Wireless telecommunications in railways – Flash-orthogonal frequency division modulation – a case study

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Abstract: On-board wireless telecommunications in railways operate in a challenging environment including rapidly fading radio channels and various sources of statistically variable interference. These conditions hamper seamless, high-rate data transmission by making fast handovers to ground base stations difficult. This paper addresses networking techniques wireless communication in trains by presenting a technical overview of wireless communications options and reporting field experiments using Flash-orthogonal frequency division modulation (OFDM) technology. The research is based on *in vivo* measurements recorded in high-speed Pendolino-trains in Finland. The results indicate that Flash-OFDM technology fulfils the coverage and service accessibility requirements for high-rate interactive multi-media services with respect to latency and data rate, provided that loading of the Flash-OFDM network due to other users remains low.

Keywords: train communication, communication architecture, Flash-orthogonal frequency division modulation, on-board vehicle communications

1 INTRODUCTION

Private motoring is growing in popularity and poses a serious threat to the environment in terms of pollution and waste of natural resources. Public transportation forms an economic alternative to this and brings with it many societal benefits. It often turns out to be faster and more convenient, especially for the urban environment and it even provides the opportunity to undertake work or hobbies during the journey. This is especially important in case of long haul air or train travelling.

Of various transportation modes, rail traffic has tremendous potential both in capacity and in speed, with modern trains exceeding velocities of 500 km/h [**1**].

Trains can potentially be used as mobile offices with all the expected accessories facilitated by modern integrated, mobile information and communications tools, such as laptops and printers. Trains can also enable practically uninterrupted working with adequate working space which is a highly valued asset compared with its competitors, including air traffic. The ability to work while travelling may have a significant impact on one's selection of transportation mode. Some train operators have taken this into account by offering special 'office seats' with power outlets and sometimes even with internet connections [**2**]. In terms of enabled services, on-board telecommunications provide a diverse service framework, potentially enabling and improving services for in-house users, cargo operators, and regular passengers [**3**].

This paper addresses wireless communications techniques and applications in trains by presenting a broadband networking overview and reporting on field experiments with Flash-orthogonal frequency division modulation (OFDM) technology. The research is based on *in vivo* measurements recorded in high-speed Pendolino-trains in Finland. The rest of the paper is organized as follows.

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In section 2, an overview of various train data communications technologies is presented. Section 3 introduces the research environment and investigated system architectures. Section 4 discusses trains as an ICT-service environment. Sections 5 and 6 address targeted access and on-board networking technologies, respectively. Section 7 inspects interconnection of networks and optimization of the connection manager (or multi-router). Section 8 focuses on results, and finally section 9 summarizes the concluding remarks.

2 TRAIN COMMUNICATION ARCHITECTURES

Some key acronyms for following chapters are explained in Table 1.

2.1 Introduction

Generally, telecommunication networking in trains can be divided into three types (Fig. 1): fixed/core networking, ground-to-vehicle communications (GVC), and on vehicle communications (OVC). GVC comprises base stations placed alongside the track, and data links connecting trains and carriages. OVC includes base stations placed within the trains and customer terminals.

The most important benefits of this network architecture are as follows.

1. Simplicity and cost efficiency.
2. It removes the customer's need to directly communicate with all the associated networks.
3. It enables mobile support of different classes of telecommunications' quality of services (QoS).
4. It supports modern, popular customer terminals, mobile phones, and other personal digital assistants (PDAs) which further improve the overall cost structure in a service business case.

Table 1 Key abbreviations and explanations

Abbreviation	Explanation
CM – connection manager	CM takes care of interplay of access and on-board networks. Selects the best timely train-to-ground link available.
GVC – ground to vehicle communications	A telecommunication network connecting train to ground base stations. Can be formed by using for instance WiMAX, Wi-Fi or mobile networking technologies.
ISM – industrial, scientific and medical band	This defines a set of frequency ranges allowing license free radio communications. Application of ISM bands has greatly effected to the popularity of certain networking technologies as for instance Wi-Fi networking.
OVC – on-board vehicle communications	A telecommunication network providing telecommunication services inside and between of train carriages. This can be realized for instance by Wi-Fi, or Bluetooth networking.
QoS – quality of service	A set of quality requirements on the behaviour of telecommunications network elements or services.
TS – train server	A server computer on the train. It can be used for buffered and on-demand services that enable capacity of train-to-ground-links to be reserved for real-time applications.
VS – vehicular station	VS refers to the on-board base station of OVC.
Wi-Fi - wireless fidelity	A brand licensed by the Wi-Fi Alliance to describe the embedded technology of wireless local area networks (WLANs) based on the IEEE 802.11 standard.

2.1.1 *Connection manager*

Successful interplay of access and on-board networks requires the application of an appropriate connection manager that is capable of selecting the best timely

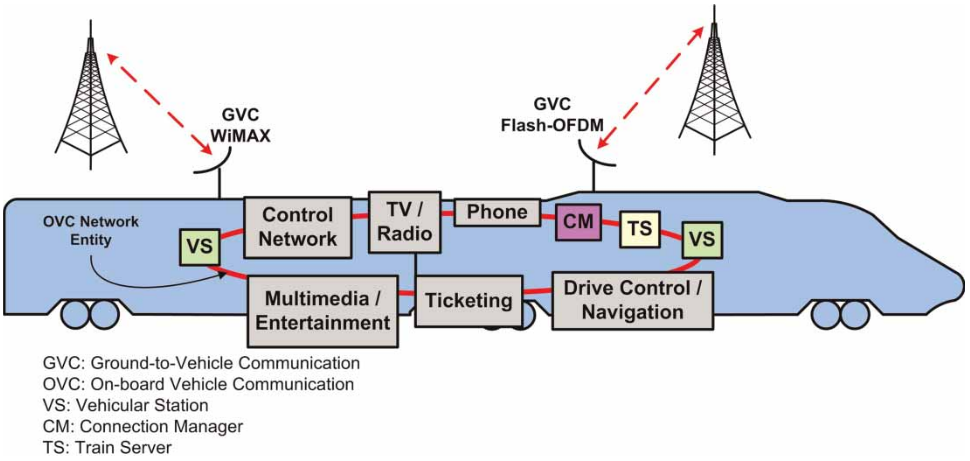

Fig. 1 Train as an ITS – service environment. GVC, ground-to vehicle communications; OVC, on vehicle communication; VS, vehicular station; TS, train server (for more discussion about these acronyms, see chapter 2. Some key acronyms are listed in Table 1)

train-to-ground link available. It is often desirable to include support for multi-homing which allows all available ground links to be utilized. One should note that multi-homing capability does not uniquely improve transmission, for instance, in the case of WiMAX/GPRS, it may only improve availability. Whichever the available GVC networks are, the connection manager usually arranges them into a ranked list. Technically, operation of the connection manager is based on an IP mobility scheme. For instance, a suitable option for the mobility management protocol is Mobile IP [**4**, **5**]. One should note that mobile IP does not currently support multi-homing. It can, however, be extended to support multi-homing and there is some ongoing standardization work in progress to enable this [**6**].

As mentioned earlier, an important objective in connection manager design is to create a capability to provide seamless services. In practice, this can be sought by establishing a new connection well before breaking the earlier one. Generally, connection breaks can be tracked by monitoring transmission quality in terms of bandwidth, signal power, and/or network delay. In addition, RF-power distribution maps can be recorded based on on-site measurements that are then addressed by an appropriate global positioning system (GPS) tracking module placed in the connection manager to assist in the seamless handovers. This is the scheme that is applied for instance in Icomera's solution [**2**]. Whatever method is applied to track the handovers of different ground networks, substantial packet congestion may follow if the supported data rate difference from higher to lower GVC network is substantially large. This must be taken into account in connection manager design, by ensuring that the rate that is available for a particular user is decreased accordingly and that the respective packet buffer is dumped.

2.2 On-board vehicle communications

Pendolino trains targeted in this study have a significant difference in respect to regular trains in that they have an integral structure that is only disassembled for maintenance. Pendolino carriages are connected by cables and locks. Optical data cabling that is used to transmit tracking information is also provided. In the test train, there was a single free optical fibre available for inter-carriage data.

Alternative ways to transmit the data between carriages include Wi-Fi, twisted pair cables, or power-line communications. The obvious candidates to deliver data further to passenger's PDAs include in particular Wi-Fi (IEEE 802.11 a/b/g) and Bluetooth networking, due to their cost-efficiency, popularity, and applicable service area. These base stations are called vehicular stations (VSs) in Fig. 1.

Connecting carriages using 802.11 wireless local area network (WLAN) technology creates some additional requirements in the vicinity of stations. This is due to the spatial capacity of the 802.11 technologies [**7**], giving rise to a potential conflict due to radio spectra congestion. An additional source of interference can be generated also from WLAN base stations supporting GVC links and/or regular passengers accessing licence-free industrial, scientific and medical band (ISM) wireless networks at stations.

Design of OVC networking should be based on practical, on-site field measurements. In most cases, these are quite straightforward. However, the range of variability of Pendolino train cabins should be taken into account. (This is in contrast to GVC network design where automated network planning tools requiring precise mapping of propagation environment are usually applied.) The experience was that for OVC networks, usually a couple of carefully aligned base stations were adequate to guarantee Wi-Fi reception anywhere in the carriages.

In order to satisfy service requirements of both in-house and regular customers, separate virtual LANs (VLANs) should be established, as VLANs can be tailored with respect to QoS and security specifications.

Pendolino trains carry some significant benefits in terms of their interconnections.

As mentioned earlier, they have integral structures (composed of six carriages in Finland), which may only require disassembly for maintenance. Therefore, optical cabling connecting the carriages enables application of fixed WLAN base stations: the carriages form a type of Faraday's cage thus efficiently suppressing most of the surrounding RF-energy. This greatly alleviates RF spectral congestion in stations. The situation with other types of trains is substantially worse due to the fact that interfering RF-leakage is more likely to happen if the 802.11 RF-signal is transmitted between carriages. In addition, the associated RF-power levels are likely to be relatively large in order to enable a reliable inter-carriage signal transmission for network operation and setup.

A multitude of techno-economically feasible on-board and off-board services can be supported by railway ITS (Fig. 2). High capacity, on-board train servers can be used for buffered and on-demand services that enable capacity of train-to-ground-links to be reserved for real-time applications such as voice and interactive multi-media services. Some examples of bandwidth-hungry applications that can well be realized by on-board servers include:

(a) stored IP video monitoring services;
(b) on-demand video;
(c) audio and gaming;

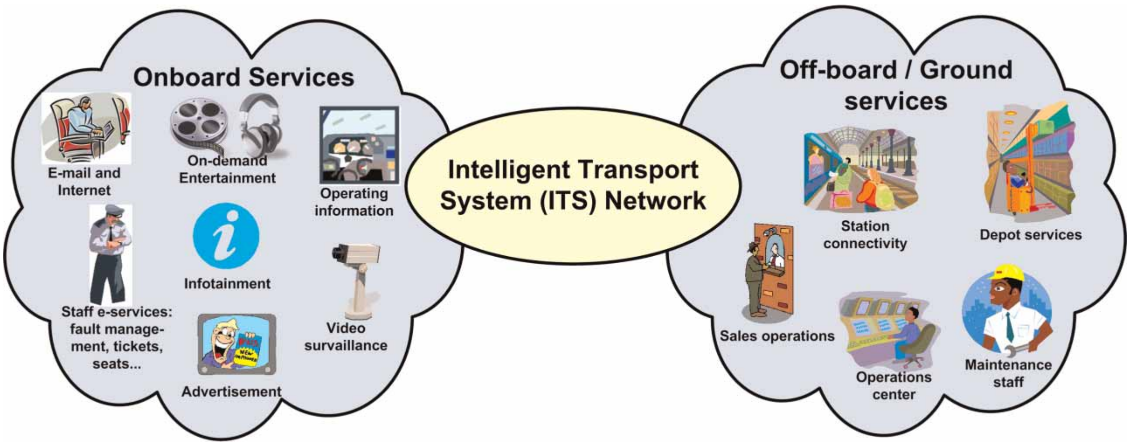

Fig. 2 Framework of ITS-services in railroads

(d) telematics (data collection) services;
(e) emails may be buffered to be transmitted while the train server is connected to the core network by high-rate radio links sited at stations.

It should be noted that the services best supported by the train server should not allocate GVC capacity. This is because GVC links have currently a much smaller capacity than the on-board network supported by the train server.

2.3 GVCs – a technology comparison

There are various data communication technologies, which are potentially applicable for GVCs solutions. Most of these have been piloted in some of the existing on-board train internet system solutions. In France, Thalys Inc. applies satellite communications. In England, Southern uses non-standard WiMAX, and in Sweden, Sverige's Järnvägar (SJ) uses GPRS/UMTS and satellites [**8**, **9**].

An overview of a couple of promising technologies is presented and their suitability for GVC networking is evaluated. The inspection has been based on using Finland as a test case environment.

2.3.1 Cellular technologies (GPRS and UMTS)

Universal roaming cellular mobile technologies GSM and 3G are designed to work at very high vehicle velocities, where the effects of multi-path fading and Doppler spread have to be overcome. Generally, these telecommunication networks are capable of supporting train speeds of at least up to 220 km/h [**10**], which is the maximum allowed train speed in Finland.

Building of 3G coverage is currently considered to be mainly cost-effective for urban areas. Therefore, in Finland, the coverage of 3G and EDGE networks is restricted to cities and suburbs. Bandwidth and network latency specifications of both technologies are relatively modest for modern multi-media applications.

Reallocation of the 900 MHz band from GSM to UMTS (the 3G technology applied in Europe, working currently solely at 2.1 GHz) is an ongoing process [**11**] that may be expected to allocate a somewhat larger coverage for 3G while still retaining a part of the earlier bandwidth for GSM. Standard GSM has a much larger coverage area, extending in practice all over Finland. It is currently relayed (by on-board relay stations) to most of the trains. However, respective data rates are quite inadequate for current internet applications.

2.3.2 WiMAX

IEEE standardized the Mobile WiMAX (802.16e) technology in 2005. It has become a synonym for the radio interface of metropolitan area network (MAN), which is based on the 802.16 and ETSI HiperMAN standards [**12**].

WiMAX is expected to offer wide coverage, broadband, cost-efficient wireless data networking avoiding potential congestion of the licence-free, ISM radio band. The first WiMAX networks – also for mobile usage – have already been set up. Applicability of mobile WiMAX for trains, however, is limited: There is no support for high-speed train communications. Asynchronous collaboration of adaptive modulation and coding (AMC), hybrid automatic repeat request (HARC), and fast channel feedback (CQICH) provides effective link modulation up to 120 km/h only. For higher speeds, the scheduler cannot operate correctly [**13**]. The issue is not, however, finally resolved. The WiMAX Forum has stated that the evolution to meet higher vehicular speeds will be considered if required for specific applications

[**14**]. However, the OFDMA-radio interface used in WiMAX supports greater speeds than 120 km/h. Nomad Digital has modified the WiMAX protocol to support this, enabling a WiMAX hybrid to be used for high-speed trains [**8**]. (One should note that the protocol modifications may result in incompatibility issues with standard WiMAX-equipment.)

A critical issue in the application of mobile WiMAX relates to spectral regulation. In Finland, the 3.5 GHz band is allocated for broadband wireless access (BWA), such as WiMAX networks. However, only static or low mobility use (e.g. nomadic) on this band is allowed, and mobile use is explicitly forbidden. In Europe, the Electronic Communication Committee (ECC) has registered the growing demand for mobile services. The latest draft of the radio resource allocation plan published in November 2006 included support for mobile usage of WiMAX. The draft is now being circulated for comments. Regulation work on the EU level will be finished in 2007 [**15**]. After that, there is likely to be a further delay to allow for the transfer of the mobility support decisions to national levels across the union.

2.3.3 *Satellite links*

An interesting way to provide universal broadband internet access for trains is by satellite. Some of the SJ's trains in Sweden and Thalys' trains in France apply a satellite access that is routed to in-carriage WLANs [**8**, **9**]. Generally, the biggest drawbacks in satellite access are relatively high costs, large delays, and modest data rates. In fact, the effective delay is likely to exceed 600 ms if the satellite link is used together with the GPRS return channel thus hindering most of the convenient two-way, real-time communications. In Finland, low positioning of satellites in geosynchronous orbit also seriously limits link availability [**16**].

2.3.4 *Flash-OFDM*

Flash-OFDM is a packet switched, proprietary wireless technology developed by Flarion. Like WiMAX, it is based on OFDM, but it has a better performance in high-speed, multi-path propagation environment. It was offered as the base for the forthcoming IEEE 802.20 Mobile Broadband Wireless Access-technology standardization. However, as a result of the slow progress in the standardization work, Flarion decided not to adhere to the timescale and released its technology. Qualcomm acquired Flarion in January 2006 and has not released any possible standardization plans yet. Currently, for instance Siemens is selling Flash-OFDM networks.

Flash-OFDM technology suits well for GVC-networking due to its wide range and promised performance for high-speed vehicles. In Finland, Digita Ltd was granted an operator licence by the Ministry of Transport and Communication to set up a network at 450 MHz [**17**]. This range is excellent for wide coverage networks due to the following points.

1. The propagation conditions that are better than at 2.1 GHz (3G), 2.4 GHz (WLAN), and 3.5 GHz (WiMAX).
2. The cell radius can be over 55 km.
3. The Doppler Effect is milder than at higher frequencies.
4. A downside: more limited bandwidth.

To operate, Flash-OFDM needs 1×1.25 MHz FDD channel – 1.25 MHz for downlink and 1.25 MHz for uplink separated by the duplexing interval – which enable a maximum of 5.3 Mbps downlink rate and 1.8 Mbps uplink rate. Currently Digita Ltd is promising $\sim$1 Mbps data transmission rates for each user.

Flash-OFDM has a low network latency of 20–50 ms that enables fluent real-time communication. There are three states reserved for connection activation: sleep, active, and on. In a single cell, there can be over 1000 users in sleep-mode, 126 users in active-mode, and 31 in on-mode. These parameters define the final cell sizes and are there important for network design. Flash-OFDM applies QoS classification, which is especially important for multi-media serve palette also in train environment. Bandwidth is allocated based on user profiles.

It should be noted that the services best supported by the train server should not allocate GVC capacity. This is because GVC links have currently a much smaller capacity than the on-board network supported by the train server. In Finland, Flash-OFDM network is a very good candidate for GVC networking, especially in rural areas. High-rate mobile cellular networks will most probably not be extended outside city areas for a considerable time to come. The most important disadvantages with WiMAX networks are the lack of suitable radio frequencies for mobile usage and the high-operating frequency. There has been agreed that the Flash-OFDM network should become country-wide in the very near future in Finland [**17**].

2.3.5 *GVC access – summary*

GVC networking in trains may be established by a variety of technologies, each of which has their advantages and disadvantages. ISM-band WLAN is a cost-efficient solution for stations. Cellular mobile and WiMAX networks suit well for urban areas. The narrow frequency band allocated for Flash-OFDM places severe limits on the number of high-rate

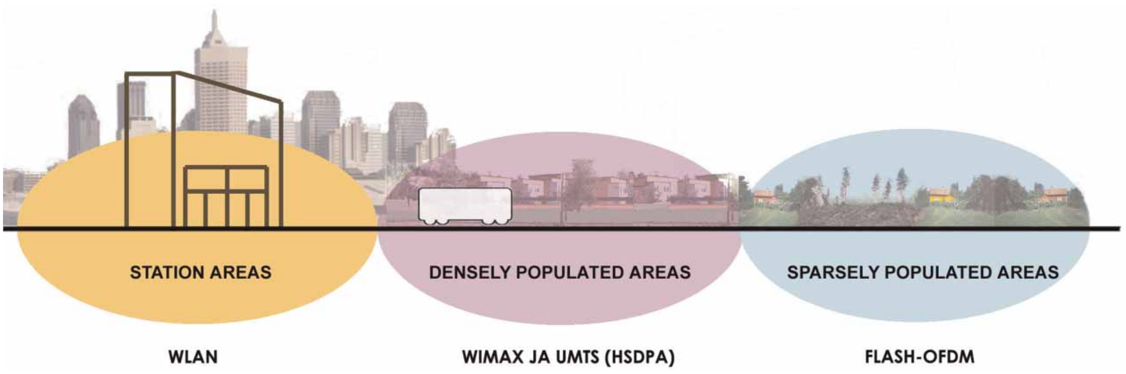

Fig. 3 GVC-link alternatives in various geographical environments

users in a cell area. Thus, complementing networking technologies are required, especially in urban areas. Seamless connection to several networks can be achieved from a moving train by using a connection manager that swaps the GVC links in different geographical environments (Fig. 3).

3 FLASH-OFDM FIELD TESTS

3.1 Setup

Even though it is claimed that Flash-OFDM should work at 250 km/h, practical field tests were undertaken to investigate the claim and also research the effect of train environment-related radio channel interferences.

The tests were done in a Pendolino-train that was equipped with a Flash-OFDM terminal, a 450 MHz antenna and a GPS-receiver. The antenna was especially designed for trains (a $\lambda/4$-antenna of 0 dB average gain). The GPS-receiver received location data for the coverage maps.

The profile of the test track was selected to be a sample of a typical Finnish railroad (Fig. 4). The length of the test track was 50 km with three base stations using diverse configuration set out throughout the length of the track. The network was specifically not optimized for railway communications, to ensure that the results would be more in line with the performance of forthcoming commercial networks. The test network was built specifically for the Flash-OFDM technology test and equipped with a first base station release. The maximum cell radius with the test network base stations was 11 km. The current base station version has a maximum cell radius of up to 55 km. The test track was chosen so that the train could speed up to 200 km/h, the maximum permitted speed in Finland at the time of the tests.

The most important objectives of the tests were to find out:

(a) achievable data rates with up- and downlink;
(b) potential to realize seamless handovers across diverse systems.

The test transmitter was set to generate as much UDP traffic as the channel could possibly transmit at a time. Both up- and downlink were tested by taking journeys in both directions and calculating the average performance of the runs. The driving speed varied from 0 to 200 km/h. An application was implemented to test the handovers notifying the packet loss in real-time. The test equipment also included a display to indicate the instantaneous target base station.

3.2 Results

It was soon evident that the Flash-OFDM appeared to suit for fast train journeys and would be a competitive choice. The measured average data rate for the downlink was 1 and 0.5 Mbps for the uplink (Fig. 4).

However, in the vicinity of the base station 2 whose antennae had not been optimized for the tests, the data rates were lower. In addition, there was a significantly lower received signal power resulting in a decrease of data rate. The respective transmission gain was lower.

Base stations 1 and 3 had a similar transmission gain. The maximum specified data rates were 2.72 and 0.78 Mbps for down- and uplink, respectively, which was measured in the tests.

Variance of data rate was larger for the down- than for the uplink. It is believed that this is due to there being a smaller number of modulation levels applied for the uplink. Therefore, with a simpler modulation technique, a more stable connection can be achieved due to the relaxed reception sensitivity.

It should be noted that the reliability of the uplink is important, because clients expect to send critical signalization data, such as handover information to a base station, while more complex modulation in the downlink can enable the higher data rates.

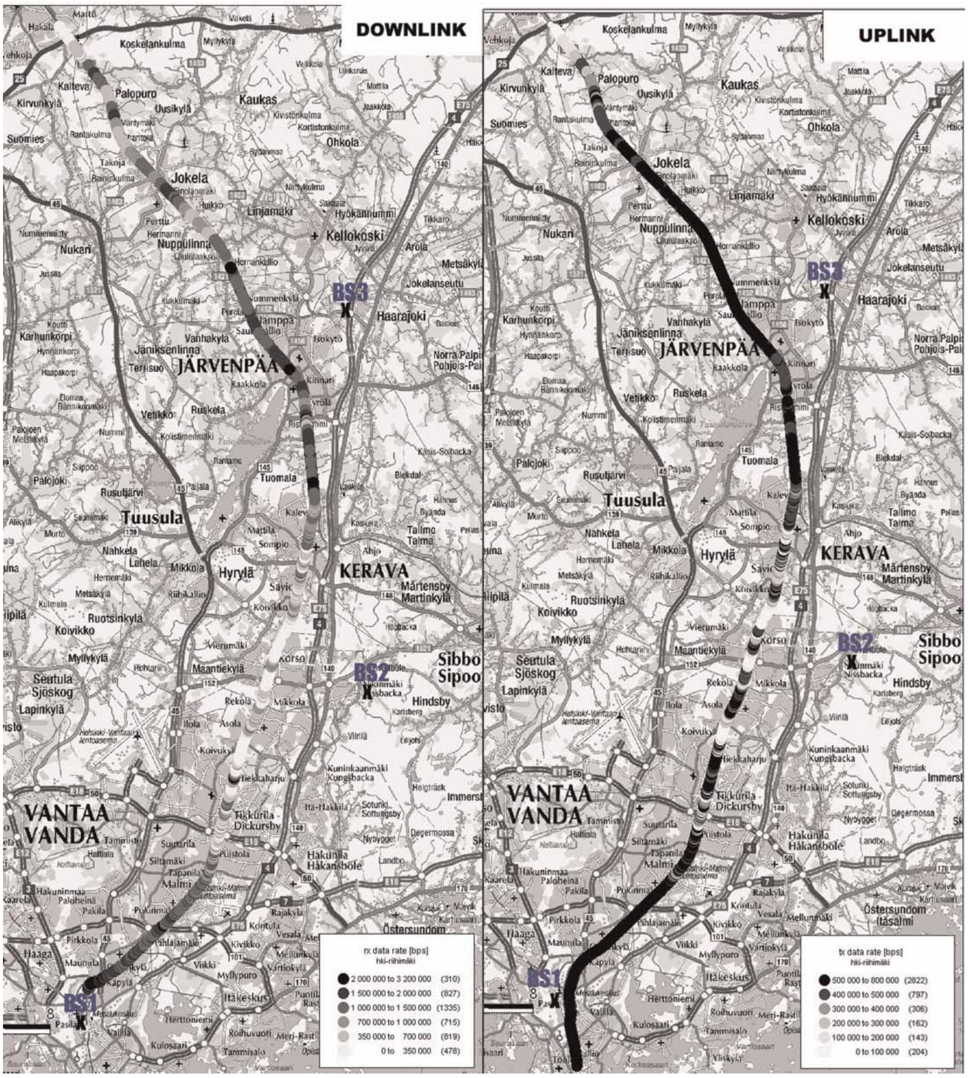

Fig. 4 Map of the test track (down- and uplink communications)

Table 2 Averaged, measured data rates of test drives

Route		Test case		Throughput		
From	To	Direction	Test	Max (Mbps)	Mean (Mbps)	Standard dev. (kbps)
Helsinki	Riihimäki	DL	UDP	2.69	1.02	633
Riihimäki	Helsinki	DL	UDP	2.72	1.28	855
Helsinki	Riihimäki	UL	UDP	0.779	0.517	193
Riihimäki	Helsinki	UL	UDP	0.779	0.448	262

The effect of driving speed was less than what was expected. In practice, no noticeable increase in interference levels were detected when the driving speed was increased up to 200 km/h. Handovers worked well regardless of the driving speed. Increasing the driving speed from 160 to 200 km/h decreased the average received SNR by 1–2 dB only.

The measured data rates are summarized in Table 2.

4 CONCLUSIONS AND FUTURE WORK

In the current paper, high-rate telecommunications architectures for railways have been discussed. Various access technologies and their suitability to train-to-ground communications have been compared. In particular, field tests with the Flash-OFDM technology used on a high-speed Pendolino-train moving at speeds of up to 200 km/h through a 50 km long test track section have been focused.

The tests indicated that the Flash-OFDM appears to suit well as a high-rate access technology for high-speed trains. The measured average down- and uplink rates were 1 and 0.5 Mbps, respectively. The peak rates were 2.72 and 0.78 Mbps. The maximum cell radius was 11 km, but with the latest base station technology this can be increased up to 55 km. High driving speeds resulted in only a small variance for signal SNR. The Doppler transition was hardly noticeable.

Data rates of Flash-OFDM can well compete against other wireless mobile technologies, and building a network at the 450 MHz band (which is available for Flash-OFDM in Finland) should be relatively cheap. However, the network capacity is somewhat limited due to the allocated narrow bandwidth at 450 MHz.

In summary, the test provided interesting results, indicating a clear potential for FLASH-OFDM technology in the area of Intelligent Transport Systems (ITSs) for railways. Flash-OFDM seemed to be surprisingly immune to interferences of the train environment and to offer relatively high data rates.

From this research, it is concluded that the technology worked even better than expected.

Now that the measurements are completed and the suitability of Flash-OFDM for trains has been tested, work with railways ITS development is set to continue.

The next step is to research the functionality of the technology by using a longer track section and a set of pilot users and services. Thus, the adequacy of the network capacity for real life user cases can be investigated, and estimation of required base station densities can be started.

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