Gap Filler Architectures for Seamless DVB-S2/RCS Provision in the Railway Environment

Gianluigi Liva, Núria Riera Díaz, Sandro Scalise, Balázs Matuz, and Cristina Párraga Niebla
Institute of Communication and Navigation, German Aerospace Center (DLR), 82234 Westling, Germany
Email: {Gianluigi.Liva, Nuria.Riera, Sandro.Scalise, Balazs.Matuz, Cristina.Parrraga }@dlr.de
Joon-Gyu Ryu, Min-Su Shin, and Ho-Jin Lee
Global wireless technology research group, ETRI, 161 Gajeong-dong Yuseong-gu Daejeon, Republic of Korea
Email: {jgryt, msshin, hjlee}@etri.re.kr

Abstract—In this paper, we study the provision of broadband interactive services to passengers of Korean High-speed train in the ISM 2.4 GHz band. We address in particular the design of tunnel gap-fillers (GFs) able to provide bi-directional connectivity to train-based terminals. The work has been developed in the broader context of interactive services provision for high-speed trains through satellite networks. First, a channel model for the in-tunnel propagation is derived. Taking into account the results of the propagation analysis, a comparison between commercial technologies (belonging to both the IEEE and the DVB standard families) is provided, showing the possible strengths and weaknesses of the proposed solutions with respect to architectural and performance point of views.

Index Terms—Railroad satellite services, tunnel propagation, gap-filler, DVB-S2/RCS Mobile

I. INTRODUCTION

In this paper, we study the provision of broadband interactive services to passengers of Korean High-speed train in the 2.4 GHz ISM band. We address in particular some design issues for tunnel gap-filler (GF) able to provide bi-directional connectivity to train-based terminals. The work has been developed in the broader context of interactive services provision for high-speed trains through satellite networks. In such a context, interactive services are provided to the users traveling on (high-speed) trains through a distribution network inside the coaches. The connectivity between the train and the network is the guaranteed by a bi-directional satellite link. When long interruptions in the satellite visibility occur, the loss of the connectivity would inevitably impact the quality-of-service (QoS) experienced by the users on board. It is therefore necessary to design GF solutions, able to provide seamless connectivity to the users.

Our focus is on the design of GFs to counteract the outages in the satellite signal provision due to tunnels without addressing handover (HO) issues and QoS guarantee, that will be topic of a further work. Several challenges shall be faced in this respect. First of all, a proper model for the in-tunnel propagation environment shall be derived. Several approaches are proposed in literature, mainly based on either wave-guide electromagnetic (EM) theory [1]–[4], ray-optical modeling [5] or statistical modeling. Wave-guide EM theory is chosen in this work because a good accuracy can be achieved and much less computational effort is required.

A further challenge consist in the selection of an appropriate technology for the GF, able to provide a sufficient robustness respect to the impairments introduced by the propagation environment. As a consequence of the technology selection, a specific architecture must be adopted. In this work, we identified three basic architectures:

- a transparent architecture, where the GF provides the in-tunnel coverage by just replicating the signal present on the satellite segment in a different frequency band;
- a semi-transparent architecture, where the GF just suites the signal waveform to the in-tunnel channel conditions (i.e. layers above the physical one are left unchanged);
- a non-transparent architecture, where the GF modifies not only the waveform of the signal, but also provides further functionalities (e.g. traffic filtering, QoS scheduling, etc.) up to the IP level.

The rest of the paper is organized as follows. In Section II a selection of technologies fitting with the above-defined architectures is provided, including an analysis of possible benefits/drawbacks on the overall system architecture. Section III provides a characterization of the in-tunnel propagation environment. In Section IV, the performance of the proposed solutions is compared, providing an estimate of the tunnel repeater densities for the different technologies. Some concluding remarks follow in Section V.

II. PROPOSED ARCHITECTURES

In this section, we provide a classification of the technologies available for the gap fillers into three groups depending on their suitability for the three GF architectures defined above. For the non-transparent case, the selected technology is based on the WiMAX standard (in the S-OFDMA transmission mode included in the IEEE 802.16e amendment to the IEEE 802.16d standard [6]). The semi-transparent architecture will rely on DVB-H [7], considering the additional protection provided by the multi-protocol encapsulation (MPE) forward error correction (FEC). For transparent architectures, the DVB-S2 [8] signal will be extended by the gap filler into the tunnel for the the forward link, after amplification and frequency
TABLE I
REQUIRED DATA RATES. (F)=FORWARD LINK, (R)=RETURN LINK.

<table>
<thead>
<tr>
<th></th>
<th>Average (F)</th>
<th>Peak (F)</th>
<th>Average (R)</th>
<th>Peak (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger</td>
<td>250 kbps</td>
<td>1.2 Mbps</td>
<td>40 kbps</td>
<td>120 kbps</td>
</tr>
<tr>
<td>Train</td>
<td>1.8 Mbps</td>
<td>2.1 Mbps</td>
<td>300 kbps</td>
<td>450 kbps</td>
</tr>
<tr>
<td>Fleet</td>
<td>7.5 Mbps</td>
<td>8.5 Mbps</td>
<td>1.2 Mbps</td>
<td>1.8 Mbps</td>
</tr>
</tbody>
</table>

conversion. The return link will be based on DVB-RCS [9]. Additional protection can be provided through a packet-level FEC scheme (MPE-FEC or another [10]). The ISM bandwidth limit considered for this study is 26 MHz. The requirements, in terms of data rates for the service provision, are depicted in Table I. The rest of the section will provide an overview of the main architectural issues related to each of the proposed solutions.

A. Non-transparent architecture

In the ISM (2.4 GHz) band, the adoption of the S-OFDMA mode included in the IEEE 802.16e [6] standard is advisable. The WiMAX-based GF protocol stack is depicted in Fig. 1(a). The 26 MHz limitation considered for this study is compliant with the 10 MHz bandwidth required by the standard. Considering the TDD scheme included in the 802.16e-profiles by the WiMAX Forum [11], the same bandwidth will be shared by the forward and the return links.

B. Semi-transparent architecture

This solution consists of the conversion at the GF between the DVB-S2 and the DVB-H signalling. Also in this case, an additional protection is guaranteed by the adoption of packet-level coding through the MPE-FEC scheme adopted by the DVB-H standard. The DVB-H-based gap filler performs a frequency and a modulation conversion, according to the DVB-S2/RCS standards. Moreover, the forward link of the satellite segment must be compliant with the bandwidth allocated inside the tunnel forward link (which is, in our case, 16 MHz). Further concerns are dictated specifically by the use in ISM band of the transparent, DVB-RCS-based return link. In particular, we remark that the resource allocation for the return link may be set in a way that only time-slots within a predetermined carrier can be used by those trains that are inside tunnels. Such dedicated allocation shall be managed by the NCC and requires the support of the satellite network service provider. Moreover, both the train terminal and the NCC shall possess precise information about when the link switches from (to) the satellite to (from) the GF. The switch of the link leads to a time jitter, whose amount could exceed the usually-implemented guard times. Larger guard times can be adopted (with the support of the satellite network service provider) at the price of reducing the link efficiency.

C. Transparent architecture

This configuration adopts a DVB-S2/RCS link between the GF and the train terminal. This solution could in principle simplify the hardware architecture of the GF, consisting of a simple frequency conversion and the signal amplification. However, many issues concerning synchronization and resource allocation could however rise up and will be the core of further work. A high level of protection can be addressed introducing packet level coding in combination with either MPE/MPEG or Generic Stream Encapsulation (GSE), which should be designed to mitigate the effects of the multipath propagation. The adoption of a 16 MHz bandwidth is advisable to achieve sufficiently high data rates for the forward link, while for the return link a 6 MHz band should be allocated. Note that, with the transparent solution, the in-tunnel signal must replicate the signal related to the whole fleet.

A drawback of this solution resides in its sensitivity to multipath fading, due to the single-carrier modulation adopted by the DVB-S2/RCS standards. Moreover, the forward link of the satellite segment must be compliant with the bandwidth allocated inside the tunnel forward link (which is, in our case, 16 MHz). Further concerns are dictated specifically by the use in ISM band of the transparent, DVB-RCS-based return link. In particular, we remark that the resource allocation for the return link may be set in a way that only time-slots within a predetermined carrier can be used by those trains that are inside tunnels. Such dedicated allocation shall be managed by the NCC and requires the support of the satellite network service provider. Moreover, both the train terminal and the NCC shall possess precise information about when the link switches from (to) the satellite to (from) the GF. The switch of the link leads to a time jitter, whose amount could exceed the usually-implemented guard times. Larger guard times can be adopted (with the support of the satellite network service provider) at the price of reducing the link efficiency.

III. RAILROAD TUNNEL PROPAGATION CHARACTERISTICS

Wave propagation characteristics impact the performance of each of the architectures proposed in Section II. In this section the approach followed to model wave propagation in tunnels will be justified and their main characteristics summarized. Characteristics of radio wave propagation in tunnels are highly dependent on the physical characteristics of the tunnel (cross-section shape and dimensions, tunnel materials), the working frequency, the type of antennas used and their positions. These parameters, together with the target applications, determine the most suited way to model radio wave propagation, e.g. ray optical modeling [5], wave-like propagation modeling [1]–[4], numerical methods [12], or statistical
modeling derived from site measurements. The purpose of this propagation analysis is to derive a path loss law that can be used in a link budget calculation to later assess the suitability of the technologies presented in Section II.

While performing site measurements is out of the scope of this work, ray optical modeling and numerical methods as the finite-element methods provide information on the impulse response of the channel and the direction of arrival of the different echoes, which are not relevant to derive a path loss law. Additionally, they require a detailed model of the propagation environment and imply a huge computational effort. Hence, for the purpose of this work channel propagation modeling by means of wave-guide theory seems the most appropriate and efficient method.

The application of wave-guide theory requires a geometrical model for the tunnel cross-section, typically rectangular or circular. [4] states that the assumption of rectangular cross-section in arched-shaped tunnels as the Korean ones (see Fig. 2) does not compromise the results. This model will be assumed here. The cross-section size differs when considering propagation in an empty or in a loaded tunnel (with the presence of a train), because the common way to model a loaded tunnel consists in changing its dimensions to the size of the cavity left empty by the trains loading it [3], [12], [13].

The reduction of the tunnel cross-section size increases the longitudinal attenuation of the signal along the tunnel. Hence, the worst case for link budget purposes is when two trains cross simultaneously the tunnel, i.e. tunnel having smallest equivalent cross-section size. Furthermore, the communication shall be established when the train crosses the tunnel. This is the situation in which we will model the propagation.

The dominant propagating mode is the hybrid electromagnetic mode $H.E.M_{1,1}$ and the corresponding equations for the electric and magnetic field can be found in [1]. These are the ones used to calculate the received EM field and from it the received power.

To derive a path loss law, attenuation due to roughness of the walls ($L_r$) and antenna insertion loss ($L_i$) are additionally considered [1]. For reasonable values of the root mean square of the walls roughness ($h$), which are assumed to have imperfect surface with Gaussian distributed irregularities, $L_r$ at 2.465 GHz is below 0.01 dB/m. For $h = 0.1$ after 10 km the losses are roughly 6.5 dB. The antenna insertion loss are due to the inefficient coupling of standard dipole antennas to the wave mode [1]. This is a very critical parameter, since it is very sensitive to the antennas position. It must be noted that small displacements of the antenna can modify considerably $L_i$ if the antenna is close to the tunnel edges and that it is minimized if both antennas are placed in the center of the tunnel. The optimal antenna locations are chosen below.

The following assumptions have been made to simplify the complexity of the propagation environment:

- assume tunnels infinitely long,
- ignore the train tracks and power lines,
- GF and train antennas are aligned with the longitudinal tunnel axis (to apply $L_i$ as expressed in [1]),
- antennas are rectangular (used to calculate the received power from field illuminating the antenna)
- EIRP is fixed to 10 dBm (for regulatory restrictions)

This last assumption, permits accounting for $L_i$ only at the receiver side. With all these parameters, the path loss law to be used for link budget calculation purposes is given by:

$$L(d_{km}) = L_0 + L_i + \alpha \cdot d_{km} + M_{99\%}$$  \hspace{1cm} (1)

where $L_0$ are the initial losses, $\alpha$ is the longitudinal attenuation including the attenuation due distance and $L_r$, and $M_{99\%}$ is the fading margin satisfied during 99% of the time to consider the deep fades characteristic of the received power in in-tunnel propagation.

For practical reasons it is convenient to have the same constant losses, i.e. $L_0 + L_i$ of Eq. (1), in both sides of the link. These losses are fixed in the forward link because of the constraints when placing the train antenna on the top of one wagon, which yield to $L_i \sim 52$ dB. To obtain the same $L_0 + L_i$ value on the return link, the GF antenna horizontally shall be placed centered and 70 cm below the tunnel roof.

Table II summarizes all parameters required to determine the parameters of Eq. (1) with the equations reported in [1].
TABLE II  
INPUT PARAMETERS FOR THE PATH LOSS MODEL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loaded tunnel width (a’)</td>
<td>13.5 m</td>
</tr>
<tr>
<td>Loaded tunnel height (b’)</td>
<td>3 m</td>
</tr>
<tr>
<td>Conductivity of the tunnel walls</td>
<td>0.01 S/m</td>
</tr>
<tr>
<td>Relative permittivity of the tunnel walls</td>
<td>10</td>
</tr>
<tr>
<td>Root mean square roughness</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Conductivity of the train</td>
<td>0.001 S/m</td>
</tr>
<tr>
<td>Relative permittivity of the train</td>
<td>2</td>
</tr>
<tr>
<td>Antenna efficiency</td>
<td>0.6</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>15 dB</td>
</tr>
<tr>
<td>Diploe resistance</td>
<td>50 Ω</td>
</tr>
<tr>
<td>GF antenna position (loaded tunnel)</td>
<td>(-6.25 m, -0.5 m)</td>
</tr>
<tr>
<td>Train antenna position (loaded tunnel)</td>
<td>(-3.375 m, -1.3 m)</td>
</tr>
</tbody>
</table>

Fig. 2. Korean High-Speed train tunnel cross-section information.

IV. LINK PERFORMANCE COMPARISON

In this section we provide a link performance analysis for the three proposed architectures using the path loss law derived in the previous section. First, the selection of the coding and modulation schemes for each solution will be carried out. Then, the link budget assumption will be briefly recalled. Finally, the results of the link budget analysis will be presented.

A. Selection of coding and modulations

The technologies mentioned in Section II provide a widespread range of possible coding/modulation combinations. Each of them provides a different trade-off between spectral efficiency and robustness against the channel impairments. The selection of the different modulation and coding schemes for the evaluation of the in-tunnel coverage has been carried out by first selecting the modulation orders and the coding rates that are able to provide the minimum required data rates (according to the requirements specified in Section II), and then restricting the selection to the transmission modes providing better performance in terms of signal-to-noise ratio (SNR) for a given error rate target. The results of this selection are summarized in Table III.

B. Constraints to the link budget

The channel reference model assumed for the computation of the link margins is the uncorrelated Rayleigh channel. This choice is particularly conservative, since a LOS component in the received signal will be quite likely present. Furthermore, the deep fades that the signal experiences in tunnels are taken into account by an additional link margin. The receiver sensitivity values (listed in Table III are not homogeneous: the are referred to different channel models, and some of them includes implementation losses. For the sensitivity values provided on the AWGN channel, a further penalty of 5 dB is applied. The implementation losses are set to 3 dB, while the antenna pointing loss is assumed to be 2 dB. The central frequency for the forward link is \( f_0 = 2.458 \) GHz, while for the return link \( f_0 = 2.474 \). The antenna gains of both sides are supposed to be \( G_t = G_r = 15 \) dB (directive antennas are considered in this case). The use of a Omni-directional antenna on the coach is also investigated. In such case, the antenna gain is reduced to 7 dB (this loss is partially covered by the elimination of the pointing loss). The system antenna noise temperature is assumed to be \( T = 290 \) K. Finally, the EIRP is limited to 10 dBm. The parameters of the path loss model expressed in Eq. (1) have been calculated and the following values are obtained: \( L_0 = 31 \) dB, \( L_t = 52 \) dB, and \( \alpha = 3.15 \) dB/km. The fading margin \( M_{99\%} \) to account for the periodical deep fades has been set to 14 dB.

C. Tunnel coverage assessment

The tunnel coverage assessment has been carried by the link budget analysis of the solutions listed in Table III. Focusing on the forward link, the results (with directive antennas on both the gap filler side and the train side) are depicted in Fig. 3, in terms of link margin vs. distance between transmitter and receiver. It can be noted that the DVB-S2-based solution provides the largest link margins, and therefore seems to be the most suitable to provide coverage in long tunnel with a reduced number of repeaters. The result is mainly related to the highly efficient air interface of DVB-S2 and in particular to its advanced coding technique. What is not taken into account in this analysis is the effect of severe multipath on the modulation schemes (ideal synchronization is assumed). From this perspective, we shall expect that the DVB-S2 link would suffer more than the two competitors (DVB-H and 802.16e), which are based on OFDM modulation, more robust to multipath. Such drawback could be partially compensated by the antenna directivity, which provides a kind of spatial filtering of the echoes [14]. Among the OFDM-based systems, the largest link margins are provided by the DVB-H solution. The IEEE 802.16e link suffers for the weak coding scheme on physical layer (i.e., convolutional codes) and for the TDD approach, which requires for both forward and return link a larger bandwidth respect to the necessary amount for each of them. This turns into a higher noise floor. Assuming a 3 dB threshold for the link margin, the overall number of repeaters required to provide the coverage of a 5 Km tunnel varies from 2-3 for the two investigated WiMAX-based schemes, to 3-5 for the DVB-H semi-transparent system, and down to 2 for the DVB-S2/RCS solution.
TABLE III
SUMMARY OF THE SELECTED CANDIDATES FOR THE RETURN/forward LINKS

<table>
<thead>
<tr>
<th>Standard (functional model)</th>
<th>FWD/RTN</th>
<th>Bandwidth [MHz]</th>
<th>(Sub-)Carrier Modulation</th>
<th>Coding rate</th>
<th>Data rate [Mbps] fleet/train requirement</th>
<th>Required C/N (or C/N.min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.16e (non-transp.)</td>
<td>-</td>
<td>10</td>
<td>QPSK</td>
<td>Conv. 1/2</td>
<td>0.94/train req.: 0.9 τ</td>
<td>P_r,min = -83 dBm τ</td>
</tr>
<tr>
<td>802.16e (non-transp.)</td>
<td>-</td>
<td>10</td>
<td>QPSK</td>
<td>Conv. 3/4</td>
<td>1.41/train req.: 0.9 τ</td>
<td>P_r,min = -81 dBm τ</td>
</tr>
<tr>
<td>DVB-H (semi-transp.)</td>
<td>RTN</td>
<td>4.76</td>
<td>QPSK</td>
<td>Conv. + RS 1/2</td>
<td>2.80/train req.: 0.45</td>
<td>C/N = 5.40 dB 3</td>
</tr>
<tr>
<td>DVB-H (semi-transp.)</td>
<td>RTN</td>
<td>4.76</td>
<td>QPSK</td>
<td>Conv. + RS 2/3</td>
<td>3.70/train req.: 0.45</td>
<td>C/N = 8.40 dB 3</td>
</tr>
<tr>
<td>DVB-RCS (non-transp.)</td>
<td>RTN</td>
<td>6</td>
<td>QPSK</td>
<td>Turbo, 1/3</td>
<td>2.20/fleet req.: 1.80</td>
<td>C/N = 0.14 dB 4</td>
</tr>
<tr>
<td>DVB-RCS (non-transp.)</td>
<td>RTN</td>
<td>6</td>
<td>QPSK</td>
<td>Turbo, 2/3</td>
<td>2.67/fleet req.: 1.80</td>
<td>C/N = 1.13 dB 4</td>
</tr>
<tr>
<td>DVB-H (semi-transp.)</td>
<td>FWD</td>
<td>7.61</td>
<td>16-QAM</td>
<td>Conv. + RS 2/3</td>
<td>12.07/fleet req.: 8.50</td>
<td>C/N = 14.20 dB 3</td>
</tr>
<tr>
<td>DVB-H (semi-transp.)</td>
<td>FWD</td>
<td>7.61</td>
<td>16-QAM</td>
<td>Conv. + RS 3/4</td>
<td>14.97/fleet req.: 8.50</td>
<td>C/N = 16.70 dB 3</td>
</tr>
<tr>
<td>DVB-S2 (non-transp.)</td>
<td>FWD</td>
<td>16</td>
<td>LDPCC, 3/5</td>
<td></td>
<td>11.89/fleet req.: 8.50</td>
<td>C/N = 2.23 dB 4</td>
</tr>
<tr>
<td>DVB-S2 (non-transp.)</td>
<td>FWD</td>
<td>16</td>
<td>LDPCC, 2/3</td>
<td></td>
<td>13.23/fleet req.: 8.50</td>
<td>C/N = 3.10 dB 4</td>
</tr>
</tbody>
</table>

1 Aggregate value, considering the peak requirement for each train and two trains simultaneously present in the tunnel. 2 Including 7 dB noise figure and 5 dB of implementation losses. AWGN channel. 3 Including 7 dB noise figure and 5 dB of implementation losses. AWGN channel. 4 Values provided for the AWGN channel.

Fig. 3. Forward link margins as a function of the distance. Directive antennas for both the gap filler and the train terminal.

V. CONCLUSIONS

In this paper, the problem of the signal gap-filling in railway tunnel has been faced from different perspectives. A waveguide model of the in-tunnel propagation in ISM band has been provided, and has been used to derive a path loss law. Three GF architectures have been proposed. The so-called transparent solution reduces the complexity in the GF, and provides larger link margins thanks to the efficient air interfaces of DVB-S2/RCS. The main drawbacks are the sensitivity of the modulation scheme respect to the severe multipath (which is expected to play an important role in the envisaged scenario), and the lack of traffic filtering, i.e., the whole satellite service must be dimensioned in a way that the bandwidth fits in the portion of spectrum allocated for the GFs. We introduced a semi-transparent architecture as well, which is based on the adoption of a DVB-H link for the GF segment. The main advantage respect to the DVB-S2/RCS-based solution deals with the OFDM modulation, which is more robust respect to the multipath propagation.

However, also in this case, the whole satellite service must be dimensioned in a way that the bandwidth fits into the portion of spectrum allocated for the gap fillers. The non-transparent solution (IEEE 802.16e) is able to overcome this issue, by implementing in the gap filler the protocol stack up to IP level, and therefore filtering the traffic that is not addressed to the GF segment.

REFERENCES