A Satellite-Based Infrastructure Providing Broadband IP Services on Board High Speed Trains

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Abstract. After the earlier technologies that offered satellite mobile services for civil and military applications, today's specific antenna design, modulation techniques and most powerful new generation satellites also allow a good level of performance to be achieved on-board high speed modes of transport such as aircraft and trains. This paper reports the Eutelsat's experience in the developing and deploying architecture based on a spread spectrum system in order to provide broadband connectivity on board of high speed trains. After introducing the adopted technologies, the architecture and the constraints, some results obtained from analysis, testing and measuring of the availability of the service are reported and commented upon.

1 Introduction

Two reasons explain the development of broadband communication on boats, aircraft and trains: first, the need for service and security information transmission (e.g. monitoring and alarms) and second, the need for additional public services such as Internet access and multimedia applications (video and rich content distribution on board) so as to make the mode of transport that offers the application a more attractive option for the passengers.

To provide IP based services on board of civil aircraft as well as of high speed trains, Eutelsat developed a satellite infrastructure based spread spectrum transmission and special antennas designed to meet the constraints of operating a mobile environment.

This paper provides an outline of the architecture designed to provide IP services on board of high speed trains. Such an architecture is aimed at improving the quality of the perceived service by integrating terrestrial links between the train and the ground where the satellite is not visible.

Analysis of the results of measurements performed during certain tests campaigns highlights the difficulties of the satellite transmission from a train and explains that several optimization techniques are necessary, but in so doing clearly demonstrates the effectiveness of this kind of service.

2 The Railway Environment

2.1 Mobile Satellite Communications in the High Speed Trains

In principle, railway mobile communications would benefit from having a static path, which would reduce the complexity of transmission infrastructure, e.g. using radio

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networking throughout the railway. Unfortunately, most parts of the high speed railway network are placed in isolated areas where a dedicated terrestrial communications infrastructure is not economically viable. For this reason satellite communications is considered the most suitable alternative for the IP services provisioning due to the possibility of the entire fleet or fleets of trains used by one or more railway companies sharing the same infrastructure.

But in this way, satellite communications on board trains must take account of several additional issues. First, the presence of persistent obstacles in the satellite's line of sight (LOS), e.g. tunnels, forests, acoustic insulators, buildings and the stations themselves, interrupts the communicability for long periods. In such cases, the problem can be solved with a vertical hand-over, i.e. by automatically switching the traffic into a local link: in this project a WiFi link has been chosen. The vertical hand-over alone does not fulfil the task of reducing the unavailability of the IP link: indeed, a very fast satellite link recovery procedure both in terms of antenna tracking and system re synchronization, has to be available at the exit of the non-LOS area in order to reduce the unavailability.

Other disturbances are caused by occasional obstacles (e.g. electrical poles, single trees and pass-overs) or periodical obstacles (e.g. the catenaries). Their effect on the traffic depends on the transport protocol adopted on top of the IP, the worst consequences being for real time and UDP based communications. Assuming that these occasional interruptions do not impact the synchronization of the on-board system, several approaches have been analyzed with a view to mitigating for these losses: on one hand, by applying the principle of time diversity for the upper layers, for example by "controlled" repetition of datagrams, which does, however, have the drawback of a reduction in efficiency. The diversity principle can be also adopted at the physical layer, whereas transmission per time slots with repetition is adopted. A second solution is the introduction of interleaving in the modulation chains, which is already present for the DVB-S and DVB-S2 standards but which has never been yet applied to the interactive channel.

Even if a good service availability can be achieved with the available technologies, other aspects (and not the least important) of the railway environment impose additional constraints and have in fact been the driving conditions for the Eutelsat architecture and system design. We refer to environmental and security aspects, which are well described railway standards.

2.2 Mechanical and Electrical Constraints

For high speed trains capable of travelling at speed up to 350 km/h, mechanical constraints are imposed above all in terms of the equipment installed both inside the cars or and in the roof.

All equipment installed on the roof of the train, primarily satellite or radio link antennas, has to introduce only a low level of aerodynamic interference, show high resistance to shocks upon impact (and strong acceleration) and to the pressure gradients at the entrance to tunnels (particular hard when two trains cross each other) and also vibrations.

Other constraints are due to the weight, volume and shape of the antenna which for security reasons has to match several specifications. For example, the satellite antenna profile has to respect a security insulation distance from the catenaries under dynamic conditions, i.e. the train roll, yaw and pitch.

Observance of all these limitations has been possible thanks to a low profile antenna design produced by *Space Engineering* which, at the same time, assures also acceptable performances in terms of EIRP and G/T.

Additionally the equipment has to be compliant with several principle dictated by the electrical environment. In particular the equipment must be compatible with DC power supply, and all its imperfections and instability, already available on board.

2.3 Electromagnetic Emission Control

Specific regulations related to satellite communications on trains have recently been defined by ETSI [1], with one standard aimed at reducing interference for the surrounding environment as well as adjacent satellites.

Selection of the satellite system, in this case based on a spread-spectrum modulation, has been fundamental for the compliancy with the ETSI indications, as well as antenna design.

3 The Satellite System

3.1 Asynchronous Spread Spectrum Access to the Satellite

Two criteria were applied when choosing the satellite system: the possibility to provide the customer with as high a throughput as possible, and the compatibility with the ETSI requirements for reducing the interference [1].

If the first condition can be matched by all the most common commercial satellite systems, the second drove the selection of a spread spectrum system. In fact, the spreading procedure contributes to the reduction of the on-axis and off-axis spurious radiation in terms of power spectral density, which is one of the main ETSI's requirements.

The *Viasat Archlight* system implements a bi-directional star topology via satellite where the inbound is based on the Viasat patented algorithms known as *Code Re-use Multiple Access* (CRMA) [2][3]. The CRMA, which has been derived by the Spread Aloha Multiple Access technique, adopt a spreading scheme where only one direct sequence code-word, which is longer then the symbol (or burst), is used by all terminals. It is hence similar to the ALOHA method for the access to a radio channel, with different remote terminals sharing the same inbound transmitting their bursts asynchronously. Thanks to the spread spectrum process, a collision of two bursts (and consequent loss of information) happens only if the first chips in the two coded bursts are overlapped and the collision probability is strongly reduced. As shown in [3], the ratio between throughput and carrier load, i.e. the efficiency of the system, grows with the spreading factor and takes the minimum of $1/2e$ (i.e. no spreading, a well known result for ALOHA). Furthermore, the use of only one code-word reduce the complexity of the demodulators, compared with a CDMA or a Spread Aloha CDMA scheme, because only one acquisition circuit (with correlation) is required for all the remote terminals.

The CRMA scheme presents a further advantage in the simplification of the time/frequency recovery algorithm during the synchronization procedure (almost without any loop), which makes the re-acquisition and re-login processes faster. Thus, in mobile applications with frequent interruption of the LOS, the capability of a fast recovery after satellite loss-of-sight enables service availability to be increased. Additionally, the reduction of the signaling complexity has a positive contribution to the global system efficiency.

The outbound of the system is a spread TDM signal (the spreading factor can be 1, 2 or 4).

Arclight improves the spectral efficiency thanks to the *Paired Carrier Multiple Access* (PCMA) [4] where the inbound and the outbound can share the same capacity. The PCMA algorithm is based on the principle that, in a case where two signals are superposed, then if the channel between transmitter and receiver can be estimated and the pattern of one of the two signals is known a priori, this can be extracted from the received composite signal in order to recover the second one.

The drawback in this kind of technology is the higher overhead required for the inbound burst identification, with the consequent reduction of efficiency offset by the reduction of the transmitted signaling (no burst time plans, bandwidth allocation request and correction messages are required).

3.2 The Low Profile Satellite Antenna

A low profile auto-tracking antenna (see Figure 1) was specifically designed by *Space Engineering* for the application on-board high speed trains. It is a dual reflector Gregorian steerable antenna.

Some optimization has been undertaken by means of limiting the geographical area within which the antenna can be used and employing restricted subset of the Eutelsat satellite (in this case the *AtlanticBird*™ fleet). The antenna performances are described in the following section (see Table 7).

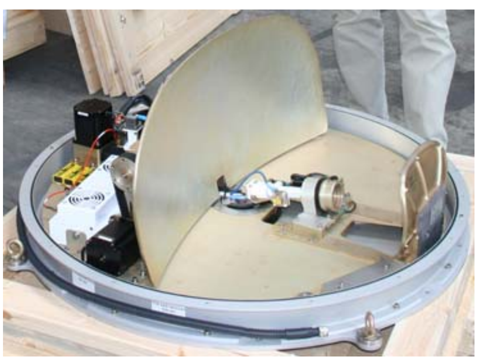

Fig. 1. The low profile satellite antenna for high speed trains (without radome)

3.3 Satellite Link Budget

3.3.1 Inbound Parameters

Table 1 to Table 3 give the details of the hypotheses from which the calculation have been done for the inbound. Two bit rates, 512 kbit/s and 1024 kbit/s, have been considered.

Table 1. Transmission parameters off the train antenna

Transmitting parameters	Values or description	
Modulation	GMSK	
Bit rate	512 kbit/s	1024 kbit/s
Code type/rate	Turbo 1/3	
G/T satellite (worst case)	+6.5 dB/K	
Spreading factor	22	12
Number of simultaneous users	21 (min)	11

Table 2. Reception parameters for the hub antenna

Receiving parameters	Values
Satellite EIRP	55.0 dBW
E/S G/T	31.2 dB/K

Table 3. Train antenna sizing

Antenna parameters calculated	Values
Transmission gain	34.0 dBi
EIRP at 512 kbit/s	40.0 dBW
EIRP at 1024 kbit/s	42.0 dBW
Required SSPA power at 512 kbit/s	4 W
Required SSPA power at 1024 kbit/s	7.9W
Clear-sky margin	0.2 dB

3.3.2 Outbound Parameters

Table 4. Transmission parameters of the fixed antenna (at the hub)

Transmitting Parameters	Value or description
Modulation	OQPSK
Bit rate	20 Mbit/s
Code type	Turbo
Code rate	1/3
G/T satellite	+9.9 dB/K
E/S EIRP	55.7 dBW

Table 5. Receiving parameters required at the train antenna

Receiving parameters	Values
XPD	25 dB
Satellite EIRP	54.2 dBW

Table 6. Train antenna sizing

Computed parameters	Values or description
Antenna G/T	10.1 dB/K
Clear-sky gain	0.0 dB

Table 4 to Table 6 report the assumptions for the outbound link budget. No spreading is adopted for the forward link.

3.3.3 The Antenna Performances

Three configurations were considered, derived from the evolution process from the prototype (configuration A), through the pre-series (configuration B) to the series foreseen (configuration C).

Table 7. Performances of the antenna

Parameters	Config. A	Config. B	Config. C
Antenna gain	30.5 dBi	33.4 dBi	33.4 dBi
XPD min	25 dB		
G/T	9 dB/K	10.5 dB/K	12 dB/K

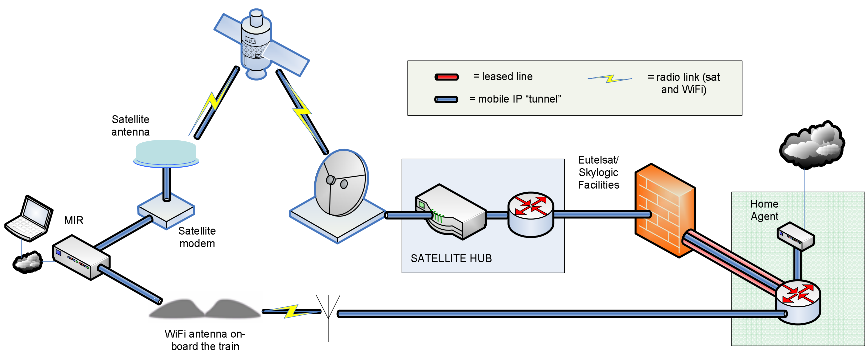

Fig. 2. Scheme of the interconnection

4 Vertical Hand-Over

When LOS is interrupted (due to a permanent obstacle), continuity of the service is assured by means of a WiFi 802.11b/g link between the train and one or more antennas. Together with the satellite antenna, this involved installing a pair of WiFi directive antennas on the roof of the train.

A mobile intelligent router (MIR) developed by Orange is responsible for switching the IP traffic into the available physical link. The MIR first assures a stable login of the WiFi subsystem on the local network and then passes the traffic on the newly created link. The position of the WiFi antennas on the ground was so as to allow the login to the new link to be completed before the satellite LOS is interrupted.

The Satellite/WiFi network layer is based on mobile IP (MIP). Satellite and WiFi are both considered part of the MIP infrastructure. The MIP Home Agent, hosted at the WiFi operator premises therefore has to be connected via a terrestrial link to the satellite hub. The MIP encapsulation/decapsulation is performed on board the train by the MIR, which plays the role of foreign agent.

As counterpart of this architecture, the TCP enhancer required to improve the satellite link performance and mitigate the effect of micro-interruptions of the link affecting the TCP connections, cannot be integrate into the satellite modem because it cannot process the encapsulated IP packets of the MIP. Thus, the TCP Performance Enhanced Proxy (PEP) is inserted behind the MIR and will process the TCP traffic passing through the satellite as well as through the WiFi. Since these two channels have very different latency and capacity, fine tuning of the PEP was necessary in order to optimize TCP through the satellite and do not interfere with the traffic when it passes through the WiFi link.

5 Tests and Measurements

5.1 The Effects on the Traffic in Non-LOS Conditions

As already stated, communications from the trains are subject to frequent loss of LOS. In this chapter, we report the results of a number of measurements that were performed during a tests campaign on board of a high speed train.

Figure 3 plots the behavior of the system over the time in the presence of interruptions. The antenna used was the pre-series model (configuration B). The first graph, the *Automatic Gain Control* (AGC) values, shows a variable proportional to the beacon level measured by the narrowband receiver of the antenna. The tracking algorithm antenna aims at maximizing this value (the periodical dropping of the AGC value due to a frequency scan used by the tracking algorithm indicates that there was perfect reception without interruptions). The second graph represents the Eb/No received at the modem (in this case the outbound used was at 3.5 Mbit/s instead of 20 Mbit/s) and gives a qualitative comparison of the effect of interruptions on the signal. The third graph shows with vertical bars the *icmp* requests having a successful reply and proves that the impact of the interruptions is rather severe for the IP packets. The

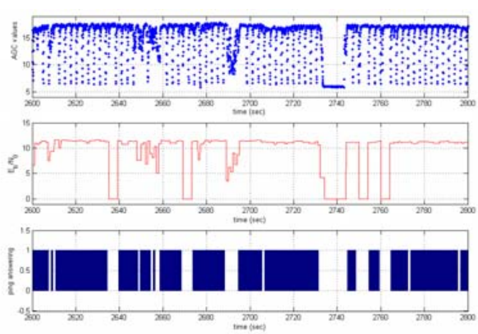

Fig. 3. Impact of the signal losses on the IP traffic (sampling in a period of 200s)

reason is due to the fact that even if the reception shows just a small attenuation, the transmission is heavily impacted. The presence of a UPC algorithm in the modem cannot solve the problem, because its reaction time is usually longer then the duration of the attenuation.

Most recent experiences have demonstrated that the effects on the TCP traffic of micro-interruption can be easily mitigated with the state-of-the-art TCP enhancer algorithms (SACK, fast recovery, accelerated slow start have been retained for the deployment on the proposed Eutelsat services). Conversely, the UDP traffic remains more sensitive to this kind of loss and its protection can be ensured only by the addition of redundancy in the transmission with the introduction of application layer FEC, as proposed in the DVB-RCS+M standard [5]. Additionally, other proprietary solutions (to be tested soon by Eutelsat) propose to mitigate the effect of short interruption with the insertion of interleaving (deepness adjustable) in the forward link coding scheme.

5.2 The Coverage Mapping

Relating the previous measurements to the geographical position (GPS coordinates) gives an idea of coverage availability.

Measurements were performed to record the level of the beacon used by the antenna for the tracking purposes and to record the geographical coordinates. Here too, this is represented by the AGC value: any unitary variation of this parameter is in fact equivalent to a 1 dB variation of the level, and recording instantaneous values of this variable corresponds to recording a trace of the fading along the railway path. Figure 4 shows a segment of the coverage measured along a high speed line (over 300 km/h). Analysis of the plot makes it possible to understand the position where the satellite link is unavailable or only attenuated, and the railway operator can thus identify the locations where the infrastructure for the secondary terrestrial link must be installed.

The same measurements enabled the aggregate availability to be defined as a function of the distance from the departing station. The aggregate availability is the ratio between the aggregate distance on which the satellite link is available and the

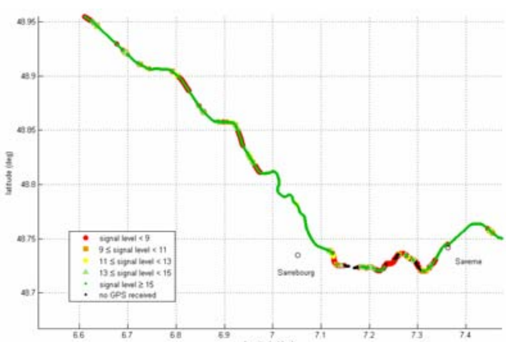

Fig. 4. Coverage representation in a segment of the train path

total distance covered. The computation was performed using the very pessimistic assumption that the satellite link is not available if there is an attenuation of 3.5 dB from the maximum. Furthermore, in the computation, a positive contribution to the aggregate availability is given only if at least two consecutive samplings proved that the satellite link was available. This assumption avoids the possibility of considering in the availability budget any isolated points at which the satellite is visible without this making a real contribution to the availability of the service.

Figure 5 shows the aggregated availability as function of the distance to the station from which the train departed and to which it returned, in a path covering both directions (in the return trip a small deviation has slightly changed the statistics). The numbers in the picture have been inserted to mark the train's passage at the same points. Note, in particular, the strong falling off of the availability between points 2 and 3 due to the presence of a long tunnel which should be equipped with WiFi for the handover purposes.

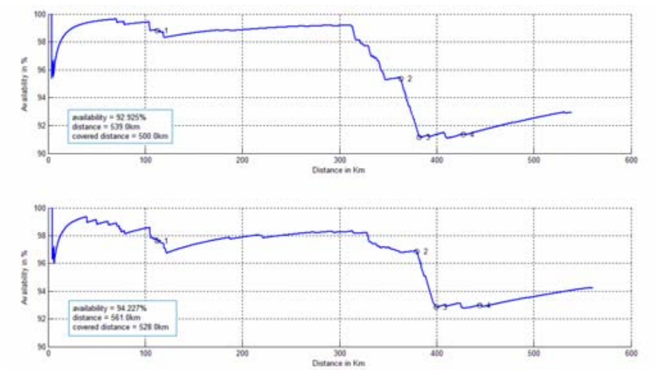

Fig. 5. Availability calculated in the same railway path covered in the two directions

Even though the aggregated availability is similar between the two paths (at the end of the path is between 93% and 94%), certain differences emerge when the two plots are compared. These differences are due to:

a. the path is not identical, because the train runs on varying side of the track (in Italy and France on the left, in Germany on the right) and also because of the effect of the of the obstacles on the degree of fading, which is different as a function of the distance from the train;

b. the speed is not the same in each directions which can have a different impact both on the statistics and on the tracking algorithm of the antenna;

The measurements have been performed on different paths and shows that the availability is strongly dependent on the path (it is not difficult to appreciate that certain regions in the middle of the mountains do not offer an ideal environment for satellite communications). The most recent analysis of the traffic generated on board a number of trains in commercial service, and also the feedback from customers, shows that 90% availability (and it was the case above described) is enough to make the service effective.

6 Conclusions and Future Work

Eutelsat is today beginning to deploy and operate one of the first satellite networks for mobile high speed railway communications. During a previous pre-operational phase several problems have been encountered, principally due to the extremely severe working conditions imposed by the railway environment, and certain elements have required further improvement. The positive feedbacks from customers and the results of the measurements of link availability prove that satellite is a promising solution and several activities must be planned for the future.

The first obstacle to be overcome in the future evolution of the technology is the reduction in the size of the antennas for installation on double-deckers trains (where the space on the roof is significantly reduced). Flat array antennas and the Ka band seem to be the most attractive solutions, even if a lot of work is necessary order to adapt these technologies to the railway domain.

Other targets will be the usage of new generation satellites, in particular in Ka band, with cellular coverage. In this case, both antennas and modems will have to include algorithms capable to hand-over from one foot-print to the other (as already described by the current DVB-RCS+M standard).

References

[1] Draft ETSI EN 302 448 V0.18.2 - Satellite Earth Stations and Systems (SES); Harmonized EN for satellite Earth Stations on Trains (ESTs) operating in the 11/12/14 GHz frequency bands allocated to the Fixed Satellite Service (FSS) covering essential requirements under article 3.2 of the R&TTE directive (November 2005)

[2] Miller, M.J., Dankberg, M.D., Pateros, C.N.: Method and apparatus for multiple access over a communication channel, International Patent. Publication Nr. WO 01/13534 A1, S. Francisco, CA (2000)

[3] Pateros, C.N.: Novel direct sequence spread spectrum multiple access technique. In: 21st Century Military Communications Conference Proceedings, MILCOM 2000, vol. 1, pp. 564–568 (2000)

[4] Paired Carrier Multiple Access for Satellite Communications, Mark Dankberg. In: Proceedings of Pacific Telecommunications Conference (January 1998)

[5] ETSI EN 301 790, DVB - Interaction Channel for Satellite Distribution Systems