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Mobile relays for enhanced broadband connectivity in high speed train systems

Elias Yaacoub [a,*], Rachad Atat [b], Ahmad Alsharoa [c], Mohamed-Slim Alouini [c]

[a] Qatar Mobility Innovations Center (QMIC), Qatar Science and Technology Park, P.O. Box 210531, Doha, Qatar
[b] Department of Electrical Engineering and Computer Science, University of Kansas, KS, United States
[c] Electrical Engineering Program, King Abdullah University of Science and Technology (KAUST), Thuwal, Makkah Province, Saudi Arabia

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ABSTRACT

With the introduction of wireless modems and smart phones, the passenger transport industry is witnessing a high demand to ensure not only the safety of the trains, but also to provide users with Internet access all the time inside the train. When the Mobile Terminal (MT) communicates directly with the Base Station (BS), it will experience a severe degradation in the Quality of Service due to the path loss and shadowing effects as the wireless signal is traveling through the train. In this paper, we study the performance in the case of relays placed on top of each train car. In the proposed approach, these relays communicate with the cellular BS on one hand, and with the MTs inside the train cars on the other hand, using the Long Term Evolution (LTE) cellular technology. A low complexity heuristic LTE radio resource management approach is proposed and compared to the Hungarian algorithm, both in the presence and absence of the relays. The presence of the relays is shown to lead to significant enhancements in the effective data rates of the MTs. In addition, the proposed resource management approach is shown to reach a performance close to the optimal Hungarian algorithm.

1. Introduction

With the significant increase in the number of Internet users, wireless communications became integrated in people's lives. Personal wireless devices such as laptops, Personal Digital Assistant (PDA), and smart phones are becoming widely used by users whether they are at homes, in their offices, inside their vehicles, on a train or a bus. In the past years, the passenger transport industry has witnessed a high demand for broadband services to ensure the safety of people and trains on one hand and to provide passengers with Internet access on the other hand [1]. Information between terrestrial control centers and trains, such as information on the location of the train, its schedule, its state, level crossings, permitted speed, etc., is usually exchanged through the Global System for Mobile communications-Railway (GSM-R) network to ensure that the railway service is under secure conditions [2]. In addition, since most of the journeys in high speed trains can last for several hours, passengers may want to have access to the Internet to be able to browse a website, read/send emails, perform real-time multimedia streaming, etc. [3]. All these services necessitate a wireless communication channel with large bandwidth and wide coverage [2]. The implementation of wireless communication systems has attracted interest from both the railway industry and the communication companies, which in turn are investigating new network architectures to provide the passengers with high speed mobile data services [4]. GSM-R can provide a maximum

* Corresponding author. Tel.: +974 77497981.
E-mail addresses: eliasy@qmic.com, elias_yaacoub@yahoo.com (E. Yaacoub), rachadatat@live.com (R. Atat), ahmad.sharoa@kaust.edu.sa (A. Alsharoa), slim.alouini@kaust.edu.sa (M.-S. Alouini).

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data rate of 200 kbps and is only used to exchange train control information rather than passengers' communication and thus, GSM-R cannot satisfy the needs of high speed data transmissions [5]. High speed mobile data services are provided by High Speed Downlink Packet Access (HSDPA) that is able to achieve a data rate of 28 Mbps with a 5 MHz bandwidth. In addition, the Long Term Evolution Network (LTE) is being extensively deployed for cellular communications since it meets increasing bandwidth demand with high spectrum efficiency and latency. LTE can achieve a higher data rate of up to 300 Mbps with 20 MHz of channel bandwidth [5]. There exist various technologies for train-to-land connections, among these technologies, the satellite which is suitable for tracks without obstructions, WiFi which is suitable for train journeys with multiple stops, 2G/EDGE which is suitable for low bandwidth applications, and 3G which is suitable in urban areas. However, LTE is best suited for high speed broadband data [6]. An extension to LTE, called LTE-R (LTE-Railway), which is based on the standard of LTE and SAE (System Architecture Evolution), is being investigated as the next generation wireless communication system for high speed railways since it was shown to provide good performance with advanced channel estimation and disperse deployed antennas on the train [7]. However, many problems and challenges arise despite the wireless broadband technology in use. First, when the Mobile Terminal (MT) communicates directly with the Base Station (BS), it will experience a severe degradation in the Quality of Service (QoS) since the wireless signal has to travel through the train, and penetrate through the metalized windows, the fact that dramatically reduces and weakens the wireless link quality [5]. Multimedia applications such as video streaming require a high bandwidth in order to be delivered with high QoS to end users. Since the train can be perceived as a moving mobile network and since the users are moving fast, a reliable direct link with the outside cellular network can be hard to establish [3,8].

In line with standardization efforts [9], we suggest in this paper the use of efficient radio resource management with an LTE multihop relay-based network architecture, where a relay is installed on top of each car of the train (on the ceiling), and the closest wireless BS in the vicinity of the train communicates with the relays using LTE technology. Then, each relay communicates with the MTs that are located inside the train car, also using LTE. This network approach aims at enhancing the perceived data rates and QoS of the MTs compared to the case where the BS communicates directly with the MTs in the train. Thus, the BS does not need to communicate with the hundreds of passengers in the train which reduces radio resource management control significantly. This approach will help in avoiding the radio signal propagation losses and low QoS, and maintaining a stable high speed wireless link between the relay and the MTs inside the train car.

The paper is organized as follows. Related work is reviewed in Section 2. The system model is presented in Section 3. The adopted propagation models are described in Section 4. Data rate calculations with the proposed relay-based approach are presented in Section 5. The problem formulation and the proposed heuristic solution based on LTE radio resource management are presented in Section 6. Simulation results are studied and analyzed in Section 7. Section 8 outlines some limitations of the proposed approach and indicates directions for future research. Finally, conclusions are drawn in Section 9.

2. Related work

Relays have been widely investigated in the literature because they can minimize the total power consumption of the network nodes, maximize the network lifetime, extend the coverage and expand the capacity in wireless systems [10]. Relays for the purpose of reducing the energy consumption in sensor networks and cooperative ad-hoc networks are investigated in [11–16]. In [11], the authors propose a new scheme to be used in wireless sensor networks which are usually composed of a number of microsensors which have limited battery power. In the scheme of [11], one cluster head is elected, and it sends the data to the BS via a relay node, and thus, energy can be saved. An algorithm to select the best relays with minimum power consumption that would form cooperative links to establish a route from source to destination is proposed in [12]. For the cooperative link, total power consumption which is taken to be the summation of the transmit power of the source node and the transmit power of the relay node is minimized subject to a target bit error rate (BER). Then, the relay node that minimizes the total power consumption is selected and a one hop cooperative route from source to destination is established. An optimal power allocation in the case of multiple relays is suggested in [13]. The formulated optimization problem is based on maximizing the network lifetime at each transmission stage where channels are slowly varying over time by applying the optimal power allocation strategy. In [15], the authors minimize the average energy consumed in the network to transmit a message from source to destination via intermediate cooperative relays subject to a target outage probability. They propose an algorithm equivalent to shortest path computation with link cost being the energy consumed of transmitting a message from one node to another. In [16], suboptimal algorithms are proposed in order to increase the device lifetime by exploiting cooperative diversity and taking both location and energy advantages under the BER constraint.

The previous references investigated relaying in a relatively low mobility scenario. However, relaying in scenarios with higher mobility, such as vehicular networks and railroad networks, is more relevant to the scope of this paper. Cooperative wireless communication systems employed in vehicular networks have been investigated in [17–21]. Vehicles traversing a route have limited time to download a file or to access the Internet as they are moving fast and the Access Point (AP) cannot cover the whole path, which means vehicles would have intermittent connectivity. In [17,18], the authors present a cooperative Automatic Repeat-reQuest (ARQ) where, after leaving the AP coverage, vehicles communicate between each other to exchange the packets that were lost during the transmission from the AP to the vehicle nodes. In this way, retransmissions of packets can be avoided and thus packet losses will