Abstract

This paper presents the work carried out by SNCF between 2005 and 2007 in order to validate two different and complementary technologies for the implementation of train-ground broadband communications able to deliver onboard Internet services to high speed trains passengers: satellite technologies and WiFi. Firstly, the previous SNCF work in that domain is introduced. Secondly, the experimented satellite technologies are presented, as well as their advantages and drawbacks. Then, the WiFi trials carried out with Orange Lab are presented in detail. Finally, the “Connexion TGV” Project, one of the first industrialization of this kind of systems in the World, is introduced.

Introduction

Within the last years, SNCF has carried out some research projects in the domain of train-ground broadband communications within the framework of its ”TGV Communicant Research Program” (TGV is the acronym for “Train a Grande Vitesse”, the French high speed trains, which operation speed is 300 km/h, 320 km/h in the case of TGV Est European high speed line going from Paris to Strasbourg). The objective of this program is to find solutions in order to deliver Internet connectivity services to passengers, but also to connect the crew and the train itself (machine-to-machine applications). Some of the results of the program were already presented at WCRR 2006 in Montréal in [1]. This introduction aims to remember this previous work. The following sections present additional work carried out by SNCF within this domain and how this research has allowed SNCF to validate some technical solutions which are today being used in the first commercial deployment of onboard broadband Internet services for passengers on the high-speed trains running TGV East-European lines.

SNCF started this “TGV Communicant Research Program” with the study and experimentation of cellular terrestrial technologies based on GSM (CSD, GPRS, EDGE) and UMTS. These technologies are mobile-operator-dependent and do not guarantee good coverage on railway lines, in particular on rural areas, which are far from populated areas. In addition, aggregation of many parallel transmission channels (in order to improve the available throughput) is not considered due to mobile operator’s network technical limitations. Moreover, these technologies are less efficient in the case of high speed movement, resulting in throughput loss, which makes impossible the implementation of broadband transmission links between high-speed trains and the Internet.

Subsequently, SNCF studied mobile satellite access technologies and have been working since, together with the European Space Agency (ESA), with some European research laboratories like INRETS, Orange Lab and DLR, and of course with the providers of the internet-on-trains emerging technologies (Thales Alenia Space, Pointshot Wireless, Icomera, 21Net…), in the definition and optimization of broadband satellite solutions for high-speed trains.

First, the Icomera solution, which had already been experimented with success by the Swedish Railway Operator Linx, was experimented. It is a hybrid solution mixing satellite connectivity for the downlink communications and cellular connectivity for the uplink communications. The experimentation was not successful, again because of the poor cellular coverage of the French railway network, and the low available throughput in the uplink communications, which makes difficult the implementation of efficient broadband communications.
Two other satellite solutions, both based on the use of geostationary satellites and a 2-way transmission scheme were tested and validated onboard TGV high-speed trains in France: The Thales Alenia Space solution, which has been also experimented by TrenItalia, and the 21Net solution, already experimented onboard Renfe and Thalys trains.

2-way satellite communication solutions represent then the first candidate technology validated from a technical point of view by SNCF onboard a TGV high-speed train running at 300 km/h. Next section presents additional research work carried out by SNCF with 2-way satellite communications and the major advantages and drawbacks of these satellite solutions.

**Satellite solutions**

Both tested satellite solutions use geostationary satellites working in Ku Band (11 and 14 GHz for respectively the downlink and the uplink communications). Geostationary satellites are the most ‘common’ satellites since they allow to cover a very large surface of the Globe (1/4 of Earth’s surface can be covered by a single geostationary satellite), which makes them ideal for broadcast service like TV and radio. Most of geostationary satellites are ‘transparent’ ones. That means that the satellite doesn’t process the information they receive, they act as repeaters: they simply catch the radio signals coming from the Earth stations in the uplink, translate them to the downlink frequency, amplify them and retransmit them. The advantage of ‘transparent’ satellites is that users will be able to choose among a large range of technologies and modulation/coding schemes, the more suitable one taking into account the considered application.

Available throughputs and operational modes will depend on the chosen satellite, on its coverage footprint and on the size of the transponder selected for operation, on the multiple access scheme (SCPC/FDMA, TDMA, CDMA, MF-TDMA…), on the transmission technology (DVB-S, DVB-S2…), on the chosen modulation and coding schemes, on the size of the considered terminals (Earth stations at the hub and onboard the train), etc… The two 2-way satellite solutions assessed during our first trials used both DVB-S technology for the downlink (from satellite to trains) and SCPC multiple access technology for the uplink (from trains to satellite).

DVB-S (Digital Video Broadcasting by Satellite) is the technology used all around the World for satellite TV broadcasting. DVB technology allows transporting MPEG-2 video flows, but it is also possible to encapsulate IP-data flows inside these MPEG-2 frames. Hence, in the downlink, a single DVB-S transmission will transport the data flows of all users (data flow of each user will be multiplexed inside the MPEG-2 frames), all the users will receive the complete DVB-S signal and will extract their own data (the flow of each user will be seen as a different data “channel” by the DVB-S decoder, in the same way a digital TV decoder will select and decode a particular TV channel). Since DVB-S has been designed for home TV broadcasting services, it allows using small antennas. In our case, the dimensions of the used antennas were L146xH45 cm in the case of Thales Alenia Space and L80xH72 cm in the case of 21Net, and the experimental campaigns onboard TGV trains running at more than 300 km/h showed that IP-data throughputs of more than 20 Mbps could be reached for downlink communications.

SCPC (Single Channel Per Carrier) is a multiple access technique in which the signals of the different Earth stations (hub and user terminals) are separated from the other Earth stations by using a particular frequency (for each one of them), that’s why this access technique is also called FDMA, for Frequency Division Multiple Access. SCPC is very frequently used in satellite communications, since it’s a very simple technique that guarantees avoiding interference between users. However, SCPC forces to allocate a specific frequency band for each Earth station in a fixed way, that is, the frequency band is assigned to a specific Earth terminal, and that, independently of the use it makes of the allocated bandwidth. Since the needs of this specific Earth station in terms of bandwidth are often flexible, the system will need to be dimensioned carefully… Depending on the considered application, if the dimensioning of the system is made in function of the peaks of consumption, the system will be over-sized most of the time. If the system is dimensioned considering the average bandwidth consumption, then
the system will be under or over sized during peak and weak hours respectively… In the case of
Internet access onboard trains, the needs of bandwidth will depend on the number of
passengers on the train, which depends on the time of the day, the day of the week… SCPC is
not flexible enough to take into account this variations. In addition, if we consider the operation
of many trains, the same problem concerning the dimensioning of the system will appear, but
this time at the total bandwidth level: how much frequency must be allocated on the satellite in
order to deliver the service for 20 trains? How this bandwidth will be used when only 5 trains will
be in operation? Figure 1 shows how much the need of a railway operator concerning satellite
capacity will change along a normal week.

![Figure 1: Estimated required data-rate for the entire SNCF TGV fleet [2]](image)

The estimated need for the TGV fleet, in Mbps is presented for each quarter of an hour for 4
different traffic models (for down and uplink communications) studied by ESA within the
framework of its ARTES1 Study “Broadband On Trains”. It can be observed that the need in the
downlink can reach 185 Mbps on Friday afternoon and just 70 Mbps on the weak time of a
Tuesday. This is to show that Internet application onboard TGV trains will need flexible
bandwidth allocation and also multiple access technologies able to dynamically assign
bandwidth to the different trains in operation at a specific moment. SCPC is not flexible enough
and then it is not suitable for this kind of operation. Some of the research work carried out in
2006 by SNCF aimed to validate another multiple access technique, the DVB-RCS technology.

DVB-RCS uses a MF-TDMA (Multi-Frequency Time Division Multiple Access), in which data
flow is transmitted using time slots on many different frequencies. The system has been
designed to be able to assign capacity on demand: many different timeslots and frequencies will
be used for a communication needing a lot of bandwidth, while only a few time slots and
frequencies will be assigned to an application requiring less throughput. DVB-RCS is then
inherently flexible and able to dynamically assign capacity to the different terminals in the
network. In our case, the DVB-RCS method will allow setting up the return link via dynamic
assignment in terms of time and frequency, thus, optimizing the total bandwidth that is required
for the entire fleet of trains.

But DVB-RCS technology was designed for fixed Earth stations and SNCF trials, carried out
with 21Net in 2006, using Nera mobile terminal modem and a Hispasat satellite, were one of the
firsts experimentations of DVB-RCS on a mobile environment. Some modifications were
required in the system in order to tolerate the little Doppler shift generated by the speed of the
train (of up to 7 KHz) and to cope with synchronization problems generated when the signal is lost (because of a tunnel for example). The Nera terminal was modified and the results showed that DVB-RCS is capable of providing bandwidth results that are consistently higher than 350 kbps in the uplink at 300 km/h on a TGV high-speed train. This technology was also validated onboard a Renfe AVE high-speed train in the framework of the European Research Project MOWGLY in Spain. These different experimentations led to an official demand of standardization to the DVB-RCS group of ETSI (European Telecommunications Standards Institute), by the Train Operators Forum, a group of European railway operators animated by the European Space Agency (ESA).

During this period, SNCF also realized coverage rate measurements in order to evaluate in a precise manner, the availability of the satellite service for Internet onboard TGVs in France. Figure 2 shows, the railway tracks (green ones) where the service availability was assessed.

![Figure 2: Satellite service availability on some of the French Railway tracks. [3]](image)

This coverage measurement campaigns were carried for many months onboard a TGV trainset running a very large part of the French railway network, and demonstrated a total availability rate of 98% along the experimented routes.

The first technology technically validated for operation on high speed trains was then the 2-way satellite solution. Next section of this document presents the work carried out in order to validate a second candidate technology, WiFi.

**Terrestrial solution**

In parallel to the study of satellite solutions, SNCF and Orange Lab teams have closely worked together within the domain of wireless LAN technologies and their use to provide train-ground broadband connectivity for trains (including high-speed trains). This section presents the architecture of the first experimental network deployed around Vendôme TGV station to assess
the feasibility of a WiFi (802.11b and g standards) network (terrestrial trackside radio network) to support seamless mobility. A field trial was led by Orange Lab in collaboration with SNCF to test a WiFi solution allowing a new communication ground/board link, this innovative internet connexion being supported by a terrestrial radio network. This new communication mode, if able to work in high speed conditions, could be used as a block to build a complementing coverage to global satellite coverage for example. This innovative architecture could also be used to deploy a terrestrial network, along railway sections to provide internet access services.

The first experimentation aimed at qualifying the WiFi technology to build up an innovative access network capable of being used in high speed trains. Architecture of WiFi experimental network has been developed and deployed in Vendôme, not far from Tours, along the TGV railway tracks in order to test broadband internet access solution. This network was based on an architecture entailing 4 access points located on bridges and pylons, making up total radio coverage of 13Km length.

In order to assess the feasibility of the radio system to support a seamless mobility, an optimized radio link was studied specifically in terms of antenna coverage.

The radio network architecture of the experimentation settled in Vendôme has been specifically tuned to the railway environment because the antennas had to be placed close to the railway and the radio coverage stretched in order to allow a maximum distance between two emitting access points to cope with an optimized business plan; (installing a given access point plus antennas far away from the next access point contributes to reduce the cost of the solution).
The antenna pattern being optimized to improve the transmission gain, the coupling design of two antennas has been studied to make up a bi-directional antenna dedicated to the particular application onboard TGV trains. This coupling scheme of the two antennas, once tested in a laboratory test, has been applied on roof of TGV.

Once the onboard antenna gain performance acquired, a predicted link budget was computed to assess margins versus radio levels conducting to performance gains in terms of data-rates. The following table gives an example of link budget showing the expected S/N margins versus communication bit rate, computed versus the coverage width.

<table>
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<tr>
<th>Distance (m)</th>
<th>Output power Tx (dBm)</th>
<th>Câble loss (dB)</th>
<th>Tx antenna gain (dB)</th>
<th>Rx antenna gain (dB)</th>
<th>Câble loss (dB)</th>
<th>Received power Rx (dBm)</th>
<th>11Mb/s bit rate S/N margin (dB)</th>
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Table 1: Link budget

The radio coverage measured in the TGV was built by combining two recording files, the first file containing registered received levels of channel 1 and the second containing received levels of channel 6. The measure is presented on Figure 5:
Figure 6 shows a recorded radio level curve performed with AirMagnet tool.

Since the first trials, the measured radio levels were extremely good, and compliant with efficient performance in the mobile communication links. Some more complex tests were conducted to assess the network performance, ping test and UDP traffic tests. An example result of these tests is given in Figure 7.
The top figure shows the connectivity performance of the early first Vendôme experimental network while the bottom one shows an UDP traffic performance test, the network being able to support a 2Mb/s traffic along the handover across the 4 access points.

Following this early experimentation, an extended network of a fifty kilometres length was deployed on the high speed tracks around Le Mans station. Ten access points were installed to build a WiFi connectivity zone of about 600sec, the TGV running in this area at a speed of about 300km/h. These access points were installed on 3G cellular sites, in order to reuse the access links, to deploy new antennas and to manage efficiently the innovative WiFi network by other network equipments located in Le Mans. The previous computed link budget was applied to this new environment in order to maximise the WiFi coverage areas.

A test campaign was performed on this pre-operational network, radio and traffic tests to prove the efficiency of the handover between different coverage areas were done. A mobile router was implemented onboard TGV to assess the handover capacity of the system. During the IP connectivity tests, a TCP proxy capable of optimising the link bandwidth was installed in the network, and this functionality demonstrated a real efficiency of the transmission during short outages of the link, due to bridges, short tunnels, etc..

Several runs allowed tuning the critical parameters in the access points and in the mobile router to perform an efficient handover between two zones and to optimise the length of each WiFi coverage area.

In addition, some trials were led to determine the maximum link throughput of the data transmission. Figure 8 shows the recorded results, and the very good performance of the system.
These field campaigns were at the beginning limited to the 802.11b throughput levels of 1 and 2 Mbps in order to study the efficient coverage, but later field campaigns showed that 802.11g is able to deliver effective data-rates higher than 10 Mbps between the high-speed train and the ground, also demonstrating that WiFi can be considered for coverage of large zones, particularly for the implementation of large gap-fillers.

SNCF has also investigated other terrestrial technologies, like pre-mobile-WiMAX solutions, iBurst and Flash-OFDM. Although these technologies offer promising characteristics, they have not been considered by SNCF until now for operational use due to the fact that they are proprietary solutions and regulation issues need to be solved.

Conclusions and perspectives: the “Connexion TGV” Project

The first technology technically validated for operation on high speed trains was 2-way satellite solutions. The principal advantages of these satellite solutions are:

- Instant geographic coverage of the entire railway network (satellite visibility in the case of France is close to 100%).
- Avoidance of long, heavy and expensive deployment of infrastructures along the large French railway network (31000 km).
- High data-rate applications are possible: data-rates of more than 20 Mbps in the downlink and up to 2 Mbps in the uplink are possible in a high speed train environment.
- Possibility to cross country borders, in the scheme of European high-speed trains.
- Ideal for 1-to-many applications (broadcast applications like digital TV broadcasting)

However, satellite solutions also present some drawbacks:

- Need of gap fillers in order to cover the zones where there's no satellite line of sight (tunnels, stations, urban canyons, deep valleys…), as the continuity of the service is one of the key elements of the quality of service delivered to passengers.
- Satellite antennas suitable for this kind of application are rather large (in average, about 1 meter diameter and 50 cm high) and as a result they are difficult to install and maintain. In addition, the use of these antennas is impossible on double-decker trains, as they do not respect the kinetic envelop of the train.
- Satellite bandwidth and operation costs are very high (above 3 M€ /year for a 36 MHz transponder allowing the simultaneous operation of ~20 trains). This recurrent cost (OPEX), which requires permanent revenues from the service, makes difficult the consolidation of business models

Terrestrial technologies can also be considered for the provision of broadband Internet services onboard high-speed trains. Their main advantages are:

- Exhaustive “0 hole” coverage can be considered since a specific radio coverage is deployed along the tracks.
- High data-rate applications are possible, since techniques like pre-mobile WiMAX allow implementing throughputs of more than 10 Mbps. Performance of these technologies evolving very fast, future throughput evolutions for the system can be considered.
- Small propagation delay (with respect to satellite technologies), which allows implementing real-time constrained services like VoIP, visioconference…
- Ideal for gap-fillers, in zones where the satellite visibility is not available.

However, terrestrial technologies have also some drawbacks:

- Deployment of the considered technology along thousands of kilometers of railway tracks remains very expensive, and that even in the case the sustaining infrastructure already exists (when the pillars, the power and the network are already there).
- Border's crossing will be a problem and requires negotiations between different railway partners.
- Use of the 2.45 GHz ISM frequency band (free of license) might be an issue, since everybody can use this frequency and then possibly interfere with other systems. Other
bands can be considered but then, some frequency and regulatory issues have still to be clarified.

All this research work has demonstrated that both terrestrial and satellite technologies have advantages and drawbacks, and that today, the optimal solution, able to deliver high data-rates and a 100 % coverage without spending years in heavy deployments along the railway tracks, is the combination of them in a single solution. This solution, resulting from the use of complementary access networks, would use the satellite access where available and terrestrial accesses in stations, tunnels and other out-of-visibility areas.

In parallel to those technical validations, SNCF TGV Marketing Department has been working in passenger needs concerning multimedia and connectivity services onboard. Different survey campaigns have been made in order to determine and consolidate which applications? for which public? in which trains? at which prize?... As a result, SNCF TGV Department launched the “Connexion TGV” Project, which aims to deploy a first real-size commercial multimedia and internet services onboard TGV trains running the TGV East-European Service. Two European tenders were launched in 2006, one for the infrastructure and one for the multimedia contents (onboard multimedia services portal). The winners of the tenders were two consortiums: OCEA (composed of Orange, Eutelsat, Cap Gemini and Alstom) for the Infrastructure and OC (Orange and CapGemini) for the multimedia contents. OCEA, OC and SNCF teams have been working together since in the development of “Connexion TGV” solution in order to deploy the service onboard 3 TGV trains at the end of 2007.

In the infrastructure side, the selected system confirms the results of the research work carried out by SNCF within the last years, since the solution is a multi-interface solution using a 2-way satellite as primary link, and a WiFi terrestrial communications solution as secondary link, for stations, tunnels… The WiFi gap fillers are able to work at 300 km/h. The selected technology for the satellite link is a very flexible solution based on CDMA multiple access techniques, which guarantees the possibility to manage the allocation of bandwidth in a dynamic way.

The service has been opened to passengers onboard the 3 equipped train sets of the TGV East European Service in December 2007 and SNCF will carry some market studies during the next months in order to assess the business model of the service.

This SNCF first deployment will be the World’s first Internet service for passengers onboard high-speed trains based on a mixed satellite/WiFi architecture for train-ground communications, able to deliver a connectivity service over 100% of the trip.

At the same time SNCF deploys its first « connected » trains, many other railway operators are working in Internet connectivity for passengers: Thalys, SJ, NS, DB, Eurostar, TrenItalia, National Express East Coast, Brighton Express, Heathrow Express, Virgin Rail West Coast, SBB... They’re all involved in the experimentation and validation of similar systems for trains, some of them with terrestrial technologies, some of them with satellite technologies, and some of them with both terrestrial and satellite technologies. That shows that constraints are different in every country (satellite will not correctly cover countries where there’s a lot of mountains such as Switzerland; mobile operators does not deliver the same quality of coverage and service in the different countries; etc...). All these experimentation shows however how much Internet and multimedia services onboard will be important for railway operators in the coming years.

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References