Ring Topology Railway Signalling with Information Sharing among Onboard and Switch Controllers

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Conventional communication-based train control (CBTC) systems enable the frequent operation of trains by detecting train’s position and the telecommunication system between the on-board and trackside controllers compared to traditional signalling systems. However, the railway signalling system is still costly, and the cost of the trackside central controllers is particularly high because high-performance failsafe hardware and software are required to control the many pieces of field equipment. Given this situation, we have proposed a concept for a cost-effective CBTC system that provides functionalities equivalent to those of existing signalling systems by using ring topology information shared among the onboard and switch controllers without trackside central controllers. Its basic mechanism is the circulation of a telegram containing information about the exclusive rights to virtual blocks in turn among the controllers within each controlled section. This mechanism reduces the equipment cost to approximately one-third that of a conventional CBTC system. We have now conducted a feasibility study to verify the practicality of this system and have identified potential problems related to system reliability and transportation capacity. This paper presents solutions to these problems and experimental results to show that the proposed system is technically valid and can be applied to many railway lines.

Keywords: communication-based train control (CBTC), rail transportation, signalling, telegram circulation

1. Introduction

Rail transportation is universally accepted as one of the safest forms of public transport and has a strong reputation for energy efficiency and dependable journey times. Many new and upgraded projects are planned worldwide to expand railway networks, including metro and monorail systems, for passenger convenience and rapid urbanization. The implementation of these railway projects depends on reducing the infrastructure cost, and a good way to do this is to reduce the cost of the signalling system (1)–(3).

Investigations of telecommunication methods supporting the signalling system (4)–(6), active train detection systems (7), and reduced-cost signalling systems such as ERTMS regional (8) have focused on the business benefits and cost reductions. Efficiency in generation and verification of interlocking control table has been improved (9)–(10). An interesting new approach for the coordination of trains inspired by self-organizing biological systems has been proposed (11).

However, since most signalling equipment still has a complex structure, the installation and maintenance costs remain high (12). This complexity is due to these systems having been developed to perform complex tasks, such as controlling train movements between stations and controlling the exclusive routes within a station area, before the electronics and wireless technologies available today were developed. In particular, the cost of the trackside central controllers, i.e. the automatic train protection (ATP) controllers and the interlocking controllers, and the signal lines connecting the field equipment is relatively high. This is because high-performance failsafe hardware and software are needed for these controllers to supervise trains and switches, generate movement authorities for trains, and control switches. Moreover, the signal lines need to be shielded from the effects of the electromagnetic noise from the feeding cables, the rails, and the power cables transmitting a large electrical current. This is generally done by laying two lines or by using an optical cable with optical equipment for each piece of field equipment.

Given this situation, we can see that the cost of railway infrastructure can be reduced by eliminating the trackside central controllers and the signal lines. We previously proposed a concept for a cost-effective communication-based train control (CBTC) system that provides train separation and route control functions without trackside central controllers and signal lines and presented its fundamental principle, i.e. ring topology information sharing among on-board and switch controllers (13).

We have now conducted a feasibility study of the proposed system. This paper addresses the problems identified in this study and provides clear solutions that ensure the technical validity of the concept.

2. Existing Signalling Systems

First, typical existing signalling system architectures are
analyzed in this section. Next, the concept of the proposed system derived from the analysis is explained in the following section.

### 2.1 Traditional Train Control Systems

In the traditional train control system, ATP controllers use information from the track circuits to control the trains so that they move safely between stations (train separation function)\(^{(14)}\), and interlocking controllers use the information from the track circuits and the switches to set the routes and control the train movements within a station area (route control function)\(^{(15)-(16)}\). These trackside central controllers are connected to the automatic train supervision (ATS) system, enabling them to receive route request information based on the timetable and/or dispatcher’s orders. A train’s onboard controller controls the train speed in accordance with control information from the trackside central controllers by issuing commands to the brake system. A typical system configuration is shown in Fig. 1.

The traditional train control system uses trackside central controllers to centrally control the onboard controllers and the many pieces of field equipment that are required for signalling (track circuits, signals, switches, etc.) in an efficient way, as illustrated in Fig. 2.

### 2.2 Conventional CBTC System

The traditional train control system controls train movements by using the fixed block principle; that is, a train is not permitted to enter a block containing another train even if there would be sufficient clearance between the two trains. One way to increase the number of trains in operation is to use the moving block principle; that is, train position information generated by the onboard controller is transmitted to the ATP and interlocking controllers via radio and used instead of the train occupancy information received from the track circuits via signal lines. The ATP controller determines the movement authorities for all the trains on the basis of the train position information received via radio and the setup route information from the interlocking controller and sends these movement authorities to the onboard controllers of the trains via radio. This is the basis of the CBTC system\(^{(17)-(19)}\) and several vendors provided their own solutions by different system configuration\(^{(20)}\). A typical system configuration is shown in Fig. 3.

The conventional CBTC system thus eliminates the need for track circuits and signals due to the use of radio transmission for train position and control information. However, the control logic is the same as that of the traditional train control system; i.e. onboard and switch controllers are centrally controlled by trackside central controllers, as illustrated in Fig. 4.

### 3. Ring Topology CBTC System

#### 3.1 Concept

As shown by the analysis in the previous section, a conventional CBTC system is not required to control many piece of field equipment. This means that central control architecture is no longer effective. The authors therefore proposed ring topology information sharing among onboard and switch controllers instead of information exchange between central and field controllers, as illustrated in Fig. 5.

In particular, a telegram containing necessary information for train separation and route control functions is circulated in turn among the controllers within each controlled section. The configuration of the proposed system (‘ring topology CBTC system’) is shown in Fig. 6.

#### 3.2 Fundamental Principles

The mechanism used by the ring topology CBTC system for achieving signalling...
functions, i.e. train separation and route control, differs from that used by existing signalling systems. It is based on the token block system, which has long been used for low-demand single-track lines (Fig. 7). It is a basic mechanism for ensuring train safety: only one train, the one with the token, is permitted to enter the track section between two stations. The token, which is a physical object such as a staff or a tablet, is controlled by the token controllers (one at each station), which communicate by telephone to ensure that only one token exists at a time.

The proposed signalling system is based on the following five principles, which are an expansion of this traditional mechanism.

1. The controlled section is divided into virtual blocks, and the exclusive right to enter each block is controlled.
2. A switch is controlled by a switch controller in accordance with the instructions received from the onboard controller that has obtained the exclusive right to the block containing the switch.
3. Information about the exclusive rights to all the blocks in the controlled section is shared among the train onboard controllers by wireless communication.
4. Information about the status of all the switches in the controlled section and the control instructions to those switches is exchanged among the onboard and switch controllers.
5. A train is controlled by its onboard controller so that it cannot enter a block without having the exclusive right to that block.

### 3.3 Circular Safety Telegram

To perform the signalling functions in accordance with these fundamental principles, the following four types of signalling information need to be shared. In the proposed system, they are integrated into a telegram (‘circular safety telegram’) for each controlled section, and this telegram is circulated in turn among the onboard and switch controllers. Table 1 shows an example telegram, which is circulated in the section illustrated in Fig. 8.

| Type of information          | Object  | Content       |
|-----------------------------|---------|---------------|
| Exclusive right to block    | Block #1|               |
| Exclusive right to block    | Block #2| Train A       |
| Exclusive right to block    | Block #3| Train A       |
| Exclusive right to block    | Block #4| Train A       |
| Exclusive right to block    | Block #5| Train A       |
| Exclusive right to block    | Block #6| Train A       |
| Exclusive right to block    | Block #7| Train B       |
| Control instruction to switch | Switch #1| Normal       |
| Control instruction to switch | Switch #2| Reverse      |
| Status of switch            | Switch #1| Normal locked |
| Status of switch            | Switch #2| Reverse locked|
| List of members             | No.1    | Train A       |
| List of members             | No.2    | Switch #1     |
| List of members             | No.3    | Train B       |
| List of members             | No.4    | Switch #2     |
| List of members             | No.5    |               |

3. At the system start-up, the operator selects one switch controller to serve as a circular safety telegram initiator through the ATS system. The selected controller generates initial telegram with TTL (Time to Live) based on train position information reported from onboard controllers. After operator’s permission, the initial telegram is to be circulated to start the system operation. Once the telegram is issued, the initiator update the TTL on each telegram circulation and another telegram should not be generated within the latest TTL.
In case of telegram loss, a controller which does not receive the telegram within the assumed time interval notifies the ATS system. The ATS system selects one controller to serve as a circular safety telegram re-issuer. The selected controller reissues a telegram based on the stored token data from all other controllers. The reissued telegram is to be circulated after the TTL of the original token. Note that the resumption procedure is to be considered in section 5.2.

In case of telegram transmission delay, onboard controller may slow to obtain and release the exclusive rights of blocks, thus it may decrease capacity of train operation. However the telegram transmission delay never causes a hazard; i.e. double booking of block, because the exclusive right of every block is controlled on the one telegram and it can be kept only by one controller. Note that the effects of telegram transmission on train operation density are to be examined in section 5.3 and 5.4.

3.4 Implementation The proposed system is able to be applied to the lines of any length by dividing the line into appropriately sized sections and issuing a circular safety telegram for each section. Each controller connects to the network via radio infrastructure along the line and transmits the circular safety telegram to the controller defined in the member list in each section. Accordingly each telegram is circulated among controllers within the section in order of the member list. For train to move to the next section, onboard controller requests switch controller in the next section to add its ID to the member list of the telegram there. On the other hand, it deletes its ID from the member list of the telegram of the previous section by itself after train has exited from there. Note that the section boarders should be between the stations or at the station entry points because onboard controller would have to wait for more than one telegram for the route setting in a short period of time if the border is at a station.

3.5 Train Supervision In contrast with signalling functionalities, train supervision and traffic management functions of the proposed system are performed by a centralized ATS system in the same way as the existing train control systems, as illustrated in Fig.6. Every onboard controller communicates with the ATS system via radio for reporting train location and receiving traffic management instructions, such as emergency stop, temporary speed restriction, work zone protection and timetable data. And it tries to obtain the exclusive right of blocks in accordance with these timetable data from the ATS system.

In view of safety, the ATS system never has a function that requires touching a circular safety telegram that is circulated only among onboard and switching controllers, in order to be completely separated from the telegram that is the key for safety of the proposed system. That means the ATS system cannot cause direct interference with the safety core functions of this signalling system. This safety architecture is same as that of the conventional interlocking controller and interlocking terminals.

4. System Benefits

4.1 Simple Architecture The ring topology CBTC system achieves the signalling functions by using onboard controllers, switch controllers, and a radio network. The functions of each component are explained as following.

1. Onboard controllers
   A train’s onboard controller controls the train in accordance with the signalling information shared by telegram circulation. To be more specific, it calculates the train’s position by using the location information received from the balises and the pulse signals received from the speed sensors in the same way as the conventional CBTC system and controls the train’s speed by using the brake system within the blocks for which it keeps the exclusive rights in the circular safety telegram.

2. Switch controllers
   The switch controllers control the switches in accordance with signalling information shared by telegram circulation. To be more specific, a switch controller turns and locks one or more switches in the required direction in accordance with the control instructions in the telegram from the holder of the exclusive right to the block containing the switch.

3. Radio network
   The radio network provides wireless data transmission among the onboard and switch controllers.

In addition to the above signalling functions, the proposed system also provides all other functions for train supervision and traffic management by the centralized ATS system, which provides traffic management instructions to each controller on the basis of the timetable and dispatcher’s orders by sharing the radio network.

In short, the ring topology CBTC system has a simpler architecture than existing signalling systems and thus facilitates system migration.

4.2 Equivalent Functionalities Despite its simple architecture, the ring topology CBTC system achieves the train separation and route control signalling functions as provided by existing signalling systems.

1. Train separation function
   In the traditional train control system, the ATP controller transmits speed signals to the onboard controllers on the basis of the train occupancy information provided by the track circuits via the signal lines, and the train movements are controlled in accordance with the fixed block principle. In the conventional CBTC system, the ATP controller transmits the movement authorities to the intelligent onboard controllers on the basis of the train position information provided by these controllers via a radio system, and the train movements are controlled in accordance with the moving block principle.

In the ring topology CBTC system, the onboard controllers recognise the train movement limits from the shared information of the exclusive rights to the blocks without an ATP controller. Furthermore, this system performs the equivalent of moving block train control by splitting a controlled section into smaller virtual blocks. Note that the telegram becomes longer with the need to control more blocks, but only a few bits are needed for each block.

2. Route control function
   In the traditional train control system, the interlocking
controller controls the signals and the switches based on the route request information from ATS system and the train occupancy information provided by the track circuits via the signal lines. In the conventional CBTC system, the interlocking controller controls the switches based on the route request information from ATS system and the train position information provided by the intelligent onboard controllers via a radio system instead of using train occupancy information from the track circuits.

In the ring topology CBTC system, the onboard controllers control the switches and confirm their status by exchanging the control instructions and status information with the switch controllers without using an interlocking controller. In more detail, a switch is controlled by instructions from the onboard controller with the exclusive right of the block containing the switch; i.e. Switch #1 is controlled by the holder of the exclusive right of Block #5 where Switch #1 is placed in Block #5 as illustrated in Fig. 8. The exclusive right of every block is controlled on the one circular safety telegram and kept/released by one onboard controller at a time in accordance with the timetable data distributed from the centralized ATS system, therefore any route conflict is not created among onboard controllers. In case of ATS system failure, the exclusive right of every block is to be kept/released by onboard controllers on a first-come first-serve basis. This way is useful enough in degraded mode operation and completely-safe, while it may cause route conflict.

### 4.3 Cost Reduction

The main feature of the ring topology CBTC system is that the signalling functions are performed without the need for expensive trackside central controllers. Table 2 compares the cost of the equipment required for the existing systems and for the proposed system. The equipment price ratio data were obtained and estimated from market report which shows that total cost of ownership for 30-km line is 71.1 million Euros and equipment cost accounts for about 28.1% (21), and cost reference data for the railway sector (22). The data shown in the table are for a typical urban railway signalling system in which there are 30 trains being operated on a 30-km double-track line, 6 ATP controllers, 120 track circuits, 6 interlocking controllers, and 24 switches.

With the ring topology CBTC system, the equipment cost is about 8.6 million points whereas the traditional train control system costs about 27.4 million points and the conventional CBTC system costs about 20.0 million points. Although this comparison is for only one case and the equipment cost depends on equipment configuration, it clearly indicates that the proposed system is more cost effective than the traditional train control and the conventional CBTC systems. Note that the cost of onboard controller of the proposed system is assumed to be same as that of the conventional CBTC by considering that the same hardware including radio equipment will be applicable and the existing and proven software assets of the basic functions, i.e. train position detection, speed supervision, braking pattern generation, brake control, and so on, will be reused without any development cost. And supplementary facilities for degraded mode of operation in case of minor failure are excluded in this comparison and such facilities will be considered according to customer requirements and actual environment in installation of system.

### 5. Technical Problems and Solutions

To validate the performance of the proposed ring topology CBTC system, a feasibility study was done as the first step toward its practical use. Several technical problems were identified and clear solutions were devised.

#### 5.1 High-Confidence Telegram Transmission for Reliability

Existing signalling systems are basically one-to-many systems. The trackside central controllers communicate with the onboard controllers and the switch controllers in a constant periodic cycle. Therefore, these systems are robust against transient failures because these operations can be recovered by using the information exchanged in the next cycle.

In contrast, the ring topology CBTC system is a token-ring system, and the information transmitted in the circular safety telegram is the key to safety. Therefore, if a telegram is corrupted or lost during transmission, the system may stop.

| No. | Equipment                  | Price ratio (10^6 points) | Number of pieces | Cost ratio (10^6 points) | Traditional train control | Conventional CBTC | Ring topology CBTC |
|-----|----------------------------|----------------------------|------------------|-------------------------|--------------------------|------------------|---------------------|
| 1   | ATP controller             | 1000                       | 6                | 6000                    | 6000                     | –                | –                   |
| 2   | Track circuit              | 80                         | 120              | 9600                    | –                        | –                | –                   |
| 3   | Signal                     | 10                         | 120              | 1200                    | –                        | –                | –                   |
| 4   | Cable (per km)             | 50                         | 30               | 1500                    | –                        | –                | –                   |
| 5   | Interlocking controller    | 1000                       | 6                | 6000                    | 6000                     | –                | –                   |
| 6   | Switch controller          | 25                         | 24               | 6000                    | 600                      | 600              | –                   |
| 7   | Switch intelligent unit and radio unit | 25 | 24 | – | – | 600 | – |
| 8   | Onboard Controller (traditional/intelligent) | 17/170 | 30 | 510 | 5100 | 5100 | 5100 |
| 9   | Radio (per km)             | 10                         | 30               | –                       | 300                      | 300              | 300                 |
| 10  | ATS system                 | 2000                       | 1                | 2000                    | 2000                     | 2000             | 2000                |

**Table 2. Comparison of Required Equipment and Cost**
Since telegram corruption and loss are critical failure modes affecting system reliability, high-confidence telegram transmission methods, such as ones using an error-detecting code, and a reliable telegram transmission protocol should be implemented in addition to using a high-reliability controller design, such as a redundant design. An example reliable telegram transmission protocol is shown in Figs. 9 and 10. Telegram transmission data is followed by reply and confirmation. The receiver replies to the sender and the sender confirms receipt of the reply. If the sender does not receive a reply within the predetermined time interval, the sender resends the telegram to the receiver. Similarly, if the receiver does not receive a confirmation from the sender within the predetermined time interval, the receiver resends the reply to the sender. If the sender fails to receive a reply for more than the predetermined number of times, the sender sends the telegram to the next receiver on the member list. The receiver does not activate the received telegram information unless it receives confirmation from the sender.

With these high-confidence telegram transmission methods and a high-reliability controller design, the sender and receiver can detect a communication failure, and the sender can resend the telegram to the receiver or send it to the next receiver on the member list without an interruption in operations. These general methods are also effective against an unexpected communication disconnection, which is the most probable failure in a radio system.

**5.2 System Resumption by Temporary Assigned Telegram Re-issuer for Reliability**

Even with the above methods and design, it is impossible to preclude the possibility of telegram loss during telegram update in a controller or during telegram transmission between controllers. Given that the system is for practical use, the telegram must be reissued for system operation to be resumed in the case of telegram loss.

The solution devised to solve this problem is to select one controller to serve as a temporary telegram re-issuer for use in obtaining the information in the latest telegram from each controller in case of telegram loss. If a controller does not receive the telegram within the predetermined time interval, it notifies the ATS system. The ATS system confirms the soundness of all the controllers on the member list and selects one healthy controller to serve as a temporary telegram re-issuer. The selected controller sends a message to all other controllers on the member list requesting their stored telegram data and reissues the telegram on the basis of the latest telegram information from the collected data after the TTL of the original token.

The selected controller does not require the high-performance processing power like the central controller in an existing signalling system because moving objects are not being controlled as all trains and switches have been stopped. This simple and easily implementable telegram reissue procedure enhances the robustness of the ring topology CBTC system for practical use.

**5.3 Section Partitioning for Transportation Capacity**

Train operation density is a key performance factor of signalling systems, and it depends largely on the blocking system used for train movement control and on the communication system used for sending control information \((23)-(25)\). The conventional CBTC system, using moving block control, increases the train operation density to nearly the theoretical limit \((26)\). While the ring topology CBTC system also uses moving block train control by splitting the sections into smaller virtual blocks, each controller receives the control information only by telegram circulation. As a result, control may be delayed occasionally compared with the one-to-many conventional CBTC system. In the worst case situation, train headway may be increased because of a delay in receiving the telegram.

Since minimum train headway is affected by delays in receiving the telegram, the controlled section partitioning and virtual block setting should be done on the basis of the required train headway and communication environment. Factors to consider include the transmission speed of the radio equipment to be used and the anticipated numbers of trains and switches.

With the ring topology CBTC system, the railway line should be divided into appropriately sized sections, and a circular safety telegram should be issued for each section. To cross over into another controlled section, a train’s onboard controller stores the address data of the switch controllers along with the track description data (speed limits, gradients, balise locations, etc.) and predicts the timing of entering the next controlled section on the basis of the train’s location. It requests the switch controller to add its ID to the member list well in advance. This request is sent with a lower priority in the same channel used for the circular safety telegrams and is processed by the switch controller during a non-busy time. For example, Aguado et al. \((27)\) demonstrated that WiMAX, worldwide interoperability for microwave access, can establish communication within 1.5 s and transmit data at 10 Mbps. After the train exits the controlled section, it deletes its ID from the member list when it releases its exclusive right to the last block in the section.

The controlled sections can be made smaller at no
additional cost since additional equipment is not needed. The only modification is the larger number of circular safety telegrams that must be created and circulated. The number of controllers circulating one telegram can be minimized by dividing the railway line into appropriately sized sections in consideration of the most crowded case as determined from the train timetable. For instance, at a double-terminus station on a double-track line, it is possible to keep the number of controllers circulating a telegram to five or less (two switch controllers and maximum three onboard controllers). Thus, the ring topology CBTC system can perform the equivalent of moving block train control, and the telegram circulation time does not affect the train operation density if it is sufficiently lower than the required train headway.

5.4 Reservation System for Transportation Capacity

However, if the required train headway is very short, it cannot be ignored that the telegram circulation time increases train headway compared with the moving block signalling system. In particular, the situation is more complicated within a station area, where route conflicts may occur due to a number of trains going in different directions. Switch is controlled by switch controller, which receives control instruction from the onboard controller of the train with the exclusive right to the block containing the switch. Depending on the circular order of the telegram, in order to recognise the new instruction for the following train, a switch controller may need to receive the telegram not once but twice after the onboard controller of the preceding train releases the exclusive right to the block including that switch. Because the new instruction is to be written in by the onboard controller of the following train after the release by the onboard controller of the preceding train, as illustrated in Fig. 11, it is blank if the telegram is received by the switch controller prior to the onboard controller of the following train.

A solution is to introduce a system for reserving the exclusive right to blocks and control instruction to switches, as shown in Table 3. The onboard controller of the following train is allowed to make a “reservation”; i.e. it can write the train ID and desired control command in the telegram once this exclusive right already has been kept by the other controllers. The onboard controller of the preceding train activates the reservation when it releases its own rights and deletes its instructions.

With this solution, the switch controller can recognise the new instruction for the following train by receiving the telegram once after the onboard controller of the preceding train releases the exclusive right to the block including the switch, as illustrated in Fig. 12. In short, it enhances the applicability of the ring topology CBTC to complex and high-density train operation areas. An experimental consideration of train headway comparative evaluation between the conventional CBTC system and this system is shown in the next section.

To further increase the train operation density, the telegram circulation mechanism must be improved. If the number of trains operating is large, for example, the ATS system estimates the appropriate timings for the onboard controllers to set a route, and the onboard controllers declare the timings in the circular safety telegram. The controllers dynamically change the circulation order on the basis of these declared timings so that the telegram is transmitted to the appropriate controller in a timely fashion. If the number of the switches is large, it would be more effective for the onboard controllers to skip the switch controllers not being instructed. Algorithms for changing the circulation order dynamically should thus be investigated.

6. Experimental Consideration

The solutions described in the previous section were tested...
using an experimental consideration in which the proposed system was applied to an actual railway line. The recovery time and the minimum train headway with this system was calculated and compared with the margin of headway and that of a conventional CBTC system, respectively. Table 4 shows the assumptions used.

### 6.1 System Recovery Time

As described in the previous section, the proposed system can be recovered from telegram loss situation, according to the following procedure:

- **Step 1:** Detecting timeout of telegram receipt by a controller.
- **Step 2:** Reporting to ATS system by the controller.
- **Step 3:** Handling reported data by the ATS system.
- **Step 4:** Assigning a telegram re-issuer by the ATS system.
- **Step 5:** Command recognition by the telegram re-issuer.
- **Step 6:** Requesting stored telegram data to other controllers from the telegram re-issuer.
- **Step 7:** Recognizing the request by the other controllers.
- **Step 8:** Transmitting stored telegram data to the telegram re-issuer by the other controllers.
- **Step 9:** Reissuing the telegram based on the transmitted data by the telegram re-issuer.

Based on the assumed parameter values in Table 4, Step 1 takes 4.0 s. Step 2, 4, 6, and 8 take 0.5 s. Step 3, 5, 7, and 9 take 0.25 s. The total time spent on system recovery is 7.0 s. This result indicates that this system can be recovered from the most critical availability problem within the margin of headway, i.e. 10 s.

### 6.2 Train Headway at Intermediate Station

The minimum train headway was calculated at an intermediate station, as illustrated in Fig. 13. The train movement curves (front and rear position) of preceding and following trains are shown in Fig. 14.

The train headway between preceding and following trains with the conventional and proposed ring topology CBTC systems is calculated, respectively. For the ring topology CBTC system, the circular safety telegram was circulated among the three controllers within this station section, and the worst-case scenario for information update and transmission from the preceding train’s onboard controller to the following train’s onboard controller was considered; i.e. the preceding train runs through block immediately after its onboard controller sent the telegram and the updated telegram is transmitted through one other controller.

Table 5 shows the calculation results of train headway. The results show that the train headway with the proposed system is greater by only 3.0 s, i.e. just 4%.

Note that the minimum train headway of the traditional train control system using track circuits, of which the length is train length with the margin 10 m, is 77.6 s. The proposed system is based on block system in the same way as the traditional train control system. However the former is virtual and latter is physical, thus train headway of the proposed system can be shortened by shortening the length of virtual blocks.

### 6.3 Train Headway at Terminus Station

The minimum train headway was also calculated at the terminus station, as illustrated in Fig. 15. In general the train headway at the terminus station affects the train operation density for the whole line. This is because the train headway at the terminus station is more restricted than at an intermediate station due to several constraining factors, such as switch turning, route setting, and train crossover.

Table 6 shows the calculated train headway with the conventional and proposed ring topology CBTC systems. Note that the minimum train headway of the traditional train
control system is not different from the conventional CBTC system using interlocking controller with block system. For the ring topology CBTC system, the circular safety telegram was circulated among five controllers within this station section, and the worst-case scenario for information update and transmission from the on-board controller of the train having the exclusive right to a block containing a switch to the corresponding switch controller was considered; i.e. the train runs through that block immediately after its on-board controller sent the telegram and the updated telegram is transmitted through three other controllers.

The calculated train headway with the ring topology CBTC system is greater by 15.0 s, i.e. 16%. Thus, algorithms for changing the circulation order dynamically to transmit the telegram to the appropriate controller in a timely fashion, as mentioned in the previous section, must be implemented if this system is to be applied to railway lines that require short train headway or a long delay recovery margin, such as some high-density mass transit systems in megacities. To put it the other way around, the calculation results show that the ring topology CBTC system can be applied to many railway lines that do not require a short train headway without preparing an additional algorithm.

The new technologies to enhance radio communication for the CBTC system have been investigated\(^{[16]–[19]}\). The application of these technologies to the proposed system would further reduce the telegram circulation time and the minimum train headway.

7. Future Work
This paper showed that the proposed system can achieve the functionalities equivalent to the conventional CBTC system and can be applied to many railway lines on a conceptual level. In order to go to the next step, it will be required to ensure the proposed system is safe for commercial viability. To that end, all necessary functions for interlocking and ATP should be identified from applicable specifications and standards\(^{[12]}\) and an implementation of every function should be documented. In particular, safe ways to perform traditional interlocking functions, such as sectional route lock, approach lock, traffic direction lock, overrun protection, etc., and traditional ATP functions, such as train location determination, safe train separation, overspeed protection, rollback protection, etc., should be documented in accordance with safety case requirements of RAMS standards\(^{[13]}\).

8. Conclusion
The proposed ring topology CBTC signalling system reduces the cost of railway infrastructure by applying ring topology information sharing among field controllers instead of information exchange between central and field controllers. Its basic mechanism is circulation of a telegram containing information about the exclusive rights to the virtual blocks, the status of the switches, and the instructions for controlling the switches in turn among the on-board and switch controllers. This mechanism provides functionalities equivalent to those in existing signalling systems, i.e. train separation and route control, without using trackside central controllers and reduces the equipment cost to approximately one-third that of the conventional CBTC system. A feasibility study revealed problems related to system reliability and transportation capacity. Solutions were devised to solve these problems, i.e. high-confidence telegram transmission, system resumption by temporarily assigning a telegram re-issuer, section partitioning, and reservation of exclusive rights to virtual blocks and control instructions to switches. An experimental consideration of minimum train headway showed that this system can be applied to many railway lines without preparing an additional algorithm except to those in high-density mass transit systems in megacities that require short train headway. The devised solutions and the experimental consideration enhance the practicality of the proposed ring topology CBTC system.

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