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NGCTCS: Next-generation Chinese Train Control System

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Abstract

The Chinese Train Control Systems (CTCS) have five levels from 0 to 4 based on the levels of the European Train Control Systems (ETCS). The complicated and redundant structures ensure the reliability and safety of CTCS. However, the requirements of the next-generation train control system to optimize system structure and to reduce cost of investment and maintenance are hardly met. First, the state of the art of CTCS was summarized in this study. Second, the system structure and characteristics of the five typical control system projects, namely, NGTC, SHIFT2RAIL, Positive Train Control, European Rail Traffic Management System-Regional, and Urbalis Fluence, were analyzed. Based on the actual construction of the CTCS, the developing demand on the next-generation Chinese train control system (NGCTCS) was analyzed. The three key technologies of moving block, cognitive radio for train-to-train (CR-T2T), and combined positioning were introduced. A system scheme for the overall structure of the NGCTCS, a train-centric train control system based on combined position technology, and CR-T2T were proposed in this study. This scheme can provide reference for Chinese railways to develop NGCTCS and to adapt to the development trend of NGCTCS to ensure security, simplify structure, optimize function allocation, and reduce the system cost of construction and maintenance.

Keywords: NGCTCS, Moving block, CR-T2T, Satellite-based train positioning, LTE-R

1. Introduction

Railway signaling systems include the centralized traffic control (CTC), train control system (TCS), computer-based interlocking (CBI), non-insulated frequency shift track circuit (ZPW-2000), and other signaling assistance systems, such as signaling microcomputer monitoring system, dynamic monitoring system, train number tracking and wireless tracking system, wireless system for scheduling transmission and power systems [1]. Although the Chinese railway TCS with different levels can meet the requirements of most railways in China, CTCS, with its high cost of construction and maintenance, are over-dependent on trackside infrastructure [2]. To improve the interoperability of different train control systems, cost-effective TCS projects implemented in Europe and the United States aim to enhance international competitiveness [3-6]. Therefore, using innovative technologies to build a next-generation train control system (NGTCS), which improves safety and interoperability while reducing infrastructure and maintenance costs, is an interesting international research topic.

Cooperating with China's "one belt, one road" strategy, the research and development of next-generation Chinese train control system (NGCTCS) is imminent. The purpose of NGCTCS is to enhance international competitiveness and to gain attention worldwide [7, 8]. Therefore, examining the requirements and key technologies and proposing a reference NGCTCS scheme are necessary to adapt to the developing trend of improving safety and efficiency and to reducing costs and complexity.

The remainder of this paper is organized as follows. Section 2 analyzes the state of the art of CTCS and compares the system structure and technical characteristics of five typical TCS projects. Section 3 presents the requirements and key technologies of NGCTCS and proposes a system scheme. Section 4 gives the conclusion.

2. State of the art of train control system

2.1 Chinese train control system (CTCS)

CTCS is a train control system developed for the mainline railways in China. At present, CTCS is divided into five levels based on the European Train Control Systems (ETCS) from level 1 to level 3. CTCS level 0 is for trains with speed less than 120 km/h with existing signal systems [2]. CTCS level 1, a theoretical level, is for trains with speed between 120 km/h and 160 km/h. This level has two general technology projects: transponder-based and radio-based CTCS level 1 [9]. CTCS level 2, a points-and-continuous control system with speed exceeding 200 km/h but less than 250 km/h, consists of trackside continuous equipment ZPW-2000 track circuits, point balises, and onboard automatic train protection (ATP). CTCS level 3, which has a global system for mobile communications for railways (GSM-R)-based advanced TCS downgrade compatibility with CTCS level 2, is for 300-350 km/h high-speed railway lines. CTCS level 4, the highest CTCS level, is considered the NGCTCS. This level adopts the moving block function for train interval control, GSM-R/long-term evolution for railway (LTE-R)

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communication system for information transmission between trains and wayside devices, and global navigation satellite systems (GNSSs), such as the global positioning system (GPS), GALILEO, and BeiDou navigation satellite system (BDS) for train positioning. Currently, the Chinese high-speed railway implements two control systems, namely, CTCS level 2 (C2) and CTCS level 3 (C3). The main physical difference between the two CTCS levels is that C2 employs track circuits to transmit train control information, with movement authority (MA) provided by an automatic block through a train control center (TCC), whereas C3 adopts GSM-R communication to transmit train control information to the trains, with MA provided by the radio block center (RBC).

Although CTCS with different levels can meet the requirements of most mainlines in China, it can hardly meet the special requirements of low-density lines in Western China because of its high cost of construction, operation, and maintenance [4, 10]. To date, CTCS commonly uses the complex "multiple equipment" solution by duplicating trackside and onboard equipment, which does not meet the performance and economic targets of the future.

On the basis of information entropy theory, the complexity of CTCS was analyzed [7]. The quantitative results given in [8] based on the case of the Wuhan–Guangzhou high-speed railway line show that the equipment structure of CTCS is extremely complex with room for improvement. The basic purposes of the NGCTCS are to develop standardized and interoperable on-board train control equipment, to reduce unreasonable redundant structures, and to satisfy the running train at different mainline control levels. Another goal of the NGCTCS is to optimize the trackside system structure by changing the trackside-dominated mode to the onboard-dominated system given the strict state of the independent dispatching, train control, and interlocking systems.

Compared with the conventional train positioning of trackside equipment, such as transponders and track circuits of railway signaling systems, a satellite-based train positioning system architecture can provide better cost efficiency with reduced trackside facilities. To achieve satellite-based train control with the advantages of cost efficiency and adaptability, GNSSs (e.g., GPS, GALILEO, and BDS) have the potential to reduce cost, realize enhanced interoperability, and provide the function of train collision early warning [11].

The GSM-R, which is the dominant railway communication system for the transmission of train control information, has some major shortcomings, such as insufficient capacity, low network utilization, and lack of advanced data service support [12]. Therefore, modern communication technology (e.g., LTE-R) was evaluated as next-generation ground wireless communication technology for railway bidirectional trains that will replace GSM-R in the near future. Applications such as collision avoidance of trains require reliable and instantaneous information exchange by an inter-vehicle communication system. Train-to-train communication is considered a novel method to avoid train collisions. Information exchange between adjacent trains in the NGCTCS and the channel models for high-speed railway were examined in [13].

2.2 Typical innovative TCS projects in Europe and the United States

The European Rail Traffic Management System (ERTMS) has become a worldwide dominant solution for railway signaling and control systems. It has the potential to offer increased functionalities (e.g., interoperability) and become even more competitive than before. New projects of train control systems are undertaken in Europe and the United States to increase the competitiveness of their own solutions globally by taking advantage of new technologies, including the use of satellite positioning technologies, innovative communications systems, and automation.

2.2.1 NGTC

In 2013, the European Commission granted substantial funds from the Seventh Research Framework Program FP7 of the commission to the NGTC project consortium [14]. The main purpose of the NGTC project is to analyze the commonality and differences of the required functionalities of the mainline railway and urban rail transit. To develop the convergence of both ETCS and communication-based train control (CBTC) systems, NGTC determined the level of commonality of architecture, hardware platforms, and system design [14]. The intention of NGTC is to develop railway scenarios in terms of increasing the commonality in system architectural items and hardware. The developing trend of the train control platform of the mainline and urban rail is presented in Fig. 1, which also shows whether the intention is impeded by different or specific elements.

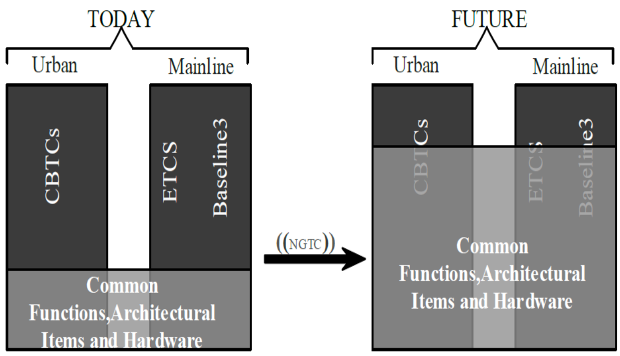

Fig. 1. Evolution trend of the train control platform for mainline and urban applications

2.2.2 SHIFT2RAIL

The promoters and the European Commission presented the European Parliament with challenges and solutions for "Horizon 2020," which focused on Shift2Rail, in November 2011 and formally established the scientific committee in May 2015 [8]. Shift2Rail has three key targets, and one of the targets includes cutting half of the life-cycle cost of railway transport, doubling railway capacity, and increasing reliability and punctuality by as much as 50%. Another target is to be the first European rail joint technology initiative to focus on research and innovation (R&I). The final target is considered the market-driven solutions by accelerating the integration of new and advanced technologies into innovative rail product solutions. Shift2Rail promotes the competitiveness of the European Rail Industry and meets the changing European Union transport needs. Through the R&I conducted in this Horizon2020 initiative, the necessary technology will be created to complete the Single European Railway Area.

Five asset-specific innovation programs (IPs) cover all the different structural and functional subsystems. These five IPs form a consolidated assembly of the railway system with a number of common cross-cutting themes (see Fig. 2).

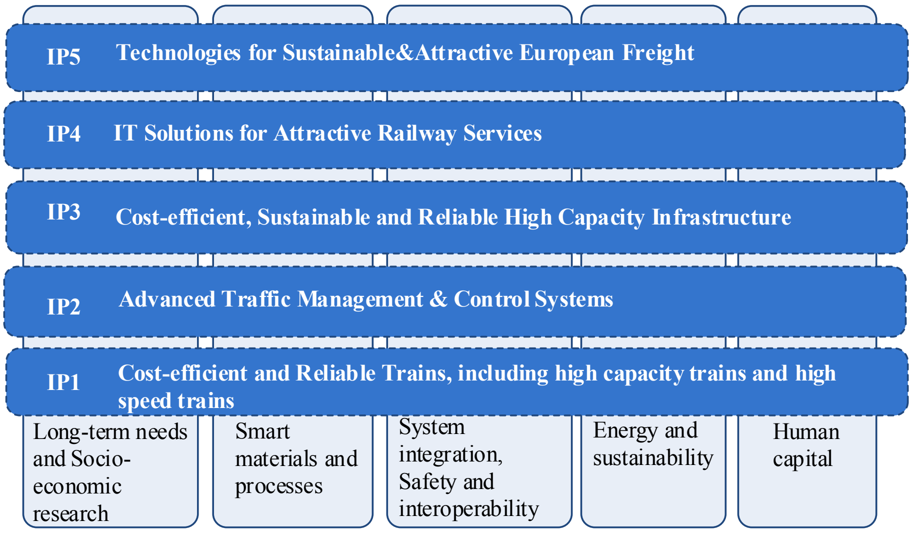

Fig. 2. Five innovation programs and their common cross-cutting themes

Signaling Innovation Program 2, namely the advanced traffic management and control system, aims to enhance the advanced traffic management and control systems without influencing the ERTMS core. R&I activities have approximately 11 technical demonstrators (TDs). New communication systems (TD 2.1) use the packet switching/IP technologies of moving block technology (TD 2.3), which aims to improve line capacity, and advanced multi-sensor Safe Train Positioning (TD 2.4).

2.2.3 ERTMS-Regional

Proposed in March 2003, ERTMS-Regional is a simplified and low-cost variant of the ERTMS suitable for train control on low-density lines. It is intended to reduce the amount of lineside and equipment required, thus reducing costs, increasing reliability, and improving the safety of track workers [4]. Object controller

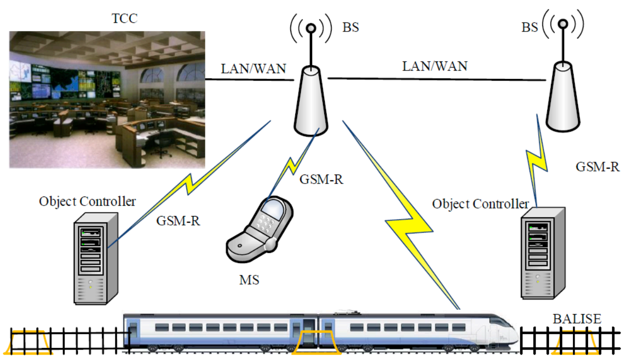

Fig. 3. System structure of ERTMS-Regional

The system is a trackside development by means of a centralized control, and the GSM-R system is used to operate relevant objects (points, level crossings, key locks, shunting areas, etc.) in the infrastructure. Calculation shows that ERTMS-Regional can obtain cost savings of 20%–35% for the operation of regional lines compared with the existing signaling equipment.

2.2.4 PTC and ITCS

Positive Train Control (PTC), a train control system mandated by the US federal government, uses communication-based train control technology that provides a system capable of reliably and functionally preventing train-to-train collisions, over-speed derailments, incursions into established work zone limits, and movement of a train through a main line switch in the wrong position [15]. The main concept of PTC is that the train receives information about its location and movement authorities. The equipment on board prevents unsafe movements.

Based on the concept of PTC, GE started developing the incremental train control system (ITCS) for Amtrak to use on its Michigan corridor between Detroit and Chicago in 1995. ITCS in Michigan is a fail-safe PTC system that overlays the existing signaling system for improved safety and provides a cost-effective solution for high-speed train operation. ITCS on the Golmud–Lhasa line in China was installed as a virtual signaling system in 2005 without physical signals or track circuits. In summary, ITCS offers potential capacity and velocity improvements as well as cost-effective options for railway signaling that can be deployed as an overlay or a stand-alone system [6].

ITCS transmitted control data based on GSM-R in the Qinghai–Tibet railway for the first time. At the same time, based on the application and configuration requirement, three typical station configurations were adopted in ITCS. The terminal stations of Golmud and Tibet, include RBC, Vital Harmon Logic Controller (VHLC), GPS differential station, and terminal RBC. Stations with CBI include RBC, GPS differential station, and VHLC (without interlocking). Stations without CBI include RBC, GPS differential station, and VHLC (with interlocking). Terminal RBC is a special RBC that does not interface with the existing signaling equipment. Its functions include assisting departure tests, uploading the entire database to onboard computers, and receiving train operation logs from the on-board system. The system structure of ITCS based on GSM-R is shown in Fig. 4.

In Tibet ITCS, the on-board computer (OBC) obtains the status and aspect of signaling equipment ahead of the current location of the train based on information from wayside RBC. It also displays the information on a man–machine interface to guide the driver in operating the train and fulfill the ATP. On-board system of ITCS is shown in Fig. 5.

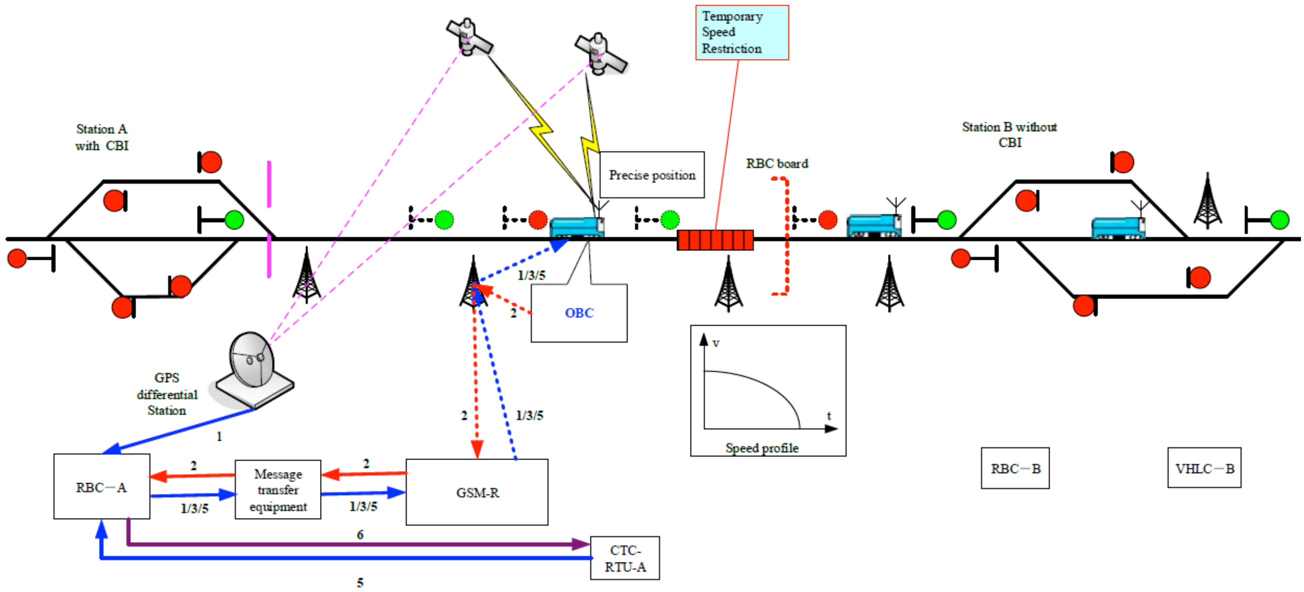

Fig. 4. System structure of ITCS based on GSM-R

Fig. 5. On-board system of ITCS

2.2.5 Urbalis Fluence

Urbalis Fluence is a CBTC solution expanded by Alstom, and its intelligence is based on the onboard train. It offers operators with high capacity, reduced headway, best-in-class operational availability, and optimized lifecycle costs. Onboard intelligence and direct train-to-train communication are used in the innovative train-centric CBTC system that reduces technical response time and the number of interfaces. Increased onboard intelligence reduces headways up to 60 s. This performance is made possible by shortening the response times via direct train-to-train communication and by optimizing the track resource locking of the train in critical sections such as turn-back tracks [16].

The technical highlights of Urbalis Fluence adopted by Lille Metro include driverless and unattended train operation, an operation system with a moving block principle, and a centralized traffic control system. An overview of Urbalis Fluence is presented in Fig. 6 [17].

2.2.6 Comparison of different TCSs

Based on the analysis on the five projects of TCS, Table 1 lists the common requirements of the different control systems. These typical innovative projects show that the main purpose is to make the construction and maintenance costs as low as possible by simplifying the system structure and function integration using advanced technologies.

The moving block system is supported by NGTC, Shift2Rail, and Urbalis Fluence to replace the fixed-block system based on track circuit and to increase efficiency. An innovative IP-based communication (4G/5G) guarantees bi-directional communication with higher capacity than GSM-R between wayside and onboard equipment. The train-centric train control method is a new trend adopted using train-to-train communication and GNSS positioning.

The requirements and innovative technologies of these representative projects are research worthy, as they will develop the NGTCS.

Table 1. Differences of future train control systems

Items	NGTC	Shift2Rail	ERTMS-Regional	PTC	Urbalis Fluence
Simplified system structure	√	√	√	√	√
Moving block	√	√			√
Advanced IP-based communication	√	√			√
GNSS positioning	√	√		√	
Intelligent train traffic management	√	√	√	√	
Train-centric enhancement	√	√		√	√

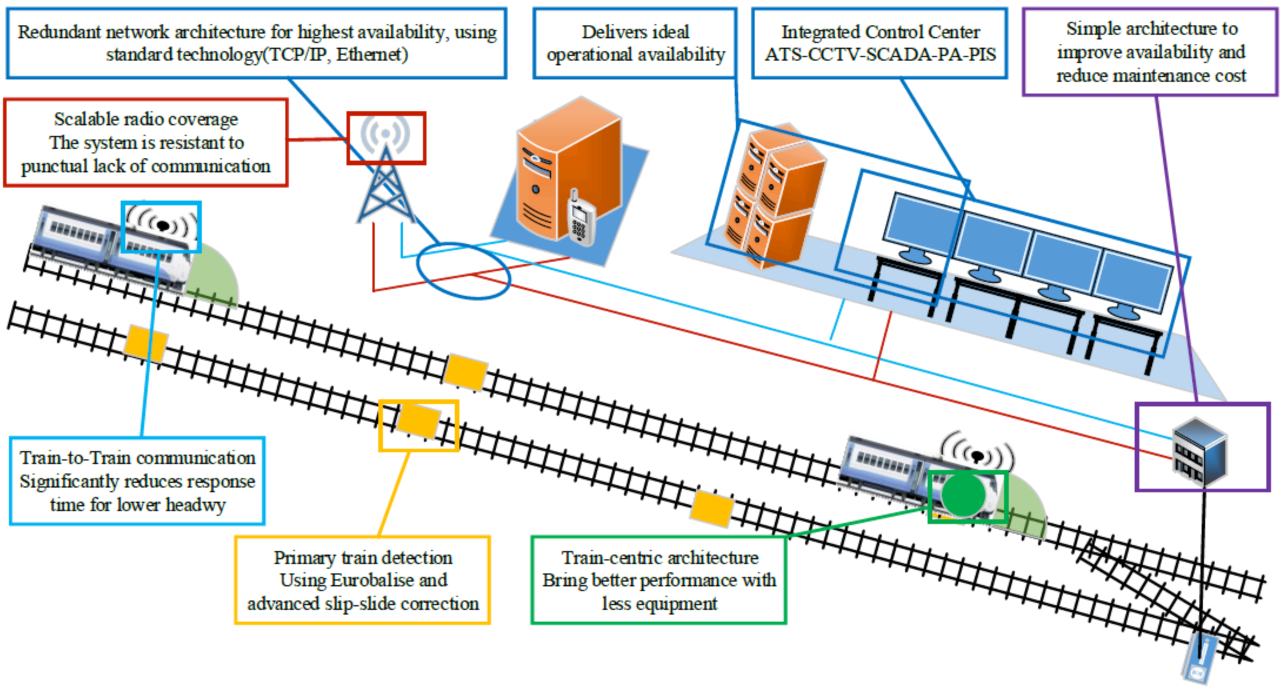

Fig. 6. Overview of Urbalis Fluence

3. Requirements, key technologies, and system scheme of NGCTCS

3.1 Requirement analysis

According to the statistics of the National Railway Administration of the People's Republic of China, the national railway mileage in China reached 121,000 km by the end of 2015, including 19,000 km of high-speed railway. In July 2016, medium- and long-term railway planning was released by the National Development and Reform Commission. Railway mileage was forecast to reach 150,000 km, including 30,000 km of high-speed railway, by the end of 2020. The Chinese government is planning to invest in the railways of West China. Based on the actual natural environment and low density in western railways, the NGCTCS must reduce the quantity of trackside signaling equipment as much as possible and effectively realize unattended duty. The railway corridor of the "one belt, one road" strategy can increase the interoperability of China and its neighboring countries. However, the high-cost of construction and maintenance of the existing standard of CTCS reduces competitiveness with the railway corridors in Southwest, Northwest, and Northeast China. Therefore, NGCTCS should be a low-cost system.

Rail transportation can be categorized into passenger-dedicated, mixed, freight rail, intercity rail, and urban rail transit according to the character of operation. Choosing a "one-fits-most" but not a "one-fits-all" system or core technology is required. Based on the practical construction and maintenance lessons of CTCS and combined with the system design experience of the typical projects, the requirements of NGCTCS are as follows:

(1) The number of trackside equipment of NGCTCS should be reduced to zero.

(2) The NGCTCS adopts a virtual block or moving block to replace the fixed block system. The block section can be adjusted flexibly according to the volume of traffic to improve the transportation capacity.

(3) By means of optimizing the system structure, NGCTCS must reduce its life-cycle cost (i.e., costs of building, operating, and maintaining) as much as possible.

(4) The system structure, logic model, and standardized interface module are designed to meet the special needs of different rail transits.

(5) NGCTCS is a train-centric system. Autonomous localization and train integrity check are conducted by vehicle on-board control.

(6) Using the next generation of railway digital mobile communication system and vehicle-to-vehicle communication technology, NGCTCS can realize real closed-loop communication.

3.2 Key technologies of NGCTCS

Based on the technical requirements of NGCTCS, the key technologies of the system should be adopted to provide the basis for its overall design.

3.2.1 Moving block

Traditional signaling systems are based on fixed blocks (i.e., track-based train control). Railway lines are divided into track sections, which are separated by signals or signal identification cards at the mechanical or electrical insulation. The succeeding train is not allowed to enter a given track section or block before the preceding train has cleared the track. The fixed block system has a number of disadvantages, one of which is its lack of flexibility. Block size is the same for all trains regardless of their speed and braking performance. Thus, the large safety distances required by fast trains are imposed on slower trains as well. Evidently, this strategy reduces track capacity.

The moving block system is increasingly implemented in urban rail transit as an important part of communication-based train control (CBTC) systems, and it must be adopted in the next-generation mainline train control system. The moving block system offers high reliability, availability, maintainability and safety (RAMS), increases mainline capacity, and reduces life-cycle costs of the railway transport, thus making it energy efficient [18]. This system does not require traditional fixed-block track circuits in determining train position. Instead, it relies on continuous bi-directional digital communication between each controlled train and a wayside control center.

On a moving block-equipped railway, the line is usually divided into virtual regions. Each train transmits its identity, location, direction, and speed to the control center, which makes the necessary calculations for safe train separation and transmits this information to the adjacent following train. The radio link between each train and the control center is continuous, so that the RBC knows the location of all the trains in its area all the time. RBC transmits to each train the location of the train in front and gives the train a braking curve to enable it to stop before it reaches the target. The former train plus a safety distance (SD) is depicted in Fig. 7.

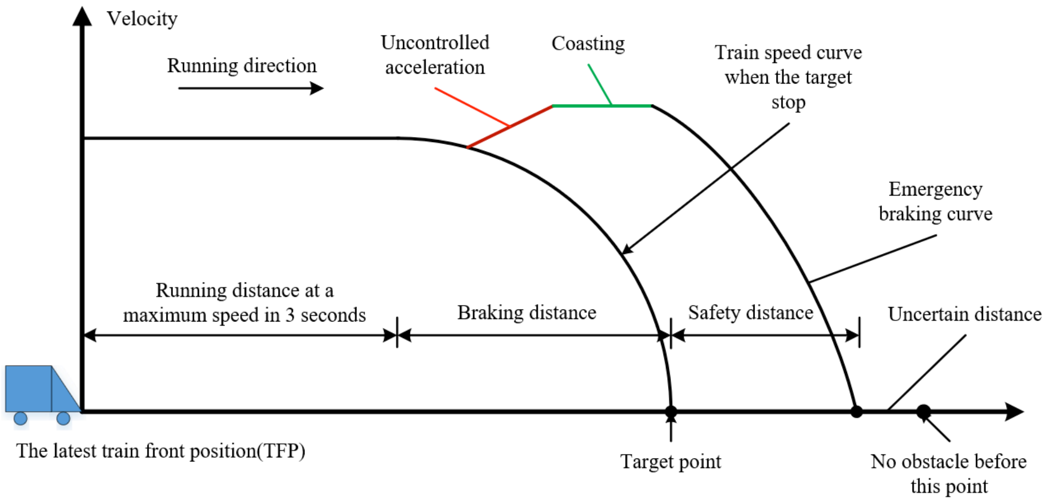

Fig. 7. Principle of the moving block system

The moving block system is a dynamic distance-to-go system. As long as each train travels at the same speed as the one in front and all have the same braking capabilities, they can, in theory, run as close together as possible. Of course, this contradicts railway safety policies. Furthermore, we can overlay train-to-train communication in the existing bi-directional communication of NGCTCS to ensure safety.

Moving block systems increase line capacity and improve traffic fluidity, thus making them energy efficient. To conduct a moving block system, NGCTCS must have the ability to ensure high accuracy in time synchronization, speed measurement, location, and control strategy.

3.2.2 Cognitive IP-based radio communication

The development of a new IP-based radio communication system aims to overcome the shortcomings in the current GSM-R of CTCS and WLAN of CBTC and to deliver an adaptable train-to-ground communication system for train control applications using packet switching/IP technologies (LTE, 4G, 5G, etc.). The new communication technology enables smooth migration from the existing systems. It provides enhanced throughput and high safety and security functionalities to support the current and next-generation requirements of signaling systems. The objective of the next-generation communication for railway is twofold. The first objective is to determine a common set of requirements for an IP-based radio communication of urban and mainline train control systems. The second objective is to explore and identify possible technical solutions for the underlying radio communication technology [19].

However, when emergencies (tornado, earthquake, disaster, public security threat, etc.) occur, the infrastructure-based communication system is easily disrupted because of the destroyed network unit, such as the base station. This situation may cause failure of the train dispatching system or train control system. Designing a new method of determining the idle communication resource to establish a cognitive radio emergency ad hoc network is important [20]. We may develop an infrastructure-less train-to-train (T2T) communication exploiting direct communication in mobile ad hoc networks. This communication system covers the current railway communication system to reveal hazardous situations by exchanging location and other relevant context information [16].

In NGCTCS, the cognitive radio approach for T2T (CR-T2T) consisting only of T2T communication components is introduced. In this approach, without the necessity for extending the railway trackside infrastructure, each train determines its own running information and broadcasts this information with other important data on the region of its current location. This information can be received and evaluated by other trains, which may, if a potential collision is detected, lead to traffic alerts, resolution advisories, and direct interventions (usually by applying the brakes) [2].

3.2.3 Satellite-based train positioning combined with LTE-R wireless positioning

Accurate and reliable train positioning remains to be greatly important in train spacing control in the train control system. With the rapid development in Chinese BDS, the GNSS is recommended as the most effective, autonomous, and cost-efficient availability choice for some safety critical location-based applications of railway transportation systems, especially the NGCTCS with a satellite-based train location structure.

BDS has adequate performance in train positioning and compatibility with other GNSS. At the same time, on-board BDS equipment can use high-frequency BDS output to calibrate the error of wheel speed sensor and to ease the dependence of trackside balise for location correction. Nevertheless, the lack of available satellite signals (i.e., no line-of-sight of satellite or weak signal) in places such as tunnels, grabens, mountains, and forests is the remarkable problem of the satellite positioning system [3]. The accuracy of track occupation is another challenge for BDS-based position given the several parallel tracks in the station and double lines in the section.

A novel GNSS-combined trackmap cooperative train-positioning method was proposed in [21]. In this method, the virtual balise enables a scheme for a new control system that is interoperable with the current CTCS. The combined positioning method of BDS with a trackmap can integrate GNSS, an odometer, speed sensors, and a map database that can be chosen as an optional strategy in NGCTCS. To solve the prevalent drawbacks of satellite-based positioning, a novel wireless positioning approach based on LTE-R was proposed in [22]. The method, in which the train receives the positioning reference signal (PRS) from a downlink channel, evaluates the impact of a multipath time delay and Doppler shift from the two reference evolved Node-B (eNB) and determines the train location using the train trajectory and time delay curves.

GNSS combined with the LTE-R positioning method can provide precise and continuous real-time location information in open terrain or obstacle environments. LTE-R sends the PRS to estimate location parameters and TCC calculates the train position. On-board equipment combines latitude and longitude information with position coordinates from TCC to gain the precise train position, as depicted in Fig. 8.

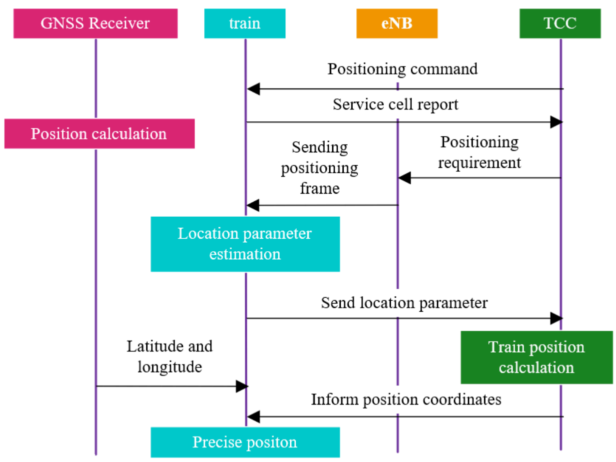

Fig. 8. Flow of GNSS combined with LTE-R positioning

3.3 Overall structure of NGCTCS

The system structure of NGCTS is presented in Fig. 9. To meet the requirements of different rail traffic scenarios, the system structure is divided into two parts: on-board system and trackside system.

The autonomous decentralized CTC is the highly automatic dispatch control system, which comprises the techniques of computers, network communication, and modern control. This system adopts the intelligent, distributed, and self-regulated design principles, focuses on control by adjusting train-running plans, and considers both train and shunting operations. CBI only collects information and controls the switch equipment in the railway station. Track occupancy in the station is judged by RBC based on the train position. Based on the eNB of LTE-R, RBC receives the train location and track occupancy information. It also sends the MA, temporary speed restriction, and line parameters to the on-board vital computer (VC). LTE-R realizes the bi-directional communication between the train and trackside equipment.

The on-board system is a train-centric system, and its positioning subsystem can combine GNSS and LTE-R with other positioning technologies to provide the precise location of running trains. As an auxiliary system of train-ground communication, CR-T2T can achieve the actual sense of closed-loop communication and avoid train collision when the train–ground communication is abnormal. Based on its own information and on that received from adjacent trains, VC generates the control mode profile to supervise the running train in safe mode. The control procedure in a railway station and section is described as follows:

Step 1: VC calculates the precise position based on GNSS combined with the LTE-R positioning method when the on-board devices are powered on.

Step 2: VC establishes the communication link with RBC via LTE-R.

Step 3: VC determines its position, direction, and speed using integrated positioning and broadcasts this information to the adjacent trains via train-to-train communication system.

Step 4: VC receives and evaluates the information broadcasted by other neighboring trains all the time, and it triggers a collision alert and provides a solution when a potential collision is detected.

Step 5: CTC center transfers the train schedule to the station autonomous machine of the CTC.

Step 6: When receiving the plan from the CTC, the station autonomous machine automatically converts the adjustment plan to the train route sequence. The station autonomous machine then sends access control commands to the CBI at a certain time.

Step 7: RBC receives information on train speed, train location, and train integrity and calculates the track occupancy in the station.

Step 8: CBI collects information on switch and track occupancy from RBC, converts the switch to the right position, and creates the approach locking of the route.

Step 9: CBI sends the route number to RBC, which receives the train information and sends an MA to the train via LTE-R.

Step 10: The OBC supervises the train-running status according to the route information and principle of moving block.

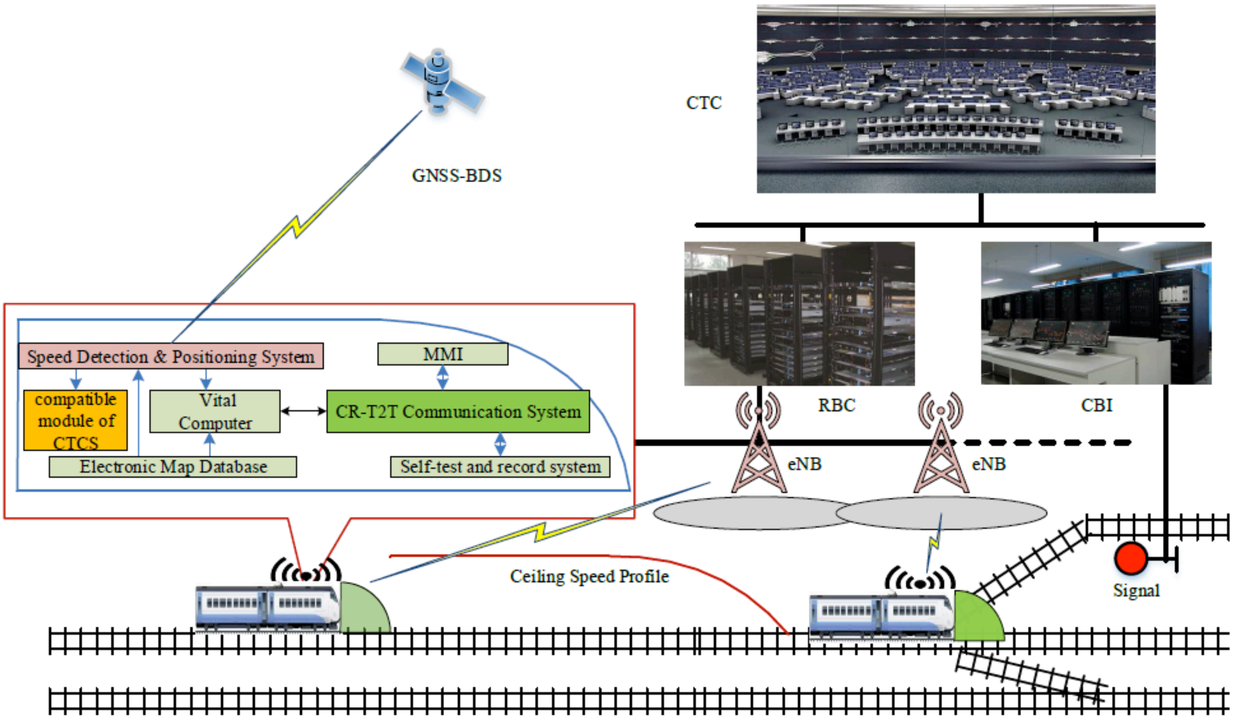

Fig. 9. System structure of NGCTCS

4. Conclusions

To adapt to the developing trend of train control systems, CTCS of different levels must immediately change the existing situation, which is over-dependent on wayside infrastructure, high cost, and excessive redundancy of system structure. After the analysis of the state of the art of CTCS and based on structure and characteristics of typical TCS projects, the overall architecture of NGCTCS has been established in the study using the requirements and key technologies of NGCTCS.

The related technologies proposed in the paper, including moving block, CR-T2T, and combined positioning, can provide technical reference to the development of NGCTCS and further improve the key architecture of a railway signaling system. However, technologies that offer scalability for different customer requirements ranging from low-density lines to high-performance lines are limited. Therefore, further study is required to improve the level of intelligence, automation, and rich train control information, to enhance control accuracy and interoperability, and to achieve the safety of train operation.

Acknowledgements
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