FAST RADIO TECHNOLOGIES FOR UNINTERRUPTED TRAIN
TO TRACKSIDE COMMUNICATIONS

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FAST-TRACKS wireless network architecture

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Abstract

FAST-TRACKS aims at defining an end-to-end network architecture that offers a novel control and management framework for train to wayside communication. This framework, enhancing data transfer of vital and non-vital informations, is dedicated to Radio Network and Information Technology within the railway metro infrastructure. In this context, this document aims at defining and clarifying the basic architecture as support to the definition of the functional and non-functional requirements.

The goal of this report is also to create a fundamental base for the other work packages and Deliverables. It will clarify a high-level view of the FAST-TRACKS architecture with the description of hardware, software and protocols in close cooperation with WP2 and WP3. These scenarios are also the fundamental base to identify and evaluate potential novel business models in FAST-TRACKS.

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1 Introduction

Nowadays, the introduction of Telecommunication Network within the railway environment have created an increasing need to implements vanguard and innovative products to support requests throughput and high data rate communications. However, the wireless coverage of the existing railway technological infrastructure does not ensure full operational standards, capacity and robustness required for a large-scale use in support of the railway signaling. The different existing solutions on the market are "general purpose" solutions, not specifically developed for the railway market, made by static and not redundant architecture for only indoor or outdoor functioning, with difficulty to adapt to the needs of mobility and the dynamics of a complex rail system.

Urban transport authorities have also deployed various specialized, and often proprietary, wireless systems: there are usually a system for signaling and control in unlicensed bands and another system for operational voice. Nevertheless, these systems are difficult to integrate and they are limited in terms of their data capabilities. This therefore significantly limits the possibility to enhance the operational efficiency, passenger security and quality of transport.

FAST-TRACKS project is a disruptive innovation based on the development of a low cost re-programmable radio infrastructure that implements simultaneously different radio propagation standard allowing efficient planning of the network, redundancy techniques, automatic-adaptive reconfiguration, able to support the constrained requirements of the railway telecommunications. The proposed telecommunication infrastructure permits to support both vital and not vital data on separate networks and independent radios.

This technique allows the increase of the life time of the hardware (both of the radio base station that the user terminal) removing the risk of obsolescence; the re-programmability of the radio allows also the reuse of the hardware in case of new services or new generation systems will make their entry into the field, thus reducing OPEX and CAPEX.

The deliverable is organized as follows: in Section 2, we briefly present the scenario of the train to ground communication, showing the existing and next generation solutions. In Section 3, the reference architecture of the FAST-TRACK project is presented. The section 4 concludes the document, presenting the technologies and the protocols to develop high-performance wireless communication systems. This section opens to the definition of the functional and non-functional requirements treated in the D1.2.

The following member organizations have allocated manpower in Task T.1.1:

ID	Short Name	Full Partner Name
1	COM	Comesvil

Table 1: Member organizations in Task T.1.1

2 FAST-TRACKS scenario: the train to ground communications

In a context of deregulation, train to ground communications is becoming a key component in the strategy of railway operators and infrastructure managers, since it has been realized that it can bring significant cost savings and a better operational efficiency, in particular in the following domains:

- Operation of the transportation system, as example for driverless vehicles
- Safety and security during the passenger's journey
- Data collection and streaming, supporting CCTV and VoIP
- Passenger experience, improving travel comfort, such as internet on the train

Telecommunications also contribute to the brand image of transport operators and in some cases even add to revenue.

Both fixed and mobile communication networks are part of these missions. A secured, robust, reliable and converged telecommunications network is therefore essential to support different information exchanges, whether man-to-man, man-to-machine or machine-to-machine. This helps transport operators to fulfil their mission while keeping the highest level of global security and increasing passenger satisfaction (through outstanding punctuality and more services).

Rail operators are not only going to compete against each other but also with other means of transportation, such as planes or cars, and in this context offering more comfort and entertainment to passengers is not an option.

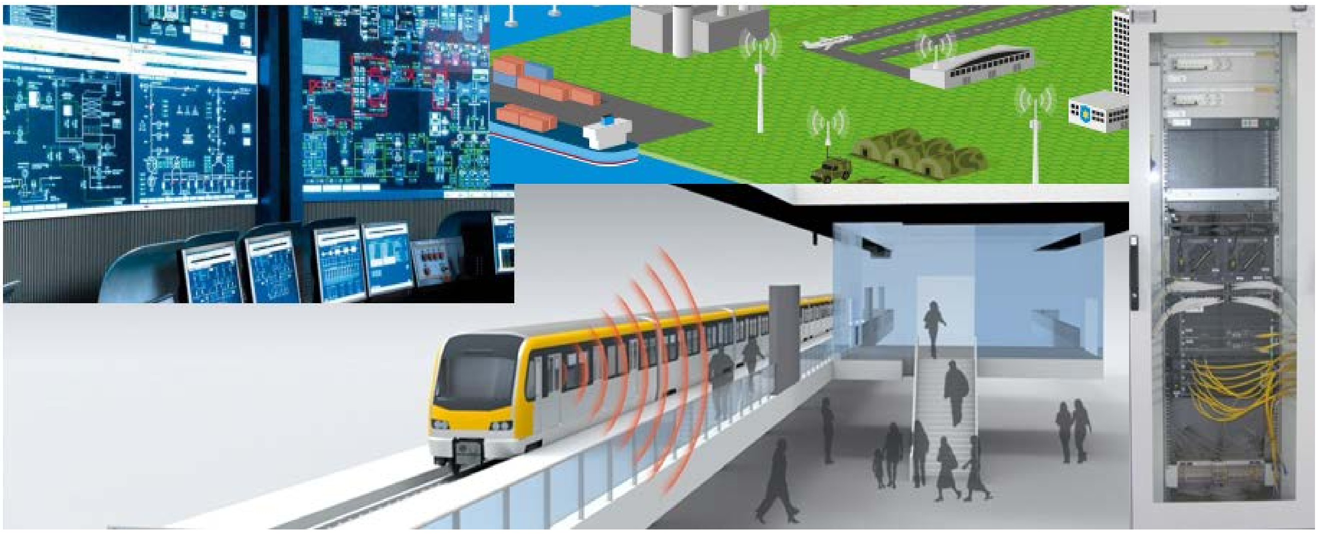


Figure 1: The FAST-TRACKS scenario

Amongst the different applications to be carried by the telecom network, in the FAST-TRACKS scenario we can distinguish two main families with very different constraints and specifications:

Vital Applications related to signalling and control/command of equipment. Such applications require generally a low bandwidth (some 10 to 100 kbps) but a very high degree of availability (at least 99.99%), robustness and liability (typically a packet error rate of 10-3 for an approximately 200 byte packet length). Such performance indicators have equally to be fulfilled under high speed mobility (handover timing when a mobile terminal must change its connexion from one fixed base station to another). These vital applications are typically CBTC (Communication Based Train Control) in case of metros or ETCS/ERTMS (European Train Control System) in case of mainline trains.

Non-vital applications related to Passenger Information, remote maintenance, on-board video surveillance (CCTV) for track or platform monitoring, internet access, etc. Such non-vital applications generally require much higher bandwidth (several 10s of Mbits/s in both direction train-to-ground and ground-to-train), together with lesser robustness constraints (a packet error rate of 10-2 for an approximately 1Mbyte packet length).

2.1 Legacy Train-To-Ground communication solutions

A moving vehicle cannot obviously be connected to ground based infrastructure by any other mean than radio communication. Such radio systems have long been based on analogue technology, dedicated to voice and not adapted to carry data. Then digital technology became available in the market, with various bandwidth capabilities and distance ranges, supplied to different standards or even totally proprietary protocols. Rail operators have implemented such technologies alongside their track and inside their vehicles, but without necessarily being interoperable, or with specific adaptation to match vital application requirements. Consequently, related CAPEX and OPEX (with high maintenance costs and rapid obsolescence) are desperately increasing, whilst non-optimized use of scarce radio spectrum is being seen, particularly in urban areas. It is quite common to see operators deploying several radios with different purposes in the same rail network and geographical area: IEEE 802.11a/b/g/n WiFi [1] as support of DCS/CBTC [2][3], GSM-R [4] as support of ETCS/ERTMS [5], ETSI TETRA [6] as support of PMR [7].

2.1.1 The Data Communication System (DCS)

The Data Communication System provides the communication between trains and ground, in a railway metro scenario, by means of a wireless access. In particular DCS carries CBTC signaling information and other telecommunication services on board, like CCTV. The DCS Network is a fully redundant broadband communications system that guarantees for a bi-directional, reliable, and secured exchange of data between equipment of the train control subsystems (e.g. Zone Controllers, Interlocking and the Carborne Controllers). An architectural and logic overview is shown in the next figure:

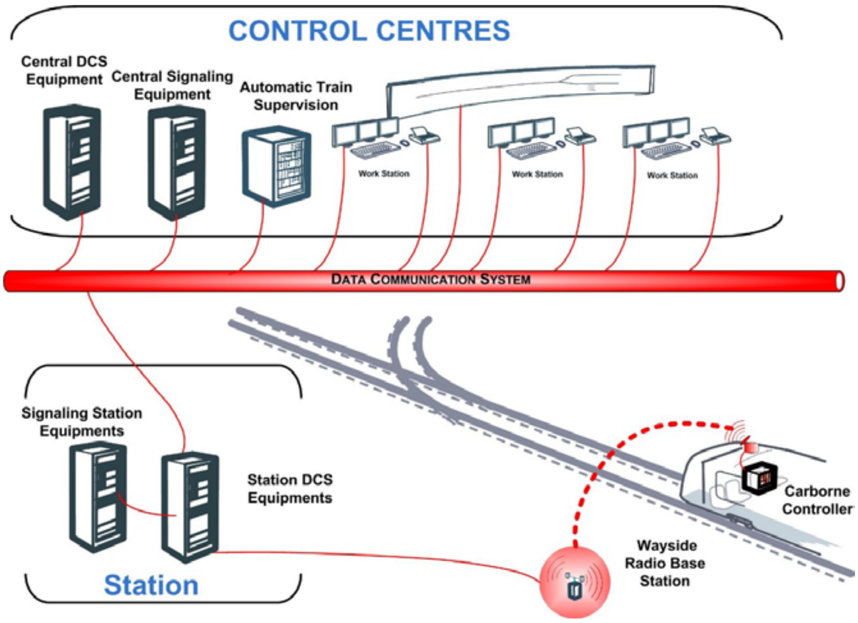


Figure 2: DCS architectural and logic overview

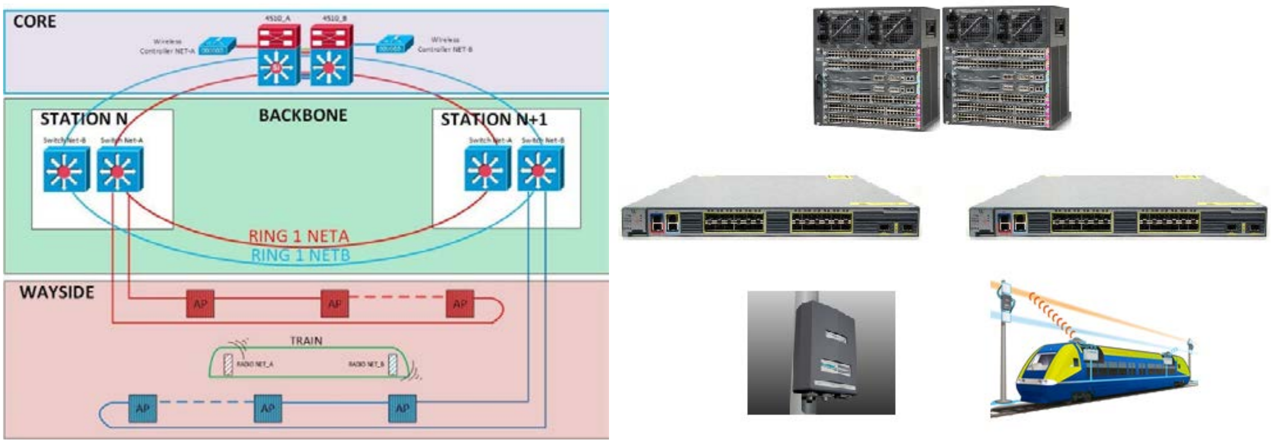


Figure 3: DCS simplified architecture

The Data Communication System (DCS) is a multiservice radio network infrastructure conceived to support vital and non-vital data communication in railway and industrial environment, such as Communication Based Train Control (CBTC). The DCS Network consists of four main networks aggregated as shown in the above figure:

- **The Core Network (CN)** conceived to enable the connection and the management of the entire network infrastructure. It is located in the control center area, subdivided in Operation Control Center and Emergency Control Center (OCC/ECC), and connected with signalling system.
- **The Backbone Network (BN)** allows the connection between the Core Network and the Wayside network (train stations).
- **The Wayside Network (WN)** implements an uninterrupted, high speed and reliable communication between moving train and the radio base station installed on trackside. It's combine different Wi-Fi technologies such as IEEE 802.11a,b,g,n and ac.
- **The Train Network (TN)** implements the onboard Ethernet network, including the wireless radio equipment.

The network architecture and the relative performances are designed to guarantee the required network security, reliability, availability and maintainability. For redundancy reason, each of DCS Networks is duplicated and independent. The Wayside Network, Backbone Network and Train Network are organized in two independent neworks: Network A (generally represented in red) and Network B (in blue). Central Network collects data from both of Network A and B.

2.1.1.1 *The Central Network*

The Central Network is designed to provide the connection of vital services (i.e. CBTC signaling) and non-vital services (i.e. CCTV) collecting the traffic generated by the clients connected via the access network. It consists of a couple of Layer 3 redundant switches located respectively in Operational Control Center (OCC) and Emergency Control Center (ECC). Each switch contains all the needed modules and manages both the backbone networks. In case of fault of one of these switches, the backbone rings re-converge and continue to work through the neighbor switches, in order to guarantee the network connectivity. The connection between the two switches is also guaranteed through a fiber optical connection link. The Central Network is connected to two independent Backbone Networks (BN-A represented in red and BN-B represented in blue); each of them is closed on the paired Layer 3 switches as reported in the figure below. Each Layer 3 Switch at OCC is generally equipped with the following active devices:

- Modules with 10/100/1000 copper Ethernet ports for connectivity to other systems
- Transceiver based on Giga Ethernet ports (SFP)
- Redundant power supply
- Management system and supervisors.

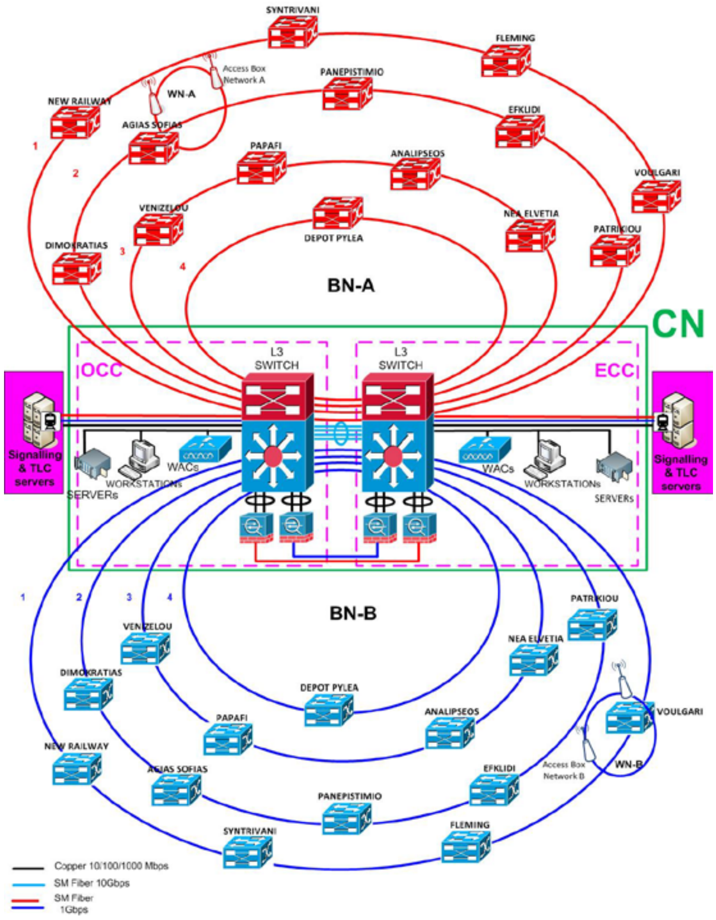


Figure 4: Central Network topology

In each control center there are also one or more network controllers, needed to manage the wireless network, named Wireless Access Controller (WAC). Usually there are a set of WACs, half of them dedicated to the BN-A and the other half dedicated to BN-B, in a redundant configuration. To enhance the cybersecurity the network integrates also firewalls. These firewalls inspect the traffic that cross the network, and permits to circulate only the traffic indicate as allowed. The center is finally completed with a set of Network Time Protocol (NTP) Server for network synchronization, a set of redundant Radius Server for Authentication and Accounting, a set of redundant Element Management Server, and finally a set of redundant Network Management Server, equipped with maintenance workstation.

2.1.1.2 *The Backbone Network*

The Backbone Network is designed to carry the access data traffic to the Central Network. In particular it allows the data communication via the Wayside Access Box (WAB), providing wireless connection to the trains and the data communication between Central Network and distributed CBTC devices installations (such as Zone Controllers). The backbone network uses 24 of 48 single mode fiber optic cable, belonging to telecommunication system. In details, 12 fibers are used for Network A and 12 fibers are used for network B. In this way, it is possible to realize four different backbone rings for each backbone network.

The Backbone Network uses a ring network topology; this is made to prevent service-interruption and increase the system availability. The ring solution is adopted because of its capability to prevent interruptions and to increase network reliability. It also represents the easiest example of a double connected structure which is capable to make each network node reachable from two distinct paths. This pattern allows the rapid reconfiguration of the network in case of a failure on a single node or on a single link, re-configuring the alternate path transparently.

The proposed model implements two different backbone networks, BN-A (red) and BN-B (blue). In the OCC and ECC are located the central network equipment so this location belongs to all the rings. Each station is equipped with two independent Layer 3 switches (one for Network A – and another one for Network B).

The switches of station belonging to the rings, just mentioned, are connected together by means of single mode optical fiber cable. Each of the rings starts from one of the center switch, and ends on the second center switch, located in OCC and ECC. A Logical Backbone Topology related to a real implementation of the DCS for Salonicco Metro (Greece) is represented in the Figure 5, in which is possible to distinguish between four Rings, thirteen Stations and one Depot:

- **Ring 1:** New Railway, Syntrivani, Fleming, Voulgari stations;
- **Ring 2:** Dimokratias, Agias Sofias, Panepistimio, Efklidi, Patrikiou stations;
- **Ring 3:** Venizelou, Papafi, Analipseos, Nea Elvetia stations;
- **Ring 4:** Depot Pylea.

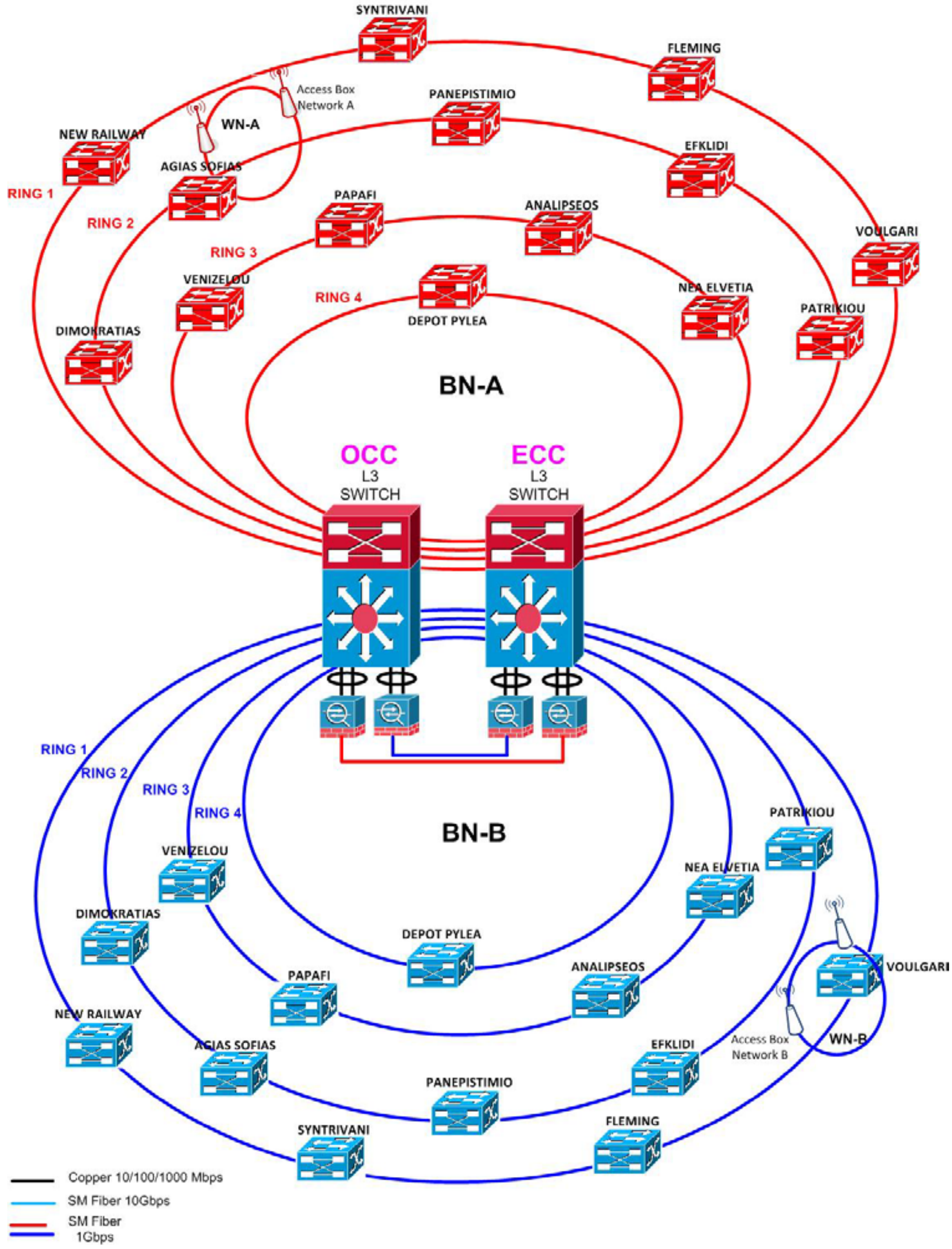


Figure 5: Backbone Network Topology

2.1.1.3 *The WaySide network*

The main purpose of the wayside network (WN), shown in the next figure, is to provide radio coverage along the main line and the depot area, in order to allow data connection between trains and the control centers. The provided radio coverage is based on a cellular distribution of the radiating sources along the trackside. The wayside network realizes the radio coverage along the section between two stations, using two separated groups of Wireless Access Points along the line: WN-A and WN-B. The first group implements the WN-A network and is represented in red; the second group implements the WN-B network and is represented in blue. The two WNs are physically separated. The mentioned physical separation is obtained through the following design pattern:

- Two different service set identifiers (SSID) are used over the radio channel
- Optical cables are separed for each part of the fixed network
- Power supply are separated for wirekess networks (WN-A and WN-B)

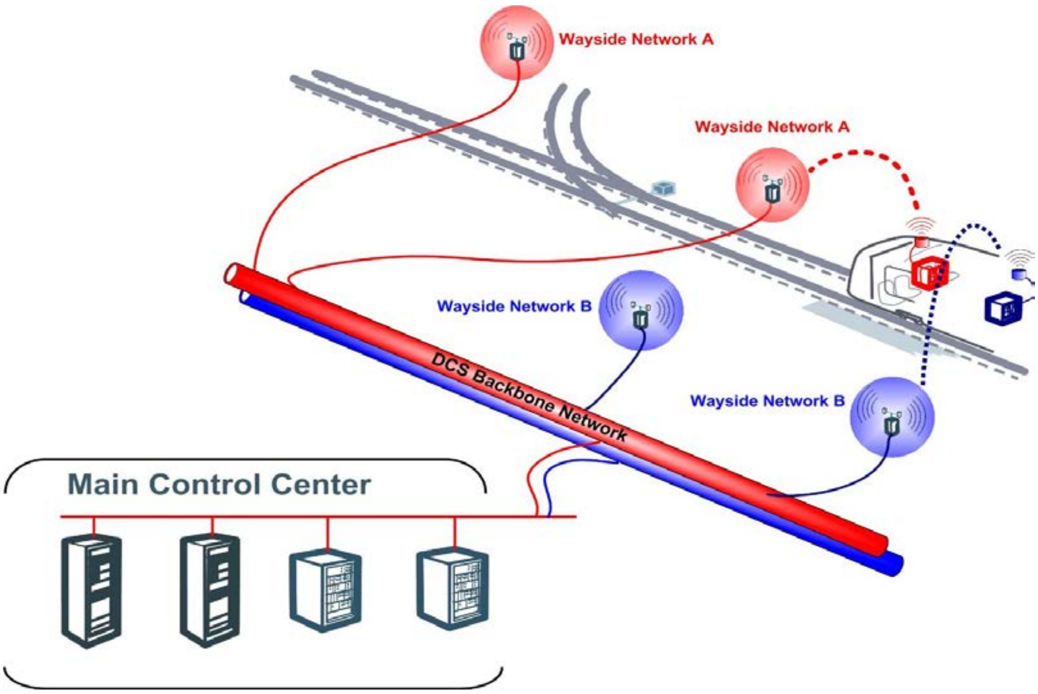


Figure 6: Generic Wayside DCS network

The Wayside Network consists of WABs (each WAB integrates two radio) and the radiating equipment. In each WN, the WABs are connected to the nearest backbone switch station through ring topology with an optical fiber in a redundant configuration. Physically, the connection is realized by means of Single Mode optical fiber. Each WAB provides the switching feature and generate the radio signal compliant to the IEEE 802.11 standard. In details implements:

- VLAN management;
- Fast convergence in case of ring failure;
- Double operative frequency (2.4 and 5.8 GHz);
- Quality of Service

The next figure shows an example of connection between Wayside Network and Backbone Network.

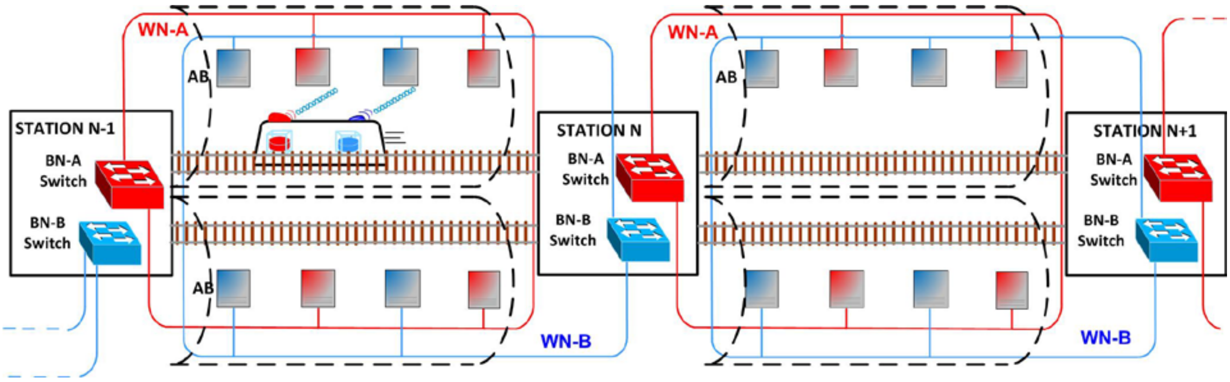


Figure 7: BN to WN connection schema

For each redundant network, a Fiber Optical Single Mode cable is used to connect the WAB with the station switches, as showed in the above figure.

For radio signal propagation on WN there will be used frequencies belonging to the range 2.4 or 5.8 GHz with no overlapping channels for each network. Each channel is used to transmit both CBTC and the CCTV service. QoS will guarantee the CBTC stream against the CCTV one. Depending on possibility to use ITS band and after an accurate radio survey procedure, the channels radio will be chosen. The solution adopted for the realization of the WN involves the use of antennas both along the tracks that on the depot. The requested radio coverage along the tracks is obtained using sequential cells provided by the radio base stations as shown in Figure 8.

The WAB will be installed along the track and will use antennas as transmission media. The antennas will be positioned in the best possible position to maximize the performance of radio coverage. Particularly, the radio coverage of the Tunnel and of the Depot area will be done considering that, in each position of the train, there will be not obstacles that can obstruct the signal radio (for example protuberances of the walls, signals ecc). Particularly, utilizing the MIMO (Multiple input Multiple output) technique as transmission criteria, not is necessary a LOS condition because, this technique, associated with the accurate wifi radiocoverage, guarantee a level of the signal power able to satisfy the throughput requirements as depicted in the next figure.

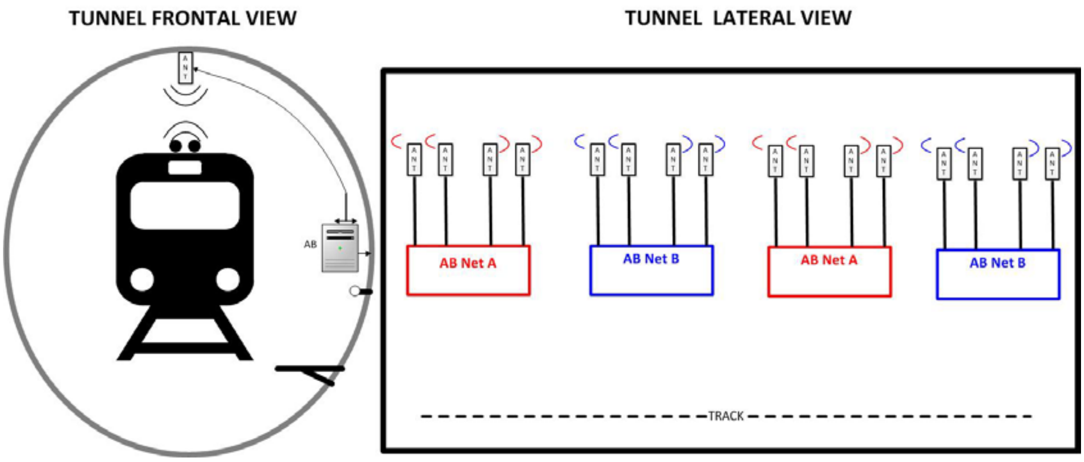


Figure 8: Tunnel ABs Installation with antenna

The radio-propagation in the depot area will provide a solution in antenna, as shown in the next figure:

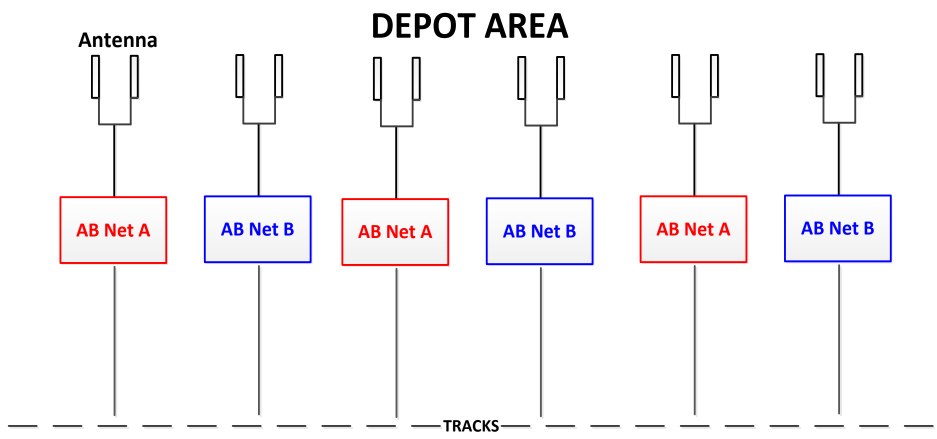


Figure 9: Antenna installation in Depot Area

The radio-propagation in the depot area, will provide a solution in antenna as the same provided in the tunnel. For radio signal propagation on WN there will be used frequencies around 5 GHz. In details, the solution consists in the use of two different channels each one of 40 MHz, in ISM band separated at least 10 MHz. The coverage plan of the wayside is the organized as follows:

- Two different channels of 20 MHz (separated at least 10 MHz) for each network in ITS Mobile band (5855 – 5905 according to the local regulation).
- Two different channels of 40MHz for each network; one in ISM band (for example network A), and one in ITS band (for example network B). The channels separation is guaranteed.

Each channel is used to transmit both CBTC and the CCTV services. QoS will guarantee that CCTV will never affect the stream of CBTC data traffic.

2.1.1.4 *The Train Network*

The on-board train Network consists of two separated networks (TN-A Red network and TN-B blue network), with all equipment duplicated. These Networks exchange data separately with WN-A and WN-B networks, using two separate radio links, one for network A and one for network B. Figure 10 shows the on-board train network architecture.

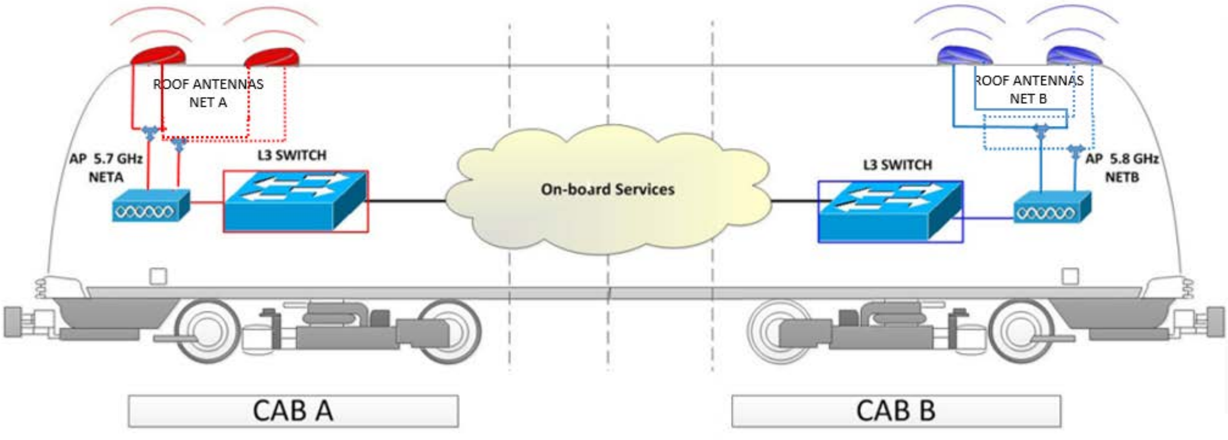


Figure 10: Train Network Architecture

The two on board networks are connected through a double Ethernet cable: this cable is also used for management and diagnostic. Each TN includes a railway Ethernet switch and radio equipment. One radio equipment is connected to the WN-A network, for CBTC and the other services. The other one is connected to the WN-B network. The RF signal is spread through four antennas installed on the top side of the vehicle, two for each side. Each chain of the radio is connected to a dedicated antenna by two different RF cables to enable diversity. CBTC and Services connection share the antenna by means QoS network protocol.

2.1.2 WIFI protocols and devices

The desire to achieve increasingly higher throughput values in order to maximize the quality of the services to customers in the wireless industry, has led over the years to a growing improvement of the IEEE 802.11 standard throughput maximum allowed. Among the most innovative techniques for wireless communication, they have made a strong contribution to the achievement of the current values of throughput, the modulation technique OFDM and MIMO [8] transmission technology. Below we listed the current IEEE 802.11 standards:

Standard	Frequency Band [GHz]	Bandwidth [MHz]	Modulation	Maximum Data Rate
802.11	2.4	20	DSSS, FHSS	2 Mb/s
802.11 b	2.4	20	DSSS	11 Mb/s
802.11 a	5	20	OFDM	54 Mb/s
802.11 g	2.4	20	DSSS, OFDM	54 Mb/s
802.11 n	2.4 GHz, 5GHz	20 MHz, 40MHz	OFDM	600Mbps
802.11 ac	5 GHz	20,40,80,80+80,160 MHz	OFDM	6.93 GB/s

Table 2: IEEE 802.11 standards

2.1.3 GSM-R

Finalized in 2000, based on the European Union-funded MORANE (Mobile Radio for Railways Networks in Europe) project, GSM-R is derived from GSM (2G+) technology and part of the new European Rail Traffic Management System (ERTMS) standard. It carries both signalling information (in case of ETCS L2) and voice communication. Based on GSM, this technology offers:

- Low bandwidth (TDM based, with GPRS packet base expected in the near future)
- Fast handover (specified up to 500 km/h)
- Operating in Frequency band of 2x 4Mhz (one uplink and one downlink) in 800/900 MHz band
- Imbedded voice rail specific features (at application level) such as group, broadcast or emergency calls
- Typical range of 7-15 km between 2 base stations
- Due to its very specific nature and market only a very few number of equipment manufacturers offer this product.

GSM-R will probably be supplanted by LTE-R with the first production implementation being in South Korea. However, LTE is generally considered to be a "4G" protocol, and some railways are considering moving to something "5G" based depending on the timing of their upgrade cycle, thus skipping a technological generation.

2.1.4 TETRA

In Urban areas, train-to-ground communications have initially relied on UHF (Ultra High Frequency) in the 420- 470 MHz band. Professional Mobile Radio (PMR, also known as Private Mobile Radio) and TETRA have had a considerable expansion and success, particularly in Europe, thanks to the development of train-to-ground radio equipment in the 450 MHz band. Initially they were used mainly for voice communication with controllers or shunting function. Then came the development of data communication dedicated to remote control and maintenance of vehicles, and it was natural to connect devices through these radios. However, two major limitations hamper this type of technology:

- Very limited bandwidth
- UHF spectrum is now overloaded and the trend is to go in the upper frequency band in order to increase the number of available communication channels.

Similar Land Mobile Radio system (P25) has been developed in North America by the APCO association and is mainly targeting the Public safety application in the 700 MHz band.

2.1.5 Wireless technology comparison

The selection of an optimal wireless communication system for railways and metros need to consider many performance parameters and service attributes such as voice support, vital traffic, priority, availability, frequency band, commercial maturity. Next table compares these different technologies in term of performance and industrial support.

Technology comparison					
	GSMR	TETRA	P25	WiFi	LTE
Operational voice support	Yes	Yes	Yes	VoIP	VoIP
Broadband data support	< 10kb/s	< 10kb/s	< 100kb/s	> 10Mb/s	> 10Mb/s
All IP (native)	No	No	No	Yes	Yes
Vital traffic support	Yes	Yes	Yes	No	Yes
P2T / call setup time	1 to 5 s	250 ms	800 ms	100 ms	100 ms
Handover mechanisms	Standard	Standard	Standard	Proprietary	Standard
Priorities / pre-emption	Yes	Yes	Yes	3 levels / No	9 levels / Yes
Choice for operating frequency	900 MHz UIC	400 MHz PMR	700 MHz + VHF	2.4/5.x GHz	400 MHz to 3.5 GHz
Market support (vendors)	3 vendors	Yes	Limited (US specific)	Yes	Yes
Maturity	End of Life 2025	Mature	Mature	Widely adopted	Emerging

Table 3: Comparision between the technical specifications of the radio vendor selected

2.2 New generation of Train-To-Ground telecommunications

To reach the necessary safety level Metro line automation projects (driverless metros) demand on-board real- time video surveillance to monitor and assess any critical or abnormal situation inside the coaches, alongside the track or platforms. Non-vital applications contributing to a better passenger comfort and journey experience such as on-board Internet access (passengers are likely not to accept losing connection any longer in the coming years), but also video on demand or other entertainment, will probably soon be must-have application in order to attract or retain customers, as well as contributing to a high level of transport companies brand images. Trains (and more specifically high-speed trains) are more and more considered as a mobile office by many passengers. A survey for the Swedish national operator found that the train journey is widely considered as an integral part of the working day. At the same time, higher comfort is also a key reason for the shift of passengers from airlines to high speed trains. To keep up with this trend and maintain competition with air travel, mainline railways operators need to enhance passenger experience with high-speed Internet access based services across the complete journey (from hospitality rooms in stations to on-board the train), both for professionals to extend their mobile office to the train and also to other passengers for infotainment.

On board and real-time information is also becoming mandatory to train operators: recent delay incidents on some European High-Speed lines can testify of passenger dissatisfaction of being stuck for hours without being informed of the situation.

Technology obsolescence – particularly in the telecommunications domain – is coming fast and often not in line with rail system lifecycle. GSM-R systems are still under deployment today, with the maturity of deployment varying according to countries and networks. However, GSM-R end of life is already a concern for infrastructure managers even though industry has committed to maintain the systems until 2025: the very limited number of GSM-R manufacturers and GSM based technology obsolescence are seen a threat by Railway Infrastructure owners.

Preventive maintenance is a more and more common tool used by railways operator to significantly enhance their operational efficiency. By permanently and remotely monitoring the status of key elements of the rolling stock, maintenance actions can be planned in advance upon detection of warning information before the fault becomes an actual problem. Today, the remote monitoring is usually performed using commercial low speed 2G technologies. Such services are driving the huge increase in bandwidth requirement, and consequently a new generation of train-to-ground transmission will soon have to address these needs, while following telecom industry standards with minimum (or no) rail specific adaption in order to avoid costly solution and rapid obsolescence.

LTE and multitransport radio seems to be the ideal candidate for this next generation of communication that would be able to support such new services, as well as vital applications at the same time.

2.2.1 Long Term Evolution (LTE)

LTE is composed of a core network: Evolved Packet Core (EPC) and an access radio network UMTS Terrestrial Radio Access Network (E-UTRAN). EPC is a native « all IP » based and multi-access network that enables the deployment and operation of a common network for every kind of 3GPP access network (2G, 3G and LTE), and even non 3GPP (WLAN). E-UTRAN LTE is connected to the EPC core network in packet mode. Protocols and user plans have been designed in order to support high bandwidth applications together with realtime constraints, Quality of Service (QOS) and high availability. LTE (Long Term Evolution) is the 4G wireless technology standardized in 2008 by the 3GPP. The main benefits of this technology are:

- LTE is the 4G convergence standard worldwide,
- LTE provides state-of-the art broadband performance,
- LTE provides flexibility of deployment,
- LTE is open, secure, reliable and easy to operate.

Today, the LTE standard is embraced by most wireless service providers across all continents. The two predominant standardization bodies 3GPP and 3GPP2 (standardization body for mobile systems that represent more than 99% of worldwide mobile subscriptions) have selected LTE as the evolution of their current 3G standards. LTE is then the first true convergence standard for mobile communications worldwide and a number of commercial networks are already live and running: in particular Verizon in US has already deployed its 4G network and sold more than 1.4 million LTE compatible terminals. 3GPP has already undertaken definition of next LTE version– called LTE advanced or “release 10”– and that will bring significant improvements:

- Multiple LTE carriers-aggregation in channels of up to 100 MHz and therefore enable a higher bandwidth
- Better radio performance at the cell level to be able to serve more terminals, thanks to MIMO evolution
- Cell coverage extension thanks to low cost radio relays
- Self Optimization Network functions (SON)

2.2.2 LTE FOR RAIL

We have seen several elements driving the demand for the next generation of communication system for Rail, namely:

- New services demanding more bandwidth
- Life duration and anticipated obsolescence of existing systems
- Cost of rail specific systems, both in terms of CAPEX but also in OPEX with high level of maintenance

In this context we can consider LTE as a good candidate for this next generation given the very stringent specificities of rail constraints:

- Network High availability and robustness demanded by signalization and control
- A Quality of Service being able to carry and prioritize both vital and non-vital services
- A bandwidth able to carry very “greedy” application such as video surveillance
- Fast handover between cells compatible with High Speed

- Communication robustness in urban environment

LTE standard therefore offers all needed features of a radio access system to match transport specific needs without specific adaptation. This will avoid developing any “LTE-R” while taking advantage of the huge telecommunications mass-market effect.

A typical LTE architecture for Railway supports vital and non-vital traffics delivered between servers in the OCC (Operation Contol Center) and applications running onboard vehicles. In the fixed infrastructure, the radio system can use either directive antennas or radiating cables to exchange the wireless signals with the Onboard Board Units.

2.2.3 Cognitive Radio and Aggregated multi-transport Radio

A cognitive radio (CR) is a radio that can be programmed and configured dynamically to use the best wireless channels in its vicinity to avoid user interference and congestion. Such a radio automatically detects available channels in wireless spectrum, then accordingly changes its transmission or reception parameters to allow more concurrent wireless communications in a given spectrum band at one location. This process is a form of dynamic spectrum management.

The concept of cognitive radio was first proposed by Joseph Mitola III in a seminar at KTH (the Royal Institute of Technology in Stockholm) in 1998 and published in an article by Mitola and Gerald Q. Maguire, Jr. in 1999. It was a novel approach in wireless communications, which Mitola later described as: “*the point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs*” [9].

Cognitive radio is considered as a goal towards which a software-defined radio platform should evolve: a fully reconfigurable wireless transceiver which automatically adapts its communication parameters to network and user demands. The first cognitive radio wireless regional area network standard, IEEE 802.22, was developed by IEEE 802 LAN/MAN Standard Committee (LMSC) and published in 2011. This standard uses geolocation and spectrum sensing for spectral awareness. Geolocation combines with a database of licensed transmitters in the area to identify available channels for use by the cognitive radio network. Spectrum sensing observes the spectrum and identifies occupied channels. IEEE 802.22 was designed to utilize the unused frequencies or fragments of time in a location. This white space is unused television channels in the geolocated areas. However, cognitive radio cannot occupy the same unused space all the time. As spectrum availability changes, the network adapts to prevent interference with licensed transmissions.

From the management point of view, in response to the operator's commands, the cognitive radio is capable of configuring radio-system parameters. These parameters include "waveform, protocol, operating frequency, and networking". This functions as an autonomous unit in the communications environment, exchanging information about the environment with the networks it accesses and other cognitive radios. A CR "monitors its own performance continuously", in addition to "reading the radio's outputs"; it then uses this information to "determine the RF environment, channel conditions, link performance, etc.", and adjusts the "radio's settings to deliver the required quality of service subject to an appropriate combination of user requirements, operational limitations, and regulatory constraints".

Some "smart radio" proposals combine wireless mesh network—dynamically changing the path messages take between two given nodes using cooperative diversity; cognitive radio—dynamically changing the frequency band used by messages between two consecutive nodes on the path; and software-defined radio—dynamically changing the protocol used by message between two consecutive nodes.

The multiple transport radio instead is an extension of the CR and smart radio concept, conceived to solve specific redundance problems, in the field of the reliable telecommunications. The multiple transport radio includes different modems coupled to the one or more signal formatters for modulating the signals, a frequency converter coupled to the modem for upconverting the signals having been modulated to a radio frequency, and a transceiver unit coupled to the frequency converter for transmitting the signals having been upconverted over a radio communications link. This architecture, in order to utilize multiple transports, devices must discover common mechanisms for communication and a procedure for signal discovery.

3 The FAST-TRACKS reference architecture

FAST-TRACKS specifies and implements a novel wireless architecture able to seamlessly and efficiently support train-to-ground communications. This new FAST-TRACKS vision is based on partitioning and composing the underlying wireless network to create mesh and centralized redundant links, on fly. Each link will be controlled by a Radio Control Plane (RCP) capable of control end-to-end network connectivity services in an on-demand basis. Thus, FAST-TRACKS architecture presents a layered approach to separate the different functions that integrates the overall framework. Next figure shows the reference model for the high-level FAST-TRACKS architecture, in which the reader can distinguish the following components: The Mobile Communication Plane (MCP), the Fixed Communication Plane (FCP), the Radio Control Plane (RCP), and the Radio Monitoring Plane (RMP).

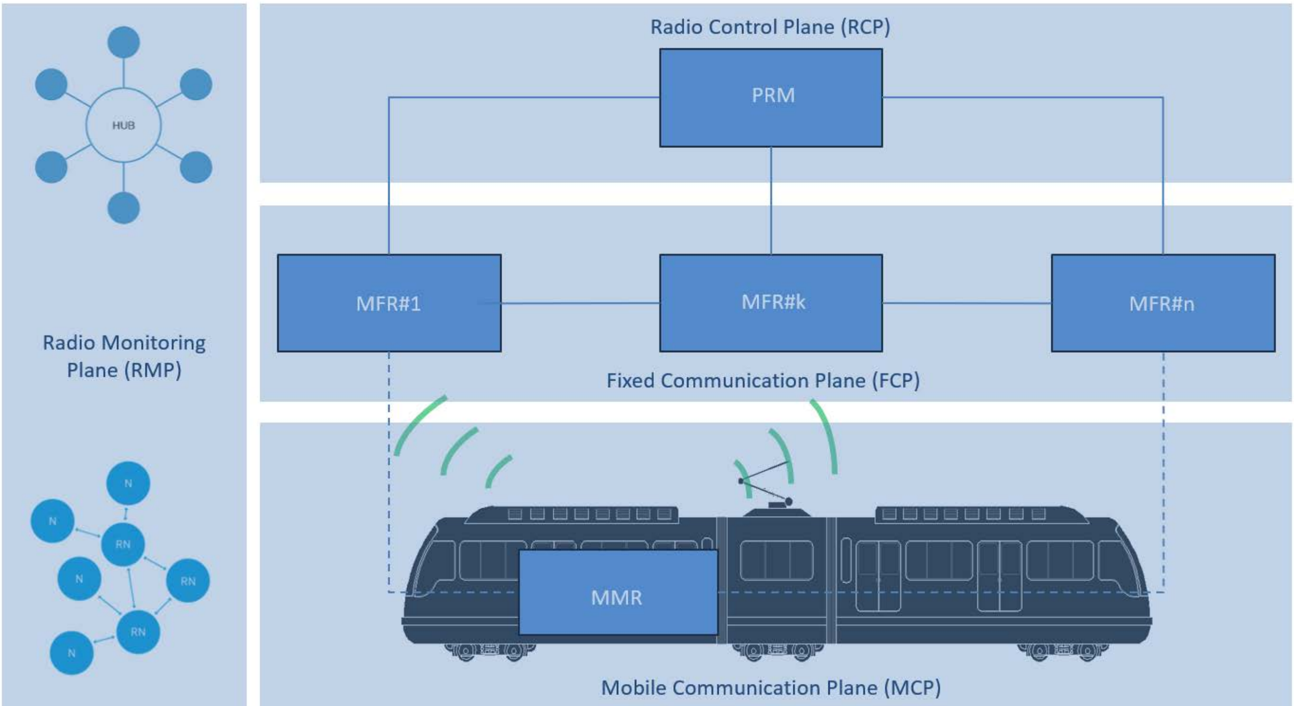


Figure 11: Reference model for FAST-TRACKS high-level architecture

MCP is a novel Multi-Transport Radio Architecture for the transmission over the air of vital and non-vital data between train and wayside. This layer comprises hardware, firmware and software and involves mainly the train side of the network infrastructure (mobile radio).

FCP provides a novel Cognitive Radio Architecture based on SDR for the bidirectional transmission over the air of vital and non-vital data to the train. This layer comprises hardware, firmware and software and involves a plurality of fixed radio installed on the wayside.

RCP provides coordinated, on-demand and seamless control of the wireless network, conceived to manage in efficient way the Multi Transport Radio. This layer, based on Software Defined Networks, comprises hardware, firmware and software implementing protocols to connect radio dynamically, using both mesh and hub-spoke configurable patterns, to provide advanced transport services coupled with IT services.

RMP is the infrastructure responsible for the realtime collection, management and monitoring of the wireless network data and parameters by means of resource abstraction and partitioning.

The scope of FAST-TRACKS architecture is focused in the functional definition and description of the first three mentioned layers, the RCP, the FCP, the and the MCP, which forms the core of FAST-TRACKS innovation. The **RMP** is part of the architecture but is mainly adapted or extended from existing developments.

Each layer is composed by a plurality of programmable radio. In details:

- The **Modular Mobile Radio** (MMR), part of the MCP, is the programmable radio based on Mutli-Transport Architecture, conceived to be installed on mobile systems (i.e. train, bus, boat, etc..).
- The **Modular Fixed Radio** (MFR), part of the RSL, is the programmable radio conceived to be installed on the fixed side (i.e. train wayside, street side etc..) and based on Cognitive Radio and SDR concepts
- The **Programmable Radio Manager** (PRM), part of the RCP, is the programmable controller conceived to manage the overall radio network infrastructure and based on SDN technology

MMR and MFR are based on the concept of Cognitive Radio (CR) and Multi-Transport Radio (MTR), introduced for the first time by Comesvil within the FAST-TRACKS phase 1 project [10]. Currently the concept is enhanced adding a set of distruptive ideas and special features, designed for railway infrastructure and covered ed by the European Patent [11] filed to the EPO [12]. The advantages of the CR and MTR, within the train to ground communication are the high adaptability of the radio to the continuous evolution of wireless standards and the development of an innovative and not yet on the market product. The proposed infrastructure, due to the high-speed capacity, dual embedded radio and configurable approach, permits to integrate vital and non-vital services on the same wireless backbone, simply dedicating different radio to different services operating with a “full mesh” redundant network architecture. Thus, the system proposed will contribute to:

- Establish a high speed, reliable and continuous communication between a train in motion and the trackside, allowing capacity enhancement
- Support Communication Based Train Control (CBTC) services
- Collect data of CCTV (Close Circuit TV)
- Provide support for VoIP and Personal Information Systems (PIS) services
- Enable preventive maintenance
- Ensure passengers’ safety and security during their journey
- Improve travel comfort

3.1 FAST-TRACKS Hardware Architecture

The FAST-TRACKS (FT) hardware architecture is conceived to support novel software features and solve most of the common issues related to the state-of-the-art telecommunications devices in a way that both security and robustness of the overall radio communication system improve. The hardware architecture is modular. Therefore, the Fixed Radio, the Mobile Radio and the Radio Controller are composed of a set of interchangeable modules.

It consists of a *mainboard,* hosting the main HW components (Figure 12), which is designed to operate in harsh environments for industrial applications.

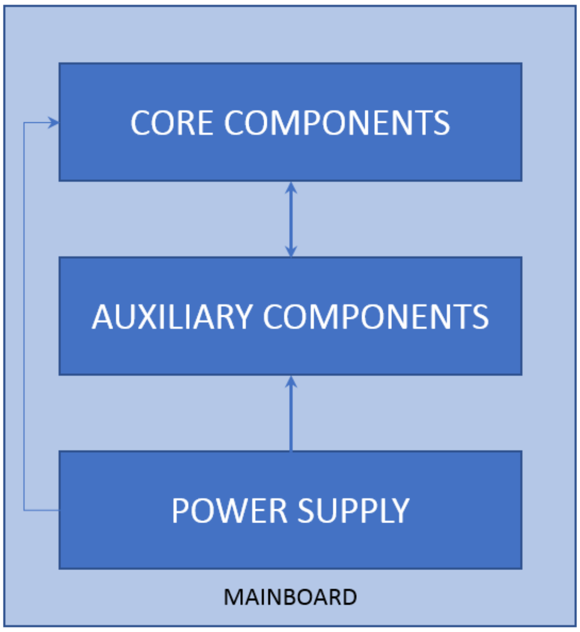


Figure 12: General HW architecture

The *core components* are responsible for processing and/or transmitting and receiving (Figure 13) the radio frequency signal. They can support multiple wireless technologies, while ensuring a reliable and secure communication channel between a train in motion and the wayside.
The *auxiliary components* are responsible for providing the radios with some auxiliary functions – e.g. converting the electrical data signals into optical data signals to be transmitted over an optical transmission channel.
The *power supply* provides electric power to each component.

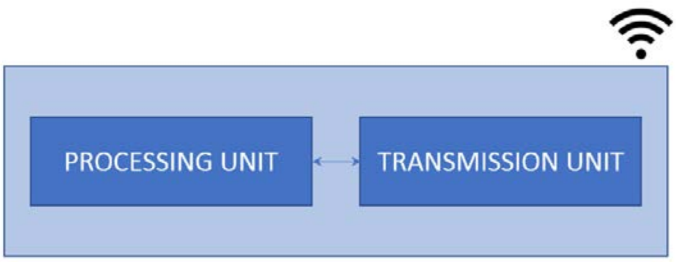


Figure 13: Core component

Such a modular architecture is a disruptive innovation in the field of railway telecommunications, bringing two main benefits. On the one hand, it is possible to easily design and develop Radios and Controllers meeting customers' requirements and upgrade them so that they can support new communication protocols and technologies. On the other hand, corrective maintenance is easier to perform for such a hardware architecture, compared to corrective maintenance for state-of-the-art non-modular radios, because failed components can be replaced with no particular effort.

3.2 FAST-TRACKS Firmware Architecture

The Firmware architecture of the FAST-TRACKS project is based on a GNU Radio/GNU Linux suite equipped with ethernet and networking driver devices. The approach followed in the FAST-TRACKS project is the customization and extension of the basic suite especially re-designed and customized for the hardware used.

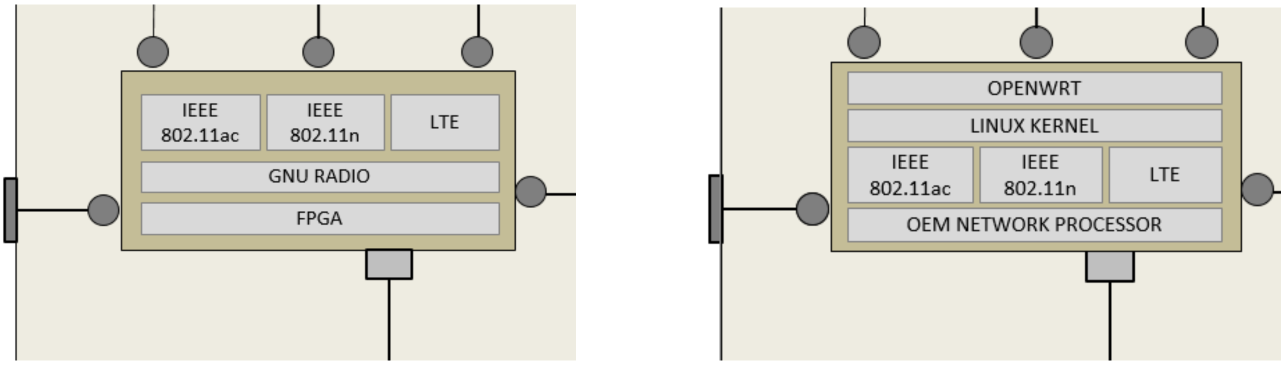


Figure 14: Detailed architecture of the two development approach proposed

The first of the two figures shows the Fixed Modular Radio firmware stack, implemented using a powerful Software Defined Radio based on ARM Cortex-M4 microcontroller. The board is completely programmable in GNURadio environment and permits to implements each kind of radio device working in the frequency range 1 MHz to 6 GHz. In this context the implementation of the standards 802.11abg/802.11n/802.11ac and Long-Term Evolution (LTE) are fully developed via software.

The second figure shows the Mobile Modular Radio firmware stack, implemented using an OEM product (Original Equipment Manufacturer) based on Atheros network processor. The board is equipped with a MiniPCI connector which permits the integration of additional modules implementing the standards 802.11abg/802.11n/802.11ac and LongTerm Evolution (LTE). The whole system is managed via linux-kernel extended to support additional drivers and multiple transport technologies. A linux based firmware completes the software equipment of the radio, providing an easy to customize management system. We will to analyse different set of Linux distribution, before to focus on a stable choice. At the moment, five principal firmware platforms were identified as starting point to create the firmware for the FAST-TRACKS MMR:

OpenWRT

OpenWrt [13] is a highly extensible GNU/Linux distribution for embedded devices. Unlike many other distributions for these routers, OpenWrt is built from the ground up to be a full-featured, easily modifiable operating system for wireless Access Points. In practice, this means that is possible to have all the features needed with none of the bloat, powered by a Linux kernel that's more recent than most other distributions. Instead of trying to create a single, static firmware, OpenWrt provides a fully writable filesystem with optional package management. This frees the developers from the restrictions of the application selection and configuration provided by the vendor and allows to use packages to customize an embedded device to suit any application. For developers, OpenWrt provides a framework to build an application without having to create a complete firmware image and distribution around it. For users, this means the freedom of full customization, allowing the use of an embedded device in ways the vendor never envisioned. Main advantages.

- Free and open-source. The project is entirely free and open-source, licensed under the GPL. The project is intended to always be hosted at an easily accessible site, with full source code readily available and easy to build.

- Easy and free access. The project will always be open to new contributors and have a low barrier for participation. Anyone shall be able to contribute. We, the current developers, actively grant write access to anyone interested in having it. We believe people are responsible when given responsibility. Just ask and you will be able to acquire the access rights you need.

- Community driven. This is not about 'us' offering 'you' something, it is about everyone coming together to work and collaborate towards a common goal.

OpenWrt has long been established as the best firmware solution in its class. It far exceeds other embedded solutions in performance, stability, extensibility, robustness, and design. It is the clear-cut goal of the OpenWrt developers to continue to expand development and ensure that OpenWrt is the foremost framework for innovative and ingenuitive solutions.

LEDE

The LEDE Project [14] (“Linux Embedded Development Environment”) is a Linux operating system based on OpenWrt. It is a complete replacement for the vendor-supplied firmware of a wide range of wireless access points and non-network devices. People install LEDE because they believe it works better than the stock firmware from their vendor. They find it is more stable, offers more features, is more secure and has better support. Extensibility: LEDE provides many capabilities found only in high-end devices. Its 3000+ application packages are standardized, so it’s possible to easily replicate the same setup on any supported device, including two (or even five) year old routers.

- Security: LEDE's standard installation is secure by default, with Wi-Fi disabled, no poor passwords or backdoors. LEDE's software components are kept up-to-date, so vulnerabilities get closed shortly after they are discovered.
- Performance and Stability: LEDE firmware is made of standardized modules used in all supported devices. This means each module will likely receive more testing and bug fixing than stock firmware which can be tweaked for each product line and never touched again.
- Strong Community Support: LEDE team members are regular participants on the LEDE Forum, LEDE Developer and LEDE Admin mailing lists, and LEDE's IRC channels. You can interact directly with developers, volunteers managing the software modules and with other long-time LEDE users, drastically increasing the chances you will solve the issue at hand.
- Research: Many teams use LEDE as a platform for their research into network performance. This means that the improvements of their successful experiments will be available in LEDE first, well before it gets incorporated into mainline, vendor firmware.
- Open Source/No additional cost: LEDE is provided without any monetary cost. It has been entirely created by a team of volunteers: developers and maintainers, individuals and companies. If you enjoy using LEDE, consider

contributing some effort to help us improve it for others! All of the above is possible because LEDE is part of the Open Source community and powered by Linux kernel.

CompexWRT

CompexWRT [15] is an operating system powering our Wireless Embedded Boards and Access Points. It is engineered with Qualcomm Atheros latest QSDK fused with Qualcomm's propriety Wireless Driver, CompexWRT is the ultimate operating system to deploy WiFi far and wide. CompexWRT is the operating system used on Compex's embedded boards. Based on OpenWRT platform paired with LuCI web interface embedded with QCA proprietary Wireless Drivers, it come with all the necessary networking features routing, firewall, wireless access point and many more. CompexWRT is an enterprise grade OS, featuring Mesh networking, native SNMP support, 802.11ac Wave 2 support and UI branding. It offers many level of customization. CompexWRT is the ultimate operating system to deploy WiFi far and wide.

CarrierWRT

CarrierWrt [16] is an OpenWrt overlay that simplifies development of commercial products like Wi-Fi routers and residential gateways, by focusing on aspects that are important to OEMs and their customers. CarrierWrt is designed to produce firmware that is usable out of the box and can be quality assured. CarrierWrt comes with commercial software from leading vendors pre-integrated.

Tomato

Tomato [17] is a small, lean and simple replacement firmware for Linksys' WRT54G/GL/GS, Buffalo WHR-G54S/WHR-HP-G54 and other Broadcom-based routers. It features a new easy to use GUI, a new bandwidth usage monitor, more advanced QOS and access restrictions, enables new wireless features such as WDS and wireless client modes, raises the limits on maximum connections for P2P, allows you to run your custom scripts or telnet/ssh in and do all sorts of things like re-program the SES/AOSS button, adds wireless site survey to see your wifi neighbors, and more.

Other platforms

Gorgoyle, Saba I-OS, FreeWRT, DD-WRT, X-WRT are other firmware platforms which will be tested in addition to the principal, during the FAST-TRACKS project.

All the additional features required by the FAST-TRACK infrastructure will be developed "ad-hoc", managed via plugin as described in the software architecture.

3.3 FAST-TRACKS Software Architecture

The FAST-TRACKS Software architecture is a pluggable platform hosting a complete set of railway-applications needed to increase the performance of the complete network platform proposed. We distinguish different software architectures for Fixed, Mobile Radio and the Programmable Manager.

3.3.1 Fixed and Mobile Modular Radio (FMR – MMR)

The programmable radio core presented for fixed and Mobile radio in the previous section hosts a software architecture based on two different layers. The architecture is specialized for both MFR and MRM. The architecture of the MMR consists of a radio communication layer implementing Rx and Tx protocols and a radio service layer implementing special features meaningful for mobile devices. The architecture of MFR consists of the radio communication layer (same of MMR) and a radio management layer specially conceived for MMR management.

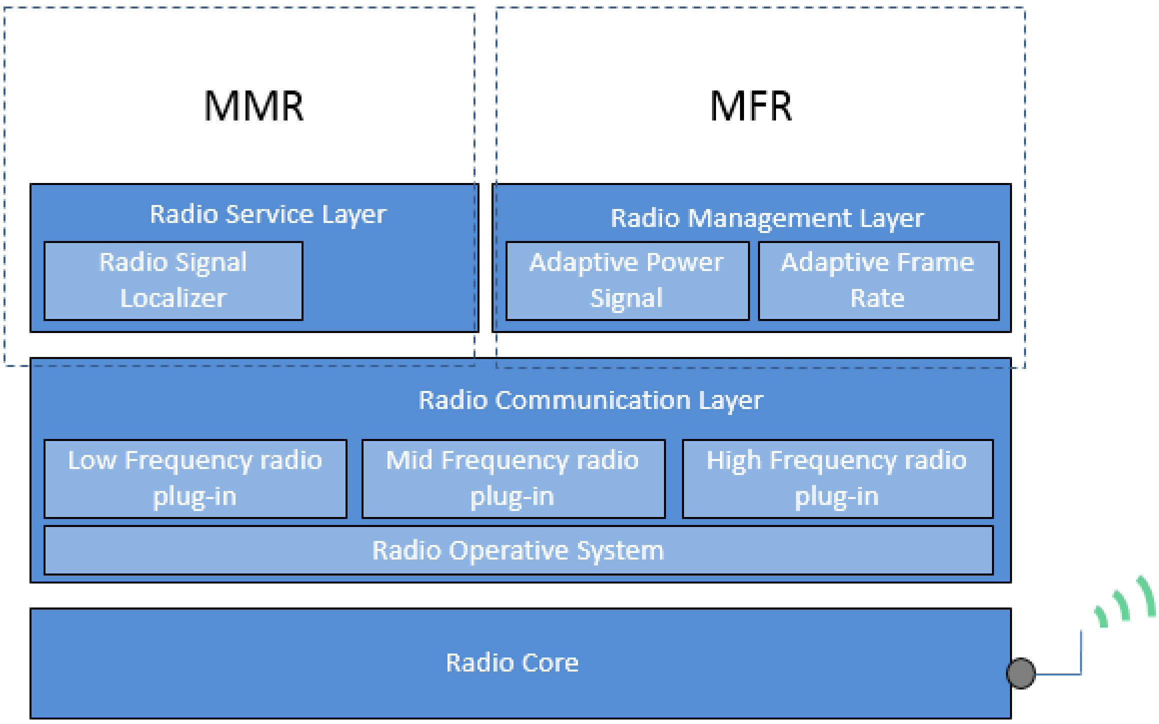


Figure 15: Detailed software architecture of the Modular Mobile Radio and Modular Fixed Radio

The Radio Communication Layer (RCL) implements the overall set of methods needed to control Tx and Rx flows. It is mainly composed by the Radio Operative System and a set of Frequency plugins.

The **Radio Operative** System implements:

- The Flow controller, which sends and receives user data packets and controls the flow of signaling packets;

- The Connection Manager, which activates and deactivates the Radio Instance according the user request and managers user data flow;
- The Resource Manager, which manages the computational resources in order to share them among simultaneously active and guarantees their real execution;
- The Configuration Manager, which install/uninstall, creates/deletes Radio Instances and manages the access to the radio parameters;

The **Frequency Plugin Set** consists of three different categories of software enablers working on different frequency ranges:

- Low Frequencies radio plugin, which permits to build radio working on frequencies between 60MHz and 1GHz.

- Mid Frequencies radio plugin, which permits to build radio working on frequencies between 1GHz and 3GHz.

- High Frequencies plugin, which permits to build radio working on frequencies between 4GHz and 6GHz.

Due the programmability of the radio, it is possible to extend the platform with new future technologies.

The **Radio Service Layer (RSL)**

The radio service layer supports special features conceived to enhance the performance of the mobile radio. The Radio Service Layer inplements the "Signal Localizer", which permits to geo-localize the Wi-Fi and in general the radio signal in real-time, for monitoring and management purpose. This feature is very important and allows acquire information from the field about the power of the Tx, Rx transmission. This service is implemented on top of the technology enabler named GPS module (presented in the hardware section).

The **Radio Management Layer** (RML)

The radio management layer supports special features conceived to manage the MMR in order to achieve the best performance. Two kinds of services are offered by Radio Management Layer:

- The Adaptive Frame Rate (AFR), The AFR is a method that, starting from the hardware and software architecture proposed, permits to separate data flow and modulate the throughput of the whole radio network preserving forever a fixed bandwidth for vital services (i.e. CBTC). In other words, AFR reserve a constant bandwidth for "Vital services" and a variable bandwidth for "Non-vital services" configuring it in adaptive way, using the SNMP protocol. This service is very useful in case of a degradation of the radio signal due to interference coming from the field or coupling of more train in the same Wi-Fi area. The dynamic coupling of two or more trains in the same Wi-Fi area can affect the throughput of the network, as example because the number of TVCC increase.

- The Adaptive Power Signal (APS), which permits to modulate the power, signal of a radio connected to the whole infrastructure based on the RSSI level. In details, the feature fully based on the software and hardware architecture proposed, permits to have a constant value of the RSSI also when on the trackside is present high noise.

3.3.2 Programmable Radio Manager (PRM)

The radio network controller presented in the hardware section hosts a software architecture based on two different layers. The architecture consists of a network communication layer implementing layer 2/ layer 3 Rx-Tx protocols and routing and a global radio management layer performing special services conceived for radio coupling, aggregation and in general radio monitoring and management in railway telecommunication infrastructures.

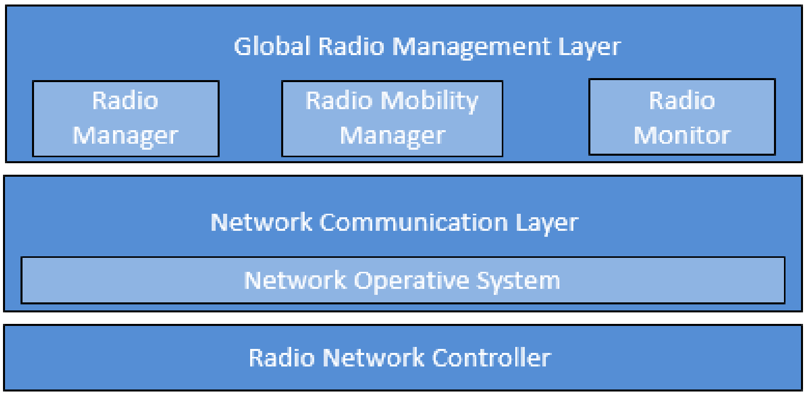


Figure 16: Detailed software architecture of the Programmable Radio Manager

The Network Communication Layer consist of a Network Operative System, specially conceived to manage and control the L2 and L3 traffic generated in the network.

The Global Radio Management Layer enhance the Network Operative System with following services:

- Radio Manager, which manages the installation of a new Radio Instance, or create/delete it. This typically includes the provision of information about the spectral and computational requirements for each Radio Instance, status and so on;
- Radio Fixed/Mobile Manager: which monitors the radio environments and specially the MFR/MMR device capabilities, requests of activation/deactivation of the Radio Instance and provides information about the Radio Instance list. It also manages the different access technologies and discovers the peer communication equipment in order to arrange the best kind of association, including the handoff management;

- Radio Monitor, which presents context information including received signal strength indication, packet error rate, precoding matrix indicator, and so on.

4 Technologies and protocols as support to high-performance wireless networks

FAST-TRACKS project aims at covering a functional gap in the railway radio telecommunication infrastructure. The project is based on the design of a reprogrammable radio (based on CR and multi transport radio concepts) supporting different Wi-Fi, LoRa and LTE standards at the same time, which will foster and guarantee the convergence between automatic train control systems and network telecommunication standards. This chapter presents the technological enablers of the FAST-TRACKS architecture:

- Software Defined Radio
- Software Defined Networks
- Protocols for high-performance wireless networks
- Cloud Computing
- Virtualization

Software Defined Radio is the technology enabler of the MMR and MFR, used respectively in the MCP and FCP. Software Defined Networks represents instead the support to the RCP. Cloud Computing and Virtualization, finally is part of the RMP.

4.1 Software Defined Radio

Nowadays, Software Defined Radio has gained a lot of importance as it provides flexibility to the radio communication by implementing radio functionality in software rather than in hardware. Some of the major advantages of software radio are that they can be reconfigured “on-the-fly”. Their features can be quickly and easily upgraded, and they can be used to build smart or cognitive radios.

Reconfigurability in radio development is not such a new technique as one might think. Already during the 1980s reconfigurable receivers were developed for radio intelligence in the short-wave range. These receivers included interesting features like automatic recognition of the modulation mode of a received signal or bit stream analysis. Reconfigurability became familiar to many radio developers with the publication of the special issue on software radios of the IEEE Communication Magazine in April 1995. We refer to a transceiver as a software radio (SR) if its communication functions are realized as programs running on a suitable processor. Based on the same hardware, different transmitter/receiver algorithms, which usually describe transmission standards, are implemented in software. An SR transceiver comprises all the layers of a communication system.

The baseband signal processing of a digital radio (DR) is implemented on a digital processor and or an FPGA. An ideal SR directly samples the antenna output. A software-defined radio (SDR) is a practical version of an SR: the received signals are sampled after a suitable band selection filter.

The next figure illustrates the block diagram of a software defined radio.

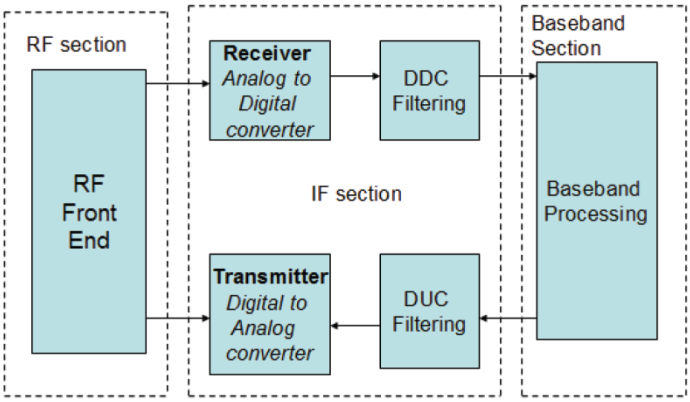


Figure 17: SDR Tranceiver

A cognitive radio (CR) is an SDR that additionally senses its environment, tracks changes, and reacts upon its findings. A CR is an autonomous unit in a communications environment that frequently exchanges information with the networks and it is able to access as well as with other CRs. According to its operational area an SDR can be considered as:

- A multiband system which is supporting more than one frequency band used by a wireless standard (e.g., GSM 900, GSM 1800, GSM 1900)
- A multistandard system that is supporting more than standard. Multistandard systems can work within one standard family (e.g., UTRA-FDD, UTRA-TDD for UMTS) or across different networks (e.g., DECT, GSM, UMTS, WLAN)
- A multiservice system which provides different services (e.g., telephony, data, video streaming)
- A multichannel system that supports two or more independent transmission and reception channels at the same time.

FAST-TRACKS project is conceived around a multimode system which is the combinations of multiband and multistandard systems. The SDR approach allows different levels of reconfiguration within a transceiver:

- Reconfiguration at commissioning time: the configuration of the system is done once at the time of product shipping, when the costumer has asked for a dedicated mode (standard or band).
- Reconfiguration at downtime: reconfiguration is only done a few times during product lifetime, for example, when the network infrastructure changes. The reconfiguration will take some time, where the transceiver is switched off. This may include the exchange of components.
- Reconfiguration on a per call basis: reconfiguration is a highly dynamic process that works on a per call decision. That means no downtime is acceptable. Only parts of the whole system (e.g., front-end, digital baseband processing) can be rebooted.
- Reconfiguration per timeslot: reconfiguration can even be done during a call. In this case an SDR transceiver can be reconfigured via a control bus supplying the processing units with the parameters which describe the desired standard. In this case such a configuration, called a parameter-controlled (PaC) SDR, guarantees that the transmission can be changed instantaneously if necessary (e.g., for interstandard handover).

Mobile Communication standards

Standards are used to publicly establish transmission methods that serve specific applications employable for mass markets. The following sections briefly introduces the presently most important mobile communication standards used in Europe.

Wireless local area networks

Today, IEEE 802.11 installations are the most widely used in Europe. Also, IEEE 802.11a/b/g/n systems are in operation. The implementation of the IEEE 802.11 with SDR require a modulation mode based on OFDM.

Personal area networks

Bluetooth is a short distance network connecting portable devices, for example, it enables links between computers, mobile phones or connectivity to the internet.

Cordless phone DECT (digital enhanced cordless telecommunications) provides a cordless connection of handsets to the fixed telephone system for in-house applications. Its channel access mode is FDMA/TDMA and it uses TDD. The modulation mode of DECT is Gaussian minimum shift keying (GMSK) with a bandwidth (B) time (T) product of BT = 0.5. The transmission is protected only by a cyclic redundancy check (CRC).

Cellular systems

GSM (global system for mobile communication) is presently the most successful mobile communication standard worldwide. Channel access is done via FDMA/TDMA and GSM uses FDD/TDD. The modulation mode of GSM is GMSK with a bandwidth time product of BT = 0.3. Error correction coding is done by applying CRC as well as a convolutional code. GSM was originally planned to be a voice communication system, but with its enhancements HSCSD, GPRS, or EDGE, it served more and more as a data system, too. In Europe, GSM systems are operating in the 900 MHz (GSM 900) as well as in the 1800 MHz (GSM 1800) bands. The North American equivalent of GSM is IS-136. Also, GSM 1900 as well as IS-95, a second-generation CDMA system, are widely used in the US. UMTS (universal mobile telecommunication system) is the European version of the third-generation family of standards within IMT-2000. One of the differences with respect to second-generation systems is that third-generation systems are mainly developed for data (multimedia) transmission. UMTS applies two air interfaces: UTRA-FDD and UTRA-TDD according to the duplex modes used. The channel access mode is CDMA. CRC, convolutional codes, as well as turbo codes [1] are employed for error protection. The basic data modulation is QPSK. Furthermore, it should be mentioned that one mobile user within an UTRA-FDD cell can occupy up to seven channels (one control and six transport channels) simultaneously.

Professional mobile radio

PMR standards are developed for police, firefighters, and other administrative applications. The main difference to cellular systems is that they allow direct handheld to handheld communication. The main PMR systems in Europe are TETRA (recommended by ETSI) and TETRAPOL.

Next figure gives an overview over the present spectrum allocation for mobile communications in Europe. Besides the spectra of the standards mentioned above, also the spectra allocated to mobile satellite system (MSS) as well as to industrial, scientific, and medical (ISM) applications are specified. The arrows within some of the bands indicate whether uplink (mobile to base station) or downlink (base station to mobile) traffic is supported. In connection with mobile communications, some additional groups of standards have to be discussed.

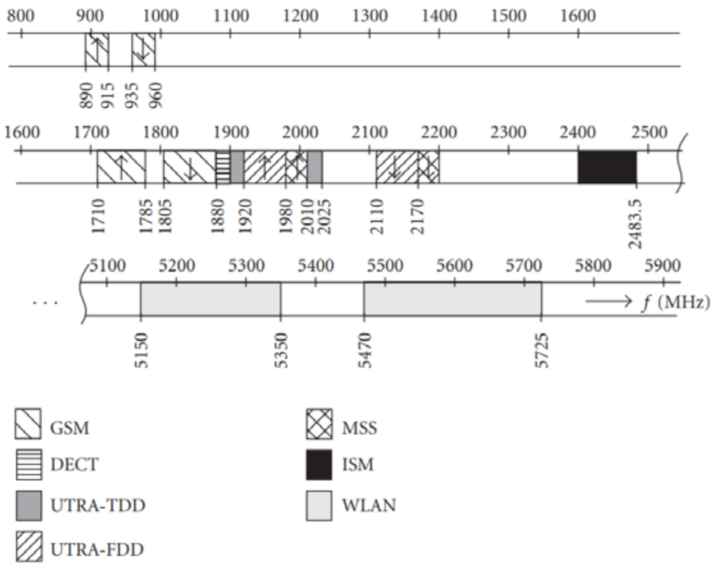


Figure 18: Mobile spectrum in Europe

The following list shows the possible modulations and technology implementation with SDR.

List of modulations	List of technologies
SSB	
AM	IEEE 802.11 a/b/g/p/n/ac
FM	GSM/GSM-R
OFDM	UMTS
PM	LTE
GSMK	BLUETOOTH
PSK	ZIGBEE
QPSK	DVB-T2
QAM	DVB-S2
CDMA	LORA
	TETRA

Table 4: List of modulation and technologies available with SDR

SDR defines a collection of hardware and software technologies where some or all of the radio's operating functions (also referred to as physical layer processing) are implemented through modifiable software or firmware operating on programmable processing technologies. These devices include field programmable gate arrays (FPGA), digital signal processors (DSP), general purpose processors (GPP), programmable System on Chip (SoC) or other application specific programmable processors. The use of these technologies allows new wireless features and capabilities to be added to existing radio systems without requiring new hardware. There are quite a few software defined radio systems today and one of them is GNU Radio/USRP system [18]. The emergence of GNU Radio software and USRP hardware has allowed the research community to develop and analyze wireless communication systems easily in software radio environment. This study will be part of the FAST-TRACK project, within the WP2.

GNU Radio

GNU Radio is an open source software toolkit which provides a library of signal processing blocks and the glue to tie these blocks together for building and deploying software defined radios. Using GNU Radio, a radio can be built by creating a graph where the vertices are signal processing blocks and the edges represent the data flow between them. The signal processing blocks are implemented in C++ and the graphs are constructed and run in Python. Conceptually, a signal processing block processes an infinite stream of data flowing from its input ports to its output ports. A block attributes include the number of input and output ports it has as well as the type of data that flows through each. Some blocks have only output ports or input ports. Input and output ports serve as data sources and sinks in the graph. For instance, there are sources that read from a file or ADC, and sinks that write to a file, digital-to-analog converter (DAC) or graphical display

Universal Software Radio Peripheral

The Universal Software Radio Peripheral, or USRP was designed as a low-cost board solely for the purpose of running GNU radio applications and allowing general purpose computers to function as high bandwidth software radios. Fully developed by Matt Ettus [19], it is a very flexible platform and can be used to implement real time applications. In essence, it serves as a digital baseband and IF section of a radio communication system. It is the bridge between the software world and the RF world. The basic design philosophy behind the USRP has been to do all of the waveform specific processing, like modulation and demodulation, on the host CPU. All of the high-speed general-purpose operations like digital up and down conversion, decimation and interpolation are done on the FPGA. The true value of the USRP is in what it enables engineers and designers to create on a low budget and with a minimum of effort. A large community of developers and users have contributed to a substantial code base and provided many practical applications for the hardware and software. The powerful combination of flexible hardware, open-source software and a community of experienced users make it the ideal platform for your software radio development.

4.2 Software Defined Networks

Traditional network architectures are suited to meet the requirements of today's enterprises, carriers, and end users. Thanks to a broad industry effort spearheaded by the Open Networking Foundation (ONF)[20], SoftwareDefined Networking (SDN) is transforming networking architecture. In the SDN architecture, the control and data planes are decoupled, network intelligence and state are logically centralized, and the underlying network infrastructure is abstracted from the applications. As a result, enterprises and carriers gain unprecedented programmability, automation, and network control, enabling them to build highly scalable, flexible networks that readily adapt to changing business needs. The ONF is a non-profit industry consortium that is leading the advancement of SDN and standardizing critical elements of the SDN architecture such as the OpenFlow™ protocol [20], which structures communication between the control and data planes of supported network devices. OpenFlow is the first standard interface designed specifically for SDN, providing high-performance, granular traffic control across multiple vendors' network devices. OpenFlow-based SDN is currently being rolled out in a variety of networking devices and software, delivering substantial benefits to both enterprises and carriers, including:

- Centralized management and control of networking devices from multiple vendors;
- Improved automation and management by using common APIs to abstract the underlying networking details from the orchestration and provisioning systems and applications;
- Rapid innovation through the ability to deliver new network capabilities and services without the need to configure individual devices or wait for vendor releases;
- Programmability by operators, enterprises, independent software vendors, and users (not just equipment manufacturers) using common programming environments, which gives all parties new opportunities to drive revenue and differentiation;
- Increased network reliability and security as a result of centralized and automated management of network devices, uniform policy enforcement, and fewer configuration errors;
- More granular network control with the ability to apply comprehensive and wide-ranging policies at the session, user, device, and application levels; and
- Better end-user experience as applications exploit centralized network state information to seamlessly adapt network behavior to user needs.

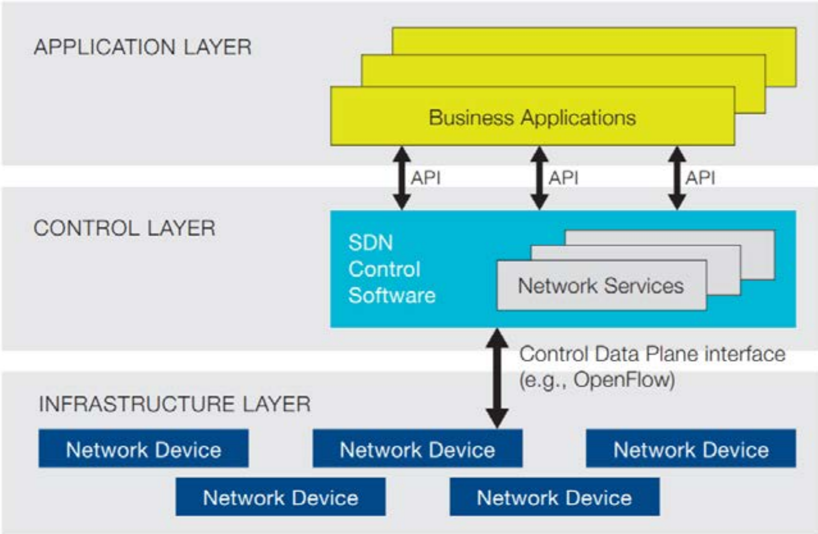


Figure 19: Software Defined Networks architecture

SDN is a dynamic and flexible network architecture that protects existing investments while future-proofing the network. With SDN, today's static network can evolve into an extensible service delivery platform capable of responding rapidly to changing business, end-user, and market needs.

Software Defined Networking (SDN) is an emerging network architecture where network control is decoupled from forwarding and is directly programmable. This migration of control, formerly tightly bound in individual network devices, into accessible computing devices enables the underlying infrastructure to be abstracted for applications and network services, which can treat the network as a logical or virtual entity. The figure above depicts a logical view of the SDN architecture. Network intelligence is (logically) centralized in software-based SDN controllers, which maintain a global view of the network. As a result, the network appears to the applications and policy engines as a single, logical switch. With SDN, enterprises and carriers gain vendor-independent control over the entire network from a single logical point, which greatly simplifies the network design and operation. SDN also greatly simplifies the network devices themselves, since they no longer need to understand and process thousands of protocol standards but merely accept instructions from the SDN controllers

Perhaps most importantly, network operators and administrators can programmatically configure this simplified network abstraction rather than having to hand-code tens of thousands of lines of configuration scattered among thousands of devices. In addition, leveraging the SDN controller's centralized intelligence, IT can alter network behavior in real-time and deploy new applications and network services in a matter of hours or days rather than the weeks or months needed today. By centralizing network state in the control layer, SDN gives network managers the flexibility to configure, manage, secure, and optimize network resources via dynamic, automated SDN programs. Moreover, they can write these programs themselves and not wait for features to be embedded in vendors' proprietary and closed software environments in the middle of the network. In addition to abstracting the network, SDN architectures support a set of APIs that make it possible to implement common network services, including routing, multicast, security, access control, bandwidth management, traffic engineering, quality of service, processor and storage optimization, energy usage, and all forms of policy management, custom tailored to meet business objectives. For example, an SDN architecture makes it easy to define and enforce consistent policies across both wired and wireless connections on a campus. Likewise, SDN makes it possible to manage the entire network through intelligent orchestration and provisioning systems. The Open

Networking Foundation is studying open APIs to promote multi-vendor management, which opens the door for on-demand resource allocation, self-service provisioning, truly virtualized networking, and secure cloud services. Thus, with open APIs between the SDN control and applications layers, business applications can operate on an abstraction of the network, leveraging network services and capabilities without being tied to the details of their implementation. SDN makes the network not so much “application-aware” as “application-customized” and applications not so much “network-aware” as “network-capability-aware”. The application of the SDN in the FAST-TRACKS project is proposed as enabler to separate the forwarding-plane from the control-plane, opening the implementation of high performance wireless communication protocols which permits to implements a constrained traffic engineering enabling the on fly configuration of mesh/hub&spoke reliable network.

4.3 Protocols for high-performance wireless communication

This section presents a set of routing protocols and computation elements which permits to enhance the performance of wired and wireless networks. These protocols are actually used to implements the constrained traffic engineering and resilience in optical networks switches. The idea, within the FAST-TRACKS project, is to reuse the same protocol architecture to ehnace wireless data transfer in a train to wayside communication scenario. The next section introduces briefly the following protocols:

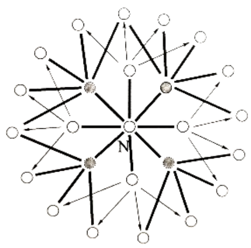
- Optimized Link State Routing Protocols (OLSR)
- Multi Protocol Label Switching (MPLS)
- Generalized Multiporotocol Label Switching (GMPLS)
- Path Computation Element (PCE)

4.3.1 Optimized Link State Routing protocol (OLSR)

Optimized Link State Routing (OLSR) [21] is a proactive routing protocol for mobile wireless ad hoc networks. The protocol hinerits the stability of the link state algorithm. Due to its proactive nature, it as an advantage of having the routes immediately available when needed. In a pure link state protocol, all the links with neighbor nodes are declared and are flooded in the entire network. OLSR protocol is an optimization of a pure link state protocol for mobile ad-hoc networks. First it reduces the size of control packets: instead of all links, it declares only a subset of links with its neighbors who are its multipoint relay selectors. Secondly, it minimizes flooding of this control traffic by using only the selected nodes, called multipoint relays, to diffuse its messages in the network. Only the multipoint relays of a node retransmit its broadcast messages. This technique significantly reduces the number of retransmissions in a flooding or broadcast procedure

This protocol is particularly suitable for large and dense networks, such train-to-ground communications networks, where the FAST-TRACKS architecture aims to enhance.

The protocol works as foolows: each node selects a set of nodes in its neighborhood, which retransmits its packets. This set of nodes is called multipoint relays (MPR) of that node. The nodes which are not in its MPR set, read and process the packet but do not retransmit the packet received. This set of nodes can change over time by the selector nodes in HELLO messages.



Each node (N) select its multipoint relay set among its one hop neighbor to cover all nodes that are two hops away. The condition to satisfy is that each node in two hop neighborhod of N must have a bidirectional link towards MPR(N). The figure beside shows this concept.

OLSR protocol selects multipoint relays and calculates its routes. Therefore, the route is a sequence of hops through the multipoint relay from source and destination. Multipoint relays are selected among the one hop neighbor with a bi-directional link, so it avoids the problems associated at the transfer on unidirectional links, i.e. acknowledgment signal.

The HELLO messages that each node broadcasts contains the information about its neighbors and their link status, exactly:

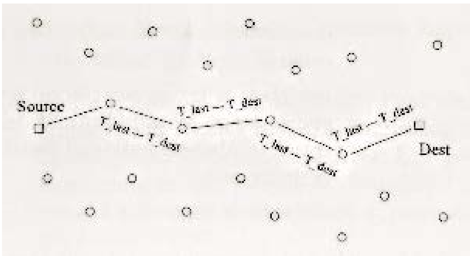
- The list of addresses of the neighbors which exists a bidirectional link
- The list of addresses of the neighbors which are heard by this node, but not yet validated at bidirectional. So, when a node finds its addresses in HELLO message, it considers the link to sender node as bidirectional.

In this scenario, each node, when obtain information from HELLO messages, construct its MPR Selector table in which it put the addresses of its one hop neighbor nodes selected ad a multipoint relay. A sequence number is associated to the MPR Selector table to specify that it is most recently modified. So, a node updates its MPR Selector table in according to the information received in the HELLO messages and increment this sequence number on each modification.

In order to build the intra-forwarding database needed for routing, each node broadcasts a control messages called Topology Control messages (TC) in the network to declare its MPR Selector set. The message contains the list of neighbors who have selected the sender node as multipoint relay.

The interval between the transmission of two TC messages depends if MPR Selector set is changed or not, since last TC message transmitted. If the pre-specified minimum interval time from last TC message sent has elapsed, a new TC message must be transmitted immediately.

Each node maintains a routing table which allows it to route the packets for other destinations in the network. The nodes, which receive a TC message parse and store some of the connected pairs of form [last-hop, node] where "nodes" are the addresses found in the TC message list. A procedure searches the pairs in the topology table [last-hop, destination] to connect route from source and destination and will select only the pairs on minimal path (see figure beside). The routing table is based on information contained in topology table and neighbor table. Therefore, if any of these tables is changed, the routing table is recalculated to update the route information about the new destination in the network.



4.3.2 Multi Protocol Label Switching (MPLS)

MPLS [22] is a scalable, protocol-independent transport. In an MPLS network, data packets are assigned labels. Packet-forwarding decisions are made solely on the contents of this label, without the need to examine the packet itself. This allows one to create end-to-end circuits across any type of transport medium, using any protocol. The primary benefit is to eliminate dependence on a particular OSI model data link layer (layer 2) technology, such as Asynchronous Transfer Mode (ATM), Frame Relay, Synchronous Optical Networking (SONET) or Ethernet, and eliminate the need for multiple layer-2 networks to satisfy different types of traffic. MPLS belongs to the family of packet-switched networks.

MPLS operates at a layer that is generally considered to lie between traditional definitions of OSI Layer 2 (data link layer) and Layer 3 (network layer), and thus is often referred to as a layer 2.5 protocol. It was designed to provide a unified data-carrying service for both circuit-based clients and packet-switching clients, which provide a datagram service model.

It can be used to carry many different kinds of traffic, including IP packets, as well as native ATM, SONET, and Ethernet frames.

A number of different technologies were previously deployed with essentially identical goals, such as Frame Relay and ATM. Frame Relay and ATM use "labels" to move frames or cells throughout a network. The header of the Frame Relay frame and the ATM cell refers to the virtual circuit that the frame or cell resides on. The similarity between Frame Relay, ATM, and MPLS is that at each hop throughout the network, the “label” value in the header is changed. This is different from the forwarding of IP packets MPLS technologies have evolved with the strengths and weaknesses of ATM in mind. Many network engineers agree that ATM should be replaced with a protocol that requires less overhead, while providing connection-oriented services for variable-length frames. MPLS is currently replacing some of these technologies in the marketplace. It is highly possible that MPLS will completely replace these technologies in the future, thus aligning these technologies with current and future technology needs.

In particular, MPLS dispenses with the cell-switching and signaling-protocol baggage of ATM. MPLS recognizes that small ATM cells are not needed in the core of modern networks, since modern optical networks are so fast (as of 2015, at 100 Gbit/s and beyond) that even full-length 1500-byte packets do not incur significant real-time queuing delays (the need to reduce such delays — e.g., to support voice traffic — was the motivation for the cell nature of ATM).

At the same time, MPLS attempts to preserve the traffic engineering (TE) and out-of-band control that made Frame Relay and ATM attractive for deploying large-scale networks.

4.3.3 Genelalyzed Multi Protocol Label Switching (GMPLS)

GMPLS [23] (Generalized Multiprotocol Label Switching), also known as Multiprotocol Lambda Switching, is a technology that provides enhancements to Multiprotocol Label Switching (MPLS) to support network switching for time, wavelength, and space switching as well as for packet switching. In particular, GMPLS will provide support for photonic networking, also known as optical communications. MPLS involves setting up a specific path for a given sequence of packets by labeling every packet so that a routing table does not have to be referred in order to figure out which outward path a packet should be switched toward its destination. MPLS is called multiprotocol because it works with the Internet Protocol (IP), Asynchronous Transport Mode (ATM), and frame relay network protocols. In addition to moving traffic faster, MPLS makes it easier to manage a network for quality of service (QoS). The use of MPLS has become widespread as networks carry increasing volumes and varieties of traffic such as Voice over IP (VoIP).

As GMPLS evolves, it will require changes to existing protocols and will spur the evolution of new ones. The Link Management Protocol, for example, arose in part as a consequence of GMPLS evolution. GMPLS also involved changes to the Open Shortest Path First (OSPF) protocol and IS-IS intradomain routing protocol. GMPLS allows for a greatly increased number of parallel links between nodes in a network. This is important in photonic networking, where hundreds of parallel links (individual fibers in a bundled fiber optic cable, for example) may exist between a pair of nodes. GMPLS also facilitates rapid fault detection, fault isolation, and switchover to alternate channels, minimizing network downtime. In FAST-TRACKS network architecture the GMPLS will be considered and analyzed from a twofold point of view. Enhance the optical backbone of the train-to-signalling network and reuse the OSPF protocol / RSVP protocol extensions [24] [25] in the wireless network architecture. The usage of this pattern needs a network controller capable to orchestrate both the protocols, obtaining a continous monitoring of the network before reconfiguration action: the path computation element.

4.3.4 Path Computation Element (PCE)

Path Computation Element (PCE) is defined in [26] as “an entity (component, application or network node) and a control plane concept, which is capable of computing a network path or route based on a network graph and applying computational constraints during the computation”. This definition suggests a decoupled architecture: when a Label Switched Path (LSP) has to be signaled over a pre-computed path, PCE performs complex route computations on behalf of the head-end MPLS Label Switching Router (LSR), which is termed Path Computation Client (PCC), delocalizing path computation from it and taking into account TE information and physical constraints. In fact, a head-end router has partial visibility of the network topology to destination (in complex multi-layer, multi-domain or multi-administrative network architecture), so it can calculate an end-to-end intra-domain path but not an inter-domain path. The PCE-based inter-AS path computation can be performed after the AS chain to the destination is known, using efficient distributed algorithms and topology information resulting from dissemination mechanisms. In addition, PCE may not have full topology visibility and, in this case, it is able to compute only a loose route. The PCE supplies optimal routes and interacts with the control plane for the set-up of the proposed paths upon receiving requests sent by a PCC, which could be another process or a node, to determine the path from a source to a destination. In order to execute this task, network state information is hoarded into a Traffic Engineering Database (TED): it contains candidate paths and it is populated with intra-domain routing protocols (OSPF-TE, IS-IS-TE) and BGP information (BGP routes available before winnowing the best route). Employing information included in the local TED, the PCE identifies primary and backup paths within a domain or an area, and it commonly consider bandwidth requirements, QoS and survivability characteristics. After the computation of an inter-domain route, the PCE converts it into an explicit route and then provides it in an Explicit Route Object (ERO) that is created and signaled. Through ERO, it is possible to signal a mix of strict and loose hops to be used in the path; in order to establish the LSP, the ingress LSR uses RSVP-TE (a signaling protocol that reserves resources) and encodes the path. A hop might also be a whole AS and it is termed “abstract” node; given a specific domain, abstract and loose hops correspond to a set of strict hops between the ingress AS border router (ASBR) and the next hop ASBR. The state of the network components is required for routing: the Interior Gateway Protocol (IGP) distributes this information through Link State Advertisement (LSA). The aim of a PCE-based model is to coordinate the establishment of LSPs among distinct areas of a single domain or within a small group of domains, by means of heuristics conceived to address path computation problems. According to the size, each domain at the inter-domain level might include one or more PCEs to facilitate load sharing and avoid single point of failures; for instance, large domains can be divided into manifold areas, in each of which it is used one PCE to manage path computations. At least one PCE per domain is required and it may or may not be located in the same node as its related PCC. A path may be computed by a single PCE if it maintains enough topology and TE information; when an individual PCE does not have sufficient TE visibility, PCEs can cooperate to compute loose hops, confidential path segments, or even thoroughly explicit constrained end-to-end inter-domain paths, without sharing any TE information with each other and solving the topology visibility issue. In particular, in a multi-domain scenario a PCE interrogates the PCEs of other domains, acting in turn as a PCC. PCE-based model can be of two types: (i) peer-to-peer or (ii) hierarchical. In the first case, PCEs of adjacent domains interact with control plane, collaborate to interchange routing information and they are sequentially queried to determine the availability of the path. In the hierarchical approach, there is a local PCE for each domain and a centralized global PCE, which computes paths after receiving information from each domain. In the latter case, the drawback is the limited scalability and the presence of a single point of failure. A PCE Communication Protocol (PCEP) [27] was defined to specify both PCC-PCE and PCE-PCE communication aimed at the computation of LSPs. When a new request subject to QoS constraints arrives, the PCC uses a discovery method to locate PCEs and it locally preserves PCE capabilities to select one of them according to the specific computation; then it submits an inquiry to the selected PCE using PCC-to-PCE communication

To enhance the GMPLS control plane with "traffic constraint capabilities" we introduce new metrics and path selection algorithms in the Path Computation Element (PCE). A PCE is a functional element that cooperates with similar entities and with network devices to compute the best possible path through multiple domains. The PCE function may implemented either as a centralized service or as a distributed architecture involving one agent in each device. Our proposal assumes that network devices are able to provide PCEs with energy consumption information. Next figure shows the role of the network management plane and the proposed extension of the GMPLS control plane, using the Path Computation Element architecture [28].

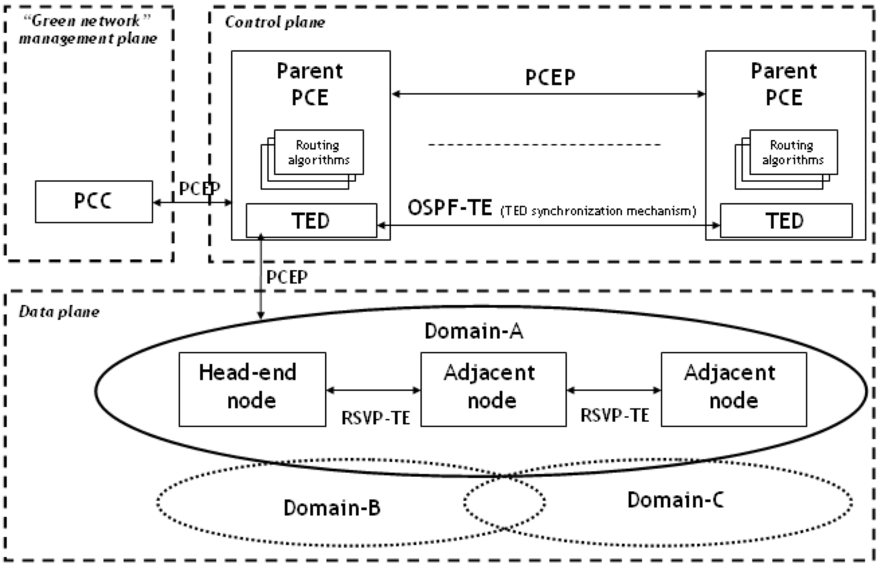


Figure 20: GMPLS/PCE architecture integration

A PCE receives path computation requests from entities known as Path Computation Clients (PCCs). A PCE holds limited routing information from other domains, allowing it to possibly compute better and shorter inter-domain paths than those obtained using the traditional per-domain approach. Among other purposes, PCEs are also being advocated for CPU-intensive computations, minimal-cost-based TE-LSP placement, backup path computations, and bandwidth protection. Along with the process of identifying the requirements and development of the architecture accordingly, a plethora of work is underway at the PCE IETF WG aimed at defining new PCE communication protocols and introducing extensions to existing underlying routing protocols. Request for Comments (RFC) 4655 specifies a PCE-based architecture. RFC 4657 covers PCE communication protocol generic requirements, and RFC 4674 discusses the requirements for PCE discovery.

4.4 Cloud Computing

Cloud Computing is being positioned as the transformation of ICT operations with many business and technical benefits. The main advantages offered by cloud services are the ability to increase/decrease resources as demand changes, to deploy complex and scalable applications with less skills, pay-per-use models that transform SW/HW costs into a variable expense instead of a large fixed expenditure, easier execution but with the same ideas, changing the value of a service/application to the user experience of the service/application instead of the infrastructure which supports it.

The National Institute of Standards and Technology identifies the following classification for Cloud services: Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a service (SaaS) [29]. In the FAST-TRACKS architecture, we focus on IaaS because it offers the highest level of control over the infrastructure. The basic enabler of the IaaS is the native virtualization (or type 1) where a layer of software, called hypervisor, supports the execution of several virtual machines (VMs). In this scenario, network and IT resources are elastic, in the sense that in the Cloud we can instantiate or delete VMs dynamically.

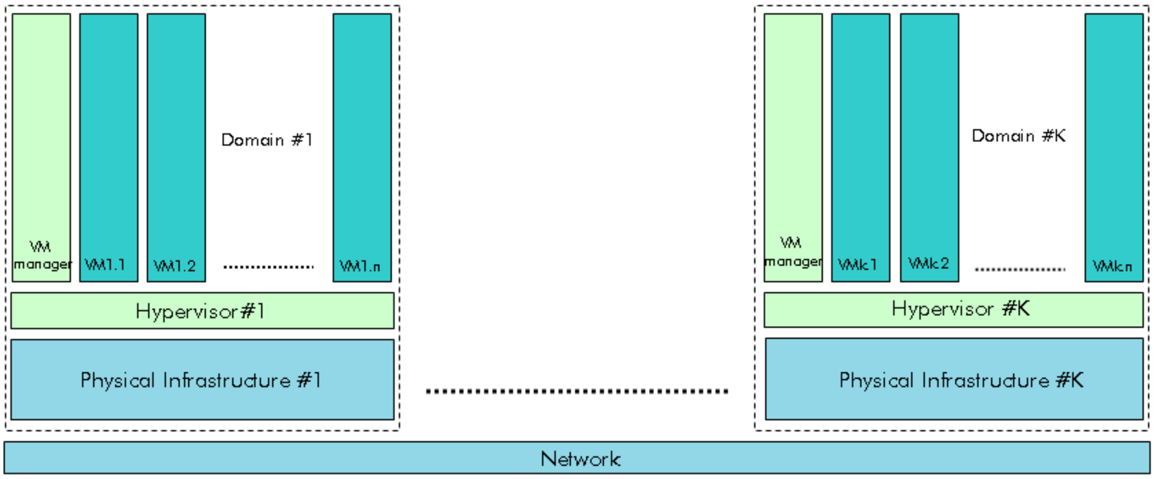


Figure 21: A simplified representation of an IaaS infrastructure

The figure above introduces a simplified representation of an IaaS infrastructure [30] that shows different Cloud domains, each abstracting heterogeneous physical resource (wireless, ip, IT resources). In this scenario, the Cloud infrastructure provider only controls the hypervisor and the VM manager.

The Cloud middleware orchestrates the local management system of each domain, exposing data flow API that permits to exchange information modifying the status of each VM as consequence of the information coming from the field.

The convergence of IT, wired and wireless network service management is an important outcome for FAST-TRACKS to reach a high level of resiliency and security of the whole architecture. This convergence could support greater flexibility and efficiency in the way IT departments operate but also how they enact outsourcing of IT capability. Next-generation wireless networks, in close cooperation with enhanced networking models such as Software Defined Networks will enable cost-efficient provisioning of flexible radio services between fixed and mobile transport infrastructure, scaling up to 867Mb/s per radio for a maximum transport capacity of 1.733 Gb/s on a single radio.

4.5 Virtualization

Virtualization is a software technology, which uses a physical resource such as a server and divides it up into virtual resources called virtual machines (VMs). Virtualisation allows for efficiently sharing physical network+IT resources (computing, networks and storage) to accommodate the demand of customers, while meeting the business expectations of ICT providers. Physical resources are virtualised to create multiple logical resources, such as virtual machines or virtual nodes and links. Virtualisation technologies aim to conceal the virtualisation layer from the users while giving them the impression of directly using the real resources, by meeting requirements such as: isolation, security, accountability, etc.

Infrastructure virtualisation is a very active topic in the industry. It spans both software and hardware technologies, with open-source and proprietary approaches that can be hosted privately by an organisation, or remotely by a third party. Virtualisation has also strong implications on non-technical issues, being the driving force that is changing the business models around ICT technologies.

Virtualisation is a key technology in the FAST-TRACKS project, whose focus is on the composition, orchestration and management of heterogeneous virtualised infrastructures (network+IT), rather than on basic virtualisation technologies research.

The main role of the virtualization within the FAST-TRACKS architecture is the storage and monitoring as support of the wireless radio planes.

5 Conclusions

FAST-TRACKS project proposes the development and commercialization of a low-cost telecommunication system, which addresses the main problems faced at present in the integration of a traditional Wi-Fi system within the railway technological infrastructure. The project aims at covering a functional gap in the railway radio telecommunication infrastructure. The project is based on the design of a reprogrammable radio supporting different Wi-Fi, Cellular and LTE standards at the same time, which will foster and guarantee the convergence between automatic train control systems and network telecommunication standards. During the project, Comesvil will develope a prototype of Wi-Fi standard like IEEE 802.11 ac – LORA and LTE technologies through two different approaches demonstrating the technical and financial-economic feasibility of the proposed idea and a large applicability of the system in the railway telecommunication infrastructures.

The innovative solution proposed is able to support each type of railway communication, using a full programmable infrastructure based on Fixed Radio, Mobile Radio and Programmable Radio Manager. Main features of the proposed infrastructure are the following:

Features	Details
Multi transport radio	IEEE 802.11 a, b, g, n/ac/LTE/GSM-GSM-R/LoRa
Frequency range	60MHz-6 GHZ
Additional technologies	Tetra, Bluetooth/ dual-core radio
Network controller	Programmable Controller based on FPGA
Handoff	Seamless handoff
Throughput	High – tunable (till 1.3Gb/s)
Firmware customization	Full
Interference rejection	High
Optical Interface	Yes
Specific features for Railway	Yes
Cost	Low

Table 5: Comesvil Radio requirements

Comesvil argue to develop the technology described during the project and implements one of the following ongoing projects on Metro DCS: Lima, Cophenagen, Stocholm, Milano, Napoli, Navi Mumbay, Taipei, Rijadh and Salonicco.

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7 Acronyms

[CAPEX]	[Capital expenditures]
[CBTC]	[Communication based train control]
[CR]	[Cognitive Radio]
[DCS]	[Data Communication System]
[ERTMS]	[European Rail Traffic Management System]
[ETCS]	[European Train Control System]
[FCP]	[Fixed Communication Plane]
[GMPLS]	[Generalized Multi Protocol Label Switching]
[GSM-R]	[Global System for Mobile Communications Railway]
[LoRa]	[Long Range]
[LTE]	[Long Term Evolution]
[LTE-R]	[Long Term Evolution Railway]
[MCP]	[Mobile Communication Plane]
[MIMO]	[Multiple Input - Multiple Output]
[MFR]	[Mobile Fixed Radio]
[MMR]	[Mobile Modular Radio]
[NCP]	[Network Control Plane]
[OTN]	[Optical Transport Network]
[OFDM]	[Orthogonal frequency division multiplexing]
[OPEX]	[Operational Expenditure]
[PAAS]	[Platform-as-a-Service]
[PHY]	[Physical Layer]
[PI]	[Physical Infrastructure]
[PMR]	[Professional Mobile Radio]
[PSC]	[Project Steering Committee]
[QOS]	[Quality of Service]
[RCP]	[Radio Control Plane]
[RMP]	[Radio Monitoring Plane]
[SDN]	[Software Defined Networks]
[SDR]	[Software Defined Radio]
[SME]	[Small Medium Enterprises]
[Telco]	[Telecommunications companies]
[TETRA]	[TErrestrial Trunked RAdio]
[VIMS]	[Virtual Infrastructure Management System]
[VM]	[Virtual Machines]