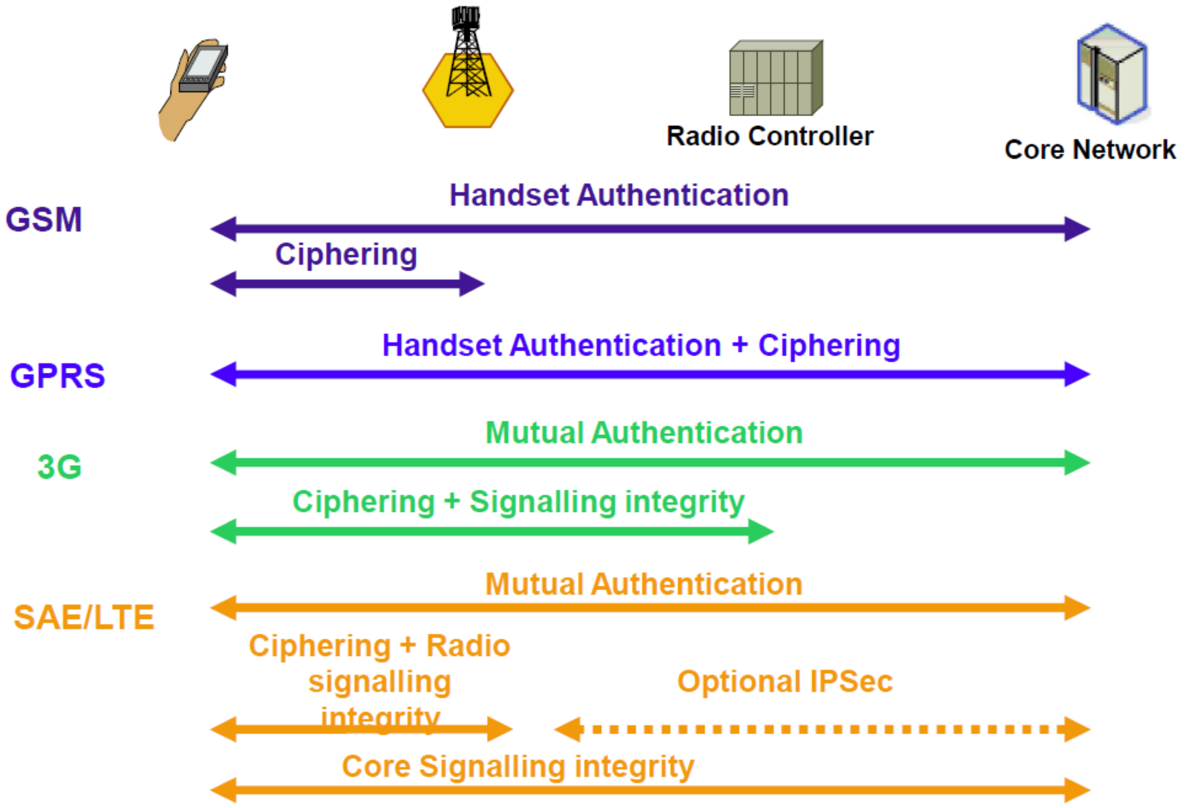


Figure 66 Evolving Security Architecture (Wierenga, 2019)

5.3.3.1 *Security in GSM mobile network*

The main objective of security in GSM network is to avoid unauthorized access and privacy of data being transmitted so that the network cannot be misused. The objective is achieved by providing users with authentication, confidentiality, and anonymity. (ETSI, 1993)

5.3.3.1.1 GSM Security Features

The features to provide privacy and security to the users in GSM are (Srinivas, 2001):

- Subscriber authentication
- Subscriber identity protection
- Data encryption during transmission
- Interoperability of user equipment
- Prohibit use of duplicate subscriber identity module (SIM)
- Key security

Subscriber authentication

The GSM system uses a SIM card, that has identity and security information, for user identification. During authentication, the validity of the SIM is checked using the challenge-response technique before providing network access. The authentication procedure is as shown in Figure 67 and uses the following steps (ETSI, 1993):

i. As soon as mobile is switched on it sends International Mobile Subscriber identity number to the network.

ii. The HLR/AuC looks for a corresponding authentication key (Ki) for the IMSI received. A signed response (SERS) is generated and kept for verification later.

iii. The HLR/AuC generates RAND, a 128bit random number, and sends it to the mobile subscriber.

iv. The mobile uses RAND and Ki in the SIM card to calculate the signed response (SERS) using algorithm A3.

v. Mobile sends the SERS back to the network where it is compared with SERS generated earlier.

vi. The authentication is complete if both SERS match and network access are granted.

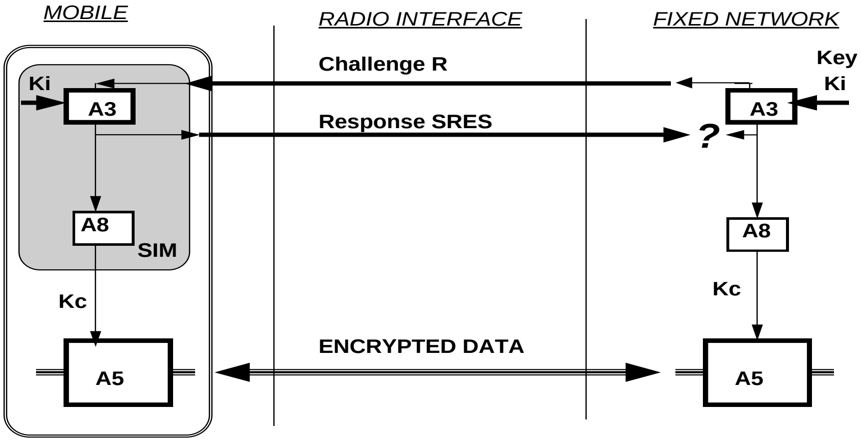


Figure 67 Authentication and Encryption in GSM (RF Telecom, 2009)

In this system, the key Ki is never transmitted over the wireless interface and resides at SIM and in AuC, HLR, and VLR databases. The algorithm A3, a one-way function, is determined by the operator as per their requirement. The A3 uses different RAND every time and hence SERS generated is also different every time making eavesdropping and impersonating a user difficult. (ETSI, 1993)

Subscriber identity protection

The transmission of IMSI is done only once at the time of switching on the equipment. After that network assigns a Temporary Mobile Subscriber Identity (TMSI) number which is used by mobile till it is switched off or user changes its location. This process avoids user identification by an attacker by finding out the IMSI number using eavesdropping. The TMSI is administered by VLR and is stored in SIM when mobile is switched off. (ETSI, 1993)

Data encryption

The data from mobile to BTS is encrypted under network control. A different key is used for each frame to protect the system from eavesdropping. The encryption uses cyphering key Kc. The Ki used during authentication is processed using ciphering key generating algorithm A8 to provide 64-bit ciphering key Kc as shown in Figure 67. The Kc along with ciphering algorithm A5, implemented in hardware for real-time encryption and decryption, encrypts the data transmitted over a wireless interface. The SIM runs algorithm A8 when algorithm A3 is used. The use of Kc is allowed through a command from the network. The ciphertext is generated by XORing the user data with binary data stream called cipher blocks. The decryption is done by XORing the cipher blocks with received data. A number called COUNT is also used while generating cipher text as shown in Figure 68. The COUNT is based on the TDMA frame number. The algorithm is reset after a burst of 2 data blocks. The use of COUNT ensures that each ciphertext is different than earlier one. (ETSI, 1993)

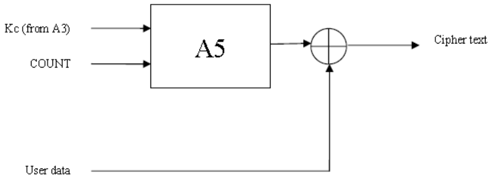


Figure 68 Ciphertext generation (Yasir Korkusuz, 2012)

The algorithm A5 has many variants such as A5/0, A5/1, and A5/2. A5/1 is strongest and used in Europe and America. A5/0 has no encryption and used where encryption technology is not available. A5/2 is used in the Asian region. (Srinivas, 2001)

The Ciphering Key Generating Algorithm A8 is defined by the operator and generates 64-bit session key Kc from 128-bit RAND and 128-bit Ki as shown in Figure 69. Most operators implement A8 and A3 together to provide COMP128 a single hash function. The COMPS128 creates Kc and SRES. Due to leakage of COMPS128, it is no longer used and instead COMP-128-2 or COMP-128-3 are used. (Srinivas, 2001)

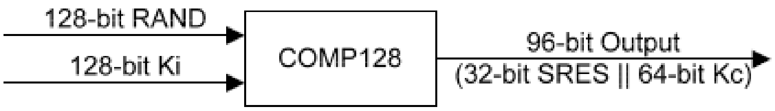


Figure 69 Comp128: SRES Session Key (Yasir Korkusuz, 2012)

5.3.3.2 GPRS Network Security

GPRS uses GSM security features and some more features. Since GPRS is IP based it is vulnerable to the weak point of IP and user can exploit it to get into the network.

The GPRS uses authentication as in case of GSM user. GPRS issues Temporary Logical Link Identity (TLLI) after the first use of IMSI instead of TMSI in GSM. The TLLI is used along with routing area identity (RAI). The relationship between TLLI and IMSI is retained by SGSN in its database. The TLLI can be generated directly by mobile or derived from TMSI. (ETSI TS 101 106 V7.0.0, 2001)

GPRS ciphering algorithm (GPRS-A5) or GPRS Encryption Algorithm (GEA) is used for data encryption in the GPRS network. Three versions of GEA namely; GEA1, GEA2, and GEA3 are used. Encryption key GPRS-Kc is used for GEA due it being stronger and more processing ability. On the network side, the serving SGSN does encryption and decryption for data and signaling over Abis, Um and Gb interfaces. During negotiations, mobile station conveys to SGSN the GEA version supported and the version used is selected by SGSN during the authentication phase. (ETSI TS 101 106 V7.0.0, 2001)

The GEA, a symmetric stream cipher algorithm, uses frame dependent input (INPUT 32-bits), transfer direction (DIRECTION 1-bit), and GPRS-Kc (64-bits) to produce output string ranging from 5 to 1600 bytes. The INPUT depends on frame type and ensures that each frame ciphering is different. (ETSI TS 101 106 V7.0.0, 2001)

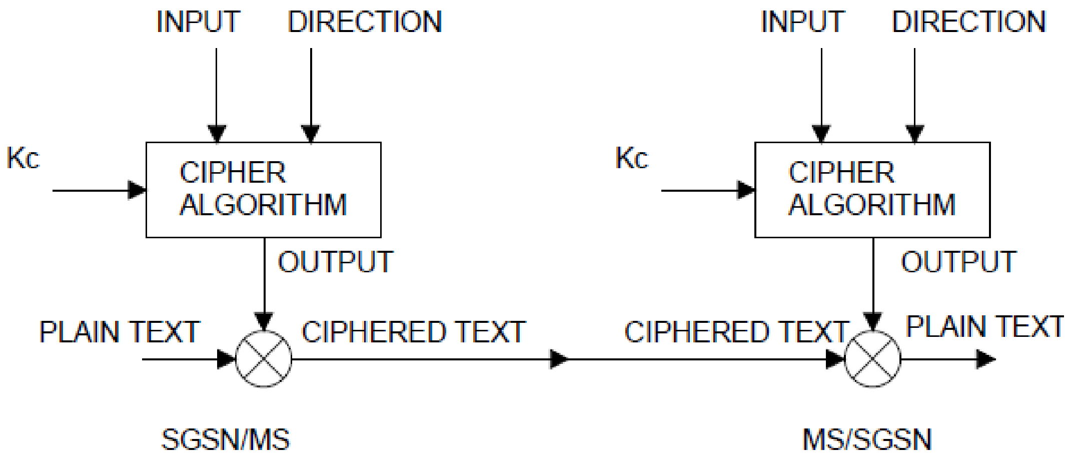


Figure 70 Basic GPRS ciphering environment (ETSI TS 101 106 V7.0.0, 2001)

The DIRECTION is 1-bit information on the uplink or downlink data transmission. The OUTPUT string is XORed with the PLAIN TEXT to get ciphertext which is sent over the radio interface. At the receiving end, the ciphered text is XORed with the OUTPUT string o get original data. When mobile moves to the different cell the parameters GPRS-Kc and INPUT are sent to new SGSN using routing area update to ensure service continuity. (ETSI TS 101 106 V7.0.0, 2001)

The data transmission in the GPRS backbone has no security features, and all the data is transmitted as plain text. The interconnection of GPRS data between various operators is based on IP with no security. To prevent unauthorized access to GPRS network, Network Address Translation and private IP address are used by the operators. The network protection is done by using a firewall at the border of the network. The system does not allow any other bandwidth demanding protocols to avoid bandwidth consumption by a group of subscribers. GPRS system allows the use of static VPN between GPRS network elements as well as GPRS backbone networks. (Christos Xenakis, 2008)

5.3.3.3 Vulnerabilities in GSM Network

In spite of various security measures adopted the GSM network was found to be vulnerable to various attacks as per details below (Toorani & Beheshti, 2008):

Unilateral authentication

The GSM system provides only one-way authentication with the user getting authenticated but no authentication for BTS. This can allow an attacker to install a rogue BTS identical to the subscriber's network and launch a man in middle attack or steal information. The cloning of BTS was not considered earlier due to the high cost of the equipment, but with prices dropping substantially the cloning is a reality. (Toorani & Beheshti, 2008)

Flaws in the implementation of A3/A8 algorithms

The selection of A3 and A8 algorithms are left to the operators. Most operators use COMP128-1 which was developed by GSM association. It was shown that COMP128-1 could be broken using reverse engineering. The analysis of around 150,000 RAND-SRES pairs can reveal Ki and also make Kc weaker. A similar problem was found with COMP128-2 and this lead to the introduction of a new version called COMP128-3 with the 64-bit session key. (Toorani & Beheshti, 2008)

SIM card cloning

The use of COMP128-1 allows derivation of Ki in SIM card using an attack called partitioning provider attacker can access SIM card for a min. The knowledge of Ki allows cloning of the SIM card. Unfortunately, software is available for cloning SIM. For cloning, a card reader scans the SIM card on its serial port and the software reveals the key. Another software can be used for creating a SIM.

Flaws in cryptographic algorithms

Algorithms A5/1 and A5/2 are weak, and both can be broken in 2 min after capturing data. (Becher et al., 2011)

Lack of user visibility

The ciphering of data can be disabled by a BTS without the user knowing about it. This allows a rogue BTS to disable ciphering and transmit mobile data in plain text.

Leaking the user anonymity

The user is required to send IMSI when entering the network for the first time. This can be exploited by a rogue BTS by sending a request for identity and in turn, get user's IMSI number.

Other Vulnerabilities

GSM does not provide message integrity to the user, and the user cannot verify the integrity of the message. The use of forwarding error correction (FEC) before cyphering makes algorithms used vulnerable.

Research showed that using Botnets on mobile devices DoS attack can be launched on the network and the HLR is the weakest link in the system. By sending a large amount of traffic to HLR, the system output can be reduced by 93% (Traynor et al., 2009).

The attack on the SMS infrastructure of GSM was shown by (Becher et al., 2011)

The GPRS network was found to have vulnerability at many points including SIM card, the interface between the SGSN and the mobile, backbone network and connectivity with outside network or operators. (Christos Xenakis, 2008)

5.3.3.4 Vulnerabilities detected in use of GSM for railway applications

A cryptographic analysis of the European Rail Traffic Management System (ERTMS) protocols showed that an attacker can forge train control messages (Chothia, Ordean, De Ruiter, & Thomas, 2017). The system uses three protocol stacks with GSM-R at the bottom provides encryption, above this, the authentication and integrity are provided by EuroRadio protocol and on top is application layer protocol for ETCS that provide a timestamp and message acknowledgments for preventing a replay attack. Since MAC (Message Authentication Code) algorithm used in EuroRadio is only 64-bit, there is a possibility of it getting repeated, and if an attacker can wait for enough time, the repeating can be captured though chances are 1%. The authors of the paper suggested mitigation of this risk by restricting the use of EuroRadio in high-bandwidth Applications or use suggested MAC algorithm, renegotiation of sessions to reduce the possibility of collisions or combine EuroRadio and Application Layers to provide secure service. (Chothia et al., 2017)

Another research showed the vulnerability of Cipher Block Chaining MAC (CBC-MAC) algorithm in EuroRadio protocol using a birthday attack on the DES cipher used. To mitigate this problem authors, propose the use of AES cipher instead of 3-DES. (Franeková, Rástočný, Janota, & Chrtiansky, n.d.)

5.3.3.5 LTE Network Security

The LTE security requirements are detailed in Figure 71. The security provided in LTE is better than that for UMTS. In addition to security in UMTS, the LTE provide forward security to prevent further attacks, use of separate key depending on purpose so that in case of compromise in one key the whole system is not compromised, and mandatory integrity for NAS and Radio Resource Control (RRC). (Prasad & Sŏ, 2011)

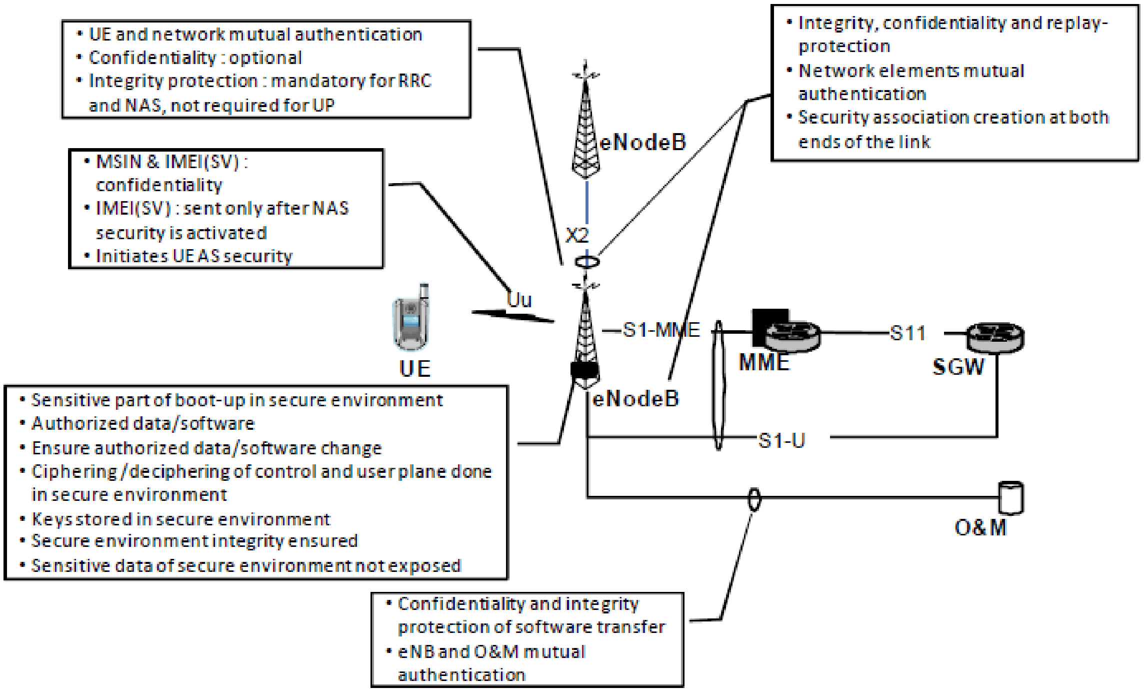

• UE and network mutual authentication
• Confidentiality : optional
• Integrity protection : mandatory for RRC and NAS, not required for UP
• Integrity, confidentiality and replay-protection
• Network elements mutual authentication
• Security association creation at both ends of the link
• MSIN & IMEI(SV) : confidentiality
• IMEI(SV) : sent only after NAS security is activated
• Initiates UE AS security
eNodeB
X2
Uu
UE
S1-MME
MME
S11
SGW
eNodeB
S1-U
O&M
• Sensitive part of boot-up in secure environment
• Authorized data/software
• Ensure authorized data/software change
• Ciphering /deciphering of control and user plane done in secure environment
• Keys stored in secure environment
• Secure environment integrity ensured
• Sensitive data of secure environment not exposed
• Confidentiality and integrity protection of software transfer
• eNB and O&M mutual authentication

Figure 71 SAE/LTE security requirements (Prasad & Sŏ, 2011)

5.3.3.5.1 3GPP LTE Security Architecture

The security architecture of LTE similar to UMTS has five security levels as shown in Figure 72.

Layer 1- Network entrance security: This layer provides user identity confidentiality, mutual authentication and key agreement (AKA), and confidentiality and data integrity. The user identity confidentiality is provided using Universal Subscriber Identity Module (USIM) which is never transmitted over the wireless network. Encrypted Temporary ID is used to mask the real identity of the user. The mutual authentication between the user (UE) and the network (HSS & ME) is provided using the AKA protocol. The authentication between mobile and non-3GPP network is provided using Extensible Authentication Protocol-AKA (EAP-AKA) or Improved EAP-AKA. The confidentiality is maintained by using f8 function and 128-bit keys *CK*(*i*) and *IK*(*i*) generated during authentication. The integrity is provided using the f9 algorithm. (Prasad & Sŏ, 2011) (Ahmed, Anwar, & Arshad, 2016)

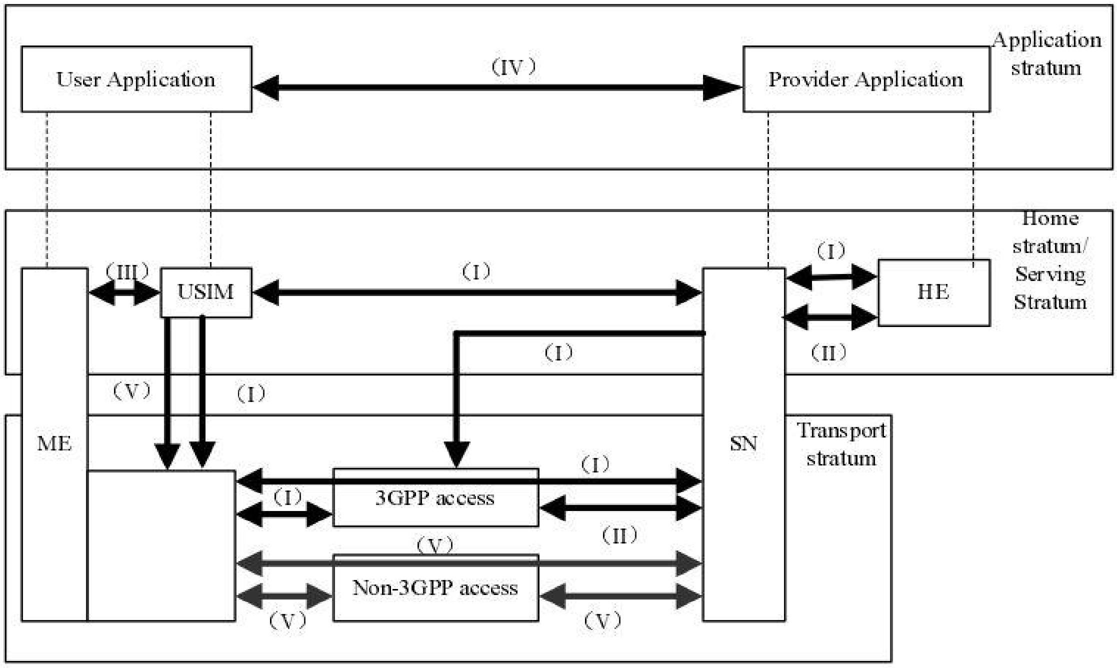


Figure 72 Security Architecture of LTE (Ahmed et al., 2016)

Layer 2- Network domain security: This layer provides parameters for secure exchange of user and signaling data along with protection against wireline type attacks.

Layer 3- User domain security: The user is allowed to access USIM only after authentication to avoid unauthorized users accessing USIM. A shared secret key (PIN) stored in USIM and with UE is used for this. The access between the terminal equipment and the user is also restricted by using the shared secret key.

Layer 4- Application domain security: A USIM application toolkit is used to develop application residing in USIM to provide security features.

Layer 5- Non-3GPP domain security: This layer provides a methodology for the user equipment to securely access the EPC using the non-3GPP system.

5.3.3.5.2 LTE Security Vulnerabilities

Femtocells: Femtocells are used for extending coverage of LTE. These are physically accessible by the user and not under control of the network. The software in these devices can be modified to drive UE to use clear text during AKA to create a breach in the network (Bilogrevic, Jadliwala, & Hubaux, 2010).

Interoperability: The LTE systems interface to legacy systems is a weak point as the protocol EAP-AKA used for interconnection is vulnerable to MiM attack, user identity disclosure, Sequence Number(SQN) synchronization, and bandwidth consumption. (Escudero-Andreu, Raphael, & Parish, 2012)

RRC Signaling: Few RRC message is sent without encryption before security domain is established. These messages can be intercepted using traffic-injection attack and the sent repeatedly to eNB to collapse the system. As the system is unable to detect attack, it leads to DoS. (D. Yu & Wen, 2012)

Location tracking: The UE location tracking is also a breach as UE is not aware of the same. A temporary UE identifier (UEID) called C-RNTI is transmitted in plain text in a cell. When the user moves to another cell new C-RNTI is transmitted. The C-RNTI can be sniffed by an eavesdropper to track the user. (Seddigh, Nandy, Makkar, & Beaumont, 2010)

Other threats: The system being IP based is vulnerable to attacks related to IP. UE switches off the radio when not transmitting to save on power. The attacker can inject a message using C-RNTI of a UE during this period and it is like stealing bandwidth. (Seddigh et al., 2010)

5.4 Defense-in-Depth for Rail communication Network

5.4.1 SCADA Security Strategy and Risk Mitigation

Security of industrial control systems which was limited to providing password-based protection in the earlier proprietary system has gained importance after use of standard hardware and software in these systems and attacks on these systems. In the face of mounting cyber threats, the secure design of the system has become a challenge for the designers. The challenges include taking care of the limitations of current technologies for securing systems, economic viability and justification for providing security and organization’s conflicting priorities for implementation of security for the control system. (GOA, 2004)

APTA recommends that approach to security for corporate information system need to be different from industrial control systems (APTA-SS-CCS-RP-002-13, 2013). In the business, the confidentiality of information is most important, and the next in line is the integrity of the information it gets. The availability is the least important of three. On the other hand, for industrial control systems availability is most important followed by the integrity of information, and the confidentiality is of least importance. The table below shows the comparison. (APTA-SS-CCS-RP-002-13, 2013).

Table 3 Comparison of priorities for Business and control systems

	Business IT Priority	Control System Priority
Confidentiality	High Importance	Lower Importance
Integrity	High Importance	High Importance
Availability	Lower Importance	High Importance

However, since both the systems are connected to each other, it is necessary that the security deployment at each side complement the other to make the system fully secure (NCS, 2004).

The NCS has provided broad guidelines for the development of security strategy to protect SCADA system (NCS, 2004). Guidelines state that the security system strategy should do an analysis of both corporate and SCADA network including security policy, operating systems, firewalls, and communication system deployed.

Figure 73 shows the relationship between defenses of corporate and SCADA network as depicted by NCS. The attacks can originate from corporate network to SCADA system using the Internet or internally from the corporate network. Similarly, the attack can be initiated from SCADA networks towards the corporate network.

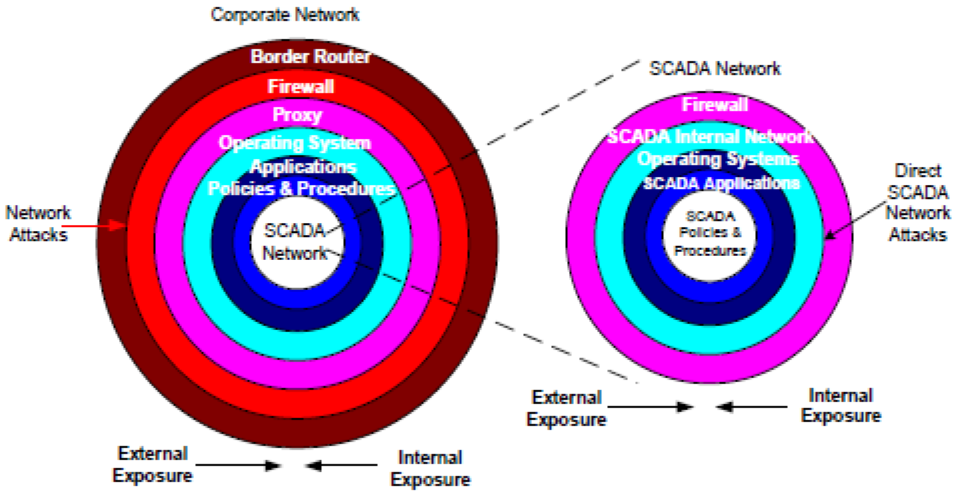


Figure 73 Relationship Between Corporate and SCADA Networks (NCS, 2004)

It is required that the security measures deployed by the corporate network are configured properly and hardened to mitigate vulnerabilities. Proper measure to secure the system against worms, virus, trojan horse, overruns and other malicious codes need to be taken as these can bypass protection of firewalls. The measure must include a separate firewall for corporate and SCADA system. SCADA system hardware and software also need to be hardened along with the deployment of a strong security policy. The complete system protection requires a ring of defense around the complete network to mitigate the risks. (NCS, 2004)

The National Institute of Standards and Technology (NIST) has published Guide to Industrial Control Systems (ICS) Security vide it's Special Publication 800-82 (Stouffer et al., 2015). The guideline is given in the report for the security of SCADA systems as well as for distributed control systems, and Programmable Logic Controllers (PLC).

As per NIST guidelines, development of security strategy should use the following steps (Stouffer et al., 2015):

- Business Case for Security: The preparation of the business case for security is required to address concerns of management, impact on business, and financial justification. The business case must include benefits of improvement in control system reliability and availability, the repercussion of non-implementation of ICS security measures, resources required and cost of implementation.
- Program development: The security implementation program needs to be comprehensive and include all aspects of security. It is important that program includes scope, charter, inventory of assets, vulnerability and risk assessment, risk mitigation, senior management's approval and support, security awareness program and training.

5.4.2 Network Architecture for ICS security

The NIST report for ICS security recommends that the ICS network should be logically as well as physically separate than the corporate network as both have different requirements. Both the network should use Defense-in-Depth Architecture by using multilayer protection. There should be an only single interconnection between the two networks and a properly configured firewall should be deployed to deny all traffic other than required. The firewall needs to be configured to provide source and destination filtering in addition to normal filtering. The use of DMZ between two networks can make all communication via the DMZ zone to isolate two networks.

The use of intrusion detection system and implementation of strong security policy is primary requirements. The workable incident response mechanisms, regular and comprehensive training programs must be part of the security management. The NIST report provides a representative architecture for providing defense in depth as shown in

Figure 74. The architecture depicts the use of firewall and demilitarized zones at appropriate places for providing security along with intrusion detection system at all locations to detect any attacks. (Stouffer et al., 2006)

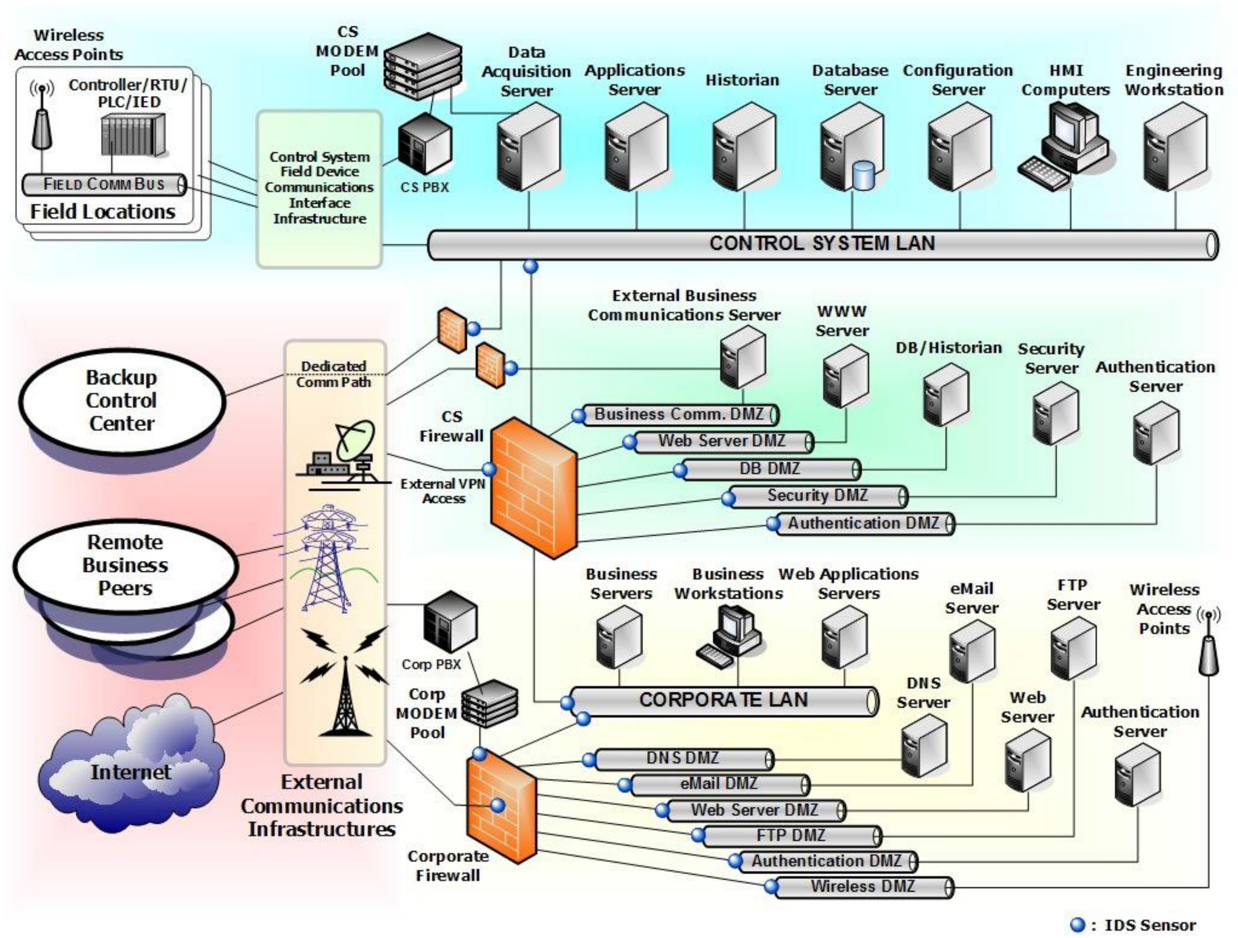


Figure 74. CSSP Recommended Defense-In-Depth Architecture (Stouffer et al., 2015)

Paganini (2013) in his report on improving SCADA security advises the use of NERC Cyber Security Standards for risk mitigation in SCADA systems (Paganini, 2014). This requires risk identification, controls to mitigate the risk identified, maintenance of risk levels acceptable using continuous monitoring and evaluation. Each point of connecting in the SCADA system is vulnerable and need to be monitored, and steps are taken to reduce the risk for each point of connecting. The risk mitigation techniques such as encryption and authentication may be used. The use of a layered approach to security with hardening of each layer is must for defense in depth. Another important part is to develop and put in place a backup and disaster management plans so that in case of any disaster the system can be brought online with minimum loss of time. (Paganini, 2014)

5.4.3 Recommendation for Defense in Depth Strategy

As per NIST, the defense in depth strategy for supervisory control system should include following (Stouffer et al., 2006):

- Development and implementation of a strong security policy along with requisite training and documentation. This should include contingency planning, business continuity planning, disaster recovery planning
- Taking care of security for the full life cycle of the system starting from design to implementation and decommissioning
- Providing physical and logical separation between corporate and train control system
- Use of DMZ network architecture between corporate and train control system.
- Provide redundancy for all critical components of the network
- Disable all unused port and service in the system.
- Restrict physical as well as logical access to the network using role-based access control. Use the principle of least privilege for configuring each role.
- Use a separate authentication mechanism for corporate and train control system.
- Use software to detect and control virus, trojan horse and other malicious software
- Use strong encryption for data transmission and storage
- Keep the entire system update with the latest security patches.
- Install intrusion detection system for each network.
- All systems and equipment must be hardened and configured for maximum security.
- The wireless network must be configured for maximum security.

6.0Train Control System Vendors

Major Train communication system vendors and key equipment offered by them:

Vendor	System/Equipment
Alstom	• Mainline/ Mass transit/ Freight & mining signaling • Urbalis CBTC • Smartlock 400: computer-based interlocking signaling system
Ansaldo STS	• OTP traffic management and railway handling system • ATC (Automatic Train Control) and ATP (Automatic Train Protection) systems for ERTMS • CBTC • WSP (Wayside Standard Platform) interlocking system • Satellite signaling • TCCS - Train Conformity Check System
Argenia	• SafeNet PTC non-vital overlay system • Axle counters for yards, crossings, blocks
Bombardier	• Mainline/ Mass transit/ Freight & mining signaling • Communications-based train control (CBTC) • Wayside Components ○ Radio block center ○ Train to track communication ○ Switch point machines ○ computer-based interlocking (CBI) • European rail traffic management system (ERTMS) • Rail control services solutions
CAF Power & Automation	• HST/Mainline/ Mass transit/ Freight & mining signaling • ITS (Intelligent Transport Systems) based on CIT technology • ERTMS level 1 and level 2

	• Electronic Interlocking • Integrated and Multifunctional Control CentresGateways. • Remote communications: data transmission (GSM / GPRS/ UMTS / HSDPA / Wi-Fi).
CellRail™	• Trackside network solution for the provisioning of onboard WIFI connectivity
Duagon	• MVB - Multifunction Vehicle Bus for train and railway • WTB to MVB Gateway • Train Real-time Data Protocol
Invensys Rail/ Siemens	• Sirius CBTC • Rail 9000 automatic train supervision (ATS) • Westrace Mark 2 electronic interlockings • Platform screen doors (PSD)
Nippon Signal	• Automatic Train Supervision system • CBTC (SPARCS) • Multi Section Digital Axle Counter • Level Crossing system
NOKIA	• GSM-R/TETRA/WiMAX solutions • Optical, IP / MPLS Networks • Video surveillance (CCTV) • Control room and train management system • Integration with security and train signaling systems • Supervisory Control and Data Acquisition -- SCADA solutions • Operation Support Systems (OSS) • Broadband ground/train communications (satellite, LTE, 3G, Wi-Fi) • Trackside wireless • Station infrastructure

	• Operational telephony and communication applications
Siemens	• Trainguard MT – automatic train control system based on CBTC • Trainguard Zub 200 – intermittent automatic train control system • Trainguard LZB 700 M – continuous automatic train control system • Trainguard Imu 100 – inductive transmission system • Operations control systems and Rail-IT solutions o Operations control systems o SCADA Railcom Manager – Communications management system • Signaling products: Frequency track circuit, Point machine, Signals, Axle counter systems • Electronic interlockings o Trackguard Sicas ECC (Siemens Computer Aided Signaling - Element Control Computer) o Trackguard Westrace Mk II is a highly flexible microprocessor-based interlocking system
Thales	• European Train Control System • LockTrac electronic interlocking • Advanced Railway Automation Management & Information System • Axle counters, track circuits, point (switch) machines, checkpoints, light signals, level crossings, etc.

7.0Conclusion

The rail communication and control system has evolved over the period in order to prevent accidents, increase density and provide safe operation of the system. Many initiatives have been taken by the governments, standard bodies, train operators, associations and manufacturers. The U.S. has mandated the use of a PTC system and Europe has gone for ETCS. The standard bodies such as ETSI, IEEE, etc. have published standards suitable for rail TCN and communication systems.

The modern train control system depends heavily on the communication network for critical data transfer from devices within train to train control system onboard, an onboard system to wayside facilities, from wayside facility to central/regional control centers, and links to the corporate network. The communication network includes wired as well as wireless networks. The SCADA and IT systems are used extensively to monitor and control rail operations. The communication and IT system play a critical role in the safe and secure operation of the train system. In order to improve the system, reduce wayside equipment and provide increased density and safety, the rail operations are using technologies such as communication-based train control system along with communication systems such as TETRA, Wi-Fi, GSM-R, and LTE-R. The CBTC system provides exact train location and allows the system to shift to moving the block from fixed block thereby increasing system capacity and safety. The communication systems provide quick transfer of information on track conditions ahead and also allow automatic application of brakes in case of laxity on the part of the driver in acknowledging the status to control system. In order to provide more information to the driver about conditions ahead using CCTV feed at strategic locations and amenities such as TV, News, Internet access to passengers in train and stations new high-speed technologies are needed. The UIC has come out with requirements of Future Railway Mobile Communications System and is looking at various options and technologies to be used for the next generation of systems. Use of operational technologies such as LTE-R and upcoming technology such as 5G is being explored. Security is another important aspect as the IT-based technologies using Cots are vulnerable to known attacks. To address security concerns, the implementation of security using defense in depth is most important and includes the use of strong security policy, updated system patches, use of firewalls, use of antivirus and anti-malware software, provide adequate training and security awareness, and hardening the system for maximum security. The use of new technologies and the implementation of security control can provide safe and secure operation of the rail system and provide modern facilities to the passengers.

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