Making a well-founded choice of the wireless technology for train-to-wayside data services

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***Abstract*—The provisioning of wireless data services in the railway environment will become increasingly important for train operators and train constructors in the upcoming years. A well-founded choice of the technology to be used for the outdoor network connection is investigated in this paper. Several wireless technologies - including HSPA, E-UTRA and WiMAX - are compared by calculating their wireless ranges for reception outside and inside trains, based on the location of the transceiver. These wireless ranges determine the number of base stations needed to cover a pre-defined area along a railway track. Results show that generally 3G (UMTS-HSPA) and 4G (E-UTRA/LTE) technologies offer the best coverage over a range of data rates, from 2 Mbps to 8 Mbps. These data rates relate to a wide variety of services, from network control data, surveillance, crew services to passenger Internet traffic.**

***Index Terms*— wireless technologies, train data services, network coverage, business case**

I. INTRODUCTION

PROVIDING wireless data services in the railway environment will become increasingly important for train operators and train constructors in the upcoming years. The deregulation of the passenger and cargo rail market will lead to the reorganization of many incumbent rail operators. Reducing the costs will involve optimizations in the current operational processes and gaining extra revenues will require offering new (interactive) passenger services. These indicated changes can gain a lot from the implementation of wireless data services, ranging from network and train control data, surveillance, crew services to passenger Internet traffic.

Although train-to-wayside communication services become more and more available for train operators and train constructors, there are still a lot of technical and business related challenges. Today many network and application issues (such as seamless network connection, reliability, privacy, scalability, etc) need further attention before a wide range of services can be offered in a dynamic train environment.

Earlier work presented the concept of a GSM-based communication system for high-speed trains [1]. The challenges of providing the full range of UMTS services to high speed trains have been addressed in [2]. Various architecture options have been tested in the resulting high level system simulator and physical demonstrators [3][4].

The presence of track-side base stations primarily characterizes railway environments. Several other factors e.g. fast fading, Doppler shift, train penetration loss and tunnels have an effect on the dynamic wireless train environment. The train penetration loss significantly reduces reception quality for users inside trains due to metallised windows [5]. Further, moving mobile stations cause Doppler shift and Doppler spread. By using a directional antenna, Doppler spread in an OFDM train communications system is reduced compared to the omni-directional antenna [6].

The choice of technology or combination of technologies to be used for the outside or inside train-to-wayside network connection is currently underinvestigated. However, this choice not only affects the technical scenarios but also the business models and economic viability for implementing wireless data services in a train environment. By taking the dynamics and parameters of a moving train, the technical train specifications and the types of track areas into account in the wireless network propagation models, the network coverage for several technologies is calculated. This enables us to obtain a good estimate about the required number of base stations and/or access points for good coverage. A choice must be made whether to make use of the data capacity of existing networks e.g. 2.5G and 3G or satellite networks, or to roll out a dedicated network e.g. Wi-Fi or WiMAX. Of course, it is possible to combine technologies to obtain a more optimized technical as well as business wise solution.

The outline of the paper is as follows. In Section II a short overview of the considered wireless technologies is given. In Section III, the configuration and preferred path loss models for outside and inside train-to-wayside scenarios are specified. Using these path loss models, we calculate the ranges for the two scenarios in Section IV. These results will be related to the effect on the overall business case for implementing wireless data services. Finally, we draw our conclusions and give an overview of future work in Section V.

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II. TECHNOLOGIES

The coverage in a dynamic wireless train environment is analyzed for five different technologies: UMTS (Universal Mobile Telecommunications System), HSPA (High Speed Packet Access), E-UTRA (Evolved Universal Terrestrial Radio Access), Wi-Fi (Wireless Fidelity) and mobile WiMAX (Worldwide Interoperability for Microwave Access).

UMTS is developed by the European Telecommunications Standardization Institute (ETSI) and operates in 5 MHz wide channels around 2 GHz [7]. UMTS has been specified as an integrated solution for mobile voice and data. HSPA provides increased performance over UMTS by using new modulation techniques and by improving the radio access network [8]. Both UMTS and HSPA use the multiple access technique W-CDMA (Wideband Code Division Multiple Access). E-UTRA (also known as LTE) is a wireless data extension of UMTS technology and the proposed successor to HSPA [9]. Unlike HSPA, E-UTRA uses a new air interface system, which consists of OFDMA radio access in the downlink and SC-FDMA on the uplink technology.

Wi-Fi is a wireless local area network (WLAN) technology based on the IEEE 802.11 standard. The most popular 802.11b and 802.11g protocols use the 2.4 GHz band [10]. This paper focuses on 802.11g, which provides multiple users with access using OFDM (Orthogonal Frequency Division Multiplexing).

Mobile WiMAX, specified in IEEE 802.16e, operates in the 2-6 GHz band [11], which is developed for mobile wireless applications. Mobile WiMAX employs the novel SOFDMA (Scalable Open Frequency Division Multiple Access) technique to address the need for various spectrum allocation and application requirements.

III. METHODOLOGY

A. *Technical scenarios*

We will consider two main scenarios for train-to-wayside network connections. The first scenario, outside train-to-wayside, specifies the transmission from a base station (BS) to a receiving antenna on the roof of the train cars. The receiving antenna is connected to Wi-Fi access points (AP) inside the train, ensuring wireless reception inside the train cars. The transmission paths, both indoor and outdoor, of scenario I are shown in Fig. 1.

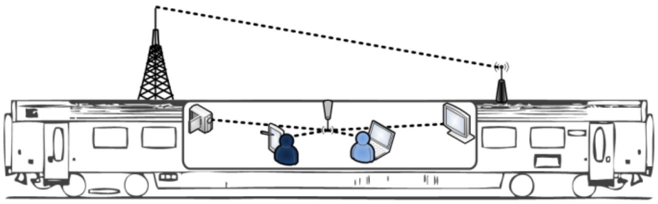

Fig. 1. Scenario I: outside train-to-wayside

The second scenario, inside train-to-wayside, specifies the transmission from a base station to a receiving antenna inside the train car. The train penetration loss has to be taken into account for calculation of wireless reception on the user equipment.

The transmission paths of scenario II are shown in Fig. 2.

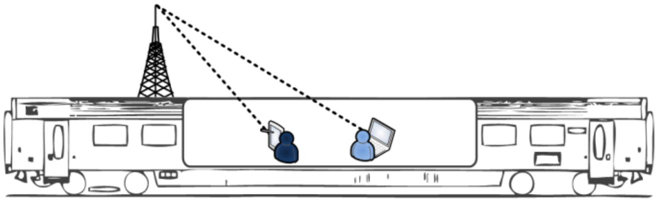

Fig. 2. Scenario II: inside train-to-wayside

B. *Configuration*

The transmitter and receiver configuration for scenario I, outside train-to-wayside, and scenario II, inside train-to-wayside, are summarized in Table I.

TABLE I
CONFIGURATION TABLE FOR DIFFERENT SCENARIOS

Scenario	***Technology***	***Height base station***	***Height receiving antenna***
I	UMTS, HSPA, E-UTRA, WiMAX	30 m	4 m
	Wi-Fi	6 m	4 m
II	UMTS, HSPA, E-UTRA, WiMAX	30 m	2 m
	Wi-Fi	6 m	2 m

We propose that the height of the receiving antenna is 4 m in scenario I, since the antenna is placed on the roof of a train car. This receiving antenna is connected to Wi-Fi access points on the ceiling of the train cars (not indicated in Table I). In scenario II, we choose a height of 2 m for the height of all mobile devices inside the train cars. In both scenarios, the height of the base stations is set to 30 m, except for Wi-Fi access points, where heights of 6 m are considered.

C. *Link budget calculations*

In order to calculate the wireless range R of a certain technology, we have to setup a link budget. A link budget gives an overview of all the gains and losses that occur from the transmitter through the medium to the receiver. The parameters of the link budget allow us to calculate the maximum path loss PL_{max}, which represents the maximum loss to which a transmitted signal can be subjected while still being detectable at the receiver. Table II gives an overview of the link budget parameters for the technologies discussed in Section II. We consider here SISO (Single-Input and Single-Output) antennas i.e. 1 transmitting antenna and 1 receiving antenna. One of the main differences between the selected technologies is the maximum input power of base stations. The WiMAX standard [12] specifies maximum WiMAX power amplification to 35 dBm, whereas 3GPP Technical Specification [13] sets the maximum input power of UMTS and HSPA base stations to 43 dBm. 802.11g EIRP (Equivalent

TABLE II

PARAMETERS FOR LINK BUDGET CALCULATIONS FOR DIFFERENT TECHNOLOGIES

Parameter	**UMTS**	**HSPA**	**E-UTRA**	**802.11g Wi-Fi**	**Mobile WiMAX**	**Unit**
Maximum input power of base station	43	43	43 - 46	13.1	35	dBm
Frequency	2100	2100	2600	2400	2500	MHz
Antenna gain of base station	17.4	17.4	18	7.4	16	dBi
Antenna gain of mobile station	0	0	0	2	2	dBi
Number of MIMO Tx antennas of base station	1					-
Number of MIMO Rx antennas of mobile station	1					-
Cyclic combining gain of base station	0					dB
Number of antenna elements of antenna array base station	1					-
Soft handover gain of mobile station	1.5	1.5	-	-	-	dB
Feeder loss of base station	2	4	2	0.5	0.5	dB
Feeder loss of mobile station	0	0	0	0	0	dB
Fade margin	10					dB
Coverage requirement	90%					-
Standard deviation of PL model	7.8					-
Shadowing margin	10					dB
Cell interference margin	6.02	8.9	2	3	2	dB
Vehicle penetration loss	20					dB
Doppler margin	3					dB
Bandwidth	5	5	1.4 - 20	20	1.25 - 20	MHz
Number of used subcarriers	1	1	72 - 1200	52	72 – 1440	-
Number of total subcarriers	1	1	128 - 2048	64	128 – 2048	-
Noise figure of mobile station	8	9	8	3	7	dB
Implementation loss of mobile station	0	0	0	0	2	dB
Guard period	25	25	4.69	0.8	11.4	μs
Target load	0.75	0.875	0.54	-	-	-
Maximum number of users	16	225	200 - 400	-	117-1170	-
Duplexing	FDD	FDD	TDD	TDD	TDD	-

Isotropically Radiated Power) is limited to 20 dBm [14], which is the sum of 13.1 dBm input power, 7.4 dBi antenna gain minus 0.5 dB feeder loss. In order to calculate the shadowing margin, we used a standard deviation of 7.8 dB and a coverage percentage of 90%. Further, we apply a Doppler margin of 3 dB [12] in order to take speeds up to 150 km/h into account. Finally, a vehicle penetration loss of 20 dB [5] is considered.

TABLE III

PATH LOSS MODELS FOR DIFFERENT TECHNOLOGIES

Technology	***PL Model***	***Area Type***
UMTS	Cost-Hata-A	Suburban
HSPA	Cost-Hata-A	Suburban
E-UTRA	Cost-Hata-A	Suburban
Wi-Fi	Cost-WI	LoS
WiMAX	Erceg-C	Flat terrain

The preferred path loss models for the selected technologies are specified in Table III. We selected the outdoor propagation Cost-Hata model [16] for UMTS, HSPA and E-UTRA. We used environmental type A of the Cost-Hata model, which is best suited to model medium-sized cities and suburban environments. Furthermore we used the COST-Walfisch-Ikegami-Model (COST-WI) to estimate path loss in a Line-of-Sight (LoS) urban environment. Next, we used the Erceg model [17] to calculate the range for WiMAX technology, as documented in [18]. We chose category C of the Erceg model, which models mostly flat terrain with light tree densities. In this way, Wi-Fi and WiMAX coverage for a omni-directional and non-dedicated trackside antenna is calculated. However, further improvements are possible by installing directional, dedicated antennas along the tracks. Typically, for (customized) Wi-Fi and WiMAX this can lead to a feasible solution, which will need attention in the future.

IV. RESULTS

A. Ranges for different scenarios

First, the heights of base station and receiving antenna for each scenario are used as input for the respective path loss models of Table III. These path loss models relate path loss values to distances from the base station. The ranges for different scenarios are obtained by combining these path loss values with the link budget parameters of Table II. A certain throughput rate can only be achieved up to a maximum allowable distance, which is defined as the range of the selected technology. The ranges for scenario I are shown in Fig. 3.

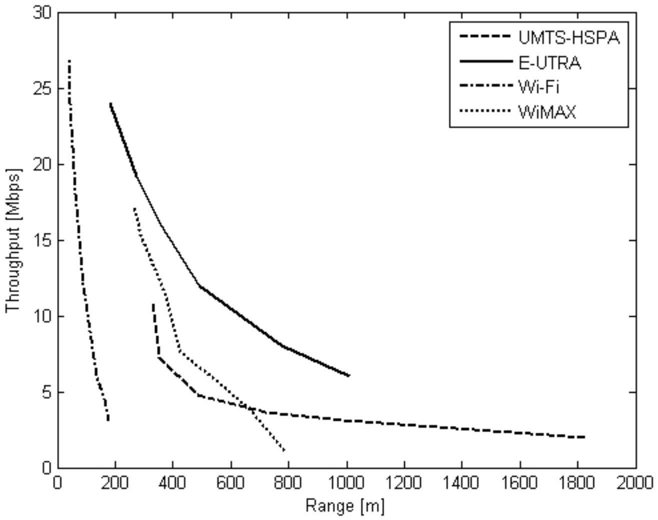

Fig. 3. Comparison of ranges R, scenario I

Larger ranges correspond of course to lower maximal throughputs. 3G technology (UMTS-HSPA) offers the largest ranges for relatively low data rates, whereas Wi-Fi technology can deliver high data rates at relatively small ranges. Both E-UTRA and WiMAX can provide high physical data rates of 6 Mbps up to about 550 m. In scenario II, the ranges R decrease compared to scenario I due to the vehicle penetration loss. Again, both E-UTRA and mobile WiMAX can provide high physical data rates of 6 Mbps up to 130 m (Fig. 4).

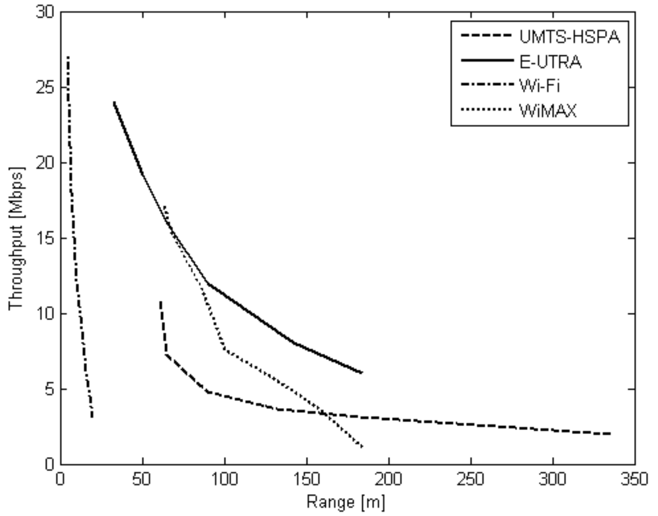

Fig. 4. Comparison of ranges R, scenario II

B. Train data services

There is a range of services that can be implemented, depending on the data provider and end user (passenger, train crew, train operators, train manufacturers, track infrastructure providers, etc). Data to and from the train has diverse purposes and thus the related transfer of this data has diverse and demanding requirements e.g. real-time vs. non real-time, secure vs. unsecure, small files vs. large files, etc.

In order to reflect the diversity in data traffic, we propose four different application groups with each a different set of requirements.

- The first group consists of vital control data that needs to be consulted in real-time with very high reliability constraints. These services include train diagnostics, remote train control (RTC), crew voice communication, etc. The required data rate is low (56 kbps should be sufficient), but a continuous network connection, preferably with a low delay, is a necessity.
- The second group contains event-driven and crew services, including surveillance monitoring (CCTV), crew video communication, seat control, passenger information system (PIS), public address (PA) and intercom, etc. A bandwidth of at least 2 Mbps is required for both downlink (wayside-to-train) and uplink (train-to-wayside) connection, as well as a continuous network connection as event-driven actions can happen any time and demand a high quality service level.
- Next, we propose an additional 2 Mbps downlink (about one fourth for uplink) for offering basic Internet services to passengers. Less network restrictions are necessary as a near real-time service is sufficient.
- Finally, we could offer extended interactive and streaming multimedia content and services to passengers. This will require high throughput (2 to 4 Mbps), mostly downlink traffic, and real-time network connections.

For vital control data, a real-time network connection is required. Currently dedicated GSM-R networks are rolled out for these vital services. For additional event-driven services, dedicated networks must be considered as reliability is of utmost importance as well as a symmetric down- and uplink connection of at least 2 Mbps. We find that UMTS technology offers larger ranges than WiMAX networks, but bandwidth for the first technology is mostly shared amongst multiple users. Increasing the data rate to 4 Mbps produces different results: WiMAX provides the largest ranges, HSPA offers second best ranges and the range of Wi-Fi technology is very limited. E-UTRA is also a possible solution from a technical point of view, but its high data rates lead to an overdimensioned network for this service offer. From a data range of 6 to 8 Mbps, E-UTRA technology becomes a very interesting solution, as it offers the largest ranges, followed by WiMAX and HSPA. However, the usage of customized WiMAX and Wi-Fi access solutions offered by a dedicated network can improve their ranges [19], and become a competitive technology compared to E-UTRA. Note that combining available technologies with dedicated networks where needed, can be a solution for meeting all requirements enforced by the service constraints. A possible technical solution to deal with different technologies is discussed in [4].

C. Coverage of the railway track Antwerp-Ghent (Belgium)

In the previous sections, we have shown the trade-off between throughput and range for each technology, and the potential services to be implemented by train operators. In this section we will determine how much base stations are needed to cover a pre-defined railway track between two Belgian cities, Antwerp and Ghent. The length L of this railway track is 62.4 km. The number of base stations (#BS) we need to cover a railway with length L is given by the following equation:

$$\#\mathrm{BS} = \left\lceil \frac{\mathrm{L}}{\mathrm{R}} \right\rceil \tag{1}$$

with $\lceil \cdot \rceil$ the ceil function.

Table IV gives an overview of the required number of base stations for the data rates defined in subsection B.

TABLE IV
REQUIRED NUMBER OF BASE STATIONS AND RANGES OF WIRELESS TECHNOLOGIES FOR DIFFERENT DATA RATES FOR THE RAILWAY TRACK ANTWERP-GHENT (62.4KM)

Data rate (Mbps)	***Tech.***	***R I (m)***	***#BS I***	***R II (m)***	***# BS II***
2	UMTS	1826	35	336	186
	WiMAX	579	108	135	463
4	HSPA	644	97	119	525
	Wi-Fi	168	372	19	3287
	WiMAX	668	94	156	401
6 - 8	HSPA	352	178	65	961
	E-UTRA	894	70	163	384
	Wi-Fi	125	500	14	4460
	WiMAX	558	112	131	477

In reality, the maximum available data rates are related to the distance to the nearest base station. We selected a trajectory (Fig. 5) between Antwerp (right) and Ghent (left). The dots indicate the nearest 3G base stations of Proximus [20], the largest Belgian mobile network operator. The antenna data was retrieved from the site of the BIPT (Belgian Institute for Postal services and Telecommunications), i.e. the national regulator [21].

Fig. 5. Antwerp-Ghent trajectory

A theoretical throughput is calculated making use of the input parameters presented in Table II. The maximum input power of base stations are set fixed at 43 dBm. This is an estimation as the real power depends on the location and the local environmental characteristics, as well as the time of day. The results for the theoretically maximum available UMTS-HSPA data rates along the railway track Antwerp-Ghent are shown for scenario I (Fig. 6) and scenario II (Fig. 7). As these UMTS-HSPA networks must be shared (and thus also the bandwidth) with other than train users, the maximum throughput will in most cases not be guaranteed, and will thus be even lower than the figures presented.

For the outdoor train-to-wayside scenario (Fig. 6), we see that most of the time, a 2 Mbps bandwidth can be obtained. On 6.6% of the trajectory, no connection can be established.

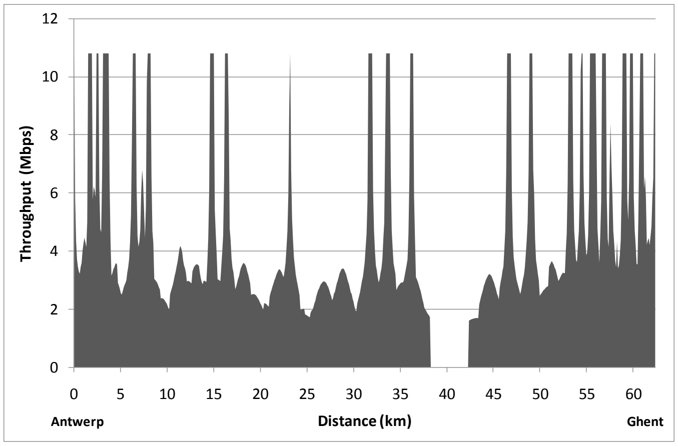

Fig. 6. Maximum throughput along track Antwerp-Ghent for scenario I

This can also be seen on the trajectory map (Fig. 5) where some of the nearest base stations are localized further from the track. A real-time connection can thus not be established for the whole trajectory, so no crucial train control and event driven services could be offered with the currently available 3G network. A combination of this 3G network and a network built dedicated for train services could be the solution. This business case has been proposed in [22] and indicates a very viable solution if deployed along a well-used railway track.

Fig. 7 shows the throughput of scenario II, the indoor train-to-wayside solution. In 71.5% of the trajectory, no connection can be established. This can be explained by the metallic coating in the windows, which is shielding most of the signals. No train operator will be involved in offering services in this scenario. Therefore the business case for this solution will not be very viable. Only a best-effort service could be provided without guaranteed throughput. This case could only relate to the use of individual mobile Internet subscriptions on the train. The mobile operators could install extra base stations along the tracks for better coverage, but the question is whether this investment will be profitable as the usage of 3G is at this moment still very low in Belgium [23].

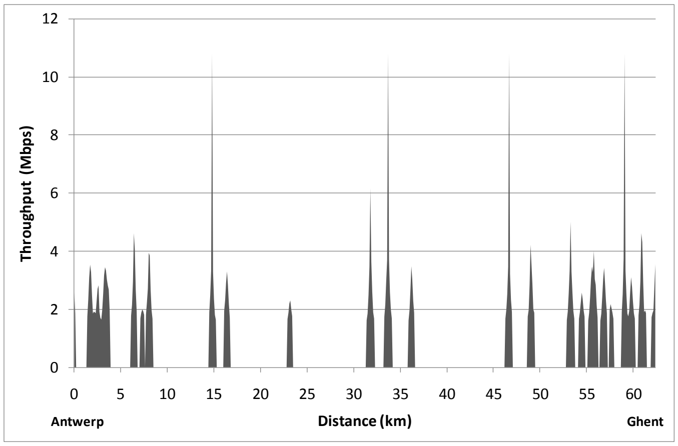

Fig. 7. Maximum throughput along track Antwerp-Ghent for scenario II

Overall we could conclude that unless there is a large investment wave in next-generation mobile networks (such as HSPA and LTE), that can provide a nationwide track coverage, the rollout of dedicated wireless networks, possibly combined with existing networks will be the most likely solution. A trade-off must then be made between investment and operational costs. Installing dedicated networks requires a large financial upfront cost, but will be cheaper in OA&M (operations, administration and maintenance) and bandwidth costs. Making use of the (shared) networks of mobile telecom operators will lead to very high operational costs (mainly due to bandwidth usage) [22]. This will all depend on the services that will be offered and the constraints put on the network.

V. CONCLUSIONS AND FUTURE RESEARCH

In this paper, the dynamic wireless train environment is investigated for several wireless technologies, including E-UTRA and mobile WiMAX. The number of base stations required to cover a railway track is determined for multiple deployment scenarios. In general, 3GPP 3G (UMTS-HSPA) and 4G technology (E-UTRA) can offer the best coverage over a range of data rates, from 2 Mbps to 8 Mbps. WiMAX base stations provide acceptable coverage for several data rates, and can offer the best coverage for a data rate of 4 Mbps. Wi-Fi technology is only suited for provision of connectivity inside the train cars. A trade-off must be made between the use of dedicated networks to be rolled out for offering train data services, or making use of existing mobile networks (currently 3G, migrating in the future towards HSPA and E-UTRA). Also the choice of services will restrict the use of possible networks due to technical constraints (reliability, real-time connections, coverage, bandwidth, etc). All these different parameters will affect the business model and its economic viability.

Future research will focus on the use of Multiple Input Multiple Output (MIMO) systems in E-UTRA, WiMAX and 802.11n. As discussed in [24], technical improvements can have a big influence on the final business case. Additional work will also include satellite broadband technology in the comparison of different technologies for the coverage of a railway track. A business model will be elaborated investigating the economic viability of implementing the different service types, related to the used networks.

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