Digital Transformation of Railway Signalling through Emerging Communication Technologies

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Abstract -- **Rail transportation is crucial for sustainable mass transportation of goods and people due to its attributes such as safety, reliability, high capacity and energy efficiency. Rail transit is undergoing rapid transformation through emerging technologies around the world. Recently, rail transit has become faster, safer and more comfortable and it has high capacity thanks to the emerging systems like Communication Based Train Control (CBTC), Train Collision Avoidance System (TCAS). Indian Railways is planning to upgrade its entire rail network with modern signals and anti-train collision system. In this paper, definition, principles and working mechanism of CBTC and TCAS systems which make use of emerging communication technologies are presented.**

Keywords: Rail signalling systems, Communication based train control, Train collision avoidance system, driver machine interface, Colour light signals

I. INTRODUCTION

HIGH speed rail and urban rail transit achieved rapid development around the world. Rail transport is crucial for sustainable transportation due to energy efficiency, reliability, high capacity and safety. Road transport, the most widely used for passenger and freight causes problems like accidents, congestion and excess energy consumption. India accounts for one per cent of world's vehicles but accounts for 11% of road crash deaths, killing one person every four minutes [1]. Accordingly, Urban rail systems are becoming widespread in major cities of India. Efforts are afoot to upgrade rail transportation to reduce such problems.

Rail transport involves considerable brake distances due to low friction and heavy weight. So, the most important aim of the signalling systems is to prevent train accidents and derailment [2]. Globally, countries started exploring technologies for more safety. Such technologies involve effective use of railway signalling and communication regimes *viz.* Communication Based Train Control (CBTC). Indian Railways is planning to upgrade its entire rail network with modern signals and anti-train collision system with indigenous Anti-collision technology, namely Train Collision Avoidance System (TCAS).

Conventional railway signalling systems used for over 100 years are based on colour light signals and train detection via track circuits and axle counters. Tracks are divided into blocks and track circuits and axle counters are installed to determine if a train or a part vehicle is inside a block. Each block is protected by a signal. If a train is inside a block, the entrance block signal will be red and the train from the adjacent block is not allowed to enter the block [3].

Modern communication-based systems enable utilizaion of track to maximum capacity. CBTC is one such radio communication-based signalling system. It enables high resolution and real-time train control information increasing line capacity by reducing the distance between trains travelling on the same line while minimizing numbers of trackside equipment. In India, CBTC is being introduced on Metro Railways using communication technology such as LTE, GSM-R and TETRA.

CBTC system, is an automatic train control system that enables continuous, high-capacity, bidirectional data exchange carrying vital information to equipment within line-of-sight. It enables determination of train location, independent of track circuits/ axle counters.

II. CBTC SIGNALLING SYSTEMS

Figure 1 depicts block schematic of a typical CBTC system.

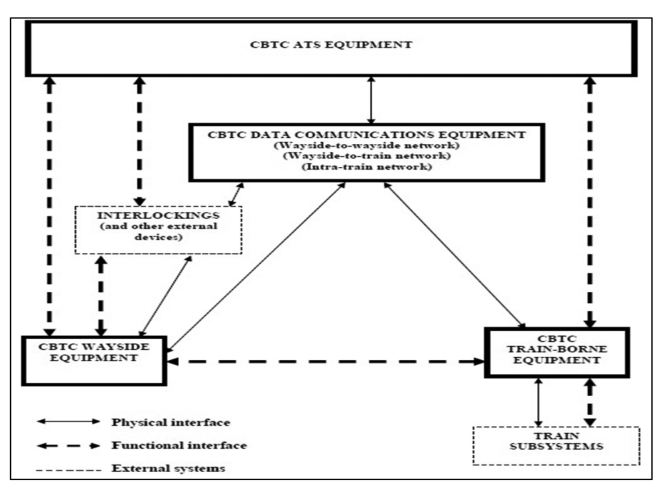

Figure 1: CBTC Subsystems.

The main subsystems are CBTC wayside equipment, train-borne CBTC equipment and Data Communications equipment of CBTC. Also, all CBTC systems comprise automatic train protection (ATP) systems and automatic train supervision (ATS) equipment. They may also contain automatic train operation (ATO) and automatic train control (ATC) systems [5].

A computer on the train manages authority to move the train using driver, train and other communication modules. CBTC Wayside equipment comprises Interlockings and Balises besides ATS-ATP or ATO control centres. Combination of software and hardware equipment forms the Radio communication system consisting of data communication computer, antenna, Wi-Fi control centre [6]. Figure 2 shows CBTC system equipment details.

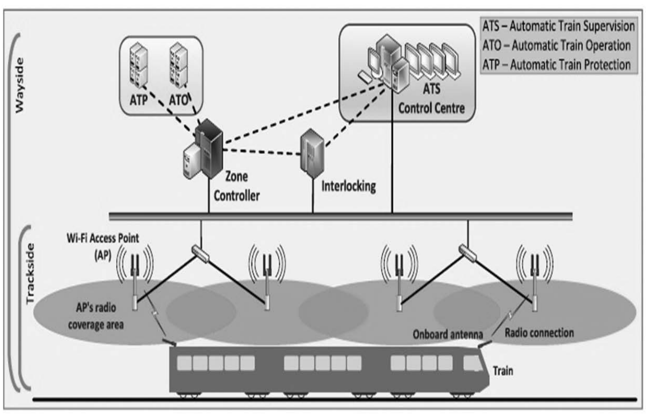

Figure 2. CBTC equipment [11].

III. CBTC WORKING MECHANISM

On a railway equipped with a mobile block system, the line is usually divided into areas or zones as shown in Figure 3. The CBTC system relies on two-way continuous digital communication between train and control centres along the railway.

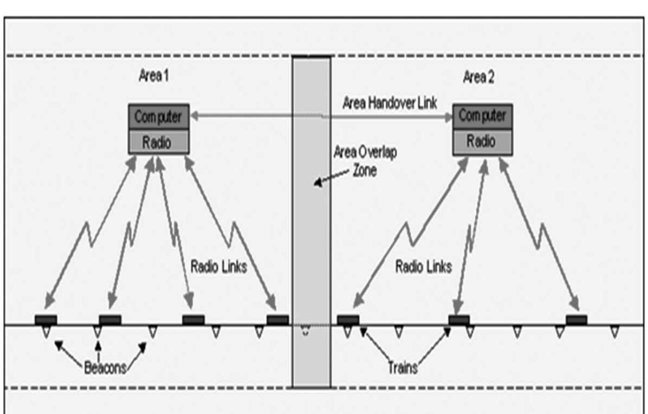

Figure 3. CBTC system.

Each zone is under computer control, having its own radio transmission system. Each train transmits its identity, location, direction and speed to the regional computer which makes calculations and sends them to the next train. The radio link between each train and zone computer is continuous. Thus the computer knows location of all trains in its territory at any time. Radio links transmit each train the position of the train in front of it and give inputs to stop before reaching the train in the front. In case train doesn't follow commands, the ATP or ATS system automatically stops the train.

Using the information, about the route status and the type of the route set, state of the elements on the route and the train location information already determined from the message received from the trains, CBTC system will determine the movement authorities as shown in Figure 4.

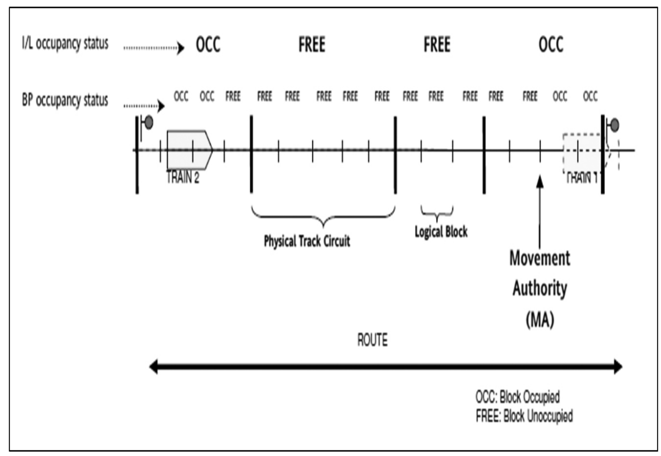

Figure 4. Movement Authority in CBTC system.

The movement authority receives following important information from CBTC system:

- Temporary speed restrictions
- Static speed profile
- Gradient profile
- ATO platform data and stopping point information
- ATP door enabling information
- Reversing area information
- EoA: End of Authority is the location to which the train is authorized to move
- DP: Danger Point is the location that can be reached by the front-end of the train
- The end of an overlap is a location beyond the danger point reachable by the front end of the train.

IV. INTERNATIONAL SCENARIO

World's busiest metros utilise CBTC systems. CBTC technology has been (and is being) successfully implemented for a variety of applications. They include complex overlays on existing railway networks carrying more than a million passengers each day and with more than 100 trains. Table 1 lists CBTC usage in Metros around the world.

TABLE 1 -- GLOBAL METROS USING CBTC TECHNOLOGY

S.N.	Location/ Country	Lines/ System
1	London Underground	Jubilee line
2	New York City Subway	IRT Flushing Line
		BMT Canarsie Line
3	Singapore MRT	North East Line
4	Hungary	Budapest Metro M4
5	Brazil	Sao Paulo Metro
6	Beijing Subway	15
7	Ankara Metro	M1
8	Riyadh Metro	L4, L5 & L6
9	Delhi Metro	Line 8
10	Madrid Metro	1, 6
11	Paris Metro	1

CBTC technology has been mostly used in modern subway systems. As shown in Figure 5, almost 156 subway lines use CBTC signalling systems. What's more, half of these systems are used in Asia, also as shown Figure 5. China, Japan and India have a lot of subway lines and most of the subway lines use CBTC technology. USA and many European countries also are the most important CBTC signalling systems user in their subway lines. To illustrate some of the important metro lines used by the CBTC: Shanghai, Beijing, Guangzhou, Tokyo, Delhi, Singapore, Kuala Lumpur, Hong Kong etc. are some important metro lines using CBTC signalling systems from Asia.

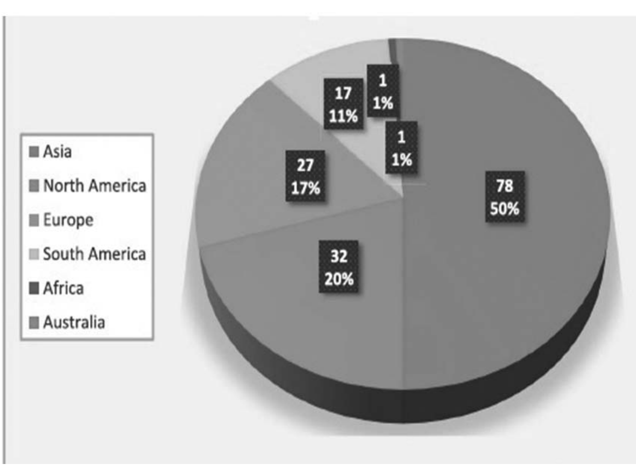

Figure 5. CBTC projects worldwide [11].

From Europe: Madrid, London, Paris, Barcelona, Istanbul, Munich, Amsterdam etc. are some important metro lines using CBTC technology. Some important subway lines using CBTC signalling systems from America are New York, San Francisco, Las Vegas, Mexico City, Buenos Aires, Sao Paulo subway lines.

CBTC systems are used with ETCS (European Train Control System).

V. BENEFITS OF CBTC SIGNALLING SYSTEM

CBTC signalling systems provide many advantages over traditional signalling systems. To explain benefits of the CBTC system some examples from across the globe are examined. Benefits are as follows:

- CBTC signalling systems provide shorter headway and that means they can also offer higher capacity. As shown in Figure 6, the distances between trains are shorter when CBTC signalling systems are used and therefore, these systems offer the possibility of making more train trips [7]. We can see three trains between two stations with short distance between them as Figure 6.

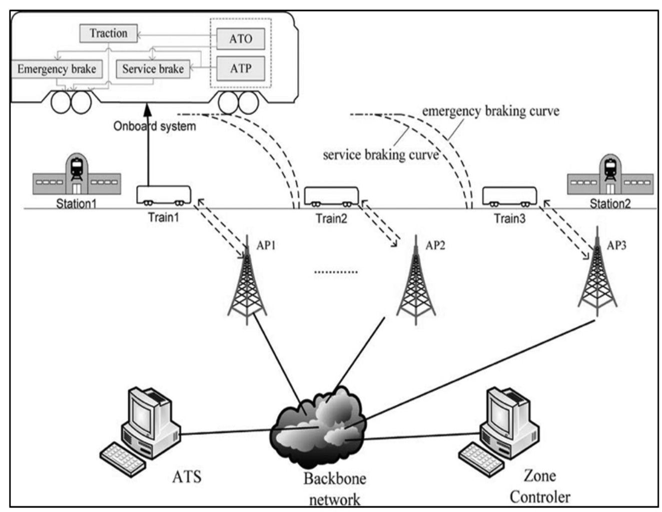

Figure 6. CBTC system [8].

- It is possible to operate trains with very short headway such as 2-3 minutes in the CBTC system. For example, trains are now operated at 5 minutes headway, but in the past the headway was between 10 and 20 minutes at suburban trains.
- CBTC signalling systems are safer than conventional signalling systems due to automatic intervention via ATP, ATO systems, when any undesired situation occurs.
- CBTC signalling systems are more energy efficient than manual driving. These systems may also enable regenerative energy by adjusting the positions of trains.
- Trains operated with CBTC are more comfortable as CBTC systems are compatible with in-train information displays. These allow information screens showing departure times of trains and wagon numbers, station map etc.

- CBTC signalling system protects against human error because this system is operated by automatic systems.

VI. TRAIN COLLISION AVOIDANCE SYSTEM (TCAS)

Indigenously developed Automatic Train Protection (ATP) System provides protection to trains against Signal Passing at Danger (SPAD), Excessive Speed and Collisions. TCAS provides continuous update of Movement Authority (MA) (distance up to which the train is permitted to travel without danger).

During unsafe situations requiring brake application, automatic brake application takes place. TCAS displays information like speed, location, distance to signal ahead in driver's cab. It generates SOS messages from Loco as well as Station unit in case of emergencies.

VII. FUNCTIONING OF TCAS

The trackside sub-system of TCAS consists of RFID tags fitted on track in station section and block section for giving trackside information to the TCAS unit installed in driver's cabin. Berthing tracks, point and block sections are assigned unique IDs called Track Identification Number (TIN). Both TIN and RFID tags determine the train direction.

The system also comprises TCAS unit installed at Station to communicate with locomotives in station area. Stationary TCAS is interfaced with station interlocking to acquire real-time dynamic signaling information. Stationary TCAS unit gets real-time information regarding locations and speed of trains in its jurisdiction through UHF [9].

Moreover, separate stationary TCAS unit is provided at mid–section interlocked level crossing gate and intermediate block signaling locations if they don't come within the coverage of station radio tower.

The onboard Loco TCAS unit installed in driver's cabin determines the location of train by reading pre-programmed RFID Tag data with the help of RFID reader.

If a signal on approach is Red, the Stationary TCAS unit transmits this information to the Loco TCAS and reduces the movement authority to zero.

Communication technique used for transfer of information between Stationary and Locomotive units in station area is Full Duplex UHF Radio Communication through Multiple Access TDMA/FDMA scheme.

Network Monitoring System (NMS) with a central server in divisional office monitors TCAS equipped trains and stations within the network. Transmission of exceptional fault/critical messages from Stationary TCAS as well as Loco TCAS to NMS is done through respective GSM interfaces. NMS enables troubleshooting of error events, off line simulation and real-time monitoring of TCAS loco.

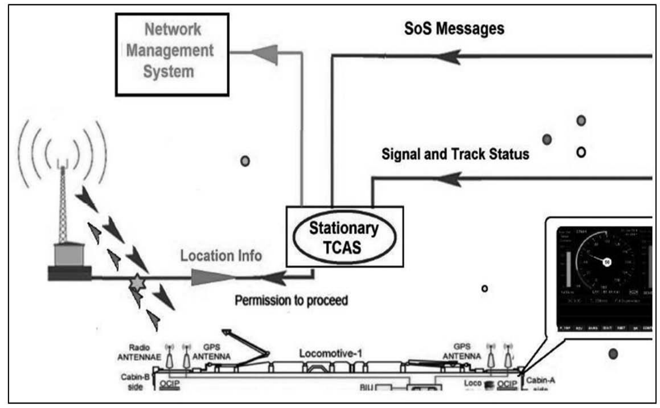

Figure 7. TCAS Functioning Schematic [10].

TABLE 2 -- SUMMARY OF TCAS FUNCTIONING [11]

Requirement	*Mechanism in TCAS*
Direction of trains	Comparing Absolute location of two RFID tags passed by train.
Location of Trains	Distance traversed beyond a RFID tag on Track Sleeper (Rail-road Tie) through speed sensing arrangement (Tachometer)
Extraction of dynamic Signaling Information	Interfacing to station interlocking (PI/RRI/EI)
Transfer of Signaling related information from Station TCAS to Train (As per SIL-4)	Radio Communication between Stationary unit & Train units through dynamic TDMA on a specific frequency pair in station area. Stationary units are allocated timeslots according to Topography and their size. Mobile units *i.e.* trains are assigned slots dynamically. This provides efficient utilization of channels.
Loco to Loco message broadcast (non-SIL-4)	In block section, in station area and in emergency situations (SoS, head-on, rear-end collisions) using a fixed frequency in its designated time slot.
Knowledge of Braking Characteristics of Train	Crude but adequately reasonable braking characteristics are determined by carrying out Brake Test at the start of mission. Adaptive braking logic to control brakes seamlessly based upon deceleration and closed loop control.
Prevention of over speed and SPAD	By reducing the movement authority based on the aspect of approaching signal.

Prevention of collisions between two trains	Through conflict between signal aspect, point position, berthing track section, signal aspect sequence and TIN in station area and through TIN conflict in block section.
Centralized monitoring of TCAS equipped trains and stations	Through Network Monitoring System (NMS)
Security of radio communication between Stationary TCAS and Loco TCAS	Using GSM/GPRS communication techniques through a Key Management System (KMS)
Real Time Clock (RTC) synchronization	Through GPS/GNSS

VIII. CONCLUSION

This paper explains CBTC signalling systems and TCAS providing technology for digital transformation of railways signalling. Such technologies like CBTC and TCAS provide safer, faster, more energy savings and more comfortable railway operations. The benefits of CBTC signalling systems will increase even more with the development of emerging communication technologies and this system will be used more for large scale networks.

TCAS would not only help avoid collisions due to human errors in signaling and invisibility of signals due to heavy rain or fog, but also alert about fire on trains and warnings about damage to the tracks during natural calamities or sabotage.

But the best is yet to come as the more advanced communication technologies like: Wi-Fi6, 5G, IPv6, IoT / M2M, AI / ML and Blockchain are becoming commercially available as use cases for railways private networks for enhanced speeds and safety as well as efficiency.

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