MANAGING ‘TRAIN-TO-EARTH’ HEAVY COMMUNICATIONS:

A Middleware Software to Manage Broadband Wireless Comunications in the Railway Scope

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Abstract: This paper describes the work done during the last 3 years in the field of wireless communications for the railway industry. Specifically illustrates the strategy followed for the management of broadband wireless communications in a hybrid network (mobile/radio). This management allows the optimization of both bandwidth and transmission rate of the applications deployed in the ground control stations (terrestrial applications) and on-board systems (train applications). It also describes the general aspects of a ‘train-to-earth’ communications architecture, which allows an easy and standard integration of applications and services both new and legacy.

1 INTRODUCTION

For many years the aim in the railway industry has been to ensure the safety of people and trains and to meet schedules, in other words, to ensure the railway service under secure conditions (Smith, J., Russell, S., and Looi, M., 2003). Nowadays, safety is a priority too, but new requirements have arisen, mainly concerning the quality improvement of the transport service provided to the passengers (Aguado, M. et al., 2005). Moreover, the current European railway regulation by establishing that railway services be managed by railway operators independent of railway infrastructure managers makes it necessary for infrastructure fixed elements to share information with mobile elements or trains (handled by railway operators). This new policy results in additional requirements on the exchange of information between different companies. How to fulfil these requirements is a new technological challenge in terms of railway communications (Shafiullah, G., Gyasi-Agyei, A. and Wolfs, P.J., 2007) that we describe in this paper.

This paper is the result of 3 years of work alongside train manufacturers, railway technology providers and railway operators. During this time we have been working in the definition of standard and interoperable wireless communications architecture for ‘*train-to-earth*’ communications. This new architecture will allow the deployment of new services that improve railway operators and infrastructure manager’s work, as well as passenger’s comfort.

The paper is organized into the following sections: the second section includes a brief description of the ‘*train-to-earth*’ communications architecture defined. The third section is the core of this paper and describes the management of wireless broadband communications. The fourth section presents the results of a real deployment. To close, the fifth section of the paper establishes the main conclusions of this work and the following steps to integrate our technological advances in the manufacture of process a new train.

2 'TRAIN-TO-EARTH' COMMUNICATIONS ARCHITECTURE

In this section we describe the core components of the Wireless Communications architecture that we have developed. This architecture allows a full-duplex transmission of information between applications and devices deployed in the trains, and applications that are in the ground control stations (Salaberria, I., Carballedo, R., Gutierrez, U., Perallos, A., 2009). The description of the architecture will be made at two levels: Conceptual and Physical level. The first level defines the basic concepts of the architecture, and the second one illustrates the technologies used to implement the architecture in a real scenario.

2.1 Conceptual Level

From a conceptual point of view, two issues are especially important: the elements that manage architecture's behaviour and the ways that the different applications (terrestrial and on-board) transmit the information.

Our architecture hosts both terrestrial and train-side applications, so in order to manage its behaviour two main entities are defined: *Terrestrial Communication Manager (TCM)* and *On-board Communication Manager (OCM)*. The former manages terrestrial aspects of the architecture and the latter train-side issues. Although the managers have a different physical location, both of them have nearly the same responsibilities:

- Delivery and reception of the information,
- Dynamic train addressing,
- Medium access control,
- Security and Encryption, and
- Communication error management.

For a correct and optimized used of the communication architecture, we have defined two types of transmission. These two types take into account characteristics of both information and communication technologies, such us: the volume and the priority of the information, the existence of coverage, and the cost of the communication. Considering these aspects, we have defined: *Slight* and *Heavy Communications*.

- *Slight Communications*: This type of communication is for the transmission of small volumes of information (few kB.) and with high priority. In general, information that has low latency (milliseconds or a pair of seconds) and needs to be transmitted exactly when it is generated or acquired (for instance, the GNSS location of a train, or a driving order to the train diver).
- *Heavy Communications*: This type of communication is tied to the transmission of large volumes of information (in the order of MB) and with low priority. The importance of this information is not affected by the passage of time, so it doesn't need to be transmitted at the exact time it is generated. The management of this type of transmission is the core of this paper.

2.2 Physical Level

In this section we describe the technological aspects of the proposed architecture. These aspects refer to the protocols and the communication technologies used for the development of the new architecture. Figure 1 shows the basic protocols and communication technologies used in the proposed architecture.

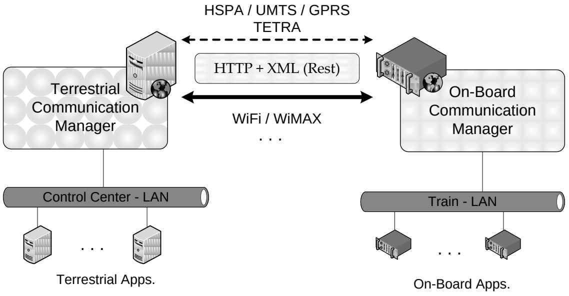

Figure 1: Wireless communications architecture

It is important to point out that the protocols and technologies for the development of the new architecture have been selected with regard to: standardization, robustness, security, scalability and compatibility with existing and potential applications and systems. The major aim has been the ease of integration of any application or system into the new communication architecture.

In accordance to this, Web Services constitute the transport technology for the communication between final applications and the "local" Communication Managers. All the information is interchanged in XML format, in order to allow future extensions.

On the other hand, the communication between the *Terrestrial* and the *On-board Communication Managers* is based on REST (Representational State Transfer) technology. This communication technology uses the HTTP (HyperText Transfer Protocol) protocol and XML formatted messages. This solution is similar to traditional XML Web Services but with the benefit of a low overload and computational resources consumption. Although the information interchanged between the *Terrestrial* and the *On-Board Communication Managers* is encrypted, using the HTTP protocol allows the easy migration to HTTPS (HyperText Transfer Protocol Secure) that offers encryption and secure identification.

It can be said that the selected technologies are well known and broadly used in different application areas or contexts, but they are novel in the railway '*train-to-earth*' communication field.

In order to establish a Wireless Communications channel between the trains and the Ground Control Centers, mobile and radio technologies have been selected (Yaipairoj, S., Harmantzis, F. and Gunasekaran, V., 2005). In this case, *Slight* and *Heavy* communications use different technologies due to different transmission characteristics.

Movable technologies such as GPRS/UMTS/HSPA (Gatti, A., 2002) are used for the *Slight Communications*. These technologies do not offer a great bandwidth nor a 100% coverage and they have a cost associated to the information transmission. Despite this, these technologies are a good choice for the delivery of high-priority and small sized information. The selection of the specific technology (GPRS/UMST/HSPA) depends on whether the service is provided or not, (by a telecommunications service provider), and the coverage in a specific area.

On the other hand, for the Heavy Communications, WiFi radio technology has been chosen. This technology allows the transmission of large volumes of information, does not have any costs associate to the transmission and its deplyment cost is not very expensive. In this case, a private net of access points is needed. This net does not need to cover the complete train route because the *Heavy Communications* are thought for the transmission of big amounts of information at the end of train service (for example the video recorded by the security cameras).

Although each separate technology can't achieve 100% coverage of the train route, the combination of both comes very close to complete coverage (Pinto, P., Bernardo, L. and Sobral, P., 2004). As the application layer protocols are standard, other radio technologies such as TETRA or WiMAX (Aguado, M., et al., 2008) can easily substitute the ones selected now. These technologies can achieve a 100% coverage and neither one has a transmission cost. However, there are certain limitations such as the cost of deploying a private TETRA network, and the cost and the stage of maturity of the WiMAX technology.

3 HEAVY COMMUNITACIONS MANAGEMENT

With the purpose of providing an innovative broadband communications architecture a number of WiFi networks have been settled in places where the trains are stopped long enough to ensure the discharge of a certain amount of information, this is: some stations and garages. In this way, we can say that the WiFi coverage is not complete, but it is important to say that broadband communications are designed to update large volumes of information, which don't need to take place in real time.

Furthermore, some additional problems have to be solved on this environment. In one hand, it is necessary to find a mechanism to locate the trains because they don't have a known IP address all the time. A dynamic IP assignment is used for every WiFi network so a train obtains a different IP address every time it is connected to a network, and a certain IP address could be assigned to different trains in different moments. On the other hand, there are several applications that want to transmit information to/from the trains at the same time. This implies the existence of a bandwidth monopolization problem. To tackle these problems a *Broadband Communications Manager* has been developed. This manager acts as a referee or moderator between applications and communication chanel.

The Broadband Communications Manager is a system that arbitrates and distributes shifts to communicate terrestrial applications and train systems. This distribution shift is managed on the basis of the state of the train connection to a WiFi network (known at all times) and a system of priorities, which are allocated according to the terrestrial application that wants to communicate with the train.

The function developed in the *Broadband Communications Manager* is given by the problem explained above. The manager needs to maintain a stable fluid communication with the agents who want to manage, so it has been established a communication protocol that is detailed in the next section. The basic functionality of the *Broadband Communications Manager* is:

- Accept connection and disconnection messages from terrestrial applications and trains. Through these messages is known the IP address of each train that arrives at a station and connects to a WiFi network, since in that message is sent that IP address.
- Accept communication requests from terrestrial applications.
- Send communication starting message to terrestrial applications and trains, and receive back another message when the communication is finished.

As important as mantainig the connection between the *Broadband Communications Manager*, trains and *terrestrial* applications, is the fact to determine the distribution of these shifts, ie, which communication request must take place between a train and a terrestrial application at any time. Therefore, the *Broadband Communications Manager* knows at every moment the status of pending and completed communication requests, and its role is to manage which communication request should be conducted on each shift and let them know to the *terrestrial* application and the train affected by that communicacion request. The determination of communication shifts is very relevant because of the limitations imposed by the problem of monopolization of bandwidth, described a few paragraphs earlier. In this way, it has been imposed some constraints such as, in each station can only take one communication at a time, or that a terrestrial application can only communicate with a train at the same time. This constraints have been used during the tests, but will they will be eliminated in the final scenario.

It is important to emphasize that the manager does not set any limitation or condition in the final communication between the *terrestrial* application and the train. The manager's work focuses on defining the time at which this final communication must be carried out, and warns of this fact the *terrestrial* application and the train. It does not define any structure or format of the information being exchanged; it only establishes a mechanism to know the IP address of the destination train (because it is dynamic), and regulates or controls the transmission shifts to prevent the monopoly of the communications channel.

The architecture of *Broadband Communications Manager* is based on XML messages exchange between the manager itself and two types of external entities:*terrestrial* applications and trains.

3.1 Communication Protocol

When the *Broadband Communications Manager* decides to give a shift for a *terrestrial* application and a train to begin a communication, it sends an authorization to each part so that it is carried out. To do this, the manager establishes a communication with the application and train’s Communications Manager through TCP Sockets. Within these, a series of messages in XML format that act as communication protocol, are defined.

To explain in a simple way the operation of the *Broadband Communications Manager*, here is a representation of a typical scenario:

- Firstly, a terrestrial application designed to communicate remotely with a train application is connected to the Manager through a TCP Socket.
- The *terrestrial* application will make a request for communication, and will give it a certain priority. By the time the manager receives the request, it orders the request in the queue of the train’s requests. The manager, on receiving the request, orders the queue of pending requests for the train.
- When a train arrives at a station, it connects to the WiFi network and gets a new IP address. This IP address is supplied by the *On-Borad Communications Manager* to the *Broadband Communications Manager*. If the train has pending requests, the *terrestrial* application and the train are notified so that they can start the communication.
- At this moment there is a direct communication between the *terrestrial* application and the train application, through the WiFi network. The responsibility for initiating the communication relies on the *terrestrial* application because it is always connected and now it knows the IP address of the train.

When the communication ends, the *terrestrial* application informs the *Broadband Communications Manager* of that, and them a new request can be served.

3.2 Software architecture

The *Broadband Communications Manager* is divided into 5 modules that handle processing and deployment of all the functionality that has been developed.

To have a global vision of the performance of the manager, we focus on two modules which develop the most important functionality: *Connetions Handler* (*terrestrial* and trains), and *Requests Manager*.

3.2.1 Connections Manager

The main task of the *Connections Handler* module lies in implementing the communication protocol described above. To this end, and bearing in mind that it is necessary to manage two types of external agents such as *terrestrial* applications and trains, the *Connections Handler* has been developed in two separate sub modules that handle communication with each one of external agents mentioned. The following describes these modules.

Application Connections Handler is responsible for managing all the XML messages exchanged between each terrestrial applications and the *Broadband Communications Manager*. Basic functionality is to receive the XML messages coming from *terrestrial* applications and generate an appropriate response. This communication is bidirectional, and it is responsibility of the terrestrial extreme to start and finish it.

Train Connections Handler is responsible for managing all the XML messages exchanged between the communication module of each train and the *Broadband Communications Manager*. This manager works like the module described in the previous paragraph. In this case, the primary goal of this handler is to indicate when a train is connected to a WiFi network and what is its IP address. This data is very important for *terrestrial* applications to communicate with train applications. Other basic functionality is setting a connection with the train, and sending XML messages to open and close a communicacition ports so that a terrestrial application can communicate with the train only through a specific one (this is very important in order to guarantee the privacy and the security of the information transmited).

There is a very important task that train communications module manages, the disconnection or closure of communication between trains and the *Broadband Communications Manager*. Related to this, two different scenarios can occur: in the first one, a train that is connected to a WiFi network and has established a communication with the *Broadband Communications Manager* has no pending requests. In this case, the manager sends an ending request message to the train and then, the train diconects from the WiFi network. In the second scenario, a train is disconnected from the WiFi network because of its movement or a connection error. In this second case the manager checks at every moment if the connection with the train is alive. There is a big problem when the fails in the middle of a transmission between the *terrestrial* application and the train, because the request of this communication has not been completed correctly. To solve this, the next time that the train connects to the *Broadband Communications Manager*; it sends back a start message of the broken communication to the *terrestrial* application and a opening port message to the train.

To carry out its work, *Connections Handler* must establish connections with multiple *terrestrial* applications and trains at the same time. To manage all these communications efficiently, it has been chosen multithreaded design for managing the connections between *Broadband Communications Manager*, terrestrial applicacions and trains. With this desing, every connection is carried out independently and concurrently, using a dedicated thread in each case.

Both the *Train* and *Application Connections Handlers* are also separate threads that are responsible for receiving connections from external agents. When a connection XML message is received, a separate and dedicated thread is created to handle all the messages interchanged between the *Broadband Communicaciones Manager* and any *terrestrial* application or train.

As it was explained above, all the communications are done through a TCP sockets architecture and XML messages exchange. A message will be defined for each requests/responses exchanged between the three elements that form the architecture: *terrestrial* applications, trains and *Broadband Communications Manager*. A sample XML message is listed below:

```
<request>
  <app name="CTV" ip="130.88.10.5"/>
  <train name="UT204"/>
  <port num="3556" priority="1"/>
</request>
```

This message represent a request of transmission between a terrestrial application called *CTV* and a train called *UT204*. In this message we can also see the priority of the request and the communication port number throught the final communication will take place

The choice of the TCP Socket schema and XML messages was taken due to the simplicity of the solution, the flexibility for expansion and addition of functionality, and the ease of implementation (independent of platform and programming language).

Moreover, all the data handled by the *Broadband Communications Manager* are stored in a relational database. These data contains information about the communication requests, trains, *terrestrial* applications, and the available communication ports between them. The *Broadband Communications Manager*'s design contains a data layer that abstracts the data source of the business layer, so that the change of this data source would not create any compatibility problem hibernate persistence framework.

To finish the description of the *Connections Handler*, we would like to make a brief introduction on the management of the applications installed on the trains, which are the target of communication from *terrestrial* applications. These on-board applications are implemented on a system that will have a private IP address (within the Ethernet network loaded) and is not accessible from outside the on-board local area network. Therefore, it has been defined an addressing scheme to allow access from a terrestrial application to the IP address of the on-board applications. This is achieved through PAT filtering. This filtering schema links a private IP address to a communication port number. Thus, whenever a train acquires an IP address from a WiFi network, a port number becomes the way to access the private IP addresses of the on-board applications.

There is a Communications Module on each train which is the responsible for performing this filtering of port numbers to IP addresses. This module is also responsible for communicating directly with *Broadband Communications Manager*, and manages the opening and closing of the ports that are associated with IP address of the boarded applications.

3.2.2 Requests Manager

If one of the most important aspects that the *Broadband Communications Manager* should handle is the communication with *terrestrial* applications and trains, the other one is to select the time at which these applications must carry out the communication with the trains.

For this purpose it has been developed an independent module called *Requests Manager* that in charge of managing communication requests between *terrestrial* applications and trains, and checking when and under what circumstances they need to be attended. Thus, it has designed an algorithm for discerning the next request to serve.

As discussed above, the *Broadband Communications Manager* splits communication shifts to *terrestrial* applications based on requests that they have performed. These requests are grouped by train, so the manager handles requests addressed to each train independently. Furthermore, requests are sorted so that stipulates the order in which applications communicate with the trains. The management of requests associated with each train is based on the following criteria: (1) priority, which represents the "urgency" by which a request must be addressed; (2) retries, it is taken into account the number of attempts to start a communication, to avoid blocking the communication channel by any request errors; and (3) parallelism, the manager can handle communications from multiple applications simultaneously with several trains, with these limitations:

- A train can communicate only with one application at the same time.
- A terrestrial application can communicate only with one train at the same time.
- In a station, it can only be established a single communication at the same time.

The priorities associated with the requests, are managed centrally and *Broadband Communications Manager* assigns these priorities to *terrestrial* applications. In addition, the manager also controls the train applications that can communicate with each single *terrestrial* application, identifying the train communication module ports that can be accesses by each of those *terrestrial* application.

To complete the communication shifts service and management algorithm, it has prepared a final criteria, variable in this case (Noh-sam P., Gil-Haeng, L., 2005). This approach takes into account two factors that are related directly with the communications that have been carried out previously. (1) The first factor is based on the calculation of average duration that takes the communications of a particular application. (2) The second factor takes into account the average duration of trains stopping in a particular station. Thus, the manager calculates a numeric value that represents the fitness of serving a request, knowing that the lower average duration of both factors will be most appropriate, since the risk of communication to be split because the train leaves the station will be less. Once calculated this criteria, it is used to discern which communication request is served, if the criteria explained a few paragraphs above is not sufficient.

4 TESTING AND RESULTS

The *Broadband Communications Manager* is currently being tested out-side a laboratory within the infrastructure of a railway opeator in the north of Spain. These tests are carried out within the maintenance installations of the company, using a new generation of train equipped with the necessary technology to communicate with the communications architecture described below.

Broadband Communications Manager has been deployed on a dedicated server for its work, and is located in a local area network designed to communicate it with different terrestrial applications. Today we can find two of these services: Closed-circuit television (CCTV), and a remote monitoring and document updating tool.

In the case of the train, it has been installed a WiFi network in a garage station which can connect the *Communications Module* of the train. Thus, it can be tested in a direct way one of the basic action scenarios of the *Broadband Communications Manager*: the communication between terrestrial applications and the train when it is in the garage. At this place a train is stopped for hours, so it is a good place to tranmit big amounts of information such as video images from the CCTV system.

At first, *Broadband Communications Manager* was tested in devising single communications between train and CCTV application. But to prove the performance improvement of the available bandwidth use, it has been necessary to include other terrestrial applications such as the document updating tool, and two other fictitious applications that simulate communications with the train. These simulators have been developed for testing purposes that are closer to actual usage scenarios.

The performance tests have been taken into account two key parameters: ‘*train-to-earth*’ data transfer time average; and average waiting time between each communication. The Table 1 shows the results obtained in the management of communications between four terrestrial applications (with different volume of data) and a train at the same station without the *Broadband Communications Manager*, while the second table shows the same scenario with the *Broadband Communications Manager*:

Table 1: Results without the Broadband Communications Manager

Volume data (MB)	Average time data transfer (seconds)	Average waiting time (seconds)
< 1	1.10	0
1-10	11.30	0
11-50	58.84	0
51-100	184.62	0

In the first table we can see that the absence of a communications manager allows communications to be made in parallel sharing the bandwidth. This greatly slows down the transfer rate, increasing the transfer time exponentially as the amount of the data transferred increased.

Table 2: Results with the Broadband Communications Manager

Volume data (MB)	Average time data transfer (seconds)	Average waiting time (seconds)
< 1	0.76	0
1-10	7.69	0.76
11-50	38.46	8.45
51-100	115.38	46.91

The second table shows how communications are conducted in order from smallest to largest amount of data transferred thanks to the algorithm developed for the request communication service. The average time of transfer is lower than in Table 1, and the fact that communications are conducted *one-by-one* implies that there is a timeout that does not exist if they were carried out all at same time. At the conclusion of the tests it was determined that communications are carried out about 30% faster with the *Broadband Communications Manager* than without it, although there are wait times.

New tests are planned in the coming months with the train making a journey through a series of stations where WiFi networks are deployed. This will test the other *Broadband Communications Manager’s* application scenario: a train arriving at a station, connecting to the Broadband Communications Manager through the WiFi, and losing that connection in the middle of a communication because the station has been abandoned by the train. In this case we hope to obtain the same good results that we have simulated in our laboratory.

Finally, it remains tests with multiple trains simultaneously, a fact that is for the last stage of the testing phase. Note that tests performed so far have been successful, solving either quickly and effectively the problems encountered.

5 CONCLUSIONS

This paper is the result of 3 years of work alongside train manufacturers, railway technology providers and railway operators. The work presented here attempts to illustrate how we have solved the problem of bandwidth management in wireless broadband communications. We have defined a new system that distributes communication shifts between different terrestrial applications and train systems that requires the exchange of large amounts of information.

At present, both the wireless communications architecture as the Broadband Communications Manager is being incorporated into the manufacturing process of a new train, which is a European-wide revolution since it enables direct and wireless communication between terrestrial and train-side applications. This technological improvement opens a new scenario in the railway industry because new systems and applications may arise in a short time.

In the coming months, our team will focus on the optimization of the wireless broadband communications management by increasing the number of trains and applications involved on it, and the definition of new services to facilitate the development and deployment of applications on the architecture presented.

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