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A DUPLICATED NETWORK STRUCTURE FOR AN LTE-BASED TRAIN CONTROL COMMUNICATION

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Abstract:
The International Union of Railways has decided to migrate railway communication technology from being GSM-based to LTE-based or LTE-R. As a leading country in LTE space, South Korea will launch the train control system based on LTE by 2016. To ensure the most reliable train operation in this system, a fully duplicated network structure with overlaid radio cells is needed. Existing methods and results often rely on a single network structure setup. Thus, in this paper, we introduce the design of an LTE-R train control communication with a duplicated network structure. We propose two different network structures with fully-overlapping cell arrangement and with partly overlapping cell arrangement, respectively for the system and discuss major problems, including handover and inter-cell interference.
Keywords: *railway communication, LTE-R, high-speed rail, train control, dual link, Korean railway.*

I. Introduction

A conventional railway communication system based on Global System for Mobile Communication Railway (GSM-R) technology had achieved great success in the past. With the development in wireless technology, a new communication paradigm called Long Term Evolution - Railway (LTE-R) has been nominated as a next-generation technology for railway communication by the International Union of Railways. The adoption of LTE-R technology introduces many advantages that can meet current and future needs in railway communication [1]. Today, South Korea is the global leader in the LTE field. South Korea will replace GSM-R with LTE-R by 2016 [2]. This is a twofold attempt by the Korean government. On one hand , it keeps the Korean railway up-to date with the leading innovative technology in the world. On the other hand, it enables communication on the Korean railway, to conform to the national LTE standard.

In this paper, we focus on the design of an LTE-R train control system (TCS). We propose new LTE-R communication network structures for the system. At first, we explain why a duplicated network structure is needed for the system. Indeed, because trains move at speeds of up to 500 km/h, any failure in the train control system may result in serious problems that threaten the safety of train operation. This safety-related requirement cannot only be satisfied with a single network structure. Therefore, a duplicate network structure is worth it, and necessary for the safety of train operations. Let's suppose that a duplicated network structure is adopted for a system and it divides the system into two logical sub-networks. Then, issues such as resource re-allocation and task re-division for those subnetworks must be addressed. We know the fact that resources dedicated for railway communication such as radio spectrum and frequency bands are somehow limited. However, the minimum data traffic demand for train operation cannot be reduced. Thus, a tradeoff between traffic demand and allocated resources should be taken into account when considering the new network structure. We will discuss in detail about these issues in the next sections. In addition, we identify and show how technical challenges with LTE technology in the railway context can be solved. In fact, there are two main problems that significantly decrease the performance of an LTE network, which are the *handover problem* and *inter-cell interference problem* [1, 3]. The handover problem is caused by the mobility of devices, while the inter-cell interference problem is due to frequency reuse in adjacent cells.

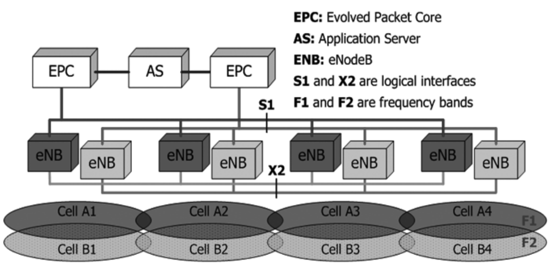
In the context of a railway, the high speed of the train makes the handover problem occur more frequently, and the time available to perform a handover procedure short. Hence, solving the handover problem in the context of a railway will be a difficult challenge. In our network design, we make use of an on-train dual-link model as the state-of-the-art approach to this problem. In addition, the inter-cell interference problem reduces the performance of the system as well. We expect that our work can provide a useful reference for the deployment of future LTE-R train control systems.

Finally, we present our conclusions and future work in the last section.

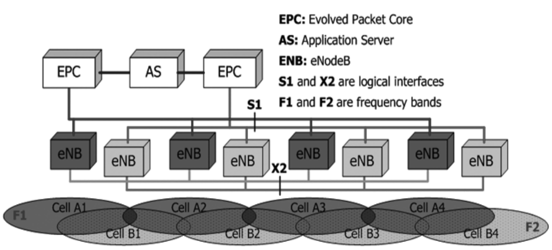
II. LTE-R TCS with a Duplicated Network Structure

1. System Architecture

In this section, we propose two different duplicate network structures for an LTE-R train control system (TCS). We have prepared two proposals for the system. Proposal 1 is characterized by a fully-overlapping cell arrangement as shown in Fig. 1 (a). Proposal 2 is characterized by a partly-overlapping cell arrangement as shown in Fig. 1 (b). Both proposals share the same components. Notice that we do not intend to explain the whole architecture of an LTE-R network. That is explained in [4, 5, 6]. Instead, we highlight the radio network layer with the main components that can be graphically represented as shown in the figure below.



(a)

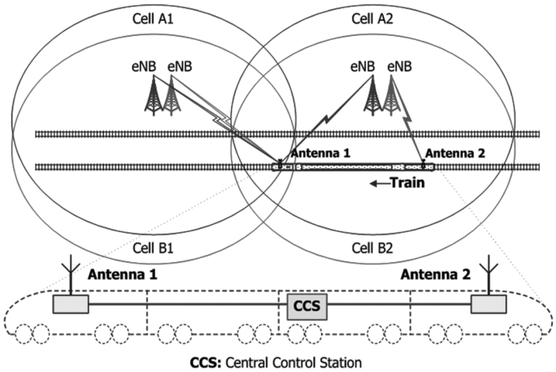


(b)

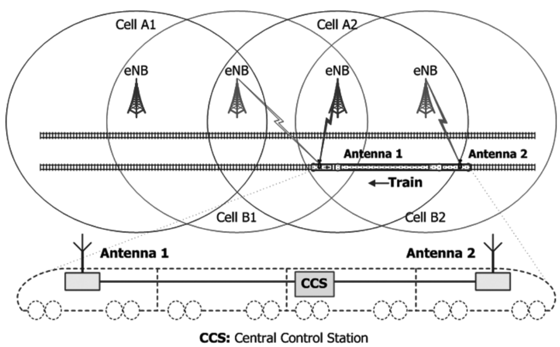
Fig. 1. *(a) Proposal 1: An LTE-R TCS with a fully overlapping cell arrangement, (b) Proposal 2: An LTE-R TCS with a partly-overlapping cell arrangement*

We recall that an eNodeB (eNB) is a network node that transmits signals to trains (or user equipment) and also receives signals from those trains. The eNBs are interconnected by means of the X2 interface. The eNBs are also connected to the Evolved Packet Core (EPC) by means of an S1 interface. An Application Server (AS) will be used to provide the applications and services needed for train operation. In our case, eNBs are deployed along rail tracks. Each eNB manages one cell. For reference, we give different cells different names. It is clear that all A cells and their associated network components (i.e. eNBs, EPC, etc.) constitute a subnetwork. Similarly, all B cells and their associated network components form another subnetwork. At any time of operation, a train should connect to both subnetworks to ensure the highest level of safety. Otherwise, an emergency treatment will be required for the continuous operation of that train. We describe below how an on-train dual-link model is established to facilitate the safety of train operation.

Originally, an on-train dual-link model is proposed in the literature to deal with the handover problem. Refer to [7, 3] for examples. In essence, this model takes full advantage of the transmission of distributed antennas and body length of the train to eliminate transmission delay. It implies that performance of the LTE-R TCS will improve, with the application of the on-train dual-link model and an effective handover algorithm. In addition, we can again see that the distributed antenna transmission will be helpful when a train connects to two subnetworks simultaneously.



(a)



(b)

Fig. 2. *An on-train dual-link model in an LTE-R TCS: (a) with a fully-overlapping cell arrangement, and (b) with a partly-overlapping cell arrangement*

Figure 2 depicts a train with an on-train dual-link operating in the LTE-R TCS as described in Proposal 1 and Proposal 2. As shown in the figure, with a center control station (CCS), we can effectively control the train and ground communication using two antenna sets mounted on the top of the train (at its front and its rear, respectively). Each individual antenna is configured to only work with one dedicated subnetwork. However, each set of antennas may include some antennas that allow it to work with two different subnetworks. It is obvious that communications in an LTE-R TCS will be more reliable with the deployment of the on-train dual-link model. As a result, train operations are safer in that system..

2. Resource Requirement and Task Division

At first, we estimate the traffic demand for train operations. This is important to calculate the bandwidth required by the LTE-R TCS. According to [2], services constituting a typical train control system are automatic train control (ATC), voice calls, data services, and video services. The data rates needed for these services are summarized in Table 1.

Table 1. *Estimated data rates for train operation*

Function	Data rate	
	Uplink	Downlink
Automatic train control	530 kbps	530 kbps
Voice call	224 kbps	224 kbps
Data service		1100 kbps
Video service	2304 kbps	2048 kbps
Total	3058 kbps	3902 kbps

Because spectrum resources dedicated for railway communication are often limited, in this work we assume that the allocated bandwidth is sufficient enough for total traffic demand, which is defined in Table 1. In order to determine a requested bandwidth, we need to consider the capacity or peak bit rate of an LTE network. Note that the peak rate is defined as the peak data rate that user equipment can achieve in an ideal RF condition. Bandwidth supported by the current LTE standard and corresponding practical peak rates are listed in Table 2. The mentioned peak rates are established in [8] for a single stream with the assumption that 64QAM and 16QAM are used for downlink transmission and uplink transmission, respectively.

Table 2. *Practical LTE peak rates in Mbit/second*

	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Downlink	2.1	9.3	17.9	35.8	53.8	73.6
Uplink	2.1	5.0	8.3	20.1	29.9	39.6

Recall that with the duplicated network structure, the LTE-R TCS has two logical subnetworks operating simultaneously. Regardless of the types of cell arrangements, as shown in Fig. 1, these subnetworks need to use different spectrum bands to avoid mutual interference. Furthermore, at least one bandwidth greater than 1.4 MHz is required for video service, as its data rate can reach 2.25 Mbps. Therefore, the preferred bandwidths for the two subnetworks will be 1.4 MHz and 3 MHz. From now on, we will refer to these subnetworks as the 1.4 MHz subnetwork and the 3 MHz subnetwork. We assume that the frequency-division duplexing method is used for communications in those networks. This means that we need 1.4 MHz of bandwidth for the uplink and another 1.4 MHz of bandwidth for the downlink in the 1.4 MHz subnetwork. Similarly, two different 3 MHz bandwidths are required for the 3 MHz subnetwork. We can assign tasks to two subnetworks depending on their own channel capacity as follows:

• 1.4 MHz subnetwork will support ATC and voice calls;

• 3 MHz subnetwork will support data and video services.

Theoretically, as expected in LTE technology, at 1.4 MHz and 3 MHz, the total downlink and uplink peak rates are 11.4 Mbps (i.e. 2.1 Mbps plus 9.3 Mbps) and 7.1 Mbps (i.e. 2.1 Mbps plus 5.0 Mbps), respectively. The total traffic demands defined in Table 1 will reach 4.5 Mbps downlink throughput and 3.5 Mbps uplink throughput. Therefore, the LTE-R TCS can serve multiple trains operating simultaneously.

3. Technical Challenges

Among the technical requirements for a train control system, the availability and reliability of its communication network are the most important. With the duplicated network structure and on-train dual-link model, the reliability is obviously enhanced for LTE-R TCS. Since the availability is typically measured as a factor of the reliability, as reliability increases so does availability. We observe that throughput performance reflects both availability and reliability, while link quality reflects the reliability of a network. Note that in LTE, the link quality is defined by the maximum acceptable block error rate (BLER). Therefore, in the following section, our main concern is to identify problems that may reduce the throughput performance and link quality of an LTE network. According to [1, 3], there are two major problems that need to be considered:

(1) *The handover problem*. This problem

is caused by train mobility. The current LTE hard handover scheme may have a large outage probability and interrupt latency, which severely affects the reliability of train-to-ground communication. As it allows the train to receive signals from only one base station at a time, the on-train dual-link model is not supported.

(2) *The inter-cell interference problem*. This problem is due to frequency reuse in adjacent cells. Methods and algorithms to deal with inter-cell interference are not available in the current LTE standard.

Tien et al. (2012) [3] proposed a seamless dual-link handover scheme in broadband wireless communication systems for high speed rail. In our case, a seamless handover scheme of similar type can be adapted to the LTE-R TCS. We deploy an on-train dual-link model for LTE-R TCS, as shown in Section II.1. A seamless handover scheme like the one introduced in [3] works as follows. At the time, the front antenna performs a handover to connect to the target eNB (i.e. after handover , the eNB becomes the serving eNB), while the rear antenna still connects with the serving eNB. When the handover procedure is done, the rear antenna should be released, and all allocated physical resource blocks and the front antenna will take the role of train and ground communication. If a handover fails with the front antenna, the rear antenna will continue to carry the handover and take on the role of train and ground communication.

Since the handover problem can be addressed efficiently using the on-train dual-link model and a seamless handover algorithm described above, we will concentrate more on methods to solve the inter-cell interference problem. Actually, there are many studies that deal with the inter-cell interference problem [9-14]. They are mainly based on dynamic frequency allocation and the power control approach that often uses the fractional frequency reuse technique. The dynamic frequency allocation approach uses a technique that requires two adjacent cells to allocate different physical resource blocks (PRBs) at a time. Clearly, these two approaches reduce the throughput of cells, since the band of each cell is narrowed. Furthermore, methods based on these approaches require two adjacent eNBs to cooperate to exchange channel allocation information. Thus, they introduce some overhead that again reduces the performance of the corresponding cells.

We remark that existing methods and results for the handover problem and the inter-cell interference often relies on a single network structure setup. Therefore, results obtained with a duplicate network structure setup such as the throughput performance and link quality may be different and interesting.

III. Conclusion

In this paper, we investigated a future LTE-based train control system. We proposed two different duplicate network structures for this system, as is required for the safety of train operations. This implies that the availability and reliability of the system can be enhanced. In addition, no existing methods or results concerning this issue are available. In the future, we will provide more results related to the reliable and continuous operation of a train operation in the system. We also consider the handover problem in the duplicated network structure contexts created by this work.

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KIẾN TRÚC MẠNG VÔ TUYẾN KÉP DỰA TRÊN CÔNG NGHỆ LTE CHO HỆ THỐNG ĐIỀU KHIỂN TÀU CAO TỐC

Tóm tắt:
Hiệp hội Đường sắt Quốc tế đã quyết định sử dụng công nghệ LTE để thay thế công nghệ GSM cho các hệ thống giao tiếp đường sắt. Hàn Quốc – quốc gia đi tiên phong về công nghệ LTE, sẽ áp dụng công nghệ này cho hệ thống đường sắt cao tốc của họ vào năm 2016. Để đảm bảo tuyệt đối an toàn chạy tàu, hệ thống thông tin điều hành tàu cao tốc phải đặc biệt tin cậy và luôn trong trạng thái sẵn sàng. Yêu cầu này chỉ có thể được đáp ứng tốt nhờ hệ thống mạng vô tuyến với các tế bào chồng lấn. Các giải pháp hiện nay chủ yếu dựa trên một kiến trúc mạng vô tuyến đơn lẻ. Vì vậy, mức độ tin cậy của hệ thống thông tin điều hành tàu chưa đảm bảo yêu cầu. Trong bài báo này, chúng tôi thiết kế một hệ thống điều hành chạy tàu với kiến trúc mạng kép. Chúng tôi đề xuất hai phương án thiết kế mạng với cách sắp xếp các tế bào vô tuyến khác nhau. Trên cơ sở các đề xuất này, chúng tôi phân tích, làm rõ những yêu cầu kỹ thuật, những ưu điểm và thách thức có thể gặp phải khi triển khai hệ thống trong thực tiễn.
Từ khóa: *Giao tiếp đường sắt, LTE-R, tàu cao tốc, điều khiển chạy tàu, kết nối kép, đường sắt Hàn Quốc*