Novel System Architecture For Railway Wireless Communications

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Abstract—Railway communications are essential nowadays enabling passengers to stay connected to entertainment as well as other bandwidth-demanding applications. This is particularly challenging because wireless communication standards are not fully customized to overcome railway environment challenges including high handover frequency, group handover and Quality of Service (QoS) guarantees.

In this paper, a novel system architecture for railway wireless communications is proposed. The proposed heterogeneous system utilizes the Parallel Redundancy Protocol (PRP), the 4G Long Term Evolution (LTE) cellular protocol and as well as the IEEE 802.11n (Wi-Fi) wireless protocol. The goal of the proposed system is to quantify the overall system performance through several metrics (such as the data loss ratio, average packets dropped, handover delay and LTE delay) thereby ensuring that the proposed system can meet the required entertainment benchmarks. A performance simulation-based study is conducted to validate the feasibility of the proposed system in an urban railway environment. Simulation results show that the proposed architecture achieves improved performance for a high-load scenario even with added background traffic as compared to a conventional railway architecture for wireless communications.

I. INTRODUCTION

Recently, trams and medium-speed trains are becoming more important in the daily lives as a fast, safe and green means of transportation. More and more people prefer to commute using trains than any other means of public transportation. Even governments around the world, especially China and some European countries, encourage the use of trains instead of cars for personal transportation in order to decrease traffic and to reduce air pollution given that cars are among the main causes of air pollution and smog in urban environments [1].

The use of wireless communications in the railway industry is now growing. On the other hand, non of the existing wireless communications standards are fully customized to overcome the challenges faced in railway environments. Typical railway communication problems include high handover frequency, group handover and Quality of Service (QoS) guarantees for high-bandwidth of multimedia and entertainment applications. Typically, these problems have been investigated individually but, when combined, they represent a challenge when designing a railway wireless communication system.

The handover problem in broadband wireless communications systems has been widely investigated in the literature with the goal of minimizing the handover interruption time and guaranteeing QoS requirements. In [2], an LTE-based communication system was proposed with a flat access network architecture in order to reduce the handover processing time. A number of handover algorithms were also proposed in [3] and [4] based on properties specific to railway communication systems such as the predictable train speed and direction of motion. Fuzzy logic was applied in [3] to reduce the number of unnecessary handovers. To increase handover decision accuracy, parameter optimization was done for some handover algorithms in [4]. However, achieving seamless handover still remains a challenge with the goal of reducing communication interruption time to zero while guaranteeing no loss of transmitted data.

The aim of this paper is to investigate the use of the Parallel Redundancy Protocol (PRP) over the 4G Long Term Evolution (LTE) cellular protocol (i.e. PRP-LTE) as a backbone for communication in the context of passenger trains. The focus is on the improvements in network performance that can be achieved using PRP-LTE considering the large amount of traffic generated by the numerous on-board users as well as the constant handover between eNodeBs (eNBs) along the trains trajectory.

In this paper, a heterogeneous architecture is proposed based on a Wi-Fi and LTE network where Wi-Fi is utilized to provide edge network connectivity to the users on-board the train. IEEE 802.11n (Wi-Fi) was chosen due to its very widespread deployment as well as its low cost and relatively high bandwidth. PRP is employed over LTE as a backbone for the train backhaul communication as LTE offers a wide coverage range, excellent support for mobility as well as high bandwidth. The on-board users Wi-Fi traffic is duplicated at a Redundancy Box (RedBox) and transmitted over two independent LTE Antennas (one at the front of the train and another at the back). Another RedBox, part of the IP Cloud, is responsible for receiving the data from the LTE eNBs. For this, PRP needs to be capable of working across IP routers, which has been discussed in [5]. The replication of traffic over PRP protects against any single packet loss over one of the two employed antennas in addition to offering better performance (decreased latency and jitter) [6], [7].

The application of the proposed PRP-LTE approach in practice does not require duplication at the infrastructure
level. Instead, PRP is utilized over LTE across two different mobile operators (for example one cellular operator for the front antenna and another operator for the back antenna). Moreover, both antennas could even operate on a single mobile operator by employing different LTE bands (for example the front antenna could camp on band 5 (850MHz) while the back antenna is locked into band 2 (1900MHz)). This use of the proposed PRP-LTE approach overcomes two common network problems which are network congestion and node failures while also offering improved performance compared to a single-channel wireless communication system.

Initial simulations carried out using Riverbed Modeler [8] demonstrated the feasibility of the proposed architecture. The performance improvements due to the use of PRP-LTE was quantified through the study. It was shown that, in a low load video streaming scenario with a small number of on-board users, the required video streaming benchmarks were met with no packet losses. Moreover, when the number of on-board users and consequently the total load were increased, the proposed architecture was still able to meet the required video streaming benchmarks while a corresponding architecture with no PRP failed.

The rest of this paper is organized as follows: Section II provides related background information. Section III illustrates the simulation results and quantifies the overall system performance using several metrics. Finally, the study is concluded in Section V.

II. BACKGROUND

A. LTE for Vehicular Communications

LTE, defined by the Third Generation Partnership Project (3GPP) [9], is characterized by a flat all-IP architecture which allows IP-based data, voice and signaling transmission. This approach allows for an increased deployment flexibility and extendibility with respect to previous cellular standards.

Compared to previous cellular protocols, LTE also offers superior performance in terms of lower latency and higher throughput which makes it ideal for today’s high-bandwidth mobile users. In a 20MHz spectrum, LTE can theoretically achieve a 150Mbps data rate on the downlink, a 50Mbps data rate on the uplink with a latency that is less than 5ms in the user plane. LTE technology is cost and performance efficient due to its simplified network architecture as well as its use of advanced algorithms for resource utilization.

The high-level LTE network architecture is comprised of User Equipment (UE), Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) and Evolved Packet Core (EPC). The E-UTRAN consists of the eNBs which are responsible for all radio control and management functionalities as well as the interaction between the user equipment and the LTE core network. The EPC is responsible for mobility management, QoS and interoperability with other access technologies.

In the literature, LTE was used along with different network technologies and architectures for use in vehicular applications. In [10], a heterogeneous LTE/WiFi vehicular system was proposed that supports both entertainment and ITS traffic control data in an urban vehicular environment. A heterogeneous LTE/IEEE 802.11p network was proposed in [11] that provides multimedia services where LTE is used for vehicle to infrastructure (V2I) communications and IEEE 802.11p for vehicle to vehicle (V2V) communications.

The International Union of Railways has decided that LTE standard will be the next generation of railway wireless communications, as LTE provides high bandwidth and low latency. LTE also increases capacity [12] and speed of wireless networks in addition to a wide coverage and a better Quality of Service (QoS) [13].

B. Parallel Redundancy Protocol (PRP)

In order to overcome single network failures, PRP was proposed by the International Electrotechnical Commission (IEC) [14]. PRP is an active redundancy approach that works without reconfiguration timeouts and provides seamless fail-over. PRP makes use of two independent networks, where each frame is duplicated at the transmitter with the same sequence number and sent over both networks. At the receiver, the first correct arriving frame is accepted while the other duplicate is discarded.

PRP is applied extensively in Networked Control Systems (NCS) and industrial applications in combination with WLAN, yielding a significant improvement in timing behavior as well as packet loss compared to a single WLAN channel [15], which makes PRP appealing to industrial applications where loss of connectivity means loss of functionality. PRP provides high availability seamless redundancy without affecting data transmission and independent of higher network protocols. Recently, PRP is used to improve the performance of wireless communication for IEEE 802.11g (Wi-Fi) and IEEE 802.15.4 (ZigBee), achieving an improved overall communication channel [16], and increasing WLAN system performance.

Each network node is attached to two different networks but must share a similar topology. Both networks are completely separated and supposed to be fail-independent. PRP provides a zero recovery time and is also able to detect lurking failures by continuously checking the redundancy.

PRP nodes have two ports, i.e, dual Network Interface Cards (NICs), attached to two different networks. Thus, PRP is considered a layer 2 redundancy protocol independent of higher layers and allows higher layer protocols to operate with no modifications. Non-PRP nodes can be connected to a single network or must be connected to a redundancy box (RedBox) to behave like doubly attached nodes.

III. SYSTEM ARCHITECTURE

To increase the performance of wireless railway communication systems using LTE, it is proposed to implement PRP on both the train transceiver as well as the backbone network. Implementing PRP on the train by placing two antennas on top of the train (one at the front and the other at the rear) to improve performance and to decrease the probability of handover failure at high speed. We propose exploiting this technique in
an urban traffic environment for a 200m long train moving with a speed of 60km/hr in a circular motion around the city center. The proposed PRP-LTE communication scheme employs two independent cellular networks (two different LTE bands for the same mobile operator or two different mobile operators) to achieve redundancy. The proposed scheme is expected to increase system performance during handover in addition to providing more immunity against fading and interference during normal operation at a low cost compared to duplicating the network infrastructure.

The use of dual layer system architectures is well known in wireless communications for ITS. As shown in Fig.1, users in each carriage communicate with the wireless Access Points (APs) directly. The Train Relay Station (TRS) onboard the train controls all APs and instructs them to forward the collected data to the eNBs. The TRS consists of two hot swappable relays to make the proposed PRP architecture fully redundant with no single point of failure. In order to reduce the handover overhead on the eNBs, the TRS acts as a single user instead of all the active users executing handovers simultaneously from the serving eNB to the target eNB. PRP is utilized to achieve dual link communication with two antennas on top of the train connected to two different transceivers.

The front antenna usually has the better signal quality when the train is approaching the serving eNB, while the rear antenna has the better signal quality when the train is moving away from the serving eNB. During handover, the front antenna first attempts to carry out the handover while the rear antenna is still connected to the serving eNB. If the handover attempt fails at the front antenna, the TRS is still able to forward traffic normally using the rear antenna.

![Fig. 1. System Architecture.](image)

The proposed architecture divides railway communication into two segments: backhaul communication between the train and the eNB, and on-board communication between the on-board users and Wi-Fi APs. The backhaul provides access to the LTE network for voice and data sessions while Wi-Fi is employed as the edge network to share data connectivity inside the train. Typically, medium speed trains are located inside cities which are typically densely covered by eNBs.

Both voice and entertainment (video on demand, video conferencing, video streaming, voice over IP and Internet data) traffic are sent over the LTE backbone network and routed inside the train using a multi interface router which is equipped with LTE, Wi-Fi (IEEE 802.11n) and Ethernet interfaces. IEEE 802.11n has been chosen for its high market penetration.

The railway system deployment requires careful selection of parameters for wireless modules such as the eNBs’ location, density, power levels and spectrum allocation in addition to mobile stations parameters in order to meet the system requirements in terms of coverage and capacity at a low cost. In [17], a new hybrid frequency reuse method was proposed for LTE to be applied to traffic congestion management for Intelligent Transportation Systems (ITS). The network configuration parameters are summarized in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>eNB</td>
<td></td>
</tr>
<tr>
<td>Transmit power</td>
<td>10Watts [17]</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>18dBi</td>
</tr>
<tr>
<td>MIMO</td>
<td>2x2 [17]</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10MHz</td>
</tr>
<tr>
<td>Frequency band</td>
<td>1.8GHz</td>
</tr>
<tr>
<td>Rx sensitivity</td>
<td>-123dB [17]</td>
</tr>
<tr>
<td>Duplexing technique</td>
<td>FDD</td>
</tr>
<tr>
<td>Antenna height ($\Delta h_b$)</td>
<td>4m</td>
</tr>
<tr>
<td>UE</td>
<td></td>
</tr>
<tr>
<td>Transmit power</td>
<td>0.2Watts [17]</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>0dBi</td>
</tr>
<tr>
<td>MIMO</td>
<td>1x2 [17]</td>
</tr>
<tr>
<td>Rx sensitivity</td>
<td>-106dB [17]</td>
</tr>
<tr>
<td>Shadow fading standard deviation</td>
<td>4dB [17]</td>
</tr>
</tbody>
</table>

The cell coverage refers to the eNB communication range. The path loss (PL) between the eNB and the mobile station is the difference between the eNB transmitted power (Pt) and the received power at the mobile station (Pr). The LTE cell coverage and inter-site distance could be calculated analytically as in (1)

\[
PL(dB) = Pt - Pr. \tag{1}
\]

In a vehicular environment, path loss is calculated using (2) [18]

\[
L = [40(1-4 \times 10^{-3}\Delta h_b)]log_{10}R-18log_{10}\Delta h_b+21log_{10}f+80. \tag{2}
\]

where $\Delta h_b$ is the height difference in meters between the base station antenna and the mean building rooftop height. $R$ is the cell radius or the distance in km from the base station to the mobile station, $f$ is the carrier frequency in MHz.

In typical urban environments, $\Delta h_b = 4m$. Thus, from (1),(2) and Table I,

\[
R = 1.6Km. \tag{3}
\]
The Inter-Site Distance (ISD) is the distance between two adjacent eNBs. For omni-directional eNBs, to achieve a good compromise between network coverage and capacity, the ISD could be calculated from (4)

\[
ISD = \sqrt{3} \times R \\
\approx 2.77 \times 1.6 \text{Km} \quad \text{for} \quad R = 1.6 \text{Km}. \quad (4)
\]

For the proposed architecture, LTE band 3 was used with a 10MHz channel bandwidth. Band 3 was chosen for its good trade-off between coverage and capacity as it offers double the coverage of the 2600MHz band and a high capacity suitable for dense urban areas. Moreover, band 3 is the most widely used for LTE deployments in Africa, Asia, Australia and Europe. Band 3 uses the 1800MHz frequency band which makes it suitable for the dual layer system architecture, avoiding interference with Wi-Fi which operates over 2.4GHz Industrial, Scientific and Medical (ISM) band.

A hexagonal honey-cell layout is used for the seven cells model where each cell is served by one eNB in the cell center similar to the one in [10]. In order to model the worst case scenario, the same operating frequency was used for all eNBs to maximize the inter-cell interference. The train is modeled moving in a circular motion radially between the 7 cells’ centers under the ITU Vehicular Environment model for path loss and Vehicular B model for multipath [18], also fading was modeled with a standard deviation \( \sigma = 4dB \) [19].

The traffic types used in the simulation of the proposed architecture are entertainment traffic and background traffic. Youtube 480p video is used for simulating the entertainment traffic which is an H.264 video streaming data flow with 1Mbps bit rate. Ten stationary LTE UEs per cell are used for simulating the background interference as shown in Fig. 2 where each UE user is engaged in a web browsing session with a data rate of 100Bytes/sec.

IV. SIMULATION RESULTS

The proposed railway architecture was simulated using Riverbed Modeler [8]. The performance evaluation metrics used to characterize the proposed system are the Data Loss Ratio (DLR), uplink and downlink average packets dropped, handover delay and LTE delay, defined as follows:

- Data Loss Ratio (DLR) is the ratio between the number of lost bytes that did not reach the receiver divided by the sent bytes from the transmitter.
- Average Packets Dropped (APD) is the average number of packets that are sent from the transmitter but did not reach the receiver.
- Handover delay is the time taken for the handover from one eNB to another.
- LTE Delay is the time elapsed at the LTE layer between sending and receiving of an LTE frame (round-trip).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>DLR</th>
<th>Uplink APD (Packet/sec)</th>
<th>Downlink APD (Packet/sec)</th>
<th>Handover Delay (ms)</th>
<th>LTE Delay (Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>2%</td>
<td>38.3</td>
<td>54.9</td>
<td>12.8</td>
<td>0.459</td>
</tr>
<tr>
<td>PRP-LTE</td>
<td>1.39%</td>
<td>29.8</td>
<td>49.9</td>
<td>11.8</td>
<td>0.435</td>
</tr>
<tr>
<td>Percentage Change</td>
<td>30.5%</td>
<td>22.2%</td>
<td>9%</td>
<td>7.8%</td>
<td>5.2%</td>
</tr>
</tbody>
</table>

In this paper, the overall system performance is investigated in a realistic urban environment. A 95% confidence analysis is performed and the mean value is considered for all the presented results in Table II.

In LTE, hard handover is the only supported mechanism (Break-Before-Connect). Hard handover requires disconnecting from the source eNB before establishing a connection with the target eNB, which reduces the architecture complexity but may result in data losses during handover. For on-demand video streaming services, it is important to maintain a DLR threshold below 2% in order to meet QoS requirements [20]. The end-to-end delay for video on demand must be less than 1 second.

Fig. 3 through Fig. 7 show the system performance of the different evaluation metrics for the single antenna scenario before applying PRP. Fig. 3 shows the current eNB to which the train is connected. Expected data drops and delay increase during handover from one eNB to another are confirmed by simulation in Fig. 4 through Fig. 7.

It is shown in Table II, for the proposed PRP-LTE architecture in a high load scenario with background interference (as mentioned in section III), that the DLR decreased by 30.5% to be less than the 2% threshold, the uplink APD decreased by 22.2%, the downlink APD decreased by 9%. Regarding the delay, applying the proposed PRP-LTE system design decreased the handover delay by 7.8% and the LTE delay by 5.2%.

To conclude, the DLR, uplink APD, downlink APD, handover delay and LTE delay show large improvements in performance across all studied metrics for the proposed PRP-LTE architecture compared to a single antenna architecture. Both DLR and delay values are within the acceptable limits for entertainment application requirements.
Railway Systems use advanced wireless communication technologies to enhance traffic efficiency, improve passengers’ traveling experience and encourage more people to use railways as a faster, safer and greener means of transportation.

In this paper, a novel system architecture was proposed combining PRP with LTE for railway wireless communications in an urban environment achieving a highly reliable and fully redundant system with no single point of failure. The proposed system was demonstrated to achieve very high performance for a low load scenario as well as a high load with added background noise, while previous architectures did not satisfy the increasing traffic demand. Moreover, simulation results show the system feasibility and that it supports entertainment services while meeting the required benchmarks. The proposed architecture improved all investigated system performance metrics including: data loss ratio, average packets dropped, handover delay and LTE delay. The proposed architecture was shown to be very effective and practical for entertainment services.
applications as it does not require duplication of the existing backbone infrastructure.

REFERENCES


