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A survey on high-speed railway communications: A radio resource management perspective

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ABSTRACT

High-speed railway (HSR) communications will become a key feature supported by intelligent transportation communication systems. The increasing demand for HSR communications leads to significant attention on the study of radio resource management (RRM), which enables efficient resource utilization and improved system performance. RRM design is a challenging problem due to heterogeneous quality of service (QoS) requirements and dynamic characteristics of HSR wireless communications. The objective of this paper is to provide an overview on the key issues that arise in the RRM design for HSR wireless communications. A detailed description of HSR communication systems is first presented, followed by an introduction on HSR channel models and characteristics, which are vital to the cross-layer RRM design. Then we provide a literature survey on state-of-the-art RRM schemes for HSR wireless communications, with an in-depth discussion on various RRM aspects including admission control, mobility management, power control and resource allocation. Finally, this paper outlines the current challenges and open issues in the area of RRM design for HSR wireless communications.

1. Introduction

For the last two decades, intelligent transportation systems (ITS) have emerged as an efficient way of improving the performance of transportation systems. As an essential element of ITS, high-speed railway (HSR) has been developed rapidly as a fast, convenient and green public transportation system and would become the future trend of railway transportation worldwide [1]. For instance, a high speed rail plan has been outlined in America and the length of HSR lines in China will reach 18,000 km by 2020 [2]. With the continuous construction of HSR in recent years, the issue of train operation safety has attracted more and more attention. The train operation control system plays a key role in train operation safety and is regarded as the nerve center of the HSR system. A standard has been set up for the train operation control system, which is known as European Train Control System (ETCS) [3,4]. In order to make ETCS work better and create a digital standard for railway communications, a dedicated mobile communication system called the global system for mobile communications for railway (GSM-R) has been proposed by International Union of Railway (UIC) [5].

GSM-R has been widely used in HSR communications and can maintain a reliable communication link between the train and the ground. However, GSM-R has some major shortcomings, such as insufficient capacity, low network utilization, and limited support for data services [6]. A broadband wireless communication system for HSR called long-term evolution for railway (LTE-R) has been presented in [7,8] and determined in the 7th World Congress on High-Speed Rail [9]. Broadband wireless communications can enhance the train operation by allowing an operation center to monitor real-time train-related data information, such as safety information and track diagnostic information [10]. In addition to the train control data transmission, LTE-R is also expected to provide passenger services such as Internet access and high-quality mobile video broadcasting [3,4,11]. With the benefit of it, passengers can treat their journey as a seamless extension of their working or leisure environment.

To improve the capacity for wireless communications on the train, the future HSR communication networks are expected to be heterogeneous with a mixture of different networks and radio access technologies that can be simultaneously accessed by hundreds of users on the train [12,13]. For instance, the heterogeneous network architecture can be considered as a combination of satellite network, cellular network and wireless data network [10], where the advantage of each access network can be taken into consideration. This architectural enhancement along with the advanced communication technologies such as

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multiple-input multiple-output (MIMO), orthogonal frequency-division multiplexing (OFDM) and radio over fiber (RoF), will provide high aggregate capacity and high spectral efficiency. Nevertheless, the demand for HSR wireless communications is increasingly growing, for example, the estimated wireless communication requirement could be as high as 65 Mbps per train [14]. To further relieve the contradiction between the increasing demand and limited bandwidth of HSR wireless communications, it is necessary to implement radio resource management (RRM) to improve resource utilization efficiency and ensure quality of service (QoS) requirements. However, the traditional RRM methods (e.g., handover, power control and resource allocation) for common cellular communications may not be efficient in HSR wireless communications due to the following reasons, which are closely related to the characteristics of HSR scenario.

- **High mobility**. The dramatic increase of train speed will cause frequent handover. Given a cell size of 1-2 km, a high-speed train of 350 km/h experiments one handover every 10–20 seconds [15]. To solve the frequent handover problem is one of the main functions of RRM in HSR wireless communications. Moreover, the fast relative motion between the ground and the train will lead to large Doppler shift and small coherence time. The maximum speed of HSR in China is currently 486 km/h, which induces a Doppler shift of 945 Hz at 2.1 GHz [14]. Thus, when implementing resource allocation for HSR communications, it is necessary to consider the fast-varying channel and inter-carrier interference (ICI) especially for OFDM technology.
- **Unique channel characteristics**. The moving train encounters diverse scenarios (e.g. cuttings, viaducts and tunnels) with different channel propagation characteristics [3,16], which causes that a single channel model could not depict features of HSR channels accurately. It brings a big challenge to RRM schemes, which should be adaptive to diverse scenarios along the rail with different channel models. Furthermore, the line-of-sight (LOS) component is much stronger than the multipath components especially in viaduct scenario, which implies that the propagation loss mainly depends on the distance between the base station (BS) and the train [17]. Since the distance varies with the train's position, the power control along the time has a large influence on system transmission performance [18].
- **Heterogeneous QoS requirements**. Many types of services with heterogeneous QoS requirements and priorities will be supported on the train [10]. The QoS performance in HSR wireless communications will be degraded because of high mobility and unique channel characteristics, especially for real-time services and critical core services that are critical for the train operation [19]. In order to improve system performance and satisfy heterogeneous QoS requirements, it is critical to design effective RRM schemes and resource optimization methods for multiple services transmission in HSR communications.

All these unique characteristics make it challenging to facilitate RRM design for HSR wireless communications. Thus, a new look into the RRM problem in HSR communications is urgently required, where the network architecture and unique characteristics of HSR scenario should be fully taken into consideration. This paper systematically reviews and evaluates the various studies performed in the area of HSR communication systems. There are also some survey papers discussing the research topics in HSR wireless communications, such as the network architectures [12,13], the handover schemes [20], and the channel characteristics and models [21,22]. Contrary to these surveys, this paper provides a comprehensible survey on HSR wireless communications from the perspective of RRM and optimization design. Our goal is to present a detailed investigation and thorough discussion of current state-of-the-art RRM schemes for HSR wireless communications, as well as provide a better understanding of the RRM research challenges and open issues in HSR wireless communications.

The paper is organized based on the structure shown in Fig. 1. Section 2 provides an overview of HSR communication systems, including potential network architecture, HSR applications and services, as well as advanced transmission technologies. This is followed by a discussion on HSR channel characteristics in Section 3, where a detailed analysis is carried out to understand the effects of channel characteristics on RRM design. Section 4 surveys the RRM schemes for HSR wireless communications from several aspects: admission control, mobility management, power control, and resource allocation. The current challenges and open issues of RRM design for HSR wireless communications are given in Section 5, prior to the conclusions in Section 6.

2. Overview of HSR communication systems

2.1. Network architecture

A proper network architecture is the basis of broadband wireless communications for high-speed trains [2]. In this subsection, we provide a potential architecture to guide our discussion of broadband Internet access on trains. A global overview of the network architecture for HSR communications is depicted in Fig. 2. This heterogeneous network architecture is responsible for the data transmission between the fast moving train and the service providers. It is layered and consists of the core network, the aggregation network, the access network and the train network [10,23]. All these four layers are briefly introduced as below.

2.1.1. Core network

The core network is responsible for providing services and data processing in HSR communication systems. There are two major actors in the core network, i.e., Internet and Railway Stakeholders (RST) [10]. The Internet can provide the multimedia services for passengers and the content servers (CSs) are deployed in order to offload data traffic [24], which have been applied in [25,26]. The RST can have remote data access to devices on the trains, such as train operating company (TOC) and train maintainer company (TMC). The former operates the trains for passenger or freight transport, while the latter is responsible for maintaining the trains. In LTE-R system, the core network is the Evolved Packet Core (EPC) [8]. The significant difference from the core network of GSM-R is that the EPC is an all-IP mobile core network. This means that all services will be transmitted on the packet-switched domain.

2.1.2. Aggregation network

The aggregation network lies between the access network and the core network, and it forwards data from the access network to the global Internet. The aggregation network can use the following technologies for forwarding data: IEEE 802.11, Ethernet, ADSL, or optical fiber [12]. Two types of gateways in the architecture play a key role in data aggregation, named the access gateway (AGW) and service gateway (SGW). The AGW serves as an interface between the access network and aggregation network. It combines the data from the access networks and forwards that data to the SGW, which serves as an interface between the aggregation network and core network.

2.1.3. Access network

The access network is close to the railway line, and it provides the last hop communication for the train. Three kinds of wireless access technologies are used to provide wireless access for high-speed trains: satellite, cellular and dedicated wireless data networks. Thus, this network architecture can be regarded as a heterogeneous network. Table 1 gives an overview of the different characteristics of these access technologies [10,12,13]. Specifically,