Platforms and Communication Architectures for ITS

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Abstract

The growing demand for mobility of people and goods will lead to a radical change of the transport paradigm, toward increasingly safe, sustainable and integrated systems: the Intelligent Transportation Systems (ITS). In this context the ICT technologies play the key role, in particular the communication technologies that are fundamental to convey the navigation information, implement active surveillance techniques, and strengthen the accuracy of localization processes. The results presented in this work cover different areas of the transport sector, specifically the rail and road transportation, as well as the Air Traffic Control (ATC). The research activities, mainly driven by industrial projects, have been carried out in order to improve safety and ensure better management of traffic flows and fleets in these different domains, through the use of communication systems, localization technologies and cybersecurity techniques.

In the railway sector, research activities mainly concerned the goods transportation, in particular the design and prototyping with a real test bench of an integrated architecture for monitoring and efficient management of trains and freight wagons based on Wireless Sensor Networks (WSN), long-range communication technologies and cloud computing for collecting and processing information in a centralized way.

In the ATC context the Automatic Dependent Surveillance - Broadcast (ADS-B) technology was addressed, with specific commitment on the enhanced reception techniques proposed by the Radio Technical Commission for Aeronautics (RTCA: through a detailed link level simulation environment, the performance of those techniques have been assessed in terms of preamble detection and data decoding over two different RF reception chains. Furthermore, a high-level hardware design was performed for future prototyping on Field Programmable Gate Array (FPGA) through RTL (Register Transfer Level) mode in VLSI Hardware Description Language (VHDL).

In the automotive domain research activities were carried out on vehicular communication as key factor for development of innovative solutions to improve the road safety and traffic efficiency, as well as to realize advanced mobility services. ITS applications were implemented in high fidelity simulation environment for vehicular communication, such as the traffic management in emergency situations and the optimization of traffic lights by means of Vehicle to Infrastructure (V2I) communication, while performing radio channel congestion analysis. Together with the different communication technologies, from Vehicular Ad-hoc Networks (VANET) to the 5G, accurate localization and cybersecurity aspects were approached within the design of a heterogeneous architecture for management of smart commercial vehicles, able to operate both in ordinary and emergency conditions thanks to an on-board equipment composed by a multi-standard communication platform and advanced localization systems based on multi-constellation satellite receivers (GPS + GALILEO).

Contents

List of Figures

Chapter 1

Introduction and motivations

1.1 ITS for Railway, Air and Road transportation

The demographic trends, globalization, climate change and technology development are the main factors driving the evolution of the transport sector which will become increasingly safe, efficient, environmentally sustainable and integrated according to the multi-mode paradigm. These aims will be achievable thanks to the heavy integration of the ICT technologies with the transport engineering that will lead to the development of the Intelligent Transportation Systems (ITS). In this context the enabling technologies are the pervasive connectivity and communication, accurate localization and cyber security.
Each transport domain has different functional characteristics and specific issues, and is also important to distinguish between the transport of people and goods, that in this work will be taken into account to analyze the potential technological enhancement in order to improve safety and efficiency.

The activities described in the following chapters will concern three different transport sectors: the rail, air and road transportation, paying particular attention to the communication technologies currently available or upcoming under the 5G umbrella. The research path illustrated in this thesis starts from previous projects and collaborations with industrial partners, thanks to which all the three different transport contexts were approached in the research and development areas described below.

All these contexts are suddenly evolving towards assisted driving systems to improve safety and efficient management of resources. To achieve these objectives, heterogeneous and highly scalable communication architectures are needed in order to provide driving support for short distance and produce medium and large scale flows management. For this purpose the constant and dynamic integration of a huge

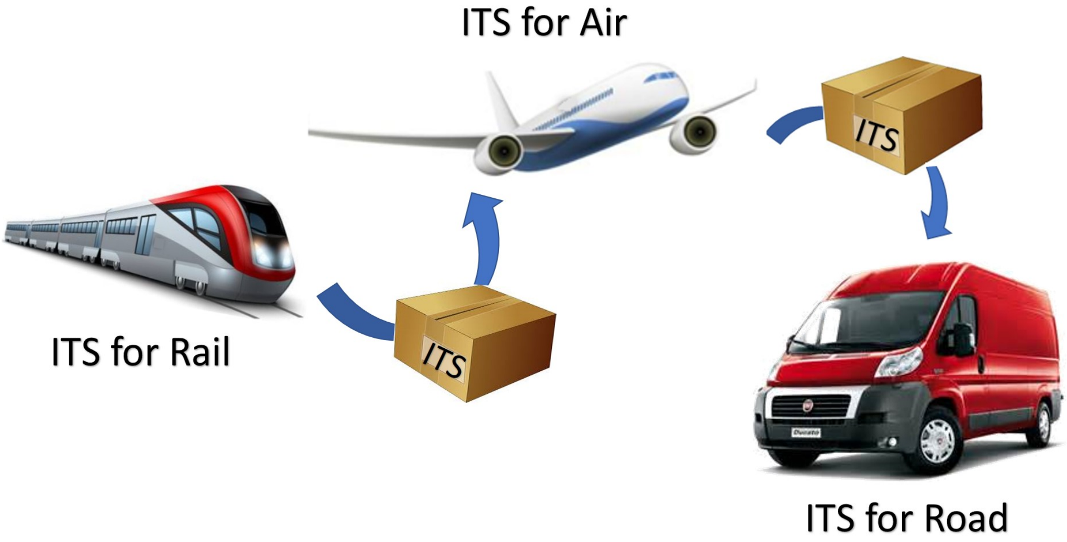


Figure 1.1: Research areas on ITS

amount of information flows is required, and their exchange enabled by ground sensors or other devices, according to the Internet of Things (IoT) paradigm. A moving entity (vehicle) must therefore be equipped with increasingly performing technologies for diagnosing of on-board conditions and accurate localization, and must be able to communicate with each other and towards the network infrastructure.

Although the long-term objectives can be considered quite similar, the various transport domains exhibit quite different behaviors and service requirements that need to be specifically considered at this stage in order to enhance the opportunities for fostering their integration.

Starting from these preliminar remarks, thesis work aims at approaching these three different transport areas through an analysis of the critical issues, the limits of the currently used technologies, the proposal of innovative solutions by exploiting current and upcoming technologies and communication architectures.

The main problems addressed are reported below, for each investigated transportation context: for each of them research activities have been developed and documented, and all include validation through simulations and experimental tests through real devices.

In the railway context the transportation of goods is considered. Currently freight trains are not able to report failures or anomalies on the rolling stock or inside the wagons, because there is no a communication network between the wagons and the locomotive or ground stations. Freight trains are composed upon specific service requests with the possibility of use different types of wagons, depending on the goods to be transported. This up to now has not allowed to install (wired) on-board communication networks, also because the electricity supply is not provided from the locomotive to the wagons.

Furthermore a freight wagons can remain parked in areas for a long time without any supervision and control, exposed to bad weather and tampering risk.

It is therefore necessary to define solutions that can increase the safety of the running trains, avoiding accidents which can be disastrous especially when dangerous goods are transported, and guarantee a constant and efficient monitoring of the wagons, mainly for the phase of train composition which is currently very expensive in terms of time and costs.

In the avionics context, the most advanced surveillance technology currently used is the ADS-B. This technique represented a technological enhancement compared to the previous technologies based on the Secondary Surveillance Radar (SSR), in particular the Mode S (selective) transmission technology: it then exhibits some critical issues in the highly interfered operating environments towards which the avionics is evolving. The introduction of technological innovation in this context is always very slow, because the need to guarantee high levels of safety leads to preferring the use of consolidated systems, which may seem obsolete compared to the constantly evolving telecommunication world.

This thesis deals with the performance analysis of advanced reception techniques for ADS-B signals, in order to evaluate their response and robustness versus high interference levels of around 40000 interferers per second, for which the receivers currently in use would not guarantee the functionality of the system.

Within the transport sector the automotive context is suddenly evolving towards the ITS paradigm. Following a market-driven approach, the vehicle is increasingly evolving towards features that will bring it in the near future to provide a large variety of services to users, besides an increasingly safe, comfortable, efficient and ecological driving. In this work, the vehicular communications topic is mainly dealt with to support traffic flows management processes.

Using the currently available Vehicle to Everithing (V2X) communication technologies, based on the IEEE 802.11p protocol, mobility applications have been designed and tested with particular reference to the management of emergency situations and the optimization of traffic light cycles at intersections.

The most commonly used optimization solutions are based on the information from

cameras, but these systems suffer from false positive and negative detection problems mainly due to adverse environmental conditions. In this work, the possibility of using V2X messages as an alternative information source for optimization has been successfully investigated, overcoming the limitations of the camera-based solution.
Looking at upcoming technologies for communication and accurate localization, a heterogeneous architecture is proposed for the efficient management of commercial vehicles with multi-platform equipment capable of smartly operating in both normal and emergency conditions.

1.2 Research activities and thesis outline

The thesis is organized as follows.

In Chapter II the research activities in the railway sector will be described, about the development of a heterogeneous wireless architecture for monitoring and management of freight trains: it allows to constantly track wagons and trains, as well as to support a real-time monitoring of operating conditions with report of anomalies.
The system has been successfully tested at a prototype level and can represent a scalable and low-cost solution able to increase the safety of running trains and facilitate the management of wagons in the parking areas for the convoy composition phase, thus reducing the management costs.
Starting from the state of the art, the functional description of the system and the implementation processes are provided, along with reports of executed tests. The implementation of the prototype was made through the creation of a real test bench that integrates both short and long range communication devices, as well as a cloud platform for high-level information management.

The analysis activities carried out in this area have produced results in the definition of an architectural low-cost and ready-to-use solution that has proven, in a prototipal way, to be effective to ensure the monitoring of trains and wagons, increasing safety and the efficiency of the freight transport system.

Chapter III describes the activities of study, implementation and validation of enhanced ADS-B reception chains in the avionics environment. Specifically an ad-hoc simulation environment will be presented, designed to test and analyze the performance of the advanced reception techniques proposed by RTCA, over different RF receivers, respectively based on the logarithmic and linear amplification.
An overview of the state of the art and the functional characteristics of the ADS-B

technology will be provided, then a detailed description of the general system architecture and of single blocks of the simulation environment will follow.
According to the simulation results, the hardware implementation of the most performing reception chain was designed, for future prototyping of the system on FPGA platforms.

The original contribution in this field concerned the definition of a better performing reception architecture than those currently in use, in highly interfered environments, based on the performance analysis of the two different RF reception chains and the enhanced detection and decoding techniques of baseband signals. The results obtained are consistent with that of studies carried out by other research teams, and show the possibility of implementing the designed architecture in HW for prototyping.

Chapter IV deals with research activities carried out in the vehicular context, starting from the enabling technologies for connected vehicles with particular focus on the vehicular communication. The main investigations carried out and the mobility applications implemented in simulation environment will be discussed.
Advanced services for traffic management have been implemented and tested in a simulation environment using the current vehicular communication technologies based on the IEEE 802.11p standard.
Particular attention is paid to event-based traffic management applications and the optimization of traffic lights through the use of communication between vehicle and infrastructure.
Regarding the emerging technologies of communication, localization and security, the EMERGE project proposal has been defined concerning the smart equipment of commercial vehicles, involving advanced communication devices and navigation systems, and fleet management through a heterogeneous platform to implement innovative services, for mobility in ordinary and emergency operating conditions. Specifically, vehicles will be equipped with multi-standard communication systems, from those based on the 802.11p protocol to the 5G ones, localization platforms based on multi-constellation satellite receivers (GPS + GALILEO), data fusion with on-board sensors and augmentation algorithms. The network infrastructure will include information gathering and processing centers at different hierarchical and geographical levels, exploiting Mobile Edge Computing and Cloud computing processes, as well as machine learning techniques.

Among the investigations reported in this application context, the main innovations concern the use of V2X information to control intelligent traffic lights and the proposal of a heterogeneous architecture for smart management of vehicles and traffic flows.

Conclusions and future works are drawn in Chapter V.

Chapter 2

ITS for Rail transport Monitoring and management of freight trains

This chapter contains research activities driven by an industrial project aimed at increasing safety and efficiency in railway transport. In particular, the railway transport of goods has been approached, for which a monitoring system has been designed able to constantly check the position of the individual wagons and the running trains, carry out the diagnostics of the mechanical and environmental parameters, send alarms in case of failure or anomaly toward cabin crews or earth stations.

Figure 2.1: Freight rail transportation

2.1 State of the art and aims of research activities

The actions of the European Community in this context provide for the financing of industrial research programs, at medium and long term, with the aim of increasing reliability, efficiency, sustainability, interoperability of the railway system to strengthen its role in the European transport system [1].

The increase of rail transportation for people and goods produces the consequent increase of potential dangerous conditions, that in some cases can become accidents, even fatal, and that are often caused by rolling stock failures or communication problems. In any case, the rail transport is the safest way of land transportation and constantly improves in terms of safety. In detail, most accidents are caused by human behavior and external factors respect to the railway system, such as the level crossing accidents, while a percentage of around 16% is referable to technical or management failures whitin the railway system itself [2].

With particular reference to this kind of accidents, the IoT (Internet of Things) will be fundamental for the development of future rail transportation. Secure, relatively low-cost and highly scalable innovative solutions can be realized in order to achieve the constant verification of the rolling stock conditions, trains tracking and the detection of any dangerous situations up to return the related alarms, in automated way, or assisted [3]. Specifically, increasingly efficient on-board sensors will be used to monitor the mechanical and environmental parameters, connected to each other through short-range wireless technology in WSN, advanced localization systems will be involved, mainly based on satellite tracking, as well as large scale communication systems for information exchanging and data processing.

Currently it is not possible to detect and signal in real time a fault or anomaly within a freight train, since there is no data connection between wagons and to the stations. The transport of goods requires that a train can be composed of different types of wagons, each of them with different physical characteristics and subjected to different risks, depending on the transported goods. Furthermore a freight wagon is typically neither provided with autonomous power supply sources nor it receives electricity from the locomotive. The control of mechanical parts and sensitive parameters is manually made by staff on board or at stations during stops.
Another problem for freight wagons is that they may remain parked for long periods under bad weather in different places, unattended and with the risk of tampering.
Nowadays there are no integrated systems that allow both to constantly monitor the status of freight trains (or single wagons) and to manage them efficiently, in particular in train composition phase, which currently leads to a great expenditure of time and personell resources, therefore of costs.

Feasibility studies and prototype solutions are in progress regarding monitoring and signaling along the railway section, which aim to prevent dangerous situations due to accidents, malfunctions or line faults; at the same time there are commercial proposals and projects under development that concern the real time control of internal train parameters.

To achieve these goals, the research activities are increasingly focusing on the use of wireless technologies.

In particular the use of WSNs, properly integrated with mobile networks, represents an already proposed solution to solve the problem of monitoring and early detection of anomalies and failures in railway transport [4], [5], [6]. The WSN solution is useful both in cases of railway infrastructure monitoring, through the use of sensors along the railway line at fixed points, e.g. bridges or tunnels, and for diagnosis of wagons to prevent breakdowns and to signal tampering [7], [8]. The use of short-range wireless networks is very suitable for this type of application as it allows the creation of a highly capillary and low-cost monitoring infrastructure, able to meet the real-time requirements needful to guarantee possibility to carry out corrective actions due to malfunctions or unwanted events. Moreover the WSN usage guarantees to setting up a diagnostic network as independent as possible from the energy sources directly connected to the rolling stock; for this reason it is therefore necessary to apply power management policies to guarantee low consumption and a long battery life, as well as innovative techniques for batteries recharging [9], [10].

Regarding the monitoring of environmental and mechanical parameters on board the train, we are moving towards standardized solutions for physical implementation, which provides for different sensors for monitoring the internal status of each wagon, connected to a local network element able to communicate with a remote control center through long-range networks. A typical architecture involves the use of distributed sensors for monitoring of railway facilities and infrastructures with wireless data transmission (via e.g. WiFi, Zigbee, Bluetooth) from sensor nodes towards a base station. Data are then collected and forwarded to a control center server by means of satellite or terrestrial mobile networks. There are several example of this architecture, such as those proposed in [11], [12].

Effective monitoring processes are even more important in cases of transportation of dangerous goods, as documented in case studies addressed in [13], [14].

The recent development of IoT systems and Machine-to-Machine (M2M) devices has evidenced how the combined use of sensor nodes, in a WSN architecture, and Cloud platforms can represent a highly performing solution for security systems [15]. Indeed the Cloud connection greatly simplifies the remote access to data, allowing high-capacity and real-time processing and the possibility to return alert notifications.

An integrated architecture is presented below as a scalable solution able to realize the real time localization and monitoring of freight trains in order to prevent accidents and manage wagons in efficient way.
Specifically, the proposed overall architecture includes the combined use of i) M2M devices, ii) WSNs for data collection, on-board communications and data exchange in parking areas, iii) Mobile network for long range communications iv) Global Navigation Satellite System (GNSS) technology for tracking the position of trains and single wagons, v) Cloud platform to manage integrated data, to detect anomalies and notify diagnostic information to on board staff or to ground stations, depending on priority and responsibility.

2.2 Functional requirements and system architecture

2.2.1 Functional characterization of system components

The research activities described in this section are part of an industrial project aimed to improve the wagons handling and increase safety for moving trains with respect to mechanical problems and risk factors related to the transported goods.

In particular, regarding the parked wagons, a centralized management processes has to be implemented, through the constant classification and tracking of them, in order to reduce times and costs, in particular in the train composition phase. About the safety of running trains, a monitoring network has to be realized, able to diagnose any anomalies or failures and communicate them in real time to the cabin crew or toward the ground control center to perform the specific countermeasures. Therefore sensor nodes are needed for the diagnosis of mechanical and environmental parameters, communication systems for information exchanging at short and long-range, local elaboration elements and a remote one to analyze data in integrated way. The application context itself leads to consider a centralized solution for management of information by a remote entity which has to be able to receive information, at any time, from all wagons.

By considering that at functional level the entire fleet can be seen as a set of trains and single wagons, such as each train can be represented as an orderly sequence of wagons, the implementation of the monitoring system must refer to a hierarchical structure.
Taking into account the power consumption problems related to the on-board sensors,

the generic wagon must be equipped of sensors with limited processing capabilities, while the locomotive must have more performing devices able to manage the information flow of the entire train, such as the local elaboration center of parking areas. All information of each wagon can be delivered toward the Remote Elaboration Center (REC), but the implementation logic envisages different paths for information flows according to different monitoring processes, depending on the alert level and energy management policies.

According to these remarks, below is the characterization of individual system components of the functional architecture:

- **Wagon**
  - represent the basic element to which the monitoring processes are applied;
  - it must refer to a unique identification code;
  - it must be equipped with on-board sensors and processing equipment that allows to check its operating status; the kind of sensors depends on the transported good and therefore from the physical characteristics of the wagon;
  - it must be constantly localized (able to send its geographical position toward the REC);
  - it must always be in radio connection with a local elaboration element and the REC to exchange data relating to surveillance processes and service information regarding the system configuration;
  - in case of anomalies, it must be able to communicate promptly the alarm toward the local elaboration element and the REC.

- **Train**
  - at logical level it can be described as an ordered sequence of wagons that the REC can see as a single unit of which the correlation properties between the internal elements are known, in terms of physical connection and communication; - it must refer to a unique identification code;
  - it must always be in radio connection with the REC to exchange data relating to surveillance processes and service information regarding the system configuration, both as integrated element and as individual wagons composing the convoy;
  - it must be constantly localized. To localize the train the locomotive positioning data can be considered. To realize a more accurate tracking we can also take into account the integration result of the locomotive position data and of the last wagon one, which can also be used to constantly verify the integrity of

the train;
- it must be equipped with a local elaboration center that manages the monitoring information of single wagons, handling data flows with different characteristics due to different sensors equipment of wagons.

- **Parking area**
  - at logical level it can be described as a set of elements without a specific correlation between them, in terms of physical connection and communication;
  - it must refer to a unique identification code and has to be equipped with a local elaboration center that manages the monitoring information of single wagons, handling data flows with different characteristics due to different sensors equipment of wagons.

- **Remote Elaboration Center (REC)**
  - represents the remote link between the different elements of the system, in terms of communication and processing, with a global view of the entire wagon and train fleets, both parked and traveling;
  - it must have high elaboration capabilities and direct communication skills with all network elements;
  - must process the information in a static and dynamic way, providing both an instantaneous data elaboration and a predictive analysis based on historical results of previous elaborations for the different variables associated to physical phenomena;
  - must have in memory the dynamic classification of the individual wagons, in terms of physical-mechanical parameters, transported goods, service status;
  - must support the train composition processes and manage network reconfiguration following changes in the status of single wagons or malfunctions;
  - must manage any anomalies detection through communication and signaling processes towards the convoy control booth and more generally towards all the emergency management units.

With respect to this classification each wagon must have the same connectivity and processing features and can connect with two sink network elements of different hierarchical levels, respectively in short and long-range network configuration. Depending on the operational status of the individual wagon, on the role of its specific processing and communication unit in the short-range network, on the alert level, the information flow follows different paths according to the energy management policies. Nevertheless, the availability of two communication interfaces produces redundancy in order to increase the system robustness.

When the wagon is parked and not assigned to a specific train, it will communicate only through the long-range network in scheduled mode to reduce power consumption. When the train is composed, all the associated radio units will activate the short-range communication interface in order to communicate frequently with the local elaboration element. In specific operating scenarios it is possible to activate simultaneously both the communication interfaces.

2.2.2 Control Units classification

According to the above functional description, each freight wagon must be equipped with a Control Unit (CU), which is connected to on-board sensors, has elaboration features, long and short-range communication abilities, GNSS receiver for positioning. This equipment guarantees an adequate level of flexibility of the system since each wagon can be managed as an independent entity.
The **CU** is described according to the following requirements:

- it refers to a single wagon and must be provided with a unique identification code;
- it stores and updates the operating status of a wagon (in rest area or in running mode) and can act as coordinator for the short-range network segment (local elaboration element);
- it must notify each status change to facilitate the network reconfiguration processes;
- it determines the wagon geographical position and makes it available to other elements of the system, such as the REC;
- it is connected to on-board sensors and is able to read measurement on the related interfaces;
- it elaborates measurements and periodically sends reports through short or long-range networks based on its own functional hierarchical level;
- it promptly notifies anomalies following an event-based approach;

- it can be reconfigured in terms of operating system update, short-range network routing configuration and port settings, by both local and remote management elements.

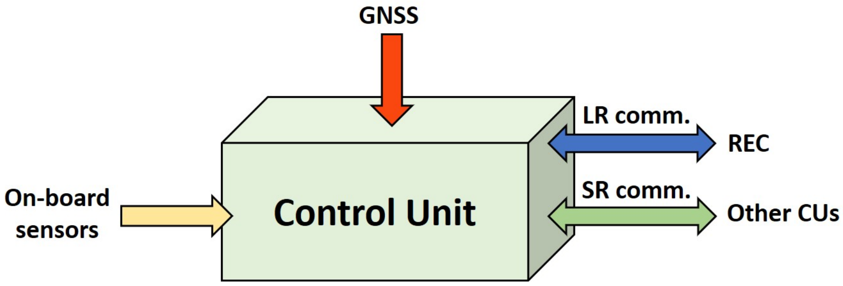


Figure 2.2: Control Unit

To make the management architecture scalable, all CUs must have the same equipment in terms of elaboration and communication, but different functional characteristics according to their hierarchical level.

With reference to the characterization of individual system components the classification of the different control units is described below:

- **Generic Control Unit (GCU)** - it represents the generic node of the short-range network attached to a network coordinator (on-board or in parking areas depending on the operating scenarios). In normal operative conditions it collects measurement data from sensors and sends parameters or pre-elaboration results through the short-range wireless interface towards the coordinator. It is able to communicate directly with the REC through the mobile network in cases of anomaly detection or system reconfiguration.

- **Engine Control Unit (ECU)** - it is the GCU of the engine wagon (locomotive) able to communicate with all GCUs associated to the train wagons through the short-range network acting as network coordinator. It is constantly connected with the REC over mobile network for service communication and information exchange about the train status. The ECU is associated with the locomotive because it needs for constant power supply.

- **Parking Area Control Unit (PCU)** - it is the network coordinator element of parking areas, able to communicate with all GCUs associated to a parked wagons. It is constantly connected with the REC over mobile network for service communication and information exchange about the set of wagons belonging to its short-range network.

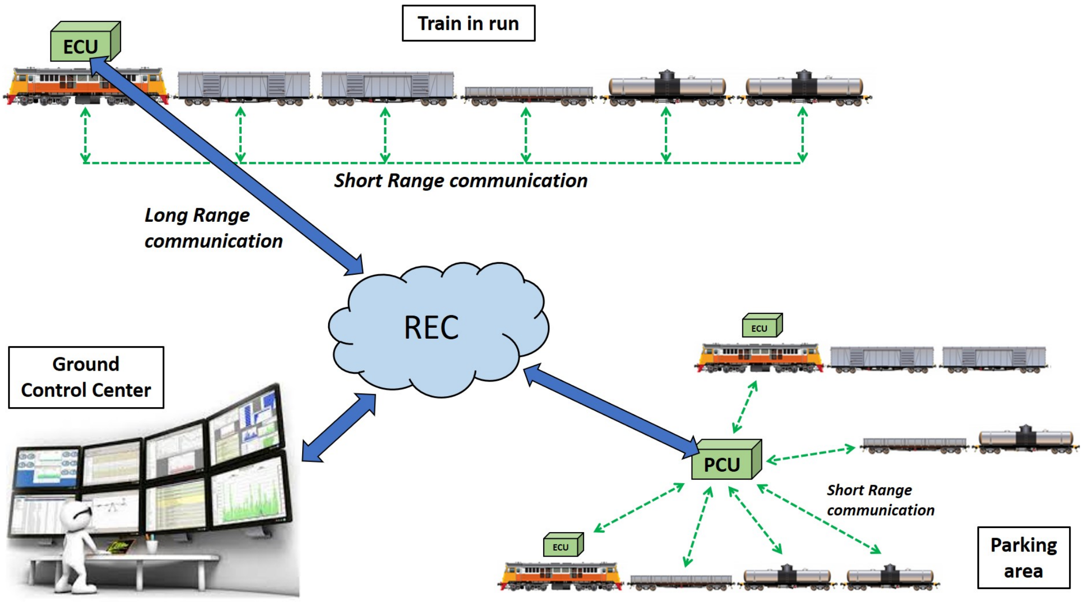


Figure 2.3: System architecture

The GCU must be shape to operate both in running trains and in parked wagons, with different requirements for report timing and information priority, as well as two wireless interfaces available for communication.

In case of parked wagon, the GCU has to be connected to a PCU coordinator (Fig.2.3), which collects data with low update rates. As long as the coordinator is connected with every entity in direct radio visibility, the logical position of the wagon in the short-range network topology is not a matter. Instead within big rest areas several coordinator units might be required, or multi-hop transmission techniques in order to overcome no radio visibility issues. When dealing with transmission timing and power saving for parked wagons, the target of six years of battery life is a qualifying feature, because this is the standard maintenance time interval for freight wagons. Therefore, in case of empty wagons only the geographical position and a few other parameters have required to keep under control, with low update rate.

In case of running train, the GCU associated to a specific wagon has to be connected to the ECU coordinator (Fig.2.3) to whom send reports with high update rate. In this case the GCU position within an ordered sequence of nodes is also relevant for supporting the train integrity monitoring. The transmission rate must be higher if compared to the previous case, because all monitoring and localization functionalities must always be simultaneously active. It will be necessary to use external power sources for battery recharging due to the higher energy consumption of devices.

In the intermediate phases concerning train composition and disassembly, the REC support is fundamentsl to manage attachment and detachment procedures of each GCU with different short-range networks. Therefore it is essential that each GCU has a wireless interface that enables direct long range communication with the REC.

2.2.3 The role of the short-range network

The WSN represent an efficient, consolidated and relatively low cost solution, for continuous monitoring of wagon parameters and autonomous data collection.
Assuming to have a short-range network with multi-hop communication support, with reference to the functional requirements of the system, two different configurations for the short-range network can be considered, with reference to the operating status and the physical connection between the wagons:

Logical topology coincident with the physical topology: all nodes are positioned along a mono-dimensional topology starting from the coordinator (e.g. engine wagon) till the last node (e.g. last wagon). The communication between the coordinator and each wagon is supported by retransmission through all intermediate nodes on the specific route. This solution is intrinsically suited to support the integrity monitoring of the train, as the presence of a physical connection guarantees the logical integrity of the related part of the train (Fig.2.4-a). A drawback of this alternative is represented by the high energy consumption of nodes, because none of them can be put in sleep mode because of the constant involvement in relaying of messages.

Mixed logical topology: the coordinator establishes direct connection with nodes in radio visibility and resorts on multi-hop transmission only for connections with nodes outside the radio coverage range (Fig.2.4-b). In this case more efficient energy operations can be envisaged for the generic node. An obvious drawback consists in the inability to use the single hop physical link as a direct indicator of the train integrity.

For monitoring process implementation in parking areas it is not important to know the logical connections status between the individual nodes and the coordinator. In this case the selection of the coordinator by any single wagon is a main topic, e.g. through the RSSI parameter usage

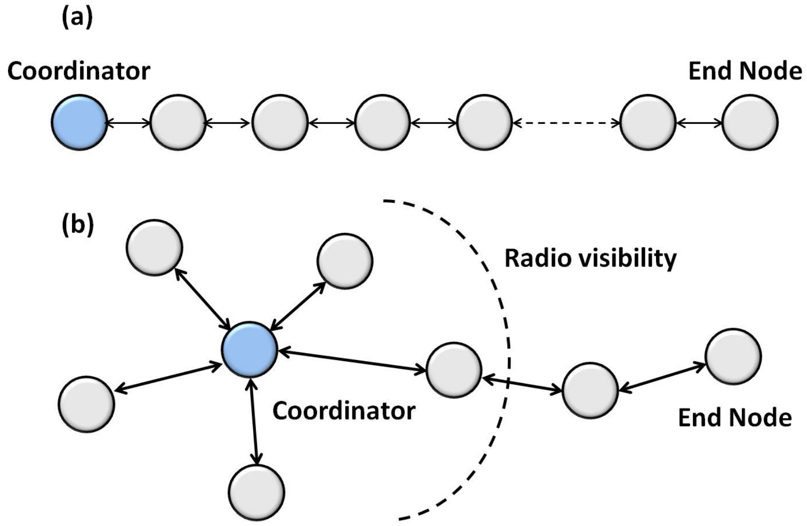


Figure 2.4: Short-range network topologies

2.3 On-board sensors overview

For these activities no real on-board sensors were used, but these were simulated through the random data transmission on the standard I/O interfaces of the local elaboration modules. Despite this in view of the future development of the system we must take into account of possible type and number of active sensors for each CU in the different operating conditions, also in order to estimate the average consumption of devices respect to data size and transmission timing. For real time monitoring of freight trains and railway infrastructures, we need to refer to both mechanical and environmental parameters. Therefore it must be taken into account that this involves the simultaneous use of a multiplicity of sensors which differ from each other for physical characteristics, as well as from an electrical point of view in terms of output levels, sensitivity, response times in relation to the speed of the specific phenomenon, and so on.

Generally the WSN sensors used in the railway context measure environmental parameters, such as temperature and humidity, and at the same time monitor vibration, acceleration, and mechanical stress mechanisms [16]. Specific solutions must be implemented for the locomotive, whose diagnostics must include the use of sensors dedicated to monitoring the functional parameters of the engine block.

The monitoring system should provide that each individual wagon is equipped with a basic equipment consisting of a set of sensors for the diagnosis of mechanical parameters, in addition to specific sensors related to the type of wagon and the transported goods. Each wagon can have a heterogeneous equipment and this means that the CUs must be able to exchange to each other different kinds of information and elaborate them in integrated and scalable way. The choice of the devices may depend on different factors, starting from the physical characteristics, like dimensions and robustness, up to the detailed specifications regarding the sensitivity and the electrical output parameters; in this context the energy consumption characteristics are fundamental, especially considering the WSN networks.

Taking into account that one of the most critical factors, regarding the safety of freight transport, is the diversion of one or more carriage axes, it is necessary to promptly verify any deviations from the normal operating conditions and quickly report the anomalies to the cabin crew to favor the timely counteract measures. About it a key role is played by the accelerometers, components widely used because robust, reliable and economical; their usage allow the diagnosis of different parameters by integrating multiple modules placed along the train structure or on single wagon.
In addition to the accelerometers, there are other widely used types of sensors that guarantee high performance and are particularly suitable for these applications.

Fiber optic sensors, for example, represent a very useful tool for monitoring parameters such as temperature, accelerations, deformations, returning wavelength variations as a function of the physical input variable; compared to traditional electrical or mechanical sensors, they have a high resolution (ability to detect very small variations in the measured size), dynamics (large detectable variation range), measurement accuracy and are immune to electromagnetic interference.

Piezoelectric sensors, whose output signal is proportional to them compression level, appear to be very robust, stable and suitable for the structural monitoring of rolling stock. Other types of sensors useful for train or wagon monitoring are the gyroscopes, ideal for measurements of angular speed around the axes (longitudinal, lateral and vertical accelerations) and extensometers, which represent an economic, simple and accurate solution for the detection of mechanical deformations.

An important aspect, especially when considering the dangerous goods transportation, is represented by the possibility of real time reporting of intrusions or tampering events on wagons; typical solutions are based on the use of motion sensors and door opening, also through the detection of light intensity [17].

The classification of the wagons, in terms of equipment, may start from their physical structure, in particular distinguishing between those for transport of general goods, typically closed with side loading and unloading doors, and open wagons dedicated to transporting mainly of goods that can be loaded from above, such as tree trunks or building material. With respect to this pre-classification, there are different application scenarios in which the closed wagon must necessarily be equipped with sensors that monitor the mechanical parameters and the internal environmental ones (the number of sensors varies according to the type of goods) as well as anti-intrusion sensors; the open carriage does not require the use of environmental sensors.
In the case of dangerous goods transportation (e.g. tank wagons) the single wagon must be equipped with basic monitoring devices for the mechanical part and a set of sensors for diagnosis of specific potential risk factors.

2.4 Communication and sensing technologies

Telit devices and platforms have been used for the development of the system prototype, because they perfectly match the required system specifications. In detail, processing and communication devices, both over short and long-range wireless network, have been used for the implementation of the CUs, as well as the Telit IoT Cloud platform, with functionalities of REC, for remote collection and processing of aggregated data, as well as the alarms management. The choice of short-range devices was made on the basis of the declared coverage range and the possibility of using multi-hop communication with a logic star topology, suitable for meeting needs of train monitoring. In addition, the interest of the industrial partner was to have a complete test of an integrated solution through a set of ready-to-use and relatively low cost platforms, with the possibility of connecting them to each other and with a cloud management platform; this possibility was offered by Telit.

Without taking into account the on-board sensors, that were not the subject of these activities, each CU has been implemented through these two devices:

- **Telit GE910-GNSS**:
  processing platform equipped with GSM/GPRS transceiver and GNSS detector (GPS + GLONASS optional);

- **Telit LE70-868**:
  module with limited processing capabilities and enabled for transmission on the g3 free band (868 MHz) for short-range radio communication.

For prototype development and testing on these devices, the EVK M2M AIR board has been used for the GE910 interfaces management, the Star Network Demo Kit for LE70-based applications.

With reference to the system functional specifications a basic structure of the generic CU was outlined, in which the GE910 has been used for interfacing with the on-board sensors, the basic elaboration processes and the transmission of data, including those relating to the geographical position, toward the REC via GSM/GPRS network.

The LE70 module has been used for information exchanging among the CUs in WSN network.

The following is a description of the Telit devices with particular reference to their usage into this specific applied scenario; in particular, the configuration modes of the LE70 modules are discussed to implement the short-range network in order to cover the entire train length, with an in-depth analysis of the Smart Repeater mode which results to be the most suitable to guarantee maximum coverage with reduced consumption.

2.4.1 Telit GE910-GNSS

The GE910 represents the brain of the CU, able to collect sensors data of the wagon and process them in a preliminary way, calculate its geographical position and communicate with the REC on Cloud over mobile network via the M2M SIM, or over the local wireless network through the connection with the LE70 module.

The GE910-GNSS is a M2M module with processing and GSM/GPRS communication skills, as well as GNSS functionality (optional GPS + GLONASS) enhanced by assisted localization through the mobile network [18]. For future developments of this work, and with reference to the estimation of the data flows to be managed that will be more and more, it is worth considering the opportunity to replace this module with its subsequent versions based on the modern technologies for mobile communication (e.g. the HE910, UMTS module with only GPS proprietary receiver). The device is equipped with an ARM11 processor and is configurable through management scripts and applications that can be implemented in python or through the Telit

AppZone platform, using Telit AT commands. It is possible to modify the internal configuration of the module also remotely by the Telit IoT platform.

To create and test the specific applications on GE910 the EVK2 M2M AIR Evaluation Kit was used, which represents a complete development environment composed by motherboard and an adaptive platform on which to insert the specific interface board (in this case the GE910-GNSS interface board) [18].

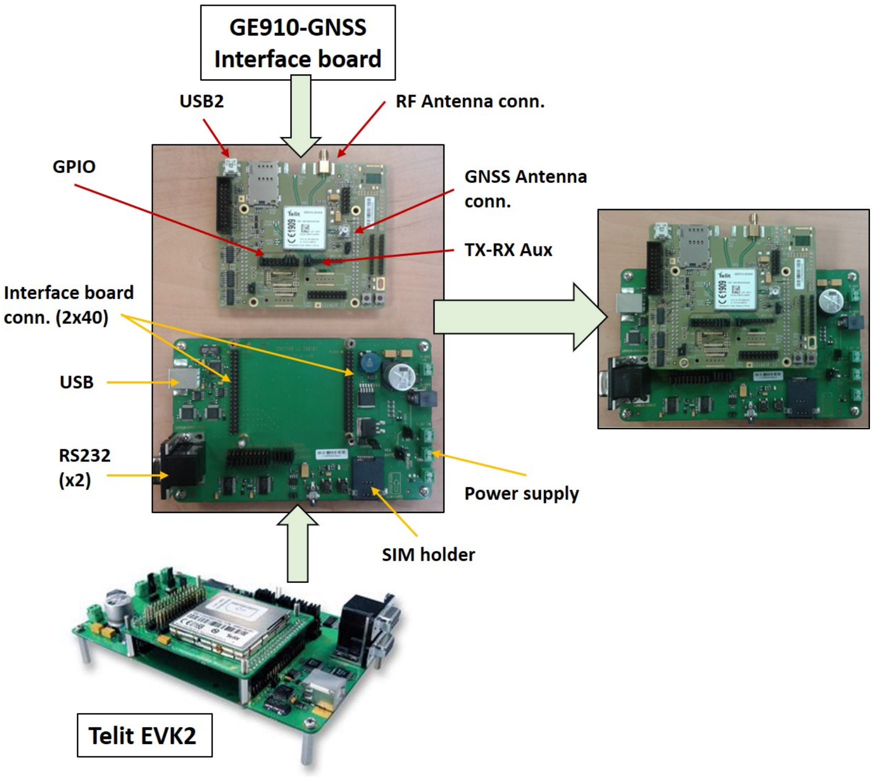


Figure 2.5: Telit GE910-GNSS

2.4.2 Telit LE70-868

The module implements the short-range communication capability of the CU allowing the information exchange with the local elaboration center (ECU or PCU), or more in general with other CUs. Therefore the LE70 represents the communication bridge between the GE910 module of the CU, connected to it via serial interface, and the GE910 of other CUs over local wireless network.

The LE70 platform belongs to the Telit xE70-868 product family, it is a multi-channel radio board enabled to transmit in ISM band at 868 MHz, up to 500 mW, and characterized by the implemented protocol stack which provides a star topology

of the logical network. Actually it can be configurable to work according to different operating modes, among which the most suitable one for applications related to the aims of the project seems to be the Smart Repeater mode.
The 868 MHz ISM band transmission was subject to limitations in terms of bandwidth, power, duty cycle and spacing between the channels, described in [19] (evolved in [20]).

The module is a complete solution from serial to RF interface and consists of the RF interface (transmission on a bidirectional link in half duplex) and of a digital module on which the Telit management software is loaded, related to the star network protocol stack. The emission power is configurable in the range 15-27 dBm.

The DemoKit has been used (composed by the LE70-868 module, development board, antenna, USB connectors and battery) to test the module functionality and develop the applications. The technical specifications about the LE70-868 and the Demokit can be found in [18].

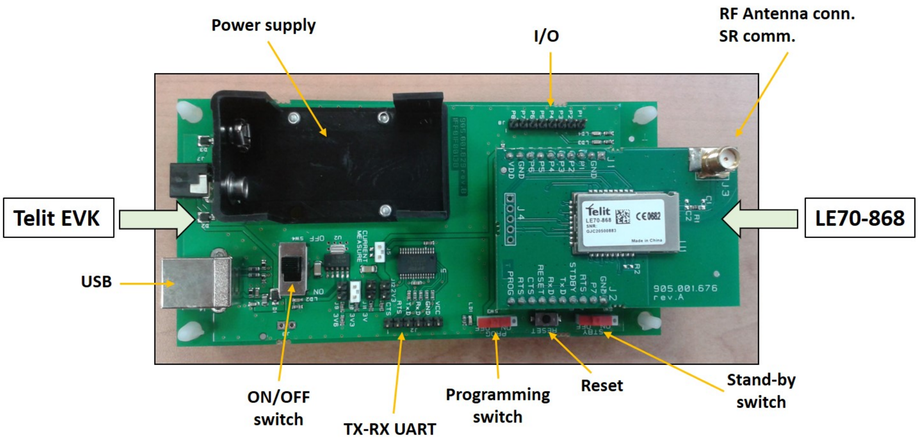


Figure 2.6: Telit LE70-868

2.4.2.1 Telit Star Network protocol

The Star Network protocol stack provides access to the module in:

- *Configuration mode* for setting of internal parameters (firmware version, register status etc.) and management of node resources. The configuration mode is implemented through Hayes AT commands via serial port or remotely. To access the module via radio, it is necessary to know the 11 characters of the serial code, as well as the radio configuration of the destination node in terms of bandwidth, channel and data rate.

- *Operating mode* for setting of network structure in terms of data transfer at logical/application level.

In Operating mode the following communication protocols are available:

- **Transparent mode**: is the default communication protocol that allows the sending of information without encapsulation and addressing;
- **Addressed secured mode**: each module can communicate with all the other elements of the same network, as long as in radio visibility. All the frames are addressed and validated through CRC (Cyclic redundancy check) code in reception phase, the acknowledgment is provided; address 0 is defined as a broadcast address. This mode is heavier from the processing point of view in transmission than the transparent mode, therefore allows the sending of frames with a maximum size of 240 bytes. Telemetry commands is envisaged to monitor accesses to network and the status of the nodes;
- **Smart repeater mode**: represents an extension of the addressed mode; allows multi-hop communication between a coordinator and external nodes, even if not in direct radio visibility, and allows the exchange of data and telemetry packages between the coordinator and the respective nodes. On a functional level, the coordinator can be seen as the central node of a star topology since there is no direct high-level communication between two generic network nodes.

In addition to these three operating modes, the following additional features can be implemented:

- *Listen Before Talk*: to avoid collisions on the radio link, the generic module ready to transmit listens for the channel and checks that there are no transmissions in progress by other nodes on the network; this functionality is provided for transparent and addressed modes;
- *Wake on Radio*: the sleeping mode node periodically listens to the channel for a few milliseconds to check for transmissions to be processed; if this condition occurs, the node activates and decodes the message, otherwise it returns to standby mode until the next scan of the radio link;
- *AES Encryption*: possibility to send encrypted data in protected mode according to the 128 bit Advanced Encryption Standard (AES) algorithm with customizable encryption key. Available only in Addressed secured mode.

2.4.2.2 Smart repeater mode

Among the different operating modes provided, the most suitable for the required application is the Smart Repeater mode, through which it is possible to create a multi-hop network with one central node (coordinator) and multiple generic nodes.

The coordinator is authorized to communicate with all the nodes of the network, even if not in direct radio coverage, through the use of the intermediate ones. The Smart Repeater mode provides the network subdivision in branches and sub-branches (optional). A branch is defined as a sequence of nodes that refers to the coordinator, a sub-branch is a sequence of nodes that starts from a non-coordinator node; two contiguous elements of branch or sub-branch are in direct radio visibility.
In Smart Repeater mode it is possible:

- send frames from the coordinator to each node of the network;
- send frames in broadcast from the coordinator to all the nodes of a branch and sub-branch;
- send frames in broadcast from the coordinator to all the sub-branches of a particular node;
- send frames from each node to the coordinator;
- send frames from each network element to itself.

The frames exchanging between two generic nodes of the network, of which one is not the coordinator, is not allowed.

In the setting phase, each node is assigned a particular position within the network used to define the logical paths followed by the information from the generic node to the coordinator and vice versa.
In case of problems that prevent the transmission of information between two contiguous nodes, the Smart Repeater protocol supports network redundancy and is able to re-establish the virtual link through the node immediately following it; this is possible only if this node is in radio visibility with the coordinator.
The routing table for the single network node contains the following information:

- Mode: indicates the operating mode of the node. Specifically, the Smart Repeater mode assigns a value 10 when the node is indicated as a coordinator, 11 in the case of a generic node;
- Branch-ID: branch identifier, of relevance exclusively for generic nodes;

- Node-ID: node identifier;
- Node-2 ID: identifier of the node of upper hierarchical level, in terms of hop number towards the coordinator, of 2 virtual positions;
- Node-1 ID: identifier of the generator node, placed a forward hop in the path toward the coordinator;
- Node+1 ID: identifier of the child node, placed a hop back in the path, on branch or sub-branch, towards the coordinator;
- Node+2 ID: identifier of the node placed two hops back in the path towards the coordinator;

In the same way the routing table of the coordinator is configured, which shows the identifiers of the nodes (maximum 2 for each main branch) placed at a distance of 1-2 hops from the coordinator for each path. A maximum of 16 branches can be created for each coordinator.

Therefore, in this operating mode each node is directly aware of the network configuration around itself up to a maximum distance of 2 hops; the fixed path of information and the lack of possibility of data exchange between generic network nodes, allows communication between the coordinator and external nodes of the network even in the absence of direct radio visibility using multi-hop transmission.

In Smart Repeater mode it is possible to directly control the I/O interfaces of each remote node by the coordinator through the exchange of telemetry messages; it is also possible to detect incoming events on the node interfaces and manage reports sent automatically by the module to the coordinator, in order to facilitate the monitoring of the event itself. This is implemented through a transmission protocol parallel to that relating to data exchanging.

Based on the transmission specifications of the LE70 module, which have been the subject of preliminary tests proposed below, the radio coverage of the WSN network of the entire train would be guaranteed by all the proposed operating modes. In particular in Smart repeater mode the possibility of transmitting in multi-hop can allow to strengthen the on-bord communication processes and at the same time to verify the train integrity, as well as to reach greater coverage than the radio visibility of coordinator for large parking areas.

2.5 Functional tests on communication devices and platforms

Before approaching the system implementation, preliminary tests were performed on the technical and functional characteristics of the processing and communication devices, as well as of the IoT management platform, in order to verify the real potential with respect to the reference application context. Before going into the discussion of the preliminary tests, the following is a list of the main devices and platforms used to implement the system, without considering the standard laboratory equipment:

- 4 LE70-868 with development board;
- 4 GE910-GNSS with evaluation kit;
- Telit IoT platform.

2.5.1 Preliminary tests on short-range communication devices

The preliminary tests carried out on the LE70-868 devices concerned the functional verification of the different communication modes and the additional features, as well as the coverage capabilities and power consumption aspects.

2.5.1.1 Operating modes and additional features

These tests aimed to verify the correct implementation of the different WSN network configurations and the additional features of the LE70-868 devices. To verify that the module features were in compliance with the system specifications, the configuration processes was also tested both via the serial port and remotely without using the Telit software; this to test the possibility of reconfiguring the network dynamically, following a change in the operating conditions of the wagons. The first phase of the tests involved the use of the dedicated Telit software for the LE70-868 modules configuration and the implementation of the short-range network in the transparent and addressed operating modes. The messages exchange between the various network nodes was performed, for verification of connectivity and correct reception with varying of distance and emission power, without implementation of the additional functionalities.

Subsequently, the network has been configured in Smart Repeater mode and, like

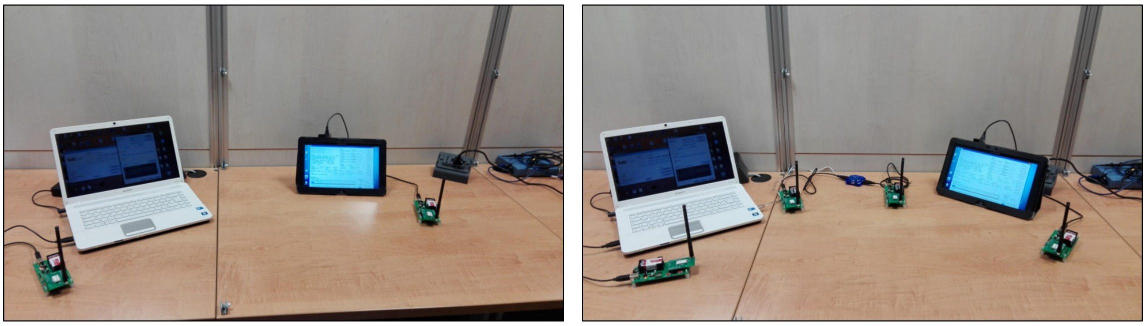


Figure 2.7: Short-range network configuration

in the previous case, real time transmission tests were carried out at different distances and emission powers. In this case, particular attention was paid to verifying the achievement of distances greater than the normal radio coverage (to the specific emission power) by relaying messages via repeater nodes in multi-hop transmission.

At the end of the preliminary analysis on the short-range network protocols, the set up of basic control units have been realized by connecting LE70-868 and GE910 modules through serial standard connectors using the evaluation boards, in order to evaluate the possibility to reconfigure the operating system and network parameters of LE70 devices, both via serial port and remotely. In a master-slave functional logic between the GE910 (Master) and the Le70 (slave) for the individual control unit, Python scripts have been created, consisting of sequences of AT commands, in order to modify the internal parameters and network settings of the LE70, both via serial connection from the GE910 and remotely via other short-range network elements. Furthermore the sending of messages on the short-range network was performed, to simulate the sending of sensors parameters with different transmission profile for each unit. The last test phase involved enabling and verifying the correct implementation of additional functions, with particular reference to the standby and LBT modes, both configuring the devices with the dedicated software and using a python configuration scripts. In particular, the LBT was tested for random waiting time, for different sensitivity levels for listening the channel and the message retransmission was verified in case of busy radio channel.

All the basic functionalities of the LE70-868 devices have been successfully tested. The results have confirmed the Smart Repeater mode as being the most suitable to be used in this context, thanks to the possibility of multi-hop transmission which guarantees robust communication and greater radio coverage. On the other hand it has been verified that the Smart Repeater mode is not compatible with the imple-

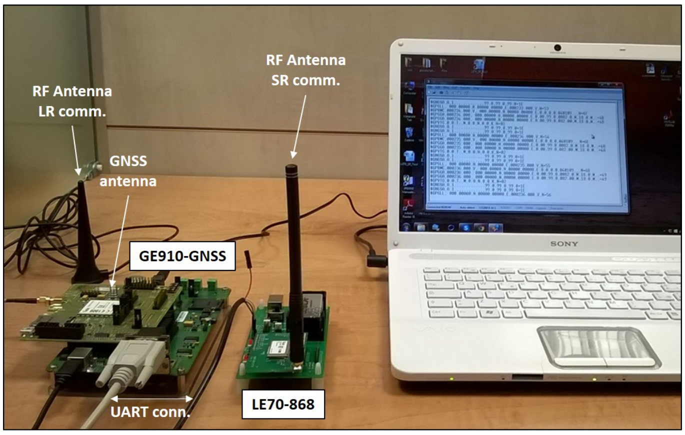


Figure 2.8: Short-range network configuration by means of GE910-GNSS

mentation of the additional features, such as the standby mode. Therefore, to use this operating mode it will be necessary to design efficient transmission profiles for short-range communication devices, in order to guarantee an adequate battery life.

2.5.1.2 Radio coverage ranges

In order to assess the transmission capabilities of the short-range devices, communication tests were carried out in different operating conditions, depending on the environmental context, on the distance and emission power. The radio coverage tests, with the exception of those relating to the Smart Repeater mode, were performed via point-to-point communication between two modules enabled to operate in transparent mode.

Starting from the assumption that the reference operating environment, in case of on-board communication, is highly interfered, the transmission capabily of the LE70 devices in different real contexts have been verified in order to estimate the minimum coverage range at maximum emission power. These tests were classified according to the following operating conditions:

- *indoor* communication, where both transmitter and receiver were inside a building;
- *indoor-outdoo*r communication, where the transmitter was inside a building and the receiver was in an open environment;
- *outdoor* communication, where both transmitter and receiver were in open environment.

The single test is based on the sending of test strings and the verification of correct reception (100% of characters) of messages at different distances and emission powers. The test execution mode, regardless of the type of reference operating context, included a sequence of test message transmissions, for different distances and emission power between +7 and +27 dBm.

The first connectivity tests have been carried out *indoor* within a building owned by the University of L'Aquila, which has characteristics of an industrial plant distributed on two levels for a total size of about 90 x 45 m per floor. The tests were carried out from all the extreme points of the building towards the receiver (RX) placed inside a room on the second floor (Fig.2.9).

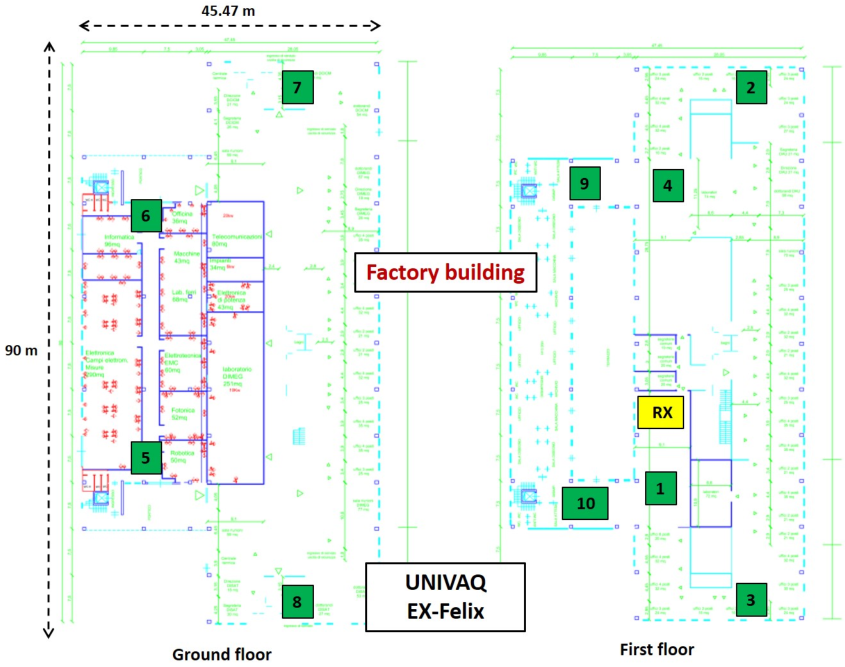


Figure 2.9: Radio coverage tests in case of indoor communication

The second series of tests involved according to the *indoor-outdoor* use-case, have concerned the connectivity with a fixed receiver placed inside a building and the transmission terminal moving outside. For obtain reliable results, the tests were carried out in two different environmental contexts under the same conditions, respectively the industrial area of L'Aquila, with RX located in the same building of the previous tests (IN-OUT1), and the village of Cocullo (AQ) with RX placed in a masonry house in a rural context (IN-OUT2).

The results are reported below, respectively in Fig.2.10 those concerning the IN-OUT1 test, while in Fig2.11 those relatet to the IN-OUT2.

Figure 2.10: Radio coverage tests in case of indoor-outdoor communication (IN-OUT1)

The last set of tests concerned the *outdoor* operating conditions (OUT), and was performed near a road route in a large flat area in L'Aquila, suitable for testing at long distance with almost total absence of obstacles.

The indoor coverage test gives a result of total reachability within the structure at the minimum power (+7 dBm). The coverage maps show how without relevant obstacles, the maximum range (at +27 dBm of power) is about 2.7 km in open environment.

However, the most indicative set of tests can be considered that related to the indoor-outdoor cases, since it is representative of a situation closer to the operating scenario on-board the train in terms of interfering conditions.

The trend in the coverage ranges highlights, on the one hand, the high transmission capabilities of the LE70-868 at maximum power in open space, on the other hand the consistency of the results for the two indoor-outdoor tests, despite having been carried out in very different environments in terms of orographic and urbanization characteristics. Considering that the maximum length of a freight train is about 600 m, it can be said that at 27 dBm of transmission power we can realize the on-board network using these devices, considering having the Smart Repeater operating mode available.

2.5.1.3 Power consumption and power management policies

A monitoring architecture must provide power supply systems for the CUs, since in the freight trains the individual wagons do not receive electricity from the locomotive. The study and design of these systems have not been objective of this work but

Figure 2.11: Radio coverage tests in case of indoor-outdoor communication (IN-OUT2)

simulations have been made to investigate the possible battery life of the devices taken into consideration, in different operating modes. This analysis, reported below, has been performed on the LE70-868 communication devices according to different short-range network logical configuration.

Although power management policies can be implemented to limit the power consumption, it must be taken into account that in Smart Repeater mode the single node can not be put on sleep/standby mode. Each element must always be awake for reception and relay of messages between other nodes and the network coordinator (e.g. alarm delivery toward the coordinator).
Therefore specific tests have been made to investigate the actual transmission consumption of the LE70-868 modules. To verify module consumptions, the pins for current measurements available on the development board were considered; a PicoScope has been used to calculate the voltage over a 1 ohm precision resistor, at different transmission power levels.

Taking into account the limitations and tolerances of the measuring instruments, the results were consistent with the manufacturer's declaration: 354 mA measured at maximum transmission power (27 dBm) compared to 335 mA declared in the datasheet [18].

The centralized management of information by local processing elements is the main condition in order to guarantee a level of consumption as much as possible in line with the project objectives; the GE910 of the GCUs should perform the least

Figure 2.12: Radio coverage tests in case of outdoor communication

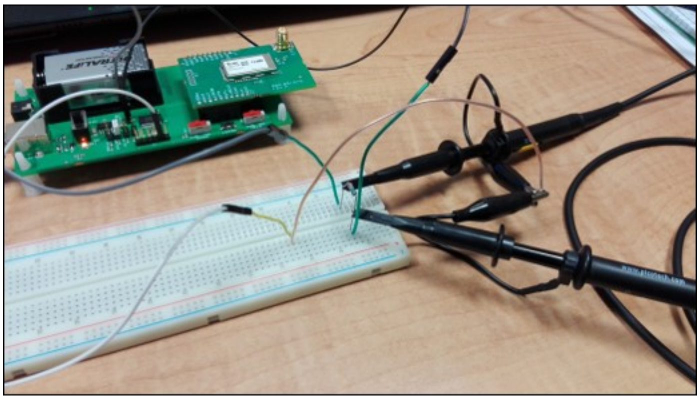
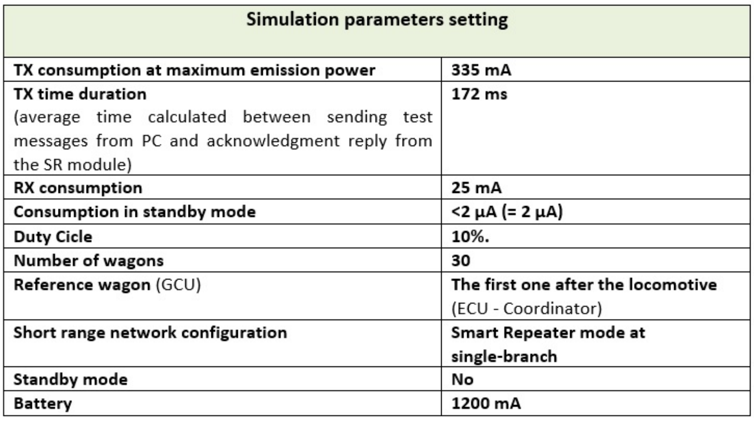


Figure 2.13: Power consumption tests

number of operations and not be constantly connected via radio to the REC, such as the ECU/PCU.

Without having real results about tests on-board the train, a possible implementation based on the Smart repeater mode has been considered, and it is therefore necessary to analyze power management policies based on transmission power levels, transmission profiles and logical network configuration.
Simulation results on battery life for a specific node of short-range network in Smart Repeater mode are reported below, for different use cases under these operating conditions, according to the parameters setting reported in Fig.2.14 (consumption data from LE70-868 datasheet): the transmission time duration of 172 ms has been considered, that corresponds to the average time calculated between the sending of test



Simulation parameters setting	
TX consumption at maximum emission power	**335 mA**
TX time duration (average time calculated between sending test messages from PC and acknowledgment reply from the SR module)	**172 ms**
RX consumption	**25 mA**
Consumption in standby mode	**<2 µA (= 2 µA)**
Duty Cicle	**10%.**
Number of wagons	**30**
Reference wagon (GCU)	**The first one after the locomotive** (ECU - Coordinator)
Short range network configuration	**Smart Repeater mode at single-branch**
Standby mode	**No**
Battery	**1200 mA**

Figure 2.14: Parameters setting for power management simulations

frames from a PC over serial connection and the acknowledgment from the LE70 module. For the purposes of this analisys it has been considered in terms of worst case.

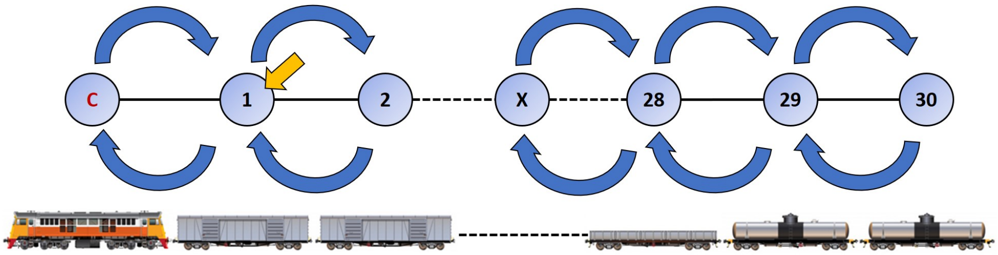
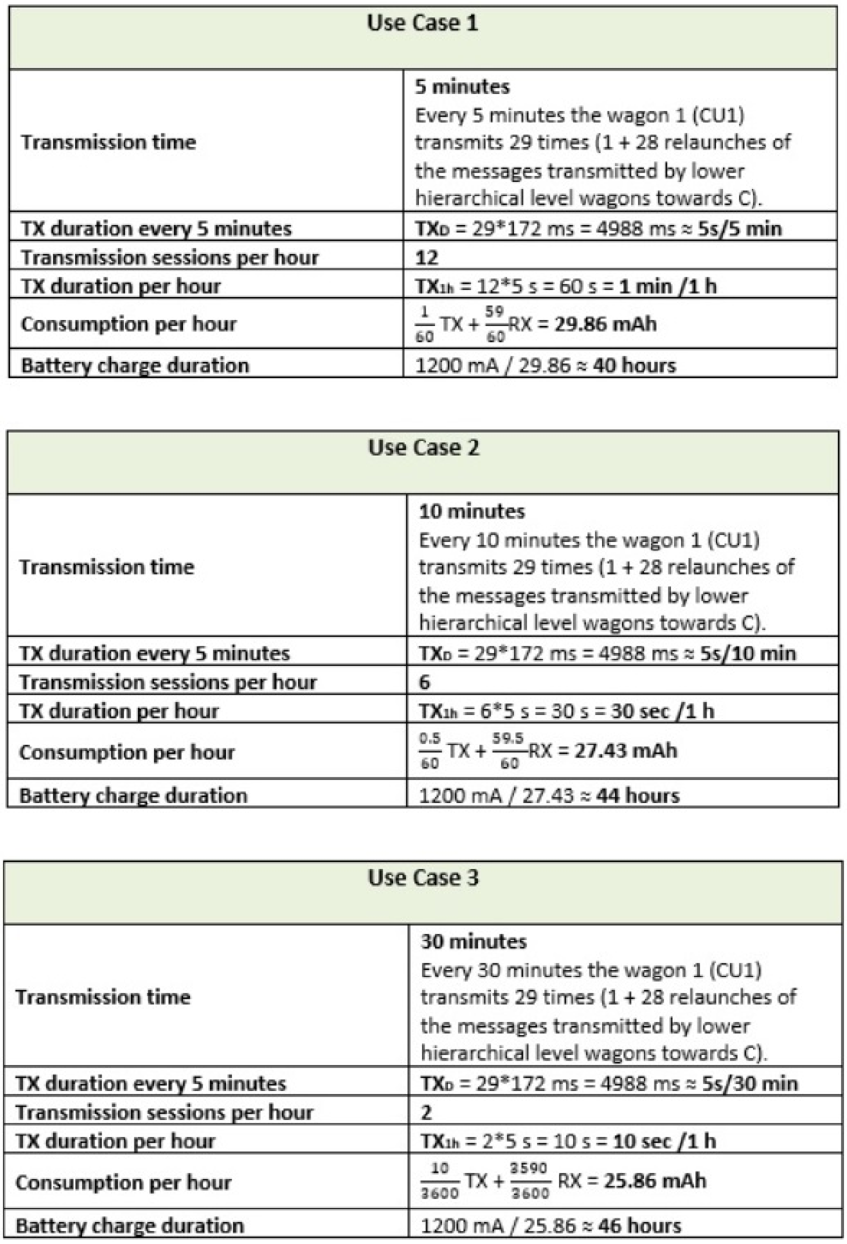


Figure 2.15: Reference scenario for power management simulations

Below are the calculation results for transmission sets every 5, 10, 30 minutes (Fig.2.16).

The results show how this logical topology in Smart repeater mode results to be too heavy from the energy consumption point of view; any implementation choice relating to the transmission timing on a single node is almost ineffective in terms of battery life.

As a case study, an example is given (configuration not applicable at the considered devices) of using the standby mode together with the Smart Repeater, in order to highlight how the switching off the modules not in transmission can bring significant benefits in terms of power saving up to potentially reaching nine days of autonomy (Fig.2.17). In this configuration it should be foreseen that any anomalies are transmitted directly from the GCU to the REC.



Use Case 1	
Transmission time	**5 minutes** Every 5 minutes the wagon 1 (CU1) transmits 29 times (1 + 28 relaunches of the messages transmitted by lower hierarchical level wagons towards C).
TX duration every 5 minutes	**TX_D** = 29*172 ms = 4988 ms ≈ **5s/5 min**
Transmission sessions per hour	**12**
TX duration per hour	**TX_{1h}** = 12*5 s = 60 s = **1 min /1 h**
Consumption per hour	$\frac{1}{60}$ TX + $\frac{59}{60}$RX = **29.86 mAh**
Battery charge duration	1200 mA / 29.86 ≈ **40 hours**

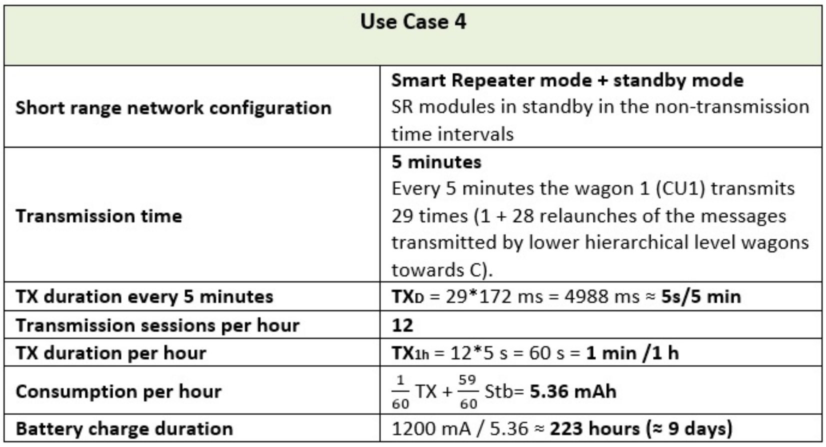
Use Case 2	
Transmission time	**10 minutes** Every 10 minutes the wagon 1 (CU1) transmits 29 times (1 + 28 relaunches of the messages transmitted by lower hierarchical level wagons towards C).
TX duration every 5 minutes	**TX_D** = 29*172 ms = 4988 ms ≈ **5s/10 min**
Transmission sessions per hour	**6**
TX duration per hour	**TX_{1h}** = 6*5 s = 30 s = **30 sec /1 h**
Consumption per hour	$\frac{0.5}{60}$ TX + $\frac{59.5}{60}$RX = **27.43 mAh**
Battery charge duration	1200 mA / 27.43 ≈ **44 hours**

Use Case 3	
Transmission time	**30 minutes** Every 30 minutes the wagon 1 (CU1) transmits 29 times (1 + 28 relaunches of the messages transmitted by lower hierarchical level wagons towards C).
TX duration every 5 minutes	**TX_D** = 29*172 ms = 4988 ms ≈ **5s/30 min**
Transmission sessions per hour	**2**
TX duration per hour	**TX_{1h}** = 2*5 s = 10 s = **10 sec /1 h**
Consumption per hour	$\frac{10}{3600}$ TX + $\frac{3590}{3600}$ RX = **25.86 mAh**
Battery charge duration	1200 mA / 25.86 ≈ **46 hours**

Figure 2.16: Simulation results on power management for 5, 10, 30 minutes of transmission timing

2.5.2 Preliminary tests on long-range communication devices

The system functional structure requires the GE910-GNSS module to be a central element for information management within the wagon monitoring block; according to the reference scheme for the CU, it performes data collection from on-board sensors,



Use Case 4	
Short range network configuration	**Smart Repeater mode + standby mode** SR modules in standby in the non-transmission time intervals
Transmission time	**5 minutes** Every 5 minutes the wagon 1 (CU1) transmits 29 times (1 + 28 relaunches of the messages transmitted by lower hierarchical level wagons towards C).
TX duration every 5 minutes	$\mathbf{TX_D}$ = 29*172 ms = 4988 ms ≈ **5s/5 min**
Transmission sessions per hour	**12**
TX duration per hour	$\mathbf{TX_{1h}}$ = 12*5 s = 60 s = **1 min /1 h**
Consumption per hour	$\frac{1}{60}$ TX + $\frac{59}{60}$ Stb= **5.36 mAh**
Battery charge duration	1200 mA / 5.36 ≈ **223 hours (≈ 9 days)**

Figure 2.17: Simulation results on power management using Smart Repeater and standby mode

pre-processing of information and communication with other CUs (e.g. ECU/PCU) on a short-range network through connection with the LE70 modules, and toward the REC through mobile network using the M2M SIM.

In the first phase the preliminary procedures indicated by the manufacturer were performed, to check the integrity of the devices and the peripherals status, update the firmware, activate the M2M SIMs. Then the basic connectivity tests toward the IoT management platform have been performed, as well as the GNSS data reception.

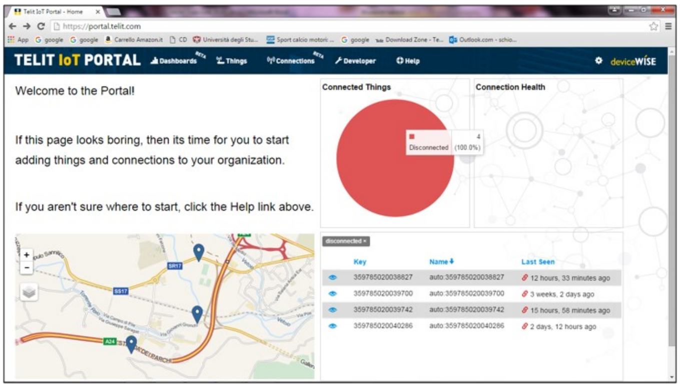
To test the serial communication features, ad hoc realized Python scripts have been used to verify the correct transmission of strings through the different serial interfaces of the module, one of which by default used as a debug line. This test was necessary to evaluate all possible configurations to realize the CU without the use of EVK development boards, specifically for the connection with the LE70 module.

2.5.3 Preliminary tests on IoT Cloud Platform

These tests concerned the analysis of the basic functionalities of the IoT cloud platform, in terms of M2M SIMs management, configuration of generic sensors parameters and activation of alarms.
A GE910 unit has been used to verify the response of the IoT platform through data transmission from onboard sensors (simulated) by means of python scripts.

Specifically, sensors parameters have been configured on the IoT platform (temperature, intrusion, generic sensor), as well as alert threshold levels for each of them, and its response has been verified in terms of alarm activation and communication,

via sms or email, due to data received from the GE910 and processed according to the reference thresholds.
As regards the management of GNSS data, the request procedure for sending position data from IoT platform to GE910-GNSSs has been tested, as well as the spontaneous sending of position data by the module, with controlled timing for opening and closing the GPRS communication session.



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359785020039742	auto:359785020039742	15 hours, 58 minutes ago
359785020040286	auto:359785020040286	2 days, 12 hours ago

Figure 2.18: Telit IoT cloud platform

2.6 System implementation and testing of basic procedures

2.6.1 Physical implementation of the Control Units

All the implementation choices related to the realization of the system prototype were mainly bound by the technical and physical specifications of the development boards of the GE910-GNSS and LE70-868 devices, which composed the CU. Regarding the CU implementation it was necessary to use the EVK2 functions to a minimum, with the aim of making the GE910 interface board autonomous, in terms of interfaces and communication ports, and using the fewest possible connections in order to achieve a CU prototype that could be as suitable as possible for eventually field tests.

To this end, the TXB0108 COTS from Texas Instruments has been used as an 8-line level translation device for the bidirectional conversion from the 1.8V CMOS lines of the GE910 to 3.3V TTL lines of the LE70-868 UART. For the technical specifications of the device, see datasheet in [21].
Fig.2.19 shows the connection circuit diagram of the device, with reference to the specific use case.

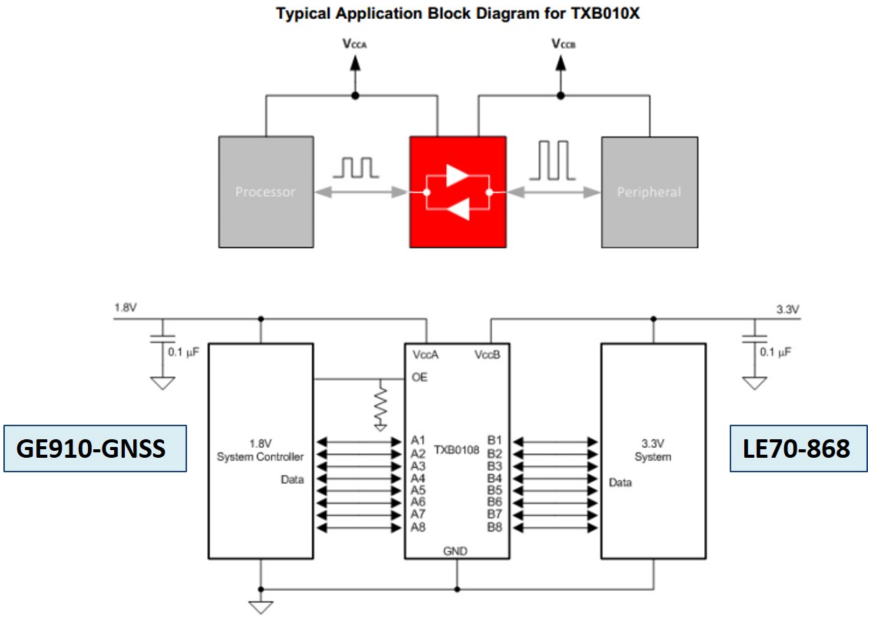


Figure 2.19: Connection scheme of voltage level translator

The basic version of the CU for laboratory tests described below provides for the use of the voltage level translator on breadboard support and separeted power supplies, with different specification, for the main modules: the LE70-868 with 9V battery and the GE910-GNSS with a 12V power supply. In phase of prototype development for future field tests it will be advisable to consider the possibility of using a single energy source with two downstream DC-DC converters to supply the individual modules.

After the physical realization of the CU, the tests on the basic functionalities were performed again, in order to verify the implementation correctness of the proposed solution.

Once the functions of a single CU have been verified, the other units (3) have been composed and consequently communication tests have been performed in order to simulate the operating scenarios related to the short-range network.
Python scripts were developed for sending the wagon status parameters according to different transmission profiles (sensors simulation) as well as a specific information processing script for the coordinator element (ECU/PCU). These tests were carried out with the configuration of the short-range network both in transparent mode and in the Smart Repeater one under several operating conditions, such as transmission power variation.

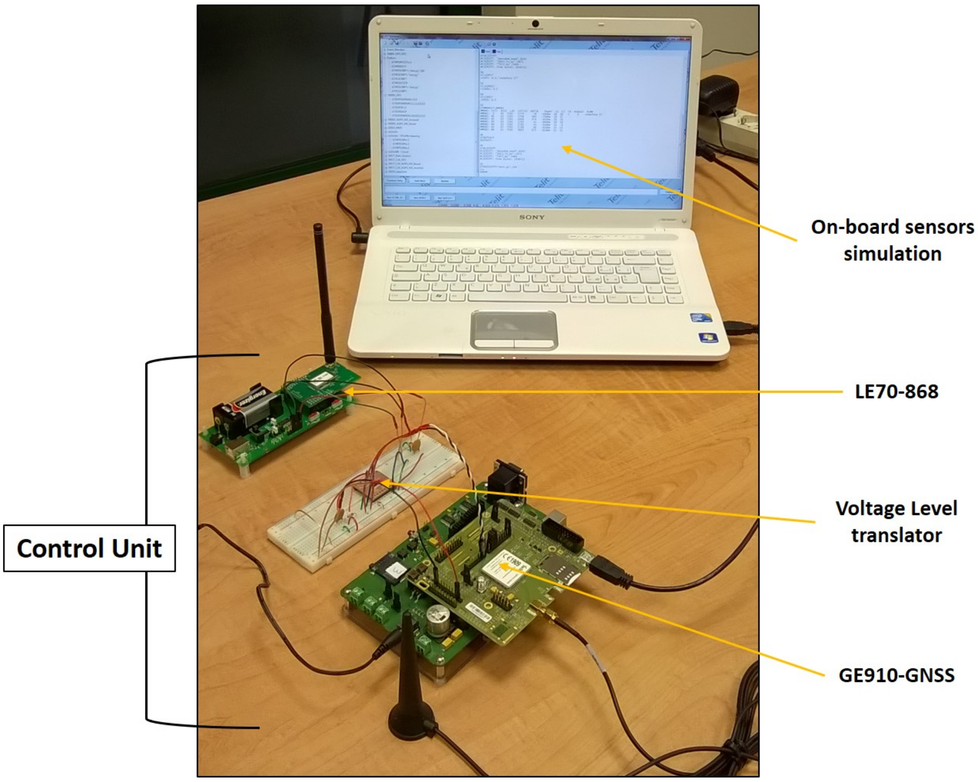


Figure 2.20: Basic Control Unit implementation

2.6.2 Implementation and validation of the integrated architecture

The complete monitoring architecture consists of three subsystems that can be analyzed separately from the functional point of view:

- the *WSN network* implemented through LE70-868 modules, with the aim of providing information exchange between the CU according to a given operating mode (eg Smart Repeater);
- the *on-board (parking area) network* composed by 4 CUs. The central element of the single CU is the GE910-GNSS which implement sensors simulation, pre-processing and transceiver via short/long-range communication towards the local elaboration element/REC;
- the *Remote Elaboration Center* on Cloud platform that carries out the monitoring function through the collection of information from the on-board network (or parking areas), the processing of them and the execution of alarm signaling actions in response to specific stimuli (anomaly simulation).

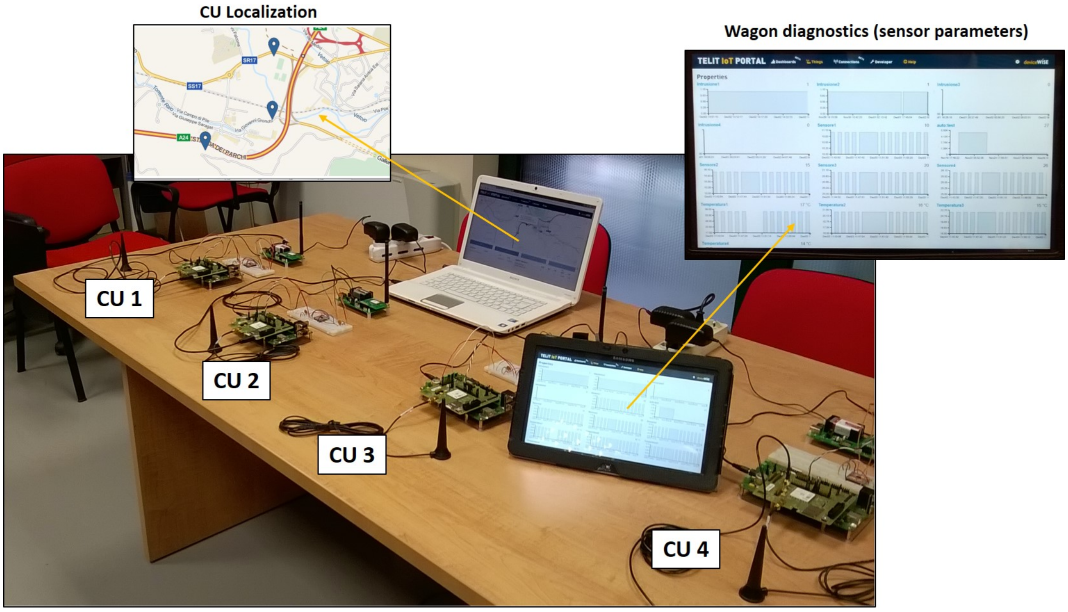


Figure 2.21: Integrated architecture testbed

The functionalities of the individual system components have been verified by the previous tests, but for the integrated network validation it was necessary to verify the robustness of the integration itself, as realized, by testing of basic application procedures of the architecture.

The basic procedures of the integrated architecture successfully tested are reported below:

- **Short-range network configuration**: the short-range network configuration processes must be executed both in phase of train composition and in case of operating condition changing of the wagons. By considering only one coordinator for the short-range network (in real cases it could be necessary more than one, e.g. in large parking areas), procedures for LE70-868 devices setting were tested, takin into account that each GE910-GNSS module can store several scripts with preloaded configurations for different short-range network topologies and node settings, both through messages received by the reference ECU/PCU and through SMSs sent by REC.

- **Simulation of on-board sensors and data transmission**: the simulation of sensors has been made through Python scripts in order to produce self generation and transmission at fixed timing of sensor data by the CUs.

  For this test a basic default frame structure has been defined as follows: Wagon

ID (n.1 decimal) - Temperature (n.2 decimal) - Intrusion (n.1 boolean) - Generic (n.2 decimal). Some procedures have been implemented for communication between CUs and REC both in direct connection mode and through intermediate nodes (ECU/PCU). In both cases the locally generated values for on-board parameters were sent by the CU and the update results were verified on the IoT management portal (REC).

- **Cloud connection request from REC towards the GCU through SMS**: a GCU is not always connected to the Cloud platform because of power saving policy; however, in some specific cases it is necessary to force the connection in direct communication (e.g. for short-range network reconfiguration). For testing of this procedure a Python script has been realized able to detect the incoming SMS on the M2M SIM number associated to GE910-GNSS of the specific CU, read and decode the received SMS content for further actions. In the case of a connection request, after reception of an SMS, the CU (GE910) decodes the text and starts the connection process to the Cloud in order to enable configuration commands reception. At the end of data exchange process the detach procedures has to be performed to return to the normal operating mode.

- **Request for operations from the REC to ECU/RCU through Methods activation**: ECU and RCU are always connected to REC, so that all requests for operations can be done directly through the use of Method.exec processes. Some methods (of string type) were implemented on the REC for activation of data sending procedures over the short-range network (towards a specific GCU) or mobile network (through SMS sending).

- **GNSS position request**: each CU is able to receive and process the GNSS position data due to GE910-GNSS features. From the IoT Platform it is possible to check the position of all connected units in manual mode. For automatic and unattended management of GNSS information, support procedures for position request and elaboration of responses are required. Depending on the destination unit we can resort to a message through Methods (only for ECU/RCU), to an SMS or a request through the short-range network.
  For implementation of the basic procedures, different Python scripts have been developed in order to elaborate requests from several functional elements, to acquire geographical position by GE910 through GNSS receiver and convert the position data in a suitable format for forwarding to the REC.

- **Pre-elaboration of sensor values**: in order to simulate the pre-elaboration of local measurements by the GCU, the following system architecture has been chosen: (i) GCU always connected to REC, (ii) data sending generated by means of Python scripts from a PC connected to the GE910 through USB serial interface, (iii) sending of pre-elaboration results from GCU towards REC. Pre-elaboration means in this case the comparison between the received values and the predefined threshold levels for sensors parameters, with alarms sent by proper strings towards the Event Log section of IoT Platform.

- **Alarm signaling**: in all tests dealing with the comparison between sensors parameters and the threshold levels, the verification of alarm signaling has been carried out. In the IoT platform the procedures were configured for sending notification of anomalies through SMS, email and posting of messages in the Event section of the IoT portal. Alarms can be either sent by REC towards cabin crews following the elaboration of aggregate data, or directly by the GCU towards control cabin and REC whenever an alarm threshold has been overcome by one or more parameters (for spontaneous sending toward the REC the communication session opening is required). All alarms must be sent with maximum priority to the train driver who is the only one able to execute the emergency procedures in case of anomaly detection.

2.7 Analysis of results

A cloud-based heterogeneous wireless platform for continuous monitoring and efficient management of freight trains has proposed in this chapter, designed and implemented in a prototype way to test the basic system functionalities. The research activities mainly concerned the definition of the general system architecture, as an integration of different technologies to reach the different aims of the project, of which the short-range network represents a key element to realize the real time moniting of wagons.

The tests carried out on the short-range devices highlighted the operational characteristics of the platforms and provided indications regarding possible implementation solutions for WSN network structuring. All the considerations proposed below are based on assumptions of operation in worst case conditions, since field test results were not available, as well as detailed analysis relating to the reference propagation environment.

The analysis of the different configurable operating modes must take into account the characteristics of the short-range network, whose main role, at least with respect to the basic functionalities relating to the preliminary specifications, is to convey the information between the local elaboration element and all wagons.

Based on this assumptions, the Smart Repeater operating mode appeared to be the most compatible with the features to be implemented:

- the protocol provides for the exchange of information exclusively between the coordinator node and all the nodes belonging to its own network - in the application under consideration the data exchange must take place between the locomotive, where the driver can apply the corrective maneuvers in case of emergency, and all wagons of the train also not in direct radio visibility, as well as between a local management element for parking areas and all parked wagons;
- the information can be conveyed on the network through multi-hop communication, so it is possible to reach distances greater than the normal radio coverage; this allows communication between locomotive and tail wagon in any interfering condition, as well as to connect any parked wagons to the coordinator, also in large parking areas;
- the possibility of multi-hop communication allows the emission powers to be reduced. On the other hand, with the implementation of this operating mode the power management functions is not allowed (e.g. standby mode).

The other operating modes may be taken into consideration only after a field tests with verification of the minimum coverage ranges in the specific context, which is highly interfered. Therefore, the verification of constant connection in direct radio visibility between the ECU and all other GCUs is fundamental.

The transparent mode can't be taken into account since the addressing of the information should be managed at the application level; as well as data protection in terms of encryption, despite the possibility to implement power saving functions.

The addressed mode could represent the compromise solution in case of verification of favorable conditions for on-board communication between the ends. This mode would allow the information exchanging in secure way, through AES encryption, and addressed between individual GCU and ECU/PCU, with the possibility of activating power saving functions. In this case there would not be realize a constant monitoring of train integrity, which should be done in another way.

In general, regardless of the specific devices taken into account, the architecture design should in any case consider the following operating goals:

- constant radio visibility (not necessarily in direct way) between the ECU and GCU of tail wagon on board the train;
- maximization of battery life for short-range communication units;
- support for monitoring the train integrity.

The GE910-GNSS modules have proven to be suitable to support the functionality of the CU in term of localization, elaboration and communication on mobile networks.

The IoT platform has been helpful to manage the data in this preliminary experimentation phase, but shows some limitation for managing of aggregated entities, like trains and wagons in parking areas. Therefore, in order to ensure adequate levels of scalability and flexibility of the system, we need for a support management platform to realize the dynamic tracking of the entire fleet of wagons.

However the designed architecture has demonstrate to be suitable to overcome the current limitations of freight transportation and increase the safety and efficient management of the wagons, independently of the devices and platforms used.

2.8 Collaborations and publications

These activities have been carried out in collaboration with **Leonardo company** and **RadioLabs Consortium**.

S. Chiocchio, A. Persia, F. Santucci, V. Di Claudio, D. Di Grande, P. Giugliano, G. Guidotti, ”A cloud-based heterogeneous wireless platform for monitoring and management of freight trains,” 2016 8th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), Lisbon, 2016, pp. 263-268. doi: 10.1109/ICUMT.2016.7765368.

Chapter 3

ITS for Air transport
Enhanced reception architectures for ADS-B signals

In this chapter research activities carried out in the Air Traffic Control context are described, concerning the modeling and performance analysis of enhanced reception architectures for ADS-B signals. Within an industry-driven research project, enhanced reception techniques proposed by the Radio Technical Commission for Aeronautics (RTCA) have implemented for detection and decoding of ADS-B signals transmitted at 1090 MHz carrier frequency in high interference conditions.

The avionic context has very slow technological advancement processes. Therefore, the detection/decoding techniques implemented are based on analyzes and principles proposed many years ago, which still remain eligible to guarantee the surveillance system reliability and that can be realized as relatively low cost solutions thanks to the HW/SW platforms currently available.

An extensive set of results has been obtained through a specifically developed simulation environment, able to closely model a wide range of operational scenarios by generating ADS-B frames and Mode A/C interfering signals. The simulation environment also includes an implementation of two RF receiver chains that refer to a logarithmic and linear amplification, respectively.

3.1 State of the art and aims of research activities

The air traffic volume is constantly growing, as indicated in the IATA last report [22], and confirmed by Eurocontrol forecasts for the next years [23]. In order to manage the increasing air traffic demand and ensure safety and transport efficiency,

Figure 3.1: ADS-B surveillance technique for Air Traffic Control

some programs for modernization of air transportation systems have been launched worldwide, e.g. NextGen (Next Generation Air Transportation System) in the US [24] and SESAR (Single European Sky ATM Research) in Europe [25]. Traffic control in crowded airspace certainly requires reliable surveillance technologies, able to identify and continuously localize the aircraft moving on both airport areas and in airspace. Therefore, new surveillance techniques have emerged to overcome limitations of many radar-based systems that are currently deployed.

In this evolution track the ADS-B (Automatic Dependent Surveillance - Broadcast) has been introduced as a promising technology to provide better performance for air traffic monitoring at smaller overall cost. ADS-B is a cooperative surveillance system based on aircraft transmitting periodically and spontaneously reports, known as Extended Squitters (ES): each report may contain surveillance parameters and navigation information extracted from on board devices. ADS-B broadcast messages can be caught both by ground stations, which can merge data with the ones coming from other surveillance systems, and ADS-B equipped aircraft. Sharing of those informations leads to a greater air situational awareness for both pilots and air traffic operators if compared to the conventional radars. Besides, ADS-B is also used to give support for ground surveillance systems in airport areas, such as for Advanced Surface Movement Guidance and Control System (A-SMGCS) [26].

ADS-B system specifications for transmission (ADS-B *Out*) and reception (ADS-B *In*) modes have been defined; both in Europe [27] [28] and in the US [29] [30], the ADS-B *Out* operating mode will become mandatory by 2020. Signals are transmitted on a 1090 MHz Extended Squitter link, the same used for a Mode S transponder. This latter technology was standardized and widely adopted in commercial aircraft, nevertheless two further solutions are currently available: VDL Mode 4 (Very High DataLink) and UAT (Universal Access Time).

By considering that surveillance systems typically exhibit a long life and that ADS-B has been conceived as an extension of Mode S, the technical literature has addressed the issue of understanding how the current surveillance systems operating in the same 1090 Mhz channel can influence the performance of the most promising ADS-B technology [31] [32] [33].
In this frame it can be observed that the increasing density of aircraft equipped with ADS-B functionalities [34] [35] and the increasing number of ground stations provided with ADS-B sensors able to capture surveillance air traffic data, make available a huge amount of ADS-B messages coming from the field for the research community [36]. Moving from those data it can be clearly evidenced that the ADS-B receiver capability is affected by the interference due to SSR replies in terms of larger loss rate of ADS-B messages in busy hours, when high traffic conditions occur [37]- [38].

Nowadays, the main interference source for ADS-B signals is represented by Mode A/C replies, which are the conventional messages sent in broadcast in response to SSR interrogations, as larger interrogation rates occur in this case if compared to selective interrogations of Mode S. The reports [39] [40] have documented a rather large False Replies Unsynchronised In Time (FRUIT) rate, with values around 40 K replies/sec in Los Angeles area and 30 K replies/sec in Frankfurt, respectively.
As a general remark, we can state that interference contributions on the 1090 MHz frequency channel may seriously degrade the performance in the reception of ES messages with detrimental effects on the reliability of functionalities for every surveillance service that relies on ADS-B data.

Indeed, currently implemented ADS-B signal reception techniques exhibit limitations when the interference becomes significant, because they are basically able to deal with only one Mode A/C FRUIT overlap and tolerate low interference levels. This seems quite obvious, as those techniques were conceived for narrow beam SSR and short range ACAS operations, where the FRUIT rate is nominally lower than 4000 Mode A/C FRUIT/sec.
Enhanced receiving techniques, that are considered able to improve ADS-B message reception performance in higher interference environments, have been suggested by RTCA itself and documented in [41].

As a matter of fact, enhanced ES reception algorithms aim to provide improvement in three phases of the signal processing chain and tackle multiple overlapping Mode A/C FRUITs. First of all, accurate selection procedures are introduced for preamble detection, in order to reduce the occurrence of false detections. Furthermore, enhanced decoding techniques are defined and tailored to support accurate bit decisions by discriminating interference through *multiple samples* and power ranges associated with the estimated signal level.
Finally, error correction techniques are introduced that entail the use of bit confidence information, assigned in the decoding phase.

Early studies on assessment of enhanced receiving techniques in the presence of interfering signals are reported in [42] [43], in terms of correct ES reception probability versus the received power level. Following the RTCA guidelines about the enhanced reception architectures, in [44] two advanced decoding techniques has been tested and compared in terms of BER (Bit Error Rate) versus SNR (Signal-to-Noise Ratio). Simulation results show that the use of multiple samples can provide improvements for the decoding process when compared to the basic technique. Furthermore, the possibility of matched filters usage for preamble detection combined with a multilevel threshold for the decoding process was also investigated [45].
Beside, in [46] a novel error correction algorithms have been proposed, based on the matched filter scheme for improving the reception of weak ADS-B signals.
Moreover, enhanced Bit and Confidence level declaration techniques have been combined with antenna arrays to improve the receiver ADS-B performance [47]. Evaluation of ES detection probability in real scenarios have been recently addressed by [48], through receivers based on the RTCA enhanced algorithms. Finally, research activities on development of SDR-based enhanced Mode S/ES receivers have been carried out [49], and study and implementation of signal separation methods, as well as solutions based on multichannel receivers for decoding of overlapped Mode S frames have been reported in [50] [51] [52] [53].

By extending a recent work [54] a detailed performance analysis of current and enhanced techniques is provided, along the whole receiver chain for an 1090 ES link. A detailed implementation of the Tx-Rx chain in ad hoc simulator (Matlab environment) is carried out in order to model the algorithms recommended by RTCA [41], and logarithmic and linear alternatives for the RF front-end model are accounted for on the receiver side. The whole setup is devoted to carry out an extensive performance analysis, with the clear goal of assessing: i) which is the real improvement provided by enhanced techniques for detection and decoding of ADS-B frames in the presence of high interference generated by mode A/C replies ii) to what extent a logarithmic receiver can provide better performance. As a practical outcome, we are able to determine the amount of interference, and then the air traffic density, that can actually be managed while guaranteeing safe operations through the considered surveillance technology.

3.2 ADS-B signals and the enhanced reception techniques

The ADS-B technology is the main current solution for Air Traffic Control, which operates in addition to the passive Primary Radar-based surveillance technique and those active alternatives based on the use of SSR (Secondary surveillance radar).

ADS-B message has a total duration of 120 μs for a 1 Mbit/s of bit rate. Each report message has the following structure:

1. Preamble: a sequence of 8 μs used for synchronizing the receiving system and prepare it for decoding;
2. Downlink Format [DF]: indicates the type of the transmitted message, set to 17 for Extended Squitter (5 bit). For the purpose of this work the DF field turns out to be of particular interest because it is used for validation of detected preambles when considering the implementation of the advanced receiving alternatives;
3. Capability [CA]: indicates the transponder transmission capacity (3 bit);
4. Aircraft Address [AA]: ICAO address (24 bit);
5. Message Extended squitter [ME]: ADS-B report (56 bit);
6. Parity/interrogator Identifier [PI]: error detection code (24 bit).

Since the ADS-B system represents an evolution of the Mode S transmission technique, the ADS-B reports have the same frame format and the same physical specifications as the Mode S replies, in particular according to the extended format (112 μs).

The following are the technical specifications of Mode S replies frame format, as well as that of Mode A/C replies which represent the main interfering signals in ADS-B systems. Both types of replies are transmitted at 1090 MHz in response to specific interrogations at 1030 MHz.

- *Mode S replies (Selective)* - the transponders can transmit in response to SSR interrogations (*replies*), or transmit signals spontaneously (*squitter*) like in ADS-B systems.
  The difference between replies and squitter relies on the information data content: the reply must contain the identification codes of both transmitter and receiver, while the squitter contains only the identification code of the transmitter. As the two signals have the same frame format, when dealing with their detection and decoding we can consider Mode S frames and only distinguish between *Short* and *Extended*, depending on the data field length.

  The frame format is composed by an 8 μs preamble which contains four pulses in the canonical positions: 0, 1, 3.5, 4.5 μs, as shown in Fig. 3.2-b , followed by a data block of 56 or 112 μs for a maximum total length of 120 μs.
  The Mode S signal is transmitted on a carrier frequency of 1090±1 MHz, modulated according to a PPM (Pulse Position Modulation) format. Each bit time is divided into two chips of 0.5 μs. A pulse transmitted in the first chip represents the bit 1, while a pulse transmitted in the second chip represents the bit 0.
  The PPM data block can contain pulses of 0.5 μs and 1 μs (in case that a sequence 01 is encoded); for both types of pulses a tolerance of 0.05 μs is admitted.
  More details about specifications of Mode S reply format can be found in [55], [56].

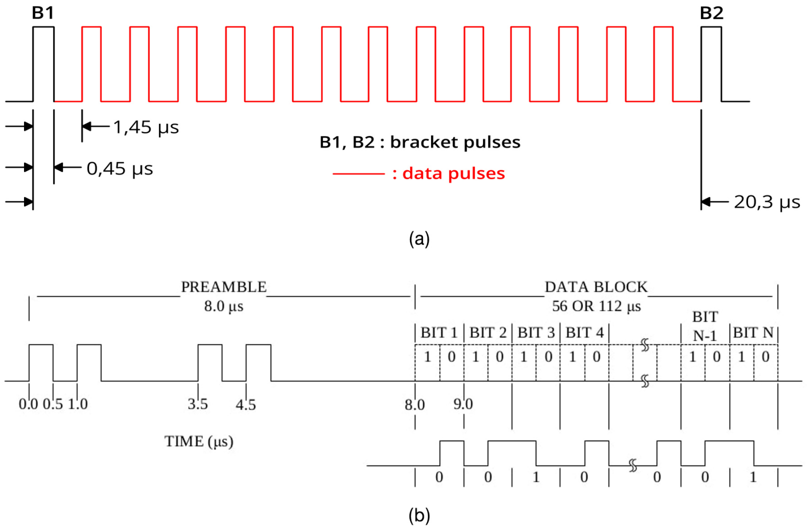


Figure 3.2: ADS-B (a) and Mode A/C reply (b) frame formats

- *Mode A/C replies* - are sent in response to two different kinds of interrogations, namely for identity (Mode A) and altitude (Mode C) requests, by a ground station. Although the interrogation formats are different for the two operating modes, the format for replies is unique: *Conventional mode reply.*
  The conventional reply, shown in Fig.3.2-a, is composed by two brackets at a fixed distance of 20.3 μs: a sequence of at most 13 data pulses of 0.45 μs is included in the middle. Different permutations of pulses corresponds to different encoded messages.
  More details about specifications of Mode A/C reply can be found in [55], [56].

In the development of the simulation model False Replies Unsynchronized In Time (FRUIT) were considered, in order to model interfering signals, represented by both Conventional and Selective mode replies. Specifically, the enhanced reception techniques for ADS-B signals have been implemented and validated in the presence of 40000 Mode A/C FRUIT/s, i.e. an average of 5 Mode A/C replies overlap per ADS-B frame interval.

The reception process consists of three main stages: (i) *preamble detection* for synchronization (ii) *data block decoding* (iii) *error detection and correction.* Specifically the simulation model was realized by implementing the advanced reception algorithms proposed by the RTCA [41].

The *preamble detection* is the most complex step of the entire baseband reception process wich includes at the beginning the pulse labeling (in Valid pulse and Leading edge), then a preliminary detection phase of potential preambles and calculation of their power reference level. A set of tests is applied on detected preambles for validation of them, in order to verify: i) any signal overlappings in standard preamble positions, ii) the consistency of power levels of preamble pulses, iii) the presence of at least one pulse in each DF (the first five bit) field bit.

Since the basic decoding block can process only one message at a time, the last stage of the detection chain, represented by the Retriggering algorithm, selects the best preamble (the most probably correct) among those validated to be handled by the decoding.

The *decoding phase* has implemented according to three different techniques: Central Sample (CS), Advanced Central Sample (ACS), Multi-Sample (MS).

The CS technique is based on the comparison between the amplitudes of central samples of the two chips whitin a bit time and involves the use of a reference threshold to determine the confidence level associated to the decision.

The ACS technique introduces a power range to discriminate the logic bit state, with the confidence level dependings on the number of chips belonging into this range (from 0 to 2).
The MS technique involves the use of multiple samples per individual chip and a more complex computation algorithms involving different power threshold.

The conservative technique for *error detection and correction* has been considered. The results analysis of error detection and correction process are not taken into consideration in this thesis since the results obtained with the conservative technique are not relevant, and more performing techniques have not been implemented.

3.3 System modeling and the simulation Environment

The system model and the related Matlab simulator implementated is depicted in Fig.3.3. It consists of the Test frame generation block and the Detection and Decoding block on the receiving side. The system setting mask is shown in Fig.3.4, through which it is possible to set all the simulation variables relating to input signals and receiver functional specifications (RF chain type and detection/decoding parameters).

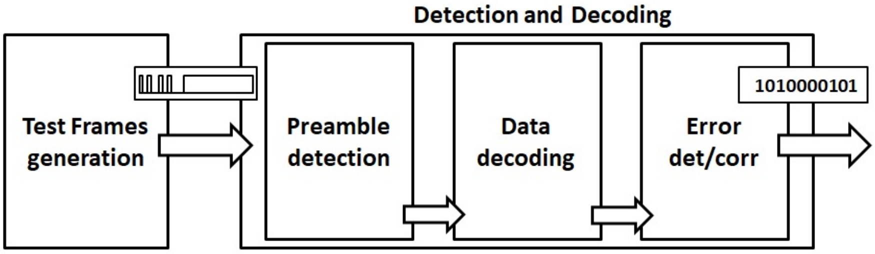
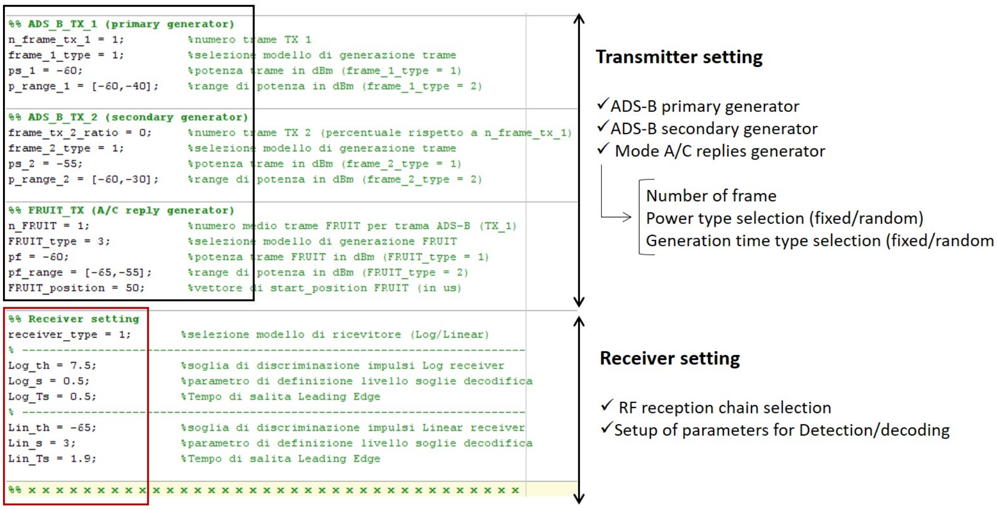


Figure 3.3: Overall system model

3.3.1 Test frame generation block

The Test frame generation block includes: i) Generation of the bit stream for all sources and creation of standard compliant frame structures, which also includes computation of CRC for ADS-B frames, ii) Generation of PPM modulated IF signals at 60 MHz, iii) modeling of the RF reception chain until the A/D conversion stage (Figure 3.5).
Each signal generation function has a specific configuration for timing and power



```
%% ADS_B_TX_1 (primary generator)
n_frame_tx_1 = 1;          %numero trame TX 1
frame_1_type = 1;          %selezione modello di generazione trame
ps_1 = -60;                %potenza trame in dBm (frame_1_type = 1)
p_range_1 = [-60,-40];     %range di potenza in dBm (frame_1_type = 2)

%% ADS_B_TX_2 (secondary generator)
frame_tx_2_ratio = 0;      %numero trame TX 2 (percentuale rispetto a n_frame_tx_1)
frame_2_type = 1;          %selezione modello di generazione trame
ps_2 = -55;                %potenza trame in dBm (frame_2_type = 1)
p_range_2 = [-60,-30];     %range di potenza in dBm (frame_2_type = 2)

%% FRUIT_TX (A/C reply generator)
n_FRUIT = 1;               %numero medio trame FRUIT per trama ADS-B (TX_1)
FRUIT_type = 3;            %selezione modello di generazione FRUIT
pf = -60;                  %potenza trame FRUIT in dBm (FRUIT_type = 1)
pf_range = [-65,-55];      %range di potenza in dBm (FRUIT_type = 2)
FRUIT_position = 50;       %vettore di start_position FRUIT (in us)

%% Receiver setting
receiver_type = 1;        %selezione modello di ricevitore (Log/Linear)
% ------------------------------------------------------------------
Log_th = 7.5;             %soglia di discriminazione impulsi Log receiver
Log_s = 0.5;              %parametro di definizione livello soglie decodifica
Log_Ts = 0.5;             %Tempo di salita Leading Edge
% ------------------------------------------------------------------
Lin_th = -65;             %soglia di discriminazione impulsi Linear receiver
Lin_s = 3;                %parametro di definizione livello soglie decodifica
Lin_Ts = 1.9;             %Tempo di salita Leading Edge

%% x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x x
```

Figure 3.4: Setting mask for system simulation parameters

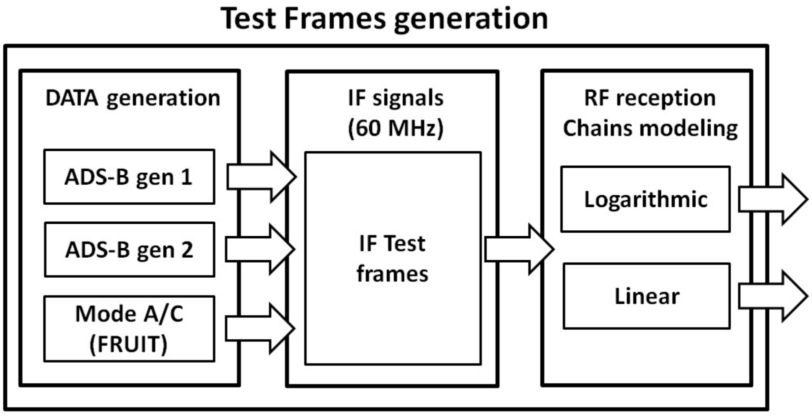


Figure 3.5: Test frames generation

levels (fixed or dynamic). A carrier frequency tolerance of ±1 MHz is introduced for IF signals and a uniformly distributed random phase shift is applied at Mode A/C replies generation.

The simulation environment enables the generation of (i) Primary ADS-B frames (ii) Secondary ADS-B frames (iii) Mode A/C replies according to the following parameters setting (Fig.3.6):

- *Primary ADS-B frames*: number of frames, power level (dBm) or power range (in case of uniformly distributed random generation), fixed timing;

- *Secondary ADS-B frames*: number of frames in terms of percentage respect to the number of primary ADS-B frames, power level (dBm) or power range (in

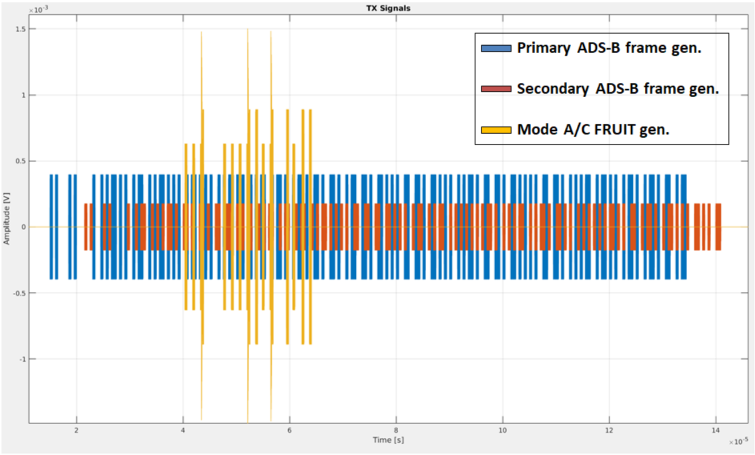


Figure 3.6: Generated signals

case of uniformly distributed random generation), random timing;

- *Mode A/C replies (FRUIT)*: number of FRUITs per primary ADS-B frame, power level (dBm) or power range (in case of uniformly distributed random generation), fixed or random timing with respect to the start of the reference ADS-B frame.

Mode A/C FRUITs represent the main interference source for the useful signal (Primary ADS-B frames). The secondary ABS-B generator can be used as a further interference source or to simulate more complex scenarios for further investigations.

3.3.1.1 IF signals generation

The following are the steps for generating the 60 MHz IF signals, both for the ADS-B (ES) frames and for the Mode A/C interferers.

The ADS-B frame generation procedure is as follows:

- basic pulse generation at 60 MHz (± 1 MHz) frequency with 0.5 μs of duration;
- preamble forming through setting of preamble pulses according to the canonical positions;
- random generation of the payload bit (88);
- calculation of the PI field (creation of CRC code through the use of the generator polynomial [55];
- Binary PPM (BPPM) encoding;

- frame creation as concatenation of preamble - payload - PI.

The sampling frequency of the simulation environment is set at 1 GHz (duration of 1 ns for each sample) which corresponds to a number of samples per pulse equal to 500 (1000 samples per bit). Fig.3.7 shows the ADS-B frame generated with the detail relating to the single pulse (chip) where the duration of 0.5 μs and the carrier frequency at 60 MHz are highlighted.

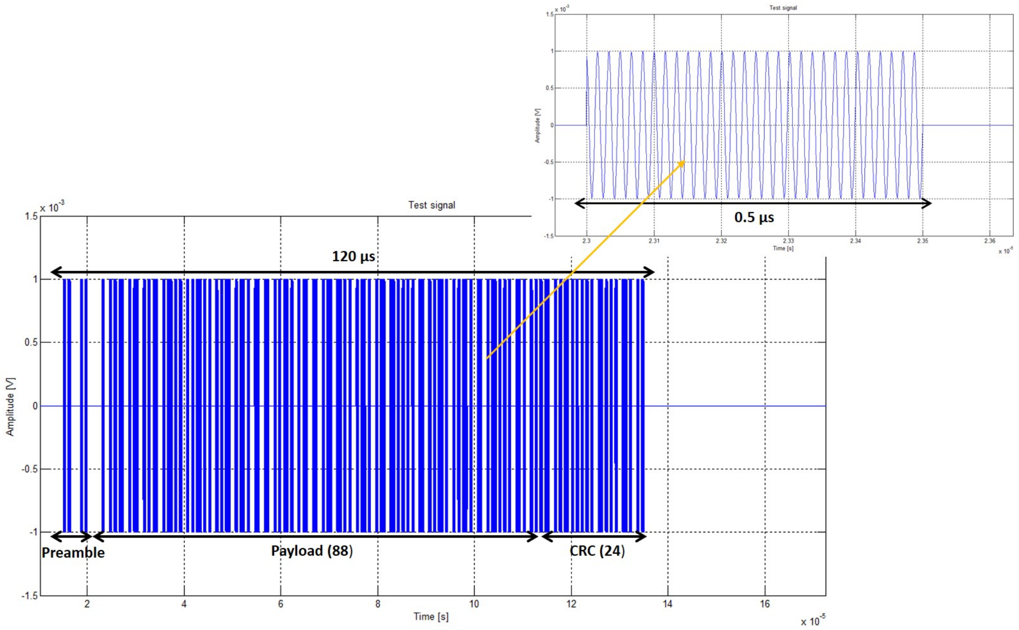


Figure 3.7: ADS-B frame generation

For mode A/C interferering signals, the replies generation process is as follows:

- basic pulse generation at 60 MHz (± 1 MHz) frequency with 0.5 μs of duration and uniformly distributed random phase sfhift;
- setting the bracket pulses;
- random generation of the payload bit;
- frame forming.

Taking into consideration the high interference level of 40000 FRUIT/s for ADS-B systems, you should have 5 generations per ADS-B frame interval on average. For this purpose a uniform distribution is used for their occurrences, and different kinds of implementation in terms of power, position of replies and number of generations per ADS-B frame interval.

3.3.1.2 RF reception chains modeling

The modeling of the logarithmic and linear RF reception chains are described below in detail.

Logarithmic RF receiver:
The equivalent system model is developed according to these three main stages: (i) RF front-end, (ii) amplifier block, (iii) A/D converter.
The RF front-end includes a first amplification stage and introduces the equivalent noise related to that portion of the receiver. The logarithmic amplification is implemented through the characteristic function of a Commercial Off-The-Shelf component (COTS) in addition to the related thermal noise modeling (Log noise). The internal structure of the device, as Log-Limiting IF Amplifier, embeds the dual function of logarithmic amplification and RF demodulation, then returning the baseband signal. The A/D conversion block operates with a 24 MHz sampling frequency and uniform quantization with a 10-bit encoding
In Figure Fig.3.8 the block diagram of the Logarithmic receiver is shown, which return the baseband signals to be sent to the detection/decoding chain.

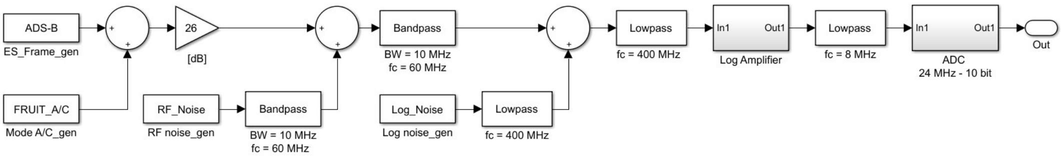


Figure 3.8: Logarithmic RF chain modeling

The RF front-end provides for a first amplifier stage with a 26 dB gain for the output signal from the antenna block and the thermal noise introduced by the front end components. Since the input signal is already amplified by the 26 dB factor, this parameter will be taken into consideration only for the RF noise introduction.
The technical specifications and related implementation details for modeling the RF front-end in the simulation environment are summarized in Table 3.1. The setup of several parameters has been defined according to the specifications provided within the above mentioned industrial research project.

The RF noise source is modeled through a typical zero mean Gaussian process with a flat power spectral density of -140 dBm/Hz, then yielding a power (process variance) of -70 dBm over a 10 MHz bandwidth.

Table 3.1: Specifications of the RF front-end and main features of its equivalent noise source.

(a) Specifications

Gain (G) 26 dB
Bandwidth (B) 10 MHz
Noise Figure (NF) 8 dB

(b) Equivalent RF noise source

1) Noise power spectral density ($\mathbf{N_0}$)
N_0 = NF + [$10\log_{10}$(KT)+30]+G = -140 dBm/Hz
(T = 290°K, K = Boltzmann's constant)
2)RF Noise power ($\mathbf{P_{RFnoise}}$)
$P_{RFnoise}$= -70 dBm over a 10 MHz bandwidth.

Fig.3.9 shows the RF noise generated both in time and frequency domain (FFT) where the effect of band-pass filtering (10 MHz with a central frequency of 60 MHz) is highlighted.

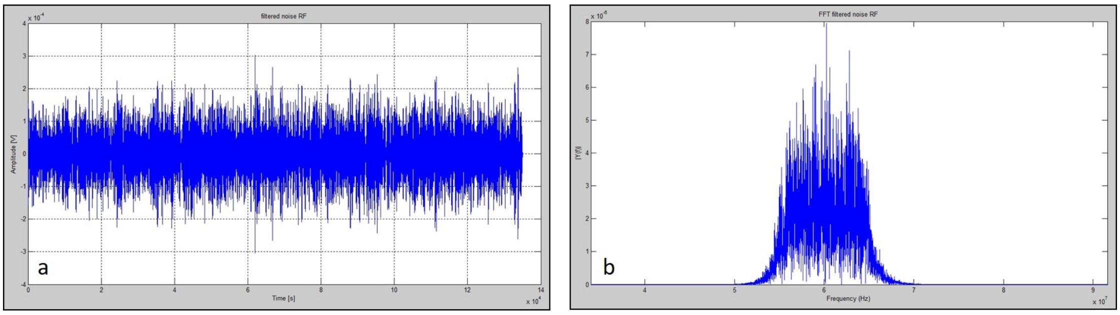


Figure 3.9: RF noise modeling: a) time domain - b) frequency domain

The logarithmic amplification stage has been implemented according to the specifications of a COTS device, whose features in terms of characteristic function and equivalent noise source are modeled according to Table 3.2 and Table 3.3. The slope and intercept are the two parameters that basically define the characteristic function (relationship between instantaneous input and output signal amplitudes) of the log amplifier.

Table 3.2: Main features of the logarithmic amplification stage.

Characteristic function of the device
$\mathbf{V_L = (P_i - P_T)*K}$ where:
$\mathbf{V_L}$ = Output signal voltage level
$\mathbf{P_i}$ = Input signal power level
$\mathbf{P_T}$ = Intercept = -95 dBm
K = slope = 20 mV/dB

Table 3.3: Main features of the equivalent noise source for logarithmic amplification.

1) Noise power spectral density (N_0)
$N_0 = 10\log_{10}[(V^2/50) * 1000]$= -165 dBm/Hz
(referred to T = 290°K)
2)Log Noise power ($P_{LOGnoise}$)
$P_{LOGnoise}$=-79 dBm over a 400 MHz bandwidth

The output level for Log noise power equal to -79 dBm over 400 MHz is obtained. Fig.3.10 show the Log noise generated both in the time domain and in frequency domain (FFT) where the effect of low-pass filtering at 400 MHz is highlighted.

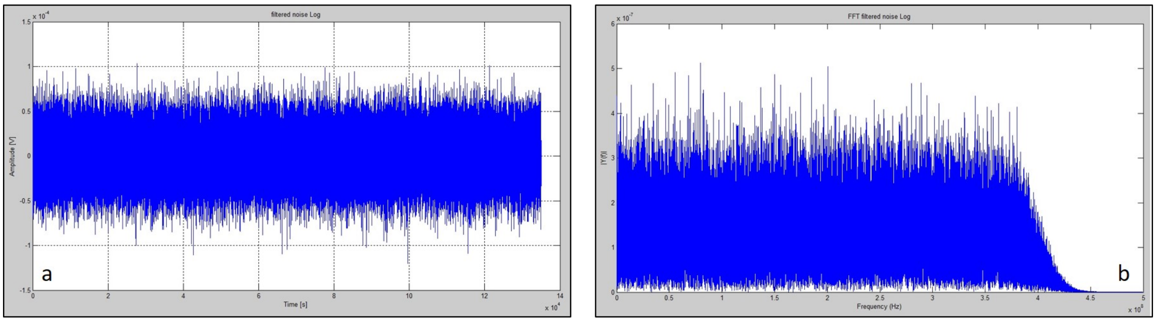


Figure 3.10: Log noise modeling: a) time domain - b) frequency domain

After the amplification process a 8 MHz low-pass filtering is introduced, which returns the baseband signal to be provided to the A/D conversion block: the latter one is based on uniform quantization with 10 bits per sample. Furthermore, the sampling frequency adopted in the simulation chain is scaled down to 24 MHz at this stage, in order to comply with the specifications of a real A/D device. A sample of the output signal for logarithmic reception chain is plotted in Figure 3.11.

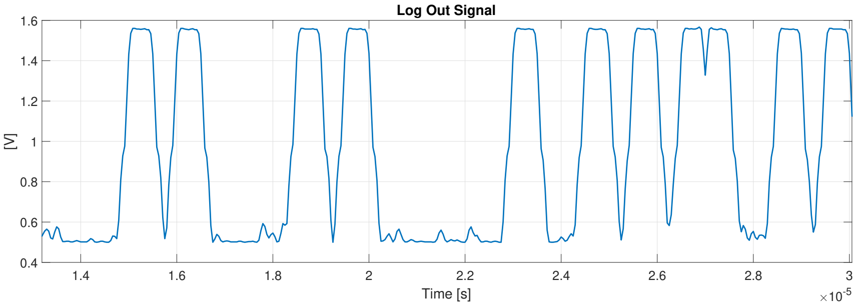


Figure 3.11: Logarithmic RF reception chain - output signal

Linear RF receiver:
The linear receiver model is composed by the cascade of two main functional macro blocks: (i) the RF front end (implemented as for the logarithmic chain) and (ii) the phase-quadrature reception stage. The second one implements two parallel lines involving: 60 MHz phase/quadrature harmonic signal generation, low pass filtering, 24 MHz A/D conversion with uniform quantization according to 16-bit encoding, envelope calculation. The RF front-end is modeled like in the prevuois case, and the already exposed analysis holds true.

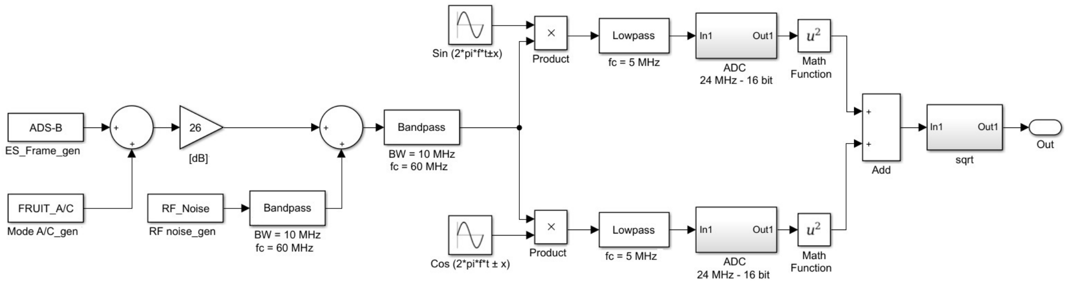


Figure 3.12: Linear RF chain modeling

Then, the generation of the in-phase and quadrature (baseband) components involves harmonic carriers at a frequency of 60 MHz ± 50 kHz (i.e. taking into account for actual tolerances with respect to the nominal frequency):

$$\mathrm{demsignalI} = \cos(2\pi \mathrm{f_p t})$$

$$\mathrm{demsignalQ} = \sin(2\pi \mathrm{f_p t})$$

The demsignalI and demsignalQ signals are respectively used to generate the quadrature (Q) and phase (I) components by taking their product with the output signal from the RF front-end. After low pass filtering (upper cut-off frequency of 5 MHz) of both I and Q components, the A/D conversion is performed on both branches. The the final stage involves the envelope calculation. A sample of the signal at the output of the linear reception chain is plotted in Figure 3.13.

In Table 3.4 the main parameters setup is reported, for both receiver alternatives with uniform quantization, obtained as a result of a series of simulation tests. In both RF reception chains the quantization step is quite low if compared to the signal dynamics involved in the decision stage, so that the effect of quantization noise on final performance can be considered negligible.

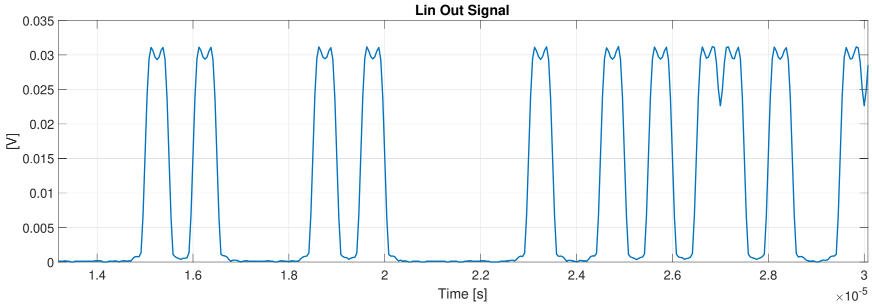


Figure 3.13: Linear RF reception chain - output signal

Table 3.4: Parameters' setting for A/D converter

Parameter	**Log receiver**	**Lin receiver**
$\mathbf{V_{max}}$	2.16 V	4 V
$\mathbf{V_{min}}$	0.5 V	- 4 V
N	10 bit	16 bit
$\mathbf{\Delta = (V_{max} - V_{min})/2^N}$	0.0016	0.00012

3.3.2 Detection and Decoding block

The enhanced detection and decoding algorithms are implemented on the received baseband signal with a sampling frequency of 24 MHz, that has been set according to the technical features of the development platforms provided by the industrial partner. The baseband reception stage includes: (i) the enhanced preamble detection chain, (ii) three parallel decoding chains implementing the three different techniques aforementioned in previous sections, (iii) one detection and error correction block

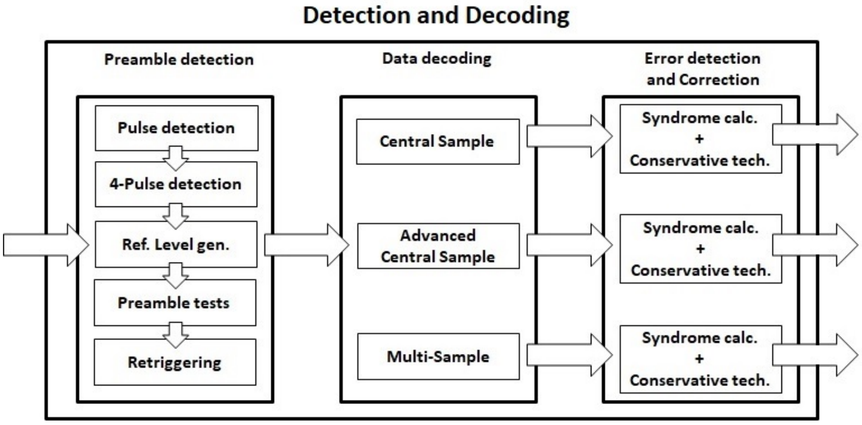


Figure 3.14: Detection and Decoding block

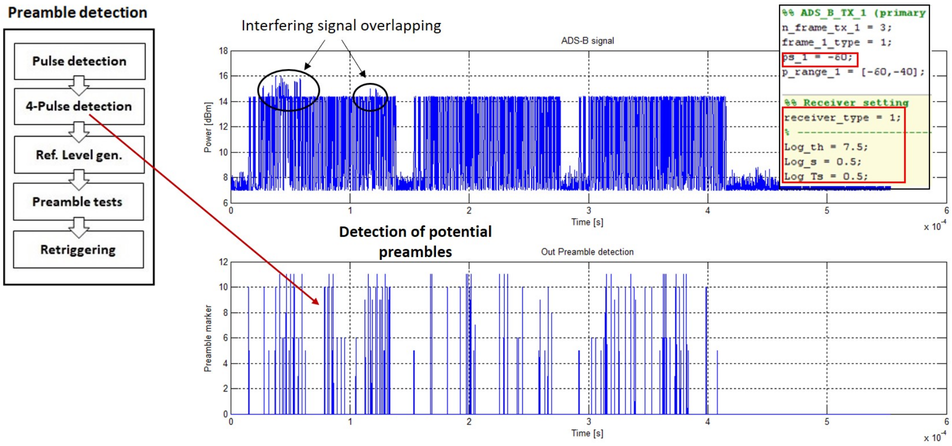
Table 3.5: Parameters' setting for preamble Detection and Decoding

Parameter	**Log receiver**	**Lin receiver**
$\mathbf{T_h}$	$\text{Log\_T}_h = 7.5$ dBm	$\text{Lin\_T}_h = -65$ dBm
$\mathbf{T_s}$	$\text{Log\_T}_s = 0.5$ dBm	$\text{Lin\_T}_s = 1.9$ dBm
s	Log_s = 1 dB	Lin_s = 3 dB

for each decoding line (syndrome calculation for error detection and conservative technique for correction). The block diagram of the detection and decoding block is shown in Fig.3.14.

In Table 3.5 the decoding parameters value are reported (in setting mask) for both Logarithmic and Linear receivers; that parameters setting was taken after an initial tuning phase, according to the signal dynamics.

Figure Fig.3.15 shows an example of a simulation result on the pre-detection algorithm which proves to be able to identify all possible preambles as a sequence of 4 pulses in the canonical preamble positions: 0, 1, 3.5, 4.5 νs, according to tolerances with respect to time (- 1 sample) and type of samples (Leading Edge or Valid Pulse). Within the set of potential preambles detected in the pre-detection phase, many of these are excluded by the test processes, then the retriggering algorithm selects the best one among those validated, as shown in Fig.3.16.



```
%% ADS_B_TX_1 (primary
n_frame_tx_1 = 3;
frame_1_type = 1;
ps_1 = -60;
p_range_1 = [-60,-40];

%% Receiver setting
receiver_type = 1;
% ------------------------
Log_th = 7.5;
Log_s = 0.5;
Log_Ts = 0.5;
```

Figure 3.15: Simulation results for preamble pre-detection algorithm

A result example of the decision process is shown in the figure, relating to the ACS technique, in which the bit declared at low confidence due to the overlapping of an interfering signal are highlighted. The number of low confidence bit drops drastically with the use of the MS technique, as can be seen from the results proposed in the following section.

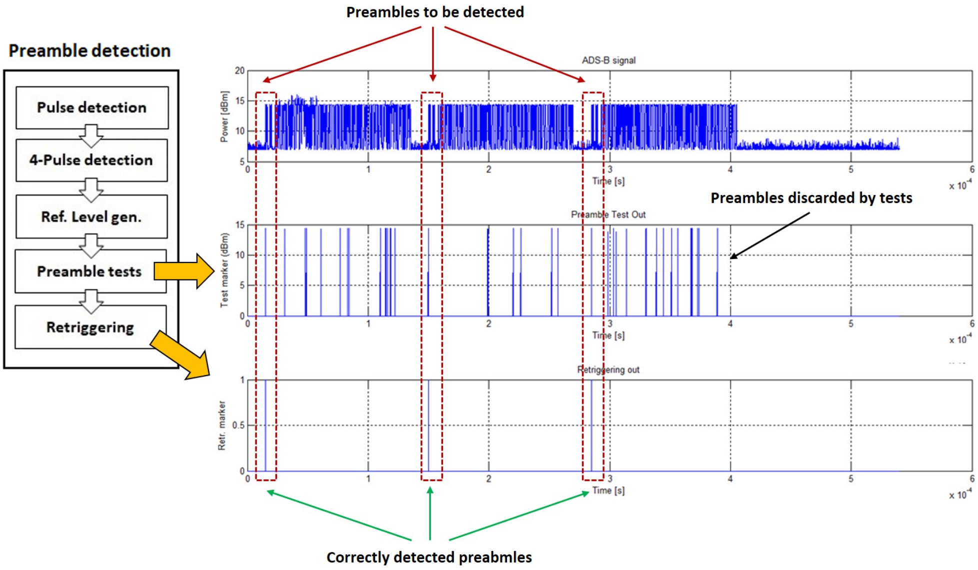


Figure 3.16: Simulation results for preamble tests and retriggering algorithm

3.4 Simulations and main results

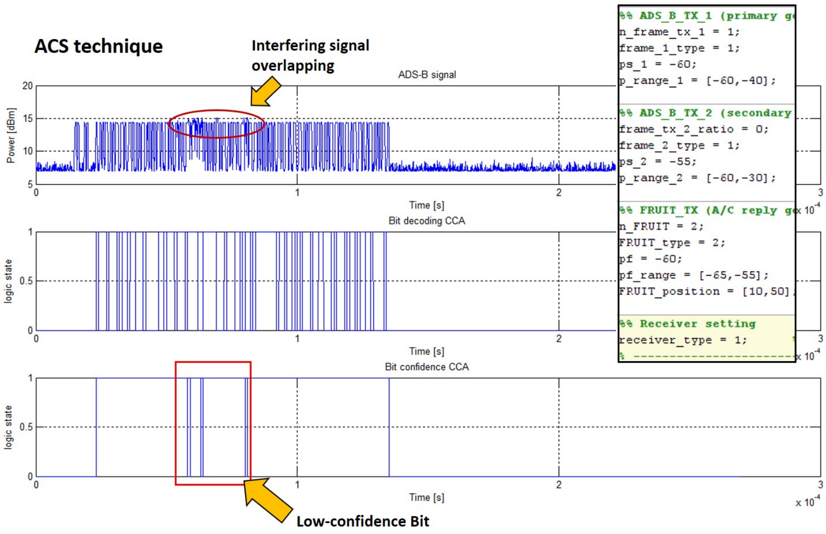
A large number of simulation runs have been executed, in order to assess the performance of the enhanced reception algorithms in terms of preamble detection and data decoding, both for Logarithmic and Linear reception chains under different interference conditions.

For the preamble detection, the eligible minimum power thresholds for correct detection in absence of interference have been firstly estimated. Additionally, performance evaluations of the enhanced detection chain in interfering scenarios have been carried out for various levels of interference. Futhermore, some specific cases have been addressed for analyzing the detection failures due to noise and interference.

For the decoding phase three decision techniques have been implemented and their performance compared in terms of BER for different interference levels up to 40000 FRUIT/sec.

Numerical results have been analyzed by also considering that the ADS-B preamble structure is inherently conceived to mitigate the overlapping effects produced by a single interfering mode A/C FRUIT.

Fig.3.18 reports the detection rate of correct preambles versus the input Signal power (Sp) for both RF reception chains, in the presence of thermal noise only. It can be seen that the increase of Sp yields increasingly better performance up to achieve almost full correct detections.



```
%% ADS_B_TX_1 (primary ge
n_frame_tx_1 = 1;
frame_1_type = 1;
ps_1 = -60;
p_range_1 = [-60,-40];

%% ADS_B_TX_2 (secondary
frame_tx_2_ratio = 0;
frame_2_type = 1;
ps_2 = -55;
p_range_2 = [-60,-30];

%% FRUIT_TX (A/C reply ge
n_FRUIT = 2;
FRUIT_type = 2;
pf = -60;
pf_range = [-65,-55];
FRUIT_position = [10,50]

%% Receiver setting
receiver_type = 1;
% -------------------------
```

Figure 3.17: Simulation results for ACS decoding technique

This first set of results is then used to determine a Detection Threshold (DT), which represents our baseline, defined as the power level of the input signal that enables almost perfect detection (e.g. detection rate larger than 99,5%) with the only presence of thermal noise (noise RF/Log). From these plots we set the DT level at: -84 dBm for the logarithmic receiver and -74 dBm for the linear one.
Taking into account that the maximum input signal power is -15 dBm, the receiver front-end can operate with a 69 dB as dynamic range in the case of RF logarithmic receiver, while the dynamic range is reduced to 59 dB when the linear RF front-end is considered.

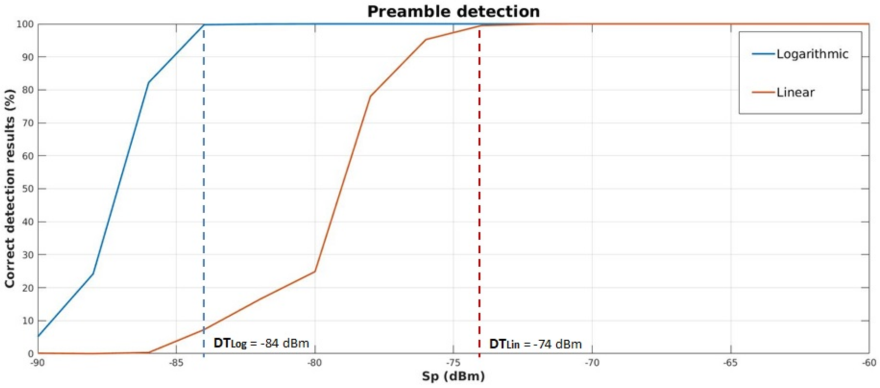


Figure 3.18: Detection Thresholds for both RF reception chains

The plots in Fig.3.19 refer to the average rate of correctly detected preambles that are obtained in the presence of mode A/C overlapping, for an increasing number of FRUITs per frame interval from 0 to 5. Both RF receiver alternatives are considered with the following settings:

- ADS-B frames with variable power level in the interval [-90 dBm, -30 dBm];
- MODE A/C FRUITs with uniformly distributed random timing and power (power ranging between -90 dBm and -30 dBm).

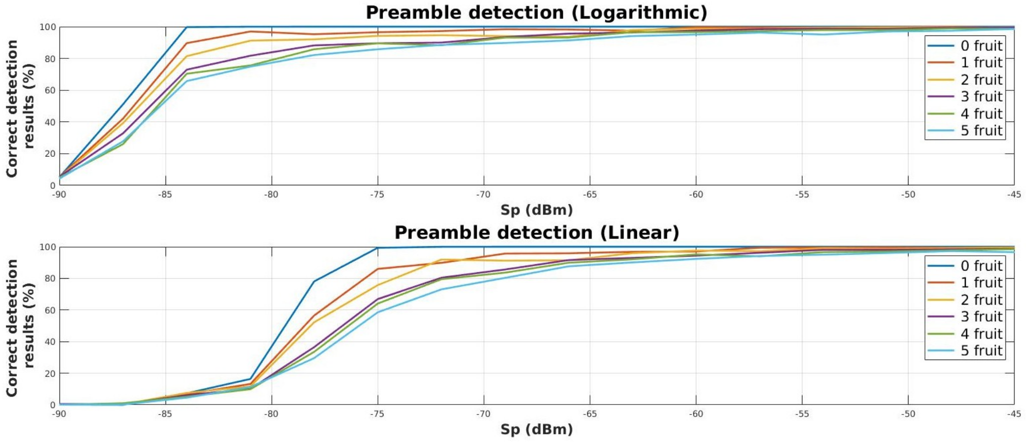


Figure 3.19: Preamble detection results VS FRUITs number

It can be easily observed that FRUIT's overlapping may seriously impact the preamble detection performance. In a highly interfered scenario (5 interferers per ADS-B frame) the preamble detection performance is remarkably degraded.
In particular, at the previously defined DT power levels (Log: -84 dBm — Lin: -74 dBm) the detection rate goes down to about 65% for the Logarithmic receiver and 62% for the Linear one.

The results shown in Fig.3.20, referred to the enhanced decision techniques previously described, have been obtained by collecting events related to more than 10.000 ES generated frames. An interference level of 40000 FRUITs/sec has been introduced (an average of 5 FRUITs per ADS-B frame), and data fields related to correct preamble detection events have been only considered.
In particular, the 5 FRUITs per frame have taken into account, not overlapping to each other, so that they can cover the whole frame duration, with uniformly distributed random power levels ranging between -90 dBm and -30 dBm. The ES power signal (Sp) varies between -70 dBm and -30 dBm, because the useful dynamic range

has been considered (with particular reference to the linear receiver) to analyze the performance of decoding techniques on correctly detected frames. Actually, the results obtained for the logarithmic receiver start from Sp equal to -84 dBm, since the dynamic range is wider than the linear one. Nevertheless, the same range is used for Sp to highlight the difference among the two RF reception chains.
The results of Fig.3.20 show that the MS technique always returns much better performance with respect to the CS one; a good improvement is also obtained with the ACS technique for the whole input power range of the useful signal. As expected, the logarithmic RF reception chain results to be more performing than than the linear one, especially for weak input signals.

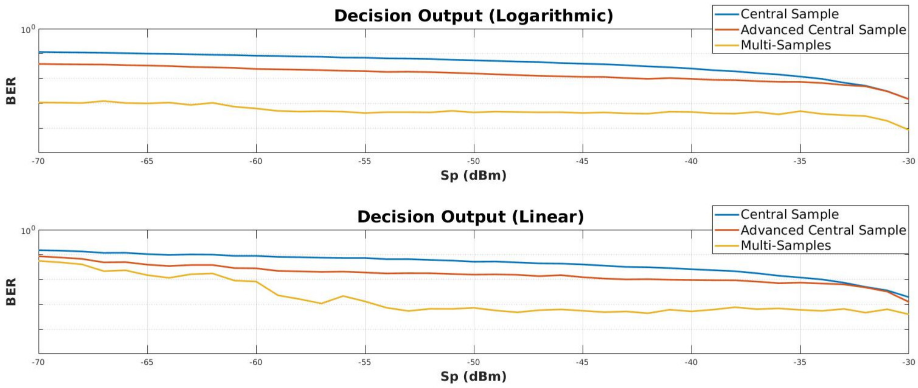
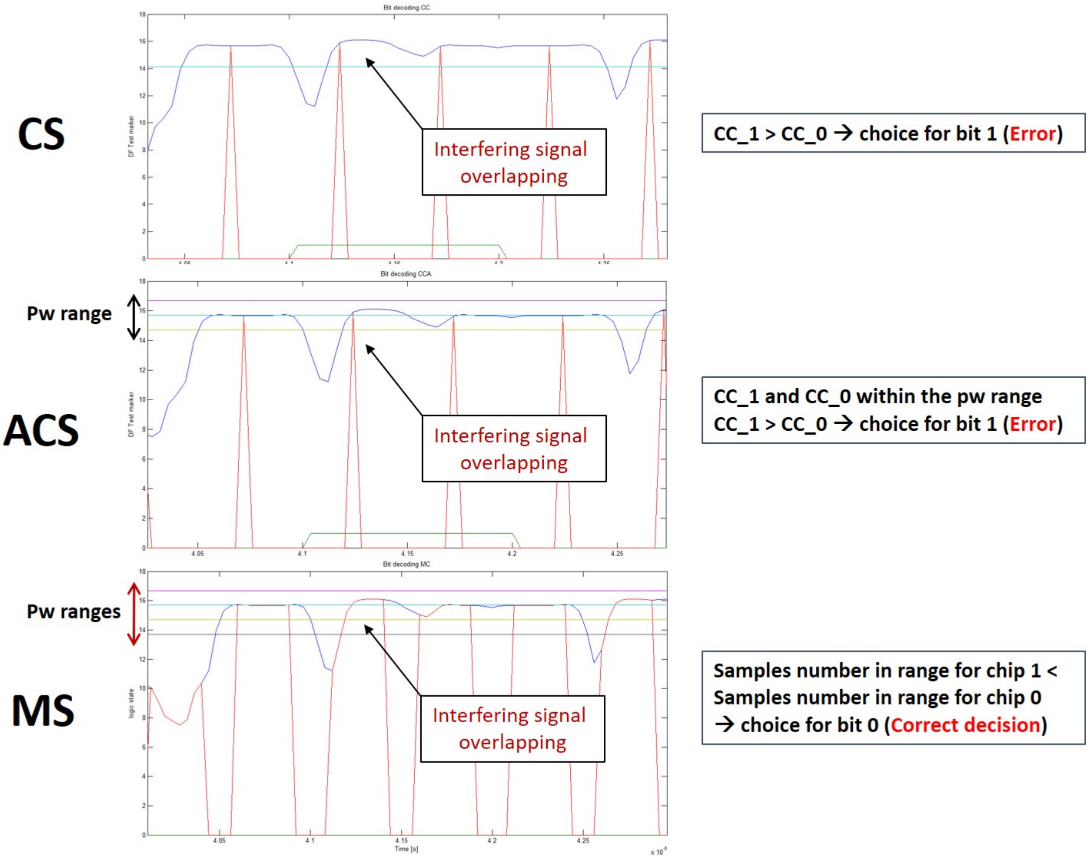


Figure 3.20: Decoding results for both RF reception chains

Fig.3.21 shows the implementation details of the three decision techniques in which it is highlighted how the multi-sample technique overcomes the limitations of the CC and ACS (results obtained with the Logarithmic reception chain).

3.5 Hardware description of the receiver

This section aims to describe an HW implementation of the detection/decoding architecture. The description below represents a functional analysis for the implementation of the algorithms up to the bit decision phase. The chosen abstraction level refers to an RTL (Register Transfer Level) description of the system and allows to deepen and analyze the complexity of the algorithms involved in order to guide and facilitate the design choices when writing the VHDL code for system prototyping.
The logic behind the following description aimed to provide a robust process fragmentation, and consequently the potential complexity of the individual blocks in terms of



CC_1 > CC_0 → choice for bit 1 (Error)

CC_1 and CC_0 within the pw range
CC_1 > CC_0 → choice for bit 1 (Error)

Samples number in range for chip 1 < Samples number in range for chip 0
→ choice for bit 0 (Correct decision)

Figure 3.21: Implementation details of decision techniques

input/output signals, number of lines and processing times, ensuring the maximum system controllability.

The simulation results have shown that the best implementation for the entire reception chain (excluding the detection and error correction stage for the considerations made previously) should be composed of: (i) logarithmic RF reception chain, (ii) enhanced preamble detection process (5 phases), (iii) decision according to the multi-sample technique.

The system specifications in terms of algorithms, sampling frequencies and characteristics of the input signals are the same described in the previous sections.

3.5.1 General system instantiation

The decoder takes in input the signal samples (words) output from the A/D converter of the RF receiver (logarithmic chain specifications are considered), and outputs the decoded binary sequence (112 bit per frame interval). With reference to the Fig.3.22 Signal_IN represents the 10-bit sample sequence of the signal output from the A/D

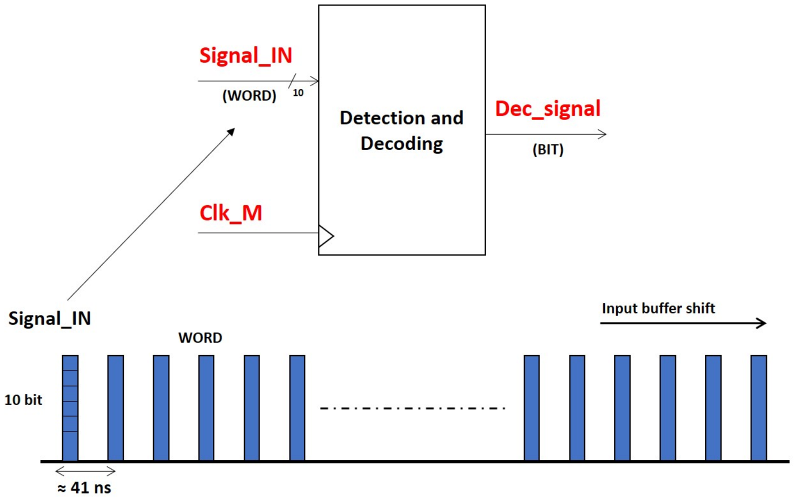


Figure 3.22: General system instantiation

converter of the logarithmic reception chain; with a sampling frequency of 24 MHz every 41 ns the system receives a new sample (word) in input.
The sampling frequency marks the general timing of the entire system, in terms of shifting the internal buffers, and represents a fundamental parameter for choosing the Clk_M which should be the same for lower consumption reasons. This HW description provides for different clock signals for the individual system functional blocks and for processing structures; if you choose to match the Clk_M with the sampling frequency (in order to guarantee low consumptions and longer processing times) then the output signals of the state machines will only represent the enable signals for the single processing clock.
The implementation of the detection and decoding chain provides for the sequential division into the three main blocks, as shown in Fig.3.23, where the following internal signals are reported:

- *Start_P*: identifies the beginning of an ADS-B frame (output of the Retriggering process). Start_P reveals the presence of an ADS-B message only if different from zero;

- *Ref_level*: reference power associated with the detected preamble (10 bit word). Ref_level signal is different from zero exclusively when StartP is different from zero;

- *Bit/Conf_level*: decoding results as 112-bit sequences per data block (logical state/confidence level).

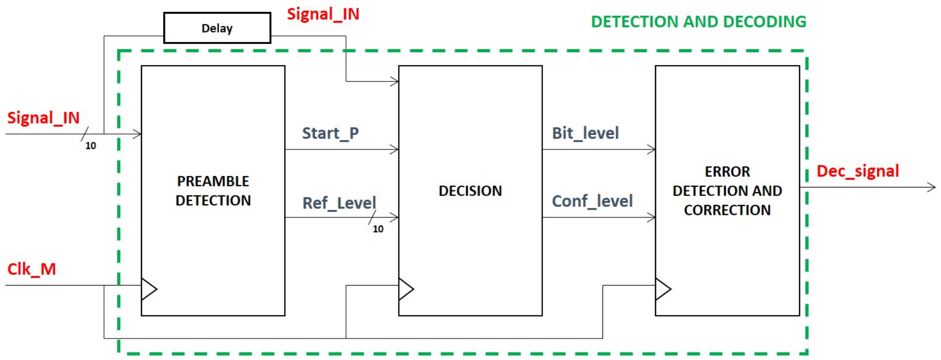


Figure 3.23: Main blocks of the Detection/Decoding HW architecture

3.5.2 HW description of the preamble detection process

Entering the details of the individual system blocks, the description of the preamble detection process is reported below (Fig.3.24).

Among the different internal signals, of which the size in terms of bit is shown, the delay block on the Signal_IN line represents the presence of a delay structure which guarantees the propagation of the signal samples in parallel to the preamble processing operations.

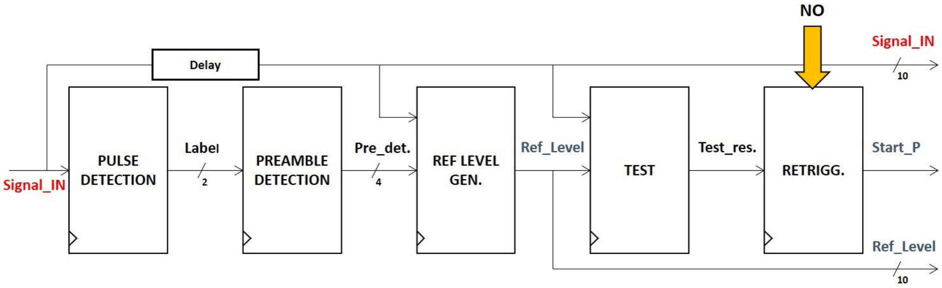


Figure 3.24: HW description of the preamble detection block

In Fig.3.25 a temporal scheme of the architecture is reported, in order to describe the processing behaviuor of the entire system. The left part of the diagram highlights the delay structure whose size is related to the specifications of the individual blocks. The value n varies according to the processing speed (choice of Clk_M) and refers to the calculation of the reference power level. The need for delay lines of this size is dictated specifically by the position of the samples useful for calculating the reference power level which must be taken in parallel; this is to have acceptable performance in terms of detection of possible overlapping preambles.

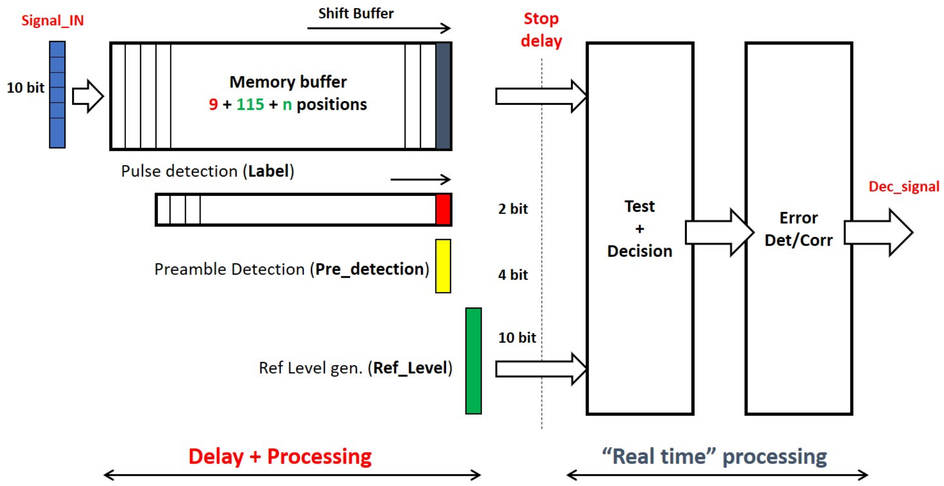
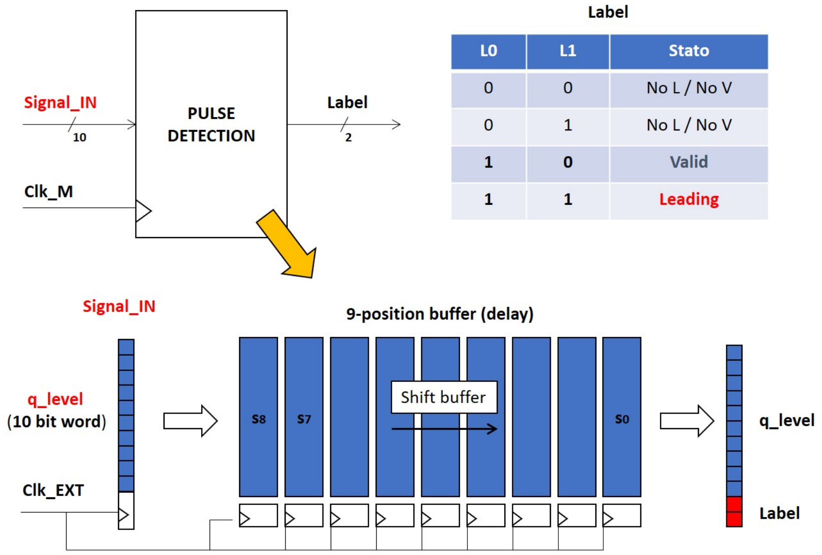


Figure 3.25: Temporal scheme of the system functionality

The output signals of the Delay/Processing functional block are the *sample start* in position 0 and the *reference power level* associated with it ($\neq 0$ only if Pre_detection $\neq 0$).
The real time processing algorithms can be carried out through the parallel execution of Test and Decision algorithms whose input lines are enabled at each Clk_M cycle in relation to the status of counters activated by Ref_level.

Any partially overlapping ADS-B frames can be decoded on parallel lines, taking into consideration that each sample brings different contributions on different lines according to its position within the frame. The whole real time process is scanned temporally through active meters on the individual lines.
Below is the high-level description of the macro blocks of the preamble detection process, taking into account that each of them must be broken down and described in its basic functional elements to realize a high-accuracy VHDL description.

The **Pulse Detection block** takes the Signal_IN samples as input and generates the Labels (2 bit to be associated to each sample) to perform the sample labeling according to this classification: Leading Edge, Valid Pulse Position, No Leading - No Valid (Fig.3.26).
The number of samples per Chip/Bit interval depends on the sampling frequency which affects the sizing of the delay lines. The reference frequency for the entire system is 24 MHz (CLK_EXT), equal or proportional to the Clk_M, this involves a number of samples per Chip interval equal to 12 (24 samples per Bit). Based on the defined sampling frequency, the block's operating specifications are as follows [41]:



Label

L0	L1	Stato
0	0	No L / No V
0	1	No L / No V
1	**0**	**Valid**
1	**1**	**Leading**

Figure 3.26: HW description of the Pulse Detection block

- *Valid Pulse* = sample above Th threshold followed by 7 samples above threshold;
- *Leading Edge* = Valid Pulse characterized by a rise time greater than Ts compared to the previous sample, less than Ts compared to the next one;
- 9-position delay structure;
- Storage for a new sample every 41 ns (CLK_EXT = 24 MHz synchronous with fc).

The **Preamble Detection block** takes the Labels (2 bit) as input and returns the detection of potential preambles as a Pre_detection (4bit), the result of identifying four pulses (Leading Edge or Valid Pulse) in canonical positions according to the rules following listed:

- *preamble canonical positions* = 4.5μs (108), 3.5μs (84), 1μs (24), 0μs (Start) with values in brackets representing samples number;
- *at least two pulses classified as Leading Edge* = 11 types of preamble;
- *time tolerance (-1 sample)* = 8 combinations per preamble type.

The **Reference power level** calculation block takes the Signal_IN and the Pre_Det as input, while returning the reference power value (10 bit) associated with the detected

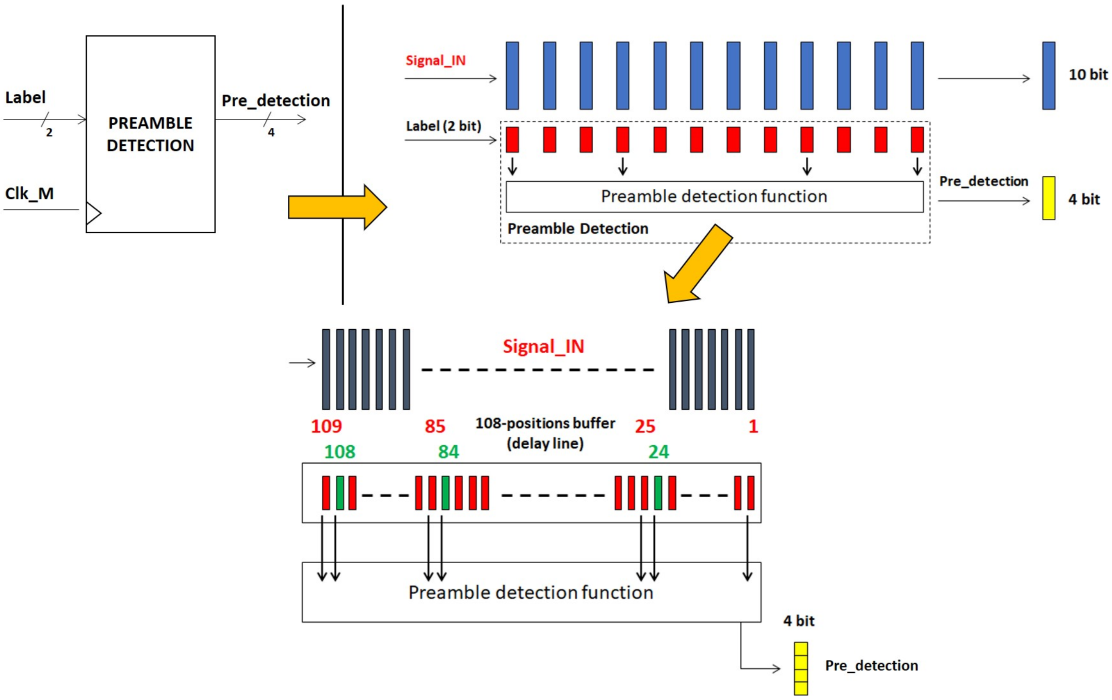


Figure 3.27: HW description of the Preamble Detection block

preamble. For a detailed description of the reference power calculation algorithm see [41]; the main sub-functions to be implement are the following:

- pre-selection of samples according to Pre_detection;
- comparison among the samples for the calculation of the statistic parameters;
- MAX statistic calculation and identification of associated samples;
- identification of the smallest sample associated to MAX (min);
- comparison between all samples at MAX statistic with min;
- average calculation.

The general structure of the block includes an external 115 position delay buffer (as extension of the 108-positions buffer of the previous block) which provides for filling the position 108 (4.5 μs from the Start sample) to the seventh sample following. The calculation of the reference power level is carried out in parallel by several processing blocks, each of which activated by the signal Pre_detection $\neq 0$ and only if the previous processor is busy.

The logic that guides the implementation of the algorithm involves the parallel loading of all 28 samples associated with the preamble pulses and the processing with fixed timing (CLK_EXT cycles number) as worst case, in order to reassociate downstream the reference power level calculated with the sample in position 0 μs.

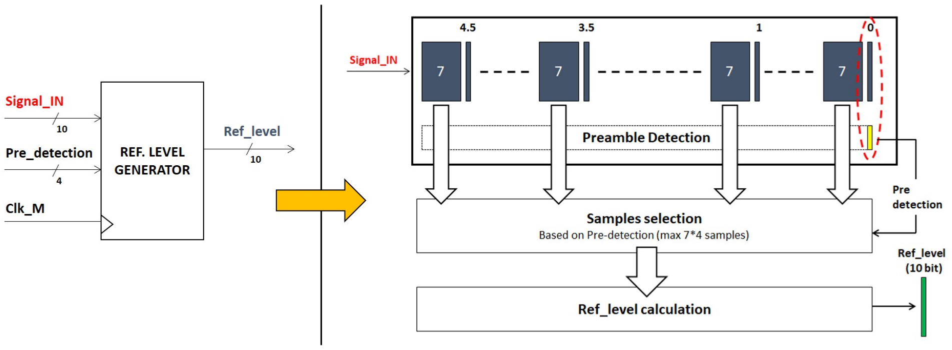


Figure 3.28: HW description of the Reference Power calculation block

The preamble tests block cannot be separated from that of the decision, since the dynamic evolution of the system involves the co-implementation of the two processes. From this point on, the HW implementation does not provide for delay lines; SignalIN samples with the associated reference power (10 bit + 10 bit in parallel) represent the input of the Test/Decision block.

A parallel line structure can be created, each of those dedicated to the validation of a potential detected preamble and to the decoding of the associated data block. To take into consideration that each reference power level is associated with a Signal_IN sample is essential ($\neq 0$ if sample at the beginning of the frame, $= 0$ otherwise).

The validation of the preamble by means of the tests and the decision process are performed in parallel since the implementation of them involves the analysis of some samples belonging to the data block; the negative result of at least one of the tests involves the false detection declaration and the reset of the decoding.

Parallelization of the process involves the implementation of a management protocol for the activation of the individual reception line. The block diagram of figure Fig.3.30 shows the input/output signals of the individual receiver blocks and explains the process management method.

A Ref_level value $\neq 0$ represents the start for the single machine (the Ref_level input line is connected in parallel to all the Test/Decision maker blocks); Machine_N_state indicates the status of the n-th block (in processing/at rest) and represents the enable signal for the n+1-th machine. The generic receiving machine is activated by the detection of potential preamble and only if the hierarchically higher machine is busy.

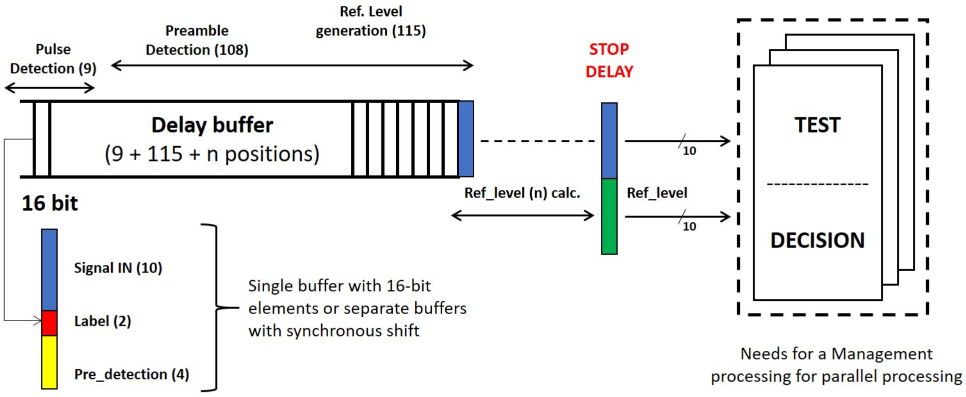


Figure 3.29: Preamble tests and Decision process in parallel execution

If Machine N state = 1 (n-th machine busy) then the n+1-th machine is enabled; the arrival of a Ref_level ≠ 0 activates the processing of the new preamble on machine n+1. The Fig.3.31 shows the general implementation scheme of the real time

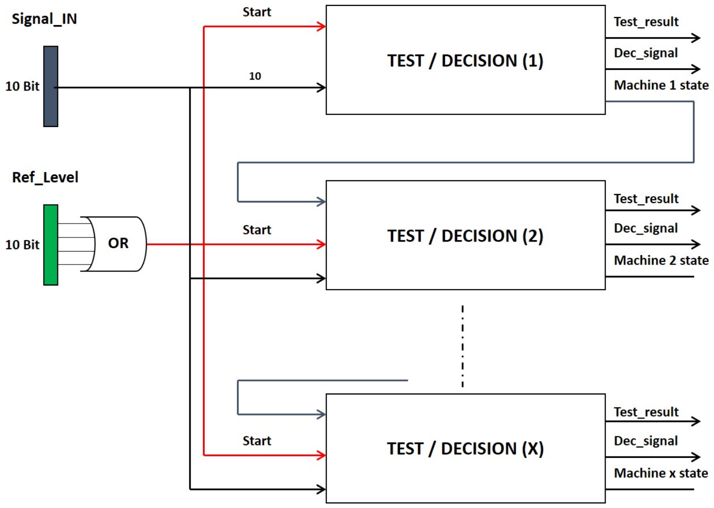


Figure 3.30: Management protocol for parallel execution of Tests/Decision algorithms

receiver, in which the description of a single Test/Decision maker block is given and the input/output control signals from the FSM (Finite State Machine).

The reference algorithms for the **Tests block** are implemented according to the 5 validation processes, divided into μs Test (3), Pw Test, DF Test. The instantiation of the Test block is shown in Fig.3.32. In Fig.3.33 the implementation details of the three test macro-blocks are reported. The Test_result output signal provides high logic level only in case of all the 5 tests return a positive result. Test_result = 0 makes the process fail and frees the reference machine by setting the Machine_N_State (0) signal.

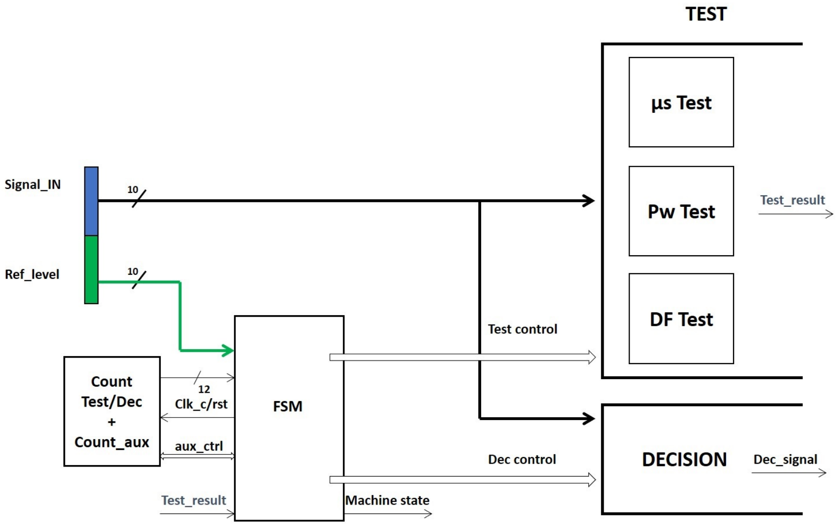


Figure 3.31: HW description of Test/Decision block

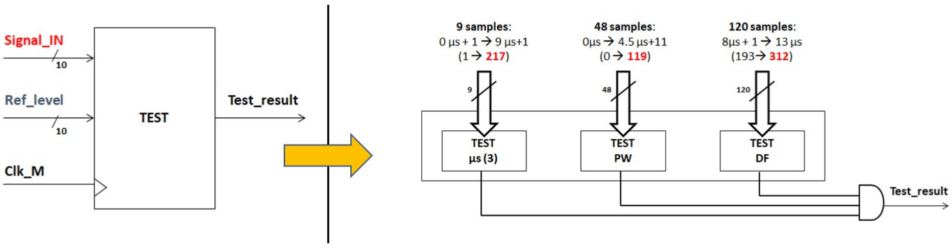


Figure 3.32: HW description of Preamble Tests block

The detailed description of the HW components related to the preamble detection process is reported in Appendix A.

3.5.3 HW description of the data decoding process

About the **decoding process** the simulation tests carried out on the Matlab model highlighted the best performance of the multi-sample technique in terms of BER compared to the others; based on these results that solution has been chosen to be implemented. The reference algorithm for the multi-sample technique involves:

- *Discrimination of all samples* of Signal_IN (24 per bit) in the following categories:
  - Chip 1A = sample of the first chip (1:12) with power inside the range at X dB with respect to Ref_level;

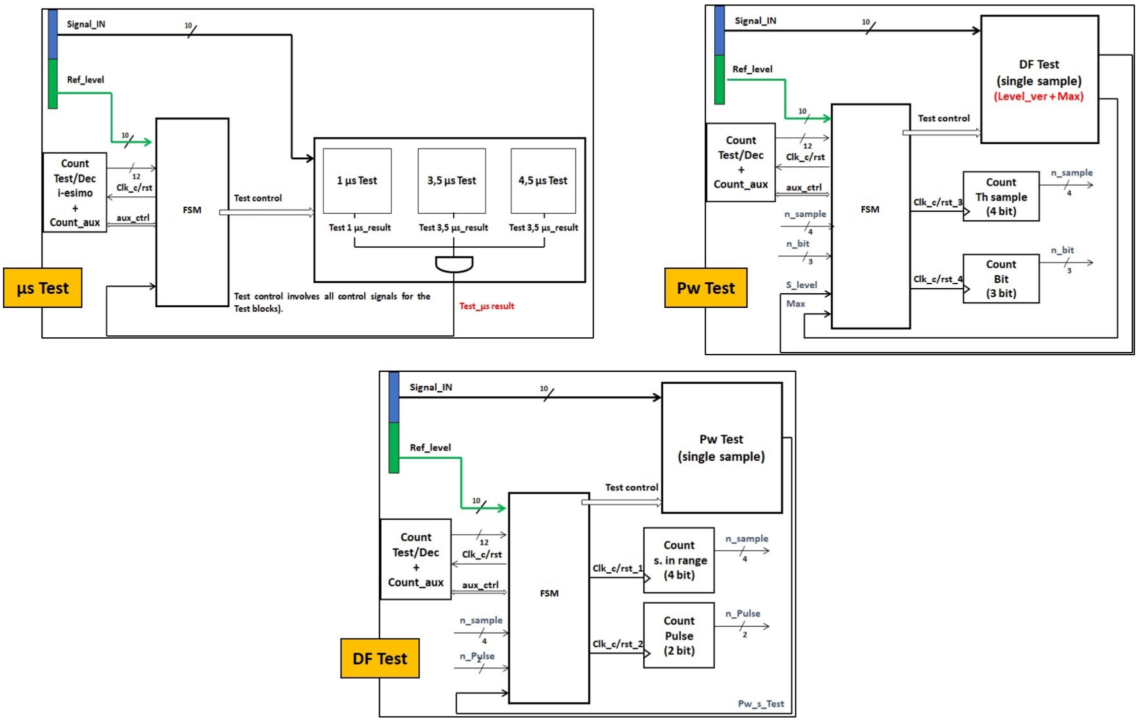


Figure 3.33: Preamble Tests details

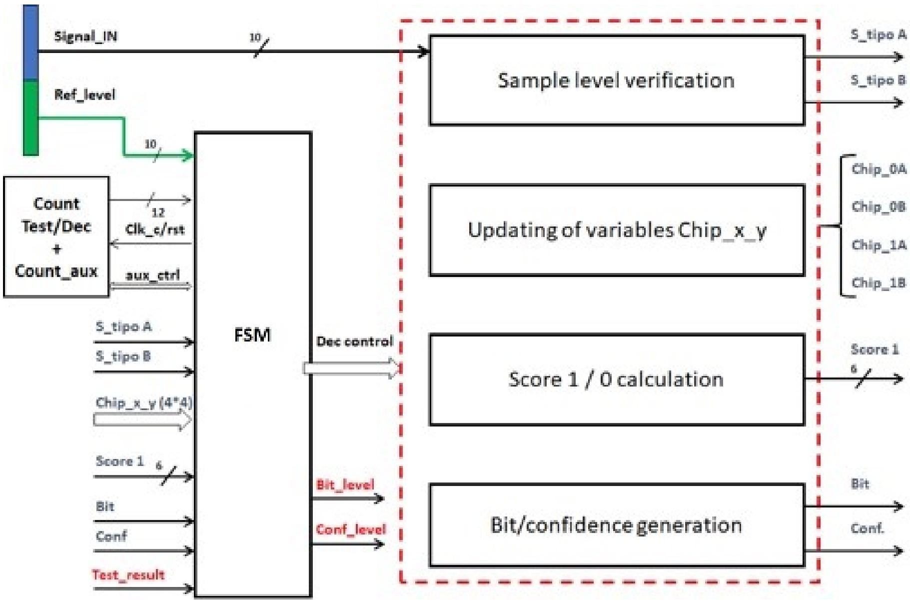


Figure 3.34: HW description of Multi-Sample decoding block

- Chip 1B = sample of the first chip (1:12) with power below Ref_level level 2X dB;
- Chip 0A = sample of the first chip (13:24) with power inside the range at X

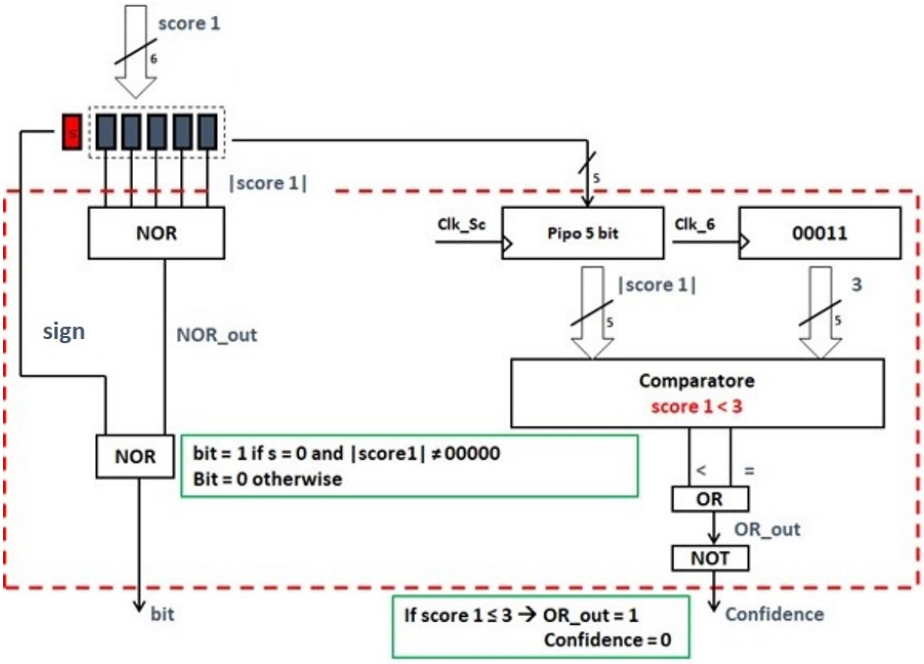


Figure 3.35: Multi-Sample decoding block detail

dB with respect to Ref_level;
- Chip 0B = sample of the first chip (13:24) with power below Ref_level level - 2X dB.

- *Calculation of score parameters*:
  - score 0 = Chip 1A - Chip 0A + Chip 0B - Chip 1B;
  - score 1 = - Chip 1A + Chip 0A - Chip 0B + Chip 1B;.
- *Return of the output signal* as:
  - Bit status (1 for score 1 > score 0, 0 otherwise);
  - Confidence level (1 for |score 1 - score 0| > 6, 0 otherwise).

The detailed description of the HW components related to the data decoding process is reported in Appendix A.

3.6 Collaborations and publications

These activities have been carried out in collaboration with **Leonardo company** and **RadioLabs Consortium**

S. Chiocchio, A. Persia, F. Santucci, F. Graziosi, M. Faccio, "Modeling and performance analysis of advanced detection architectures for ADS-B signals in high interference environments," 2017 32nd International Union of Radio Science General Assembly and Scientific Symposium (URSI GASS), Montreal, 2017.

S. Chiocchio, A. Persia, F. Santucci, F. Graziosi, M. Faccio, "Modeling and evaluation of enhanced reception architectures and algorithms for ADS-B signals in high interference environments" (in submission for publication to the Physical Communication journal).

Chapter 4

ITS for Road transport Vehicular communication systems and technologies

The World Health Organization (WHO) reports show that the road accidents annually cause approximately 1.35 million deaths worldwide, one-fourth of all deaths caused by injuries. More than half of all road traffic deaths are among vulnerable road users: pedestrians, cyclists, and motorcyclists. Also about 50 million persons are injured in traffic accidents. Furthermore, the road traffic crashes cost most countries about of 3% of their gross domestic product [57]. Road traffic injuries can be prevented. This requires the involvement of a multiplicity of factors making reference to different society and technological aspects, which does not only concern the transport sector

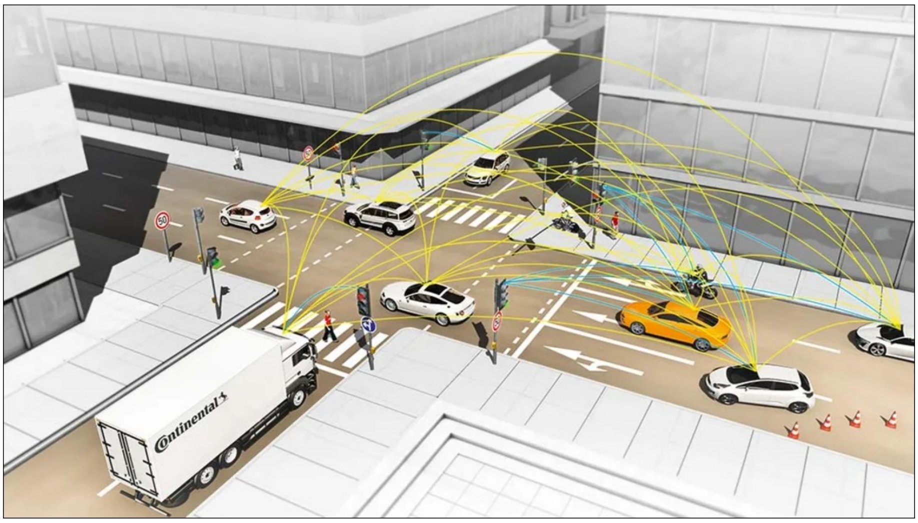


Figure 4.1: Vehicular communication context

but also the healt and education fields, as well as the public security. In this context the Cooperative-Intelligent Transportation Systems will play a key role in order to address the safety of roads, vehicles, and road users, and at the same time to achieve the other relevant goals related to the quality and efficiency of the transport systems, optimizing the use of natural resources and reducing pollution [58].

4.1 Enabling technologies for connected vehicles

The connected vehicle represents a functional extension of the classic vehicle concept, which starting from the specific additional functionalities related to the mobility context will lead to a total paradigm changing that will bring the vehicle to offer a multipliplicity of services to drivers, passengers and third parties. The connected vehicle will be equipped with on-board sensors and communication platforms through which to send and receive navigation and mobility context information from heterogeneous sources, as well as processing equipment that makes it an "intelligent" node of a network of vehicles able to be aware of the mobility scenario, in order to prevent potential dangerous situations and manage resources at best.

Pervasive digital technologies and wireless communications are the key enablers for the "smart" evolution of transportation systems, where the current development trend is oriented to increase the level of safety and comfort in driving and traveling, to reduce CO2 emissions toward the assisted and autonomous driving. Within the vehicular context, the accurate localization, pervasive connectivity and cybersecurity are expected to play the main role for the development of Cooperative and Intelligent Transportation Systems (C-ITS).

Each vehicle will be able to detect its geographical position with high accuracy, in all operating conditions, communicate with other vehicles and with the network infrastructure to exchange mobility data and report any critical issues on the road safety. To achieve this goal, vehicles shall be equipped with on-board sensors able to detect technical and environmental parameters from the car and the surrounding driving context, already embedded today in luxury or high-end cars.

At the same time techniques and methodologies have to be designed and implemented in order to develop centalized platforms able to manage mobility flows in an efficient, safe and eco-sustainable manner. The collection, processing and dissemination of an ever-increasing amount of information, originating from vehicles and road infrastructure, is necessary to support assisted driving applications. The main problem is gathering and processing a huge amounts of heterogeneous data in aggregate form, taking into account time latency constraints typically imposed by safety applications.

4.1.1 Communication

Short and long range communications techniques will be required, to mobility information exchanging among the road users (vehicles, road infrastructure, pedestrian etc.) as well as local and centrilized elaboration entities for implementation of real time mobility services and road traffic management applications. Vehicles will be able to interact with each other and with the road infrastructure or other road users, through the current and forthcoming wireless communication protocols in the different Vehicle to Everithing (V2X) modes following discussed.

Depending on the applications, several enabling technology families are considered, such as vehicular ad-hoc networks (VANETs), including IEEE 802.11p-based standard families, and cellular networks for infrastructured architectures, including long-term evolution (LTE) and the incoming 5G network paradigms [59]. A detailed description of vehicular communication technologies is reported in the following section.

4.1.2 Localization

Satellite-based localization represents the main technology for large scale operations on accurate positioning [60]. Achieving a high accuracy and integrity localization is a current challenge also for the other intelligent transport domains, such as for the railway sector in which highly performing solutions for accurate satellite tracking have already been proposed in a automated driving perspective [61], [62]. The results of these investigations can be taken into consideration for the development of vehicular mobility systems [63]. Moving on to the avionic context the incoming of UAV (Umanned Aerial Vehicles), which is leading to a revolution, in terms of research and development opportunities for the autonomous driving of aircraft, as well as legal regulations, can also support the relative localization for ground vehicles [64].

The incoming satellite families, like the european GALILEO and the low-orbit satellite constellations in deploiment, and the cooperative networks paradigms will contribute to improve the accuracy of the localization data. About that, in the last section of this chapter a heterogeneous architecture project for smart mobility is presented that will implement the combined use of GPS and GALILEO satellite constellation, with data fusion from on-board and communication systems, in order to guarantee that the position error does not exceed the maximum tolerable error (∼20 cm).

Compared to the railway context, vehicle tracking suffers of more critical conditions in particular in urban mobility environments, due to the lack of satellite coverage in some areas (e.g. tunnels) and the distorting effects of the radio channel (e.g. shadowing, multipath). Therefore improved accuracy must be achieved through data fusion from on board sensors, different terrestrial surveillance and communication technologies. Assisted and autonomous driving will require an even tighter and timely precision, to be attained with more advanced techniques and wider data sets, that are still under definition. Different soruces can be used in addition to the GNSS, both of diagnostic and of terrestrial surveillance type, as IMUs (Inertial Measurement Units) and vehicle odometer like reported in [65], [66], or OVSs (Optical Velocity Sensors) [67]. A tracking solution based on lane recognition with video camera and on-board lidar is proposed in [68], while the use of HD maps with advanced geometric calculation algorithms to reduce heavy computation is proposed in [69]. Evolving vehicular communication technologies can represent a useful information source for localization of vehicles, through consensus algorithms [70] and V2X communication: in [71] a V2I-based solution is presented, while a DSRC-based one has been proposed in [72], in which an integrating GNSS raw data exchange is given in a probabilstic positioning estimation approach. The 5G technology will play a key role in the location of vehicles, as indicated in [73] where a feasibility study is proposed concerning the positioning capabilities for future 5G-based V2I networks which show to be able to achieve localization accuracies below 30 centimetres.

4.1.3 Cybersecurity

The communication and localization systems will have to be increasingly complex in order to reach the levels of accuracy and integrity suitable for safe and efficient assisted driving. The growing number of vehicle information sources, however, leads to an exponential increase in vulnerabilities due to cybersecurity attacks which can threaten both the safety of passengers and the privacy of users.

Potential problems can concern both the systems inside the vehicle, including the intra-vehicle communication between the on-board unit and sensors, and the inter-vehicular communication, among vehicles and between vehicles and infrastructure/network, as well as localization systems. The set of systems, external architectures and signals can be subject to specific cyber attacks in order to undermine the integrity of the vehicular communication/mobility network or acquire confidential information.

About the communication aspects, specifically the integrity, authenticity and confidentiality requirements of exchanged information must be guaranteed and security of network elements must be ensured against intrusions.

The security aspects can be approached from the phases of drawing up the system requirements, up to the software design and development phase, according to Secure by Design procedures. A summary of knowledge about the core cybersecurity aspects to consider when designing a modern car is reported in [74], mainly on the in-vehicle network point of view, including its requirements, the current most used protocols and their vulnerabilities.

From the cyber intelligence point of view, solutions are being studied to recognize and counter the threats currently known, as well as to try to anticipate the development of new threats. To identify new vulnerabilities and new possible cyber-attacks the monitoring of attackers' activities has to be performed in order to prepare countermeasures even before these attacks are carried out. An overview of potential cyber attacks for the vehicular context is reported in [75], [76].

One of the main security aspects concerns the tracking information protection for location-based services. The [77] proposes an in-depth evaluation of the threats and solutions related to both GNSS and non-GNSS-based solutions, as well as certain cryptographic solutions for security and privacy of positioning and location-based services in the IoT context.

The current safety standards for the vehicular communication systems of the main standardization bodies are reported in [78], in particular in [79] the architecture model proposed by ETSI is described, based on security entities (e.g. enrollement and authorization), information protection techniques and secure message formats, mechanisms for network access and communication authorization.

Focusing on the incoming 5g technology a comprehensive overview about security and privacy solutions which can be applied to the next-generation of vehicular networks is proposed in [80], where a classification of solutions is performed according to the 4 security services: authentication, confidentiality, availability and integrity.

4.2 Vehicular communication overview

4.2.1 Vehicular communication modes

Communication between vehicles, infrastructure and other road users is crucial to increase the safety and efficiency of management processes for traffic flows within the integrated transport systems of the next future. Making a functional description of the VANETs or more generally of a vehicular communication systems, regardless of the implementation technologies that will be discussed later in the document, the V2X concept provides the following communication modes:

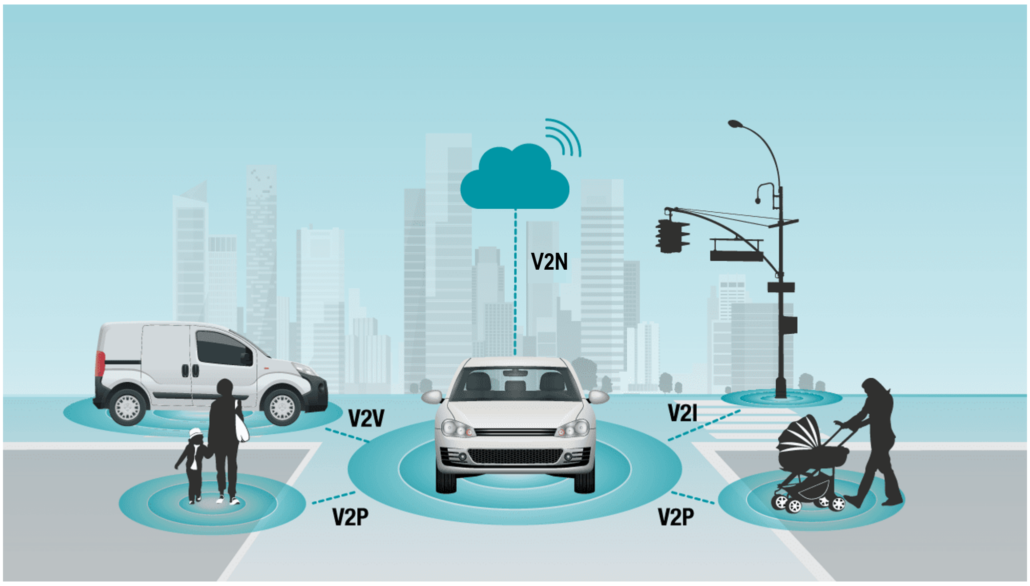


Figure 4.2: Vehicular communication modes [81]

- V2V (Vehicle to Vehicle): enables cars to communicate and relay mobility information to each other in real time, thereby greatly increasing the vehicle dinstance visibilty (electronic horizon) and furthering its ability to predict what's coming. Vehicle status parameters, traffic dynamics, location, and perception information of the surrounding are examples of mobility data exchanged in V2V mode. Message payloads should be flexible to satisfy the dynamic amount of V2V application information. If the direct communication range of V2V is limited, the forwarding of information by communication through other network elements can be exploited, such as other vehicles (e.g. multi-hop transmission), Road Side Units (RSU), application servers, edge/cloud servers.

- V2I (Vehicle to Infrastructure): the infrastructure collects information on mobility and road conditions by connected vehicles in its reference area and elaborate them in order to realize a safe and efficient management of traffic flows trhough the dissemination of traffic information to a specific fleets of vehicles. Specifically a vehicle will interact with a RSU or a locally application server based on different transmission modes, such as broadcast, unicast, and multicast. A particular application server will serve its all defined geographical area; a multiplicity of application servers can be employed to serve overlapped areas.
- V2N (Vehicle to Network): provides a centralized management of the information by a network element as in the case of V2I communication, making reference to a higher hierarchical level able to cover larger traffic areas and provide high-capacity services.
- V2P (Vehicle to Pedestrian): involves direct communication between a vehicle and pedestrians or VRU (Vulnerable Road Users) in general (e.g. cyclists), equipped of smartphone or other User Equipments (UE) like mobile devices. V2P is performed directly or through the use of network infrastructure.

4.2.2 Basic set of applications and requirements

Standardization entities, the research community and industries were focused on ITS use cases definition and study, in order to analyse potential mobility needs and evaluate appropriate solutions, with reference to the currently uses technologies and the incoming ones.
The European Telecommunication Standard Institute (ETSI) describes the main use cases for C-ITS applications in [82] where the main funtional requirements are defined, later in [83] a guidance on Local Dynamic Map (LDM) standardization has been provided; further updates are expected to review currently proposed use cases and to define new ones. Currently, use cases are classified into the following groups:

- *Co-operative road safety*: traffic situations where short range communication is fundamental. Proposed scenarios concern local traffic management in order to mitigate the risk of accidents and collisions and reduce the number of deaths among passengers [84]. Particular attention is paid to intersections, head-on, posterior and lateral vehicle collision that represent the most critical conditions to which a high percentage of accidents that occur every year are associated. These applications mainly provide information and assistance to drivers to avoid

such collisions with other vehicles. V2V and V2I communication is required to information exchanging about speed, position and heading, in order to avoid and predict collisions. Moreover, information exchange between the vehicles and the roadside units can be used to locate hazardous condition on the road, accidents signaling and so on.
Some examples of active road safety applications are: intersection collision warning, lane change assistance, overtaking vehicle warning, emergency vehicle announcement, pre-crash sensing, traffic condition information dissemination. Road safety services are characterised by their message broadcast frequency, packet error rate and round trip latency. 50 ms represent the time threshold defined by ETSI as round trip delay for pre-crash warnings (the US Department of Transportation has defined the minimum round trip delay should be less than 20 ms).

- *Traffic efficiency*: the network infrastructure plays the main role, because applications are related to management of traffic flows that must be implemented in a large scale and in centralized way, through the dissemination of messages by the roadside units providing updated local information on traffic conditions bounded in space and/or time. Speed management applications aim to assist the driver to manage the vehicle speed for smooth driving and to avoid unnecessary stopping in order to reduce consumption and increase the travel confort. Regulatory speed limit notification and green light optimal speed advisory are two examples of this class of services. For this kind of applications the low latency communication, positioning accuracy, and robust network connections are essential.

- *Others (infotainment)*: applications that can be developed by car makers and ICT players, to provide additional services that will entail exchange of large amounts of data for which V2I and V2N communication play the key role. Are divided into *cooperative local services*, related to local infotainment application (e.g. point of interest notification, local electronic commerce and media downloading) and *global Internet services* refer to large-scale application based on software and data updates (e.g. insurance and financial services, parking zone management and ITS station life cycle). Infotainment services, which can include live video transmission, augmented or virtual reality applications, will have low latency requirements and higher data rates around 100 Mbps.

Vehicular network requirements depending on the specific set of applications and use cases. For safety-critical applications, communication requirements must be more stringent, e.g. a maximum latency of 100 ms and a minimum update rate of 10 Hz. Different considerations can be drawn for use cases of the Others group (e.g. media download, remote diagnosis and just in time repair notification, map download and update), where time constrains are not of primary concern and latency requirements are less stringent (e.g. 500 ms).
Generally we can refer to the following classification for system performance requirements:

- vehicle communication performance, such as maximum latency time, frequency of updating and resending information;
- vehicle positioning accuracy;
- system reliability and dependability, such as radio coverage, bit error rate;
- performance of security operations, such as performance of signing and verifying messages and certificates.

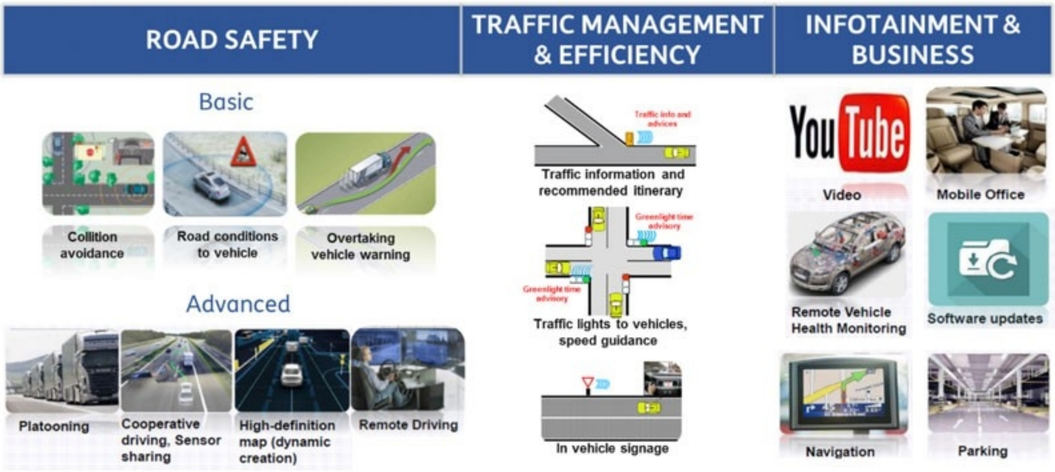


Figure 4.3: Basic Set of Applications [85]

4.2.3 Vehicular communication technologies

The vehicular communication modes and the mobility services described above can be implemented through short-medium and long-range technologies depending on the technical and operational specifications of the individual application. Specifically, we can distinguish between V2X based on short/medium range communication (or DSRC) and Cellular V2X (C-V2X) [86] [87].

For short-range communication we will mainly refer to the European ITS G5 standard and the American WAVE (Wireless Access in Vehicular Environment) architecture, both based, for physical and MAC layers, on the 802.11p which represents the facto standard for vehicular communication [88].

The limits of this technology are referred to scalability and lack of performance in highly mobile scenarios. C-V2X overcomes these limitations offering better performances in terms of link budget, better congestion control, reliability, interference and better non line of sight capabilities. Since different C-ITS applications have different communication requirements, short-medium range as IEEE 802.11p and cellular networks are not two competing technologies; rather, they complement each other [90]. Generally for applications without short delay requirements, which rely on information being spread regionally, the cellular network technologies should be more suitable; on the other hand 802.11p mode looks more promising for vehicular safety communications with stringent requirements for bounded delay [91]. However

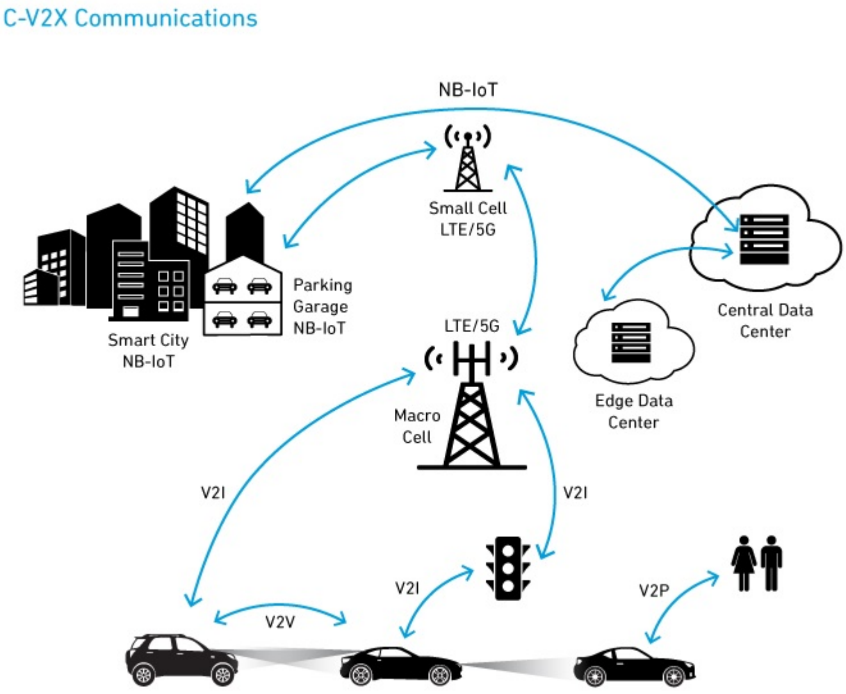


Figure 4.4: Vehicular communication technologies [89]

both technologies can deliver reliable service levels for basic safety applications, of around 100 milliseconds for low vehicle densities.

In the near future, the forthcoming 5G will represent an alternative (or a complementary) access technology for vehicular communication both for short [92] and long-range communication, thanks to its capabilities in terms of data transfer, transmission speed, and low latency. Thanks to the 5G arrival an increase in the service specifications for the new mobility applications and use cases is being defined, for which the technologies mentioned above are not currently adequate to guarantee the required performance levels.

Specifically the IEEE 802.11p supports C-ITS applications able to operate at maximum communication ranges of 1000 m in the licensed band of 5.9 GHz (5.85-5.925 GHz), both for the European (ETSI ITS G5) [93] [94] and the American one (WAVE) [95], as well as in 700 MHz band ITSs, defined in the ARIB-STD T109 Japanese standard [96].

For the purposes of the following discussion, it is necessary to distinguish mainly between the American WAVE (Wireless Access in Vehicular Environments) standard and the ETSI ITS G5 European one, which provide for a different division of the frequency band and use different types of awareness messages: Basic Safety Messages (BSMs) in the US standard [97] and Cooperative Awareness Messages (CAMs) in the European one [98].

C-V2X was standardized in the 3GPP Release 14 (2017) as the new protocol in order to define an adequate transport in terms of coverage and service continuity for both direct V2V/I/P communication and cellular network-based solutions for V2N [99]. To this aim changes to the LTE radio interface have been required, which led to define the Uu and PC5 interfaces (Fig.4.5. The goal of 3GPP is to support a very broad range of driving safety features throught enhanced cellular network performance able to support all levels of driving autonomy according to the SAE driving autonomy levels [100]. V2X services requirements supported by LTE transport, provided by 3GPP, are reported in [102] in which basic sets of use cases are reported with latency times up to a 100 ms for safety-critical applications in direct communication (vehicle maximum speed: 250 km/h, payload: from 50 to 1200 bytes, maximum transmission rate: 10 msgs/s). For non safety-critical application, messages pass through the network, being able to tolerate delays of up to 1s.

In order to meet enhanced requirements for more performing V2X services and application, such as platooning [103], remote sensing, advanced/remote driving, 3GPP

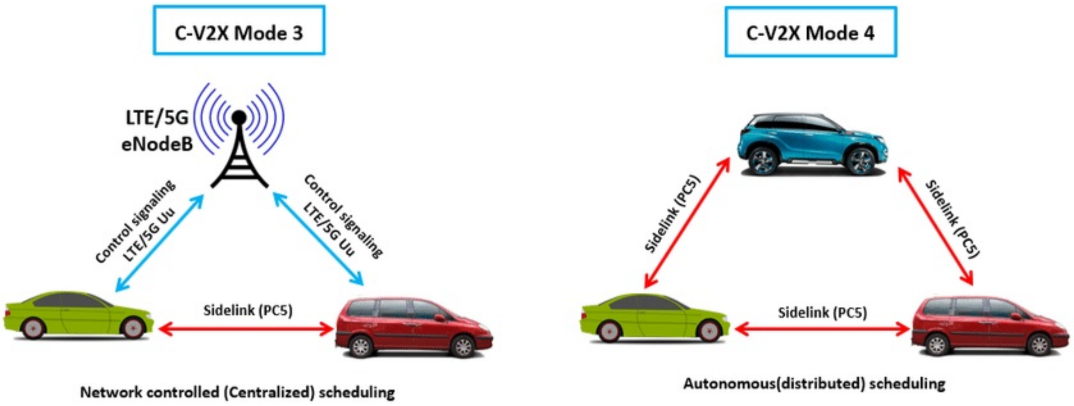


Figure 4.5: Uu and PC5 interfaces [101]

published the Release 15 in which the 5G-based solutions for vehicular communications (5G-V2X) are presented, toward the autonomous vehicles applications [104]. Specific use cases for V2X communication are already being proposed for experimentation tests of the forthcoming 5G technology [105].

C-V2X technology will be further defined and its capabilities expanded, indeed work is ongoing for the Release 16 focusing on the enhancements to the 5G architecture in order to overcome the limitations of a linear evolution of the LTE system through the introducing the New Radio (NR) technology [106] [107].

4.2.4 Simulation environment for vehicular communication

This section describes the simulation environment used to test the functionality of vehicular communication networks with respect to different operating scenarios, and summarizes the main smart mobility applications implemented and analyzed.

4.2.4.1 The simulation environment

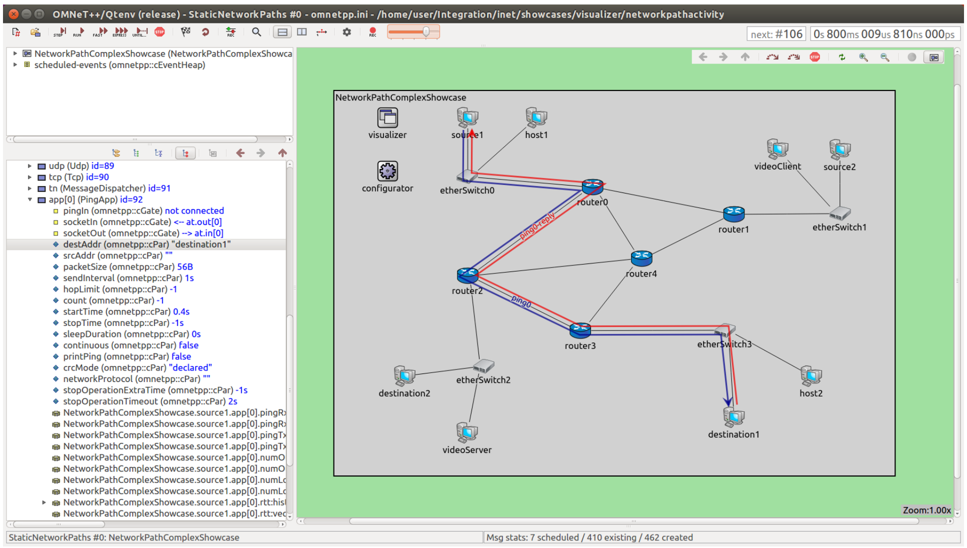
The performance analysis on vehicular communication technologies and mobility applications must often refer to a huge amount of data deriving from a large number of vehicles for a predefined area, for which an investigation based on real testbeds is not applicable, but the simulation approach must be used.

The most critical stage is the representative implementation of the system model that requires some abstraction and simplified assumptions which have to be the lowest possible impact on the final results. In order to verify the response fidelity of the simulation environments, the comparison with the results derived from real experiments is essential, as far as possible and for limited operational scenarios.

To test the performance of V2X communication in large-scale real operational scenarios, a high-fidelity simulation environment has been used involving **VEINS**: an open source simulation framework based on parallel execution of an event-based network simulator (**OMNeT++**) and a road traffic microsimulation model (**SUMO**). The basic software tools that make up the simulation environment are described below:

- **OMNeT++ - Objective Modular Network Testbed**: the network simulation is a technique in which a software reproduces the behavior of a network with the computation of the interactions between the entities (e.g., user devices, nodes, packets) through mathematical equations. By changing the model parameters in a controlled manner it is possible to observe the network behavior under different conditions.
  OMNeT++ is a simulation environment with a component-based architecture, whose elements (modules) are written in C++ and assembled by means of the NED (NEtwork Description) high-level language. It relies on the ECLIPSE platform, has a native GUI and provides a simulation kernel with the classes useful for the creation of the model components and with the features to realize their interconnections.
  Among the useful frameworks available, the VEINS is the one dedicated to vehicular networks simulation; some other useful frameworks for ITS context can be: INET which represents the standard library for network simulations as a model suite for wired, wireless and mobile networks; INETMANET specifically designed for MANETs (Mobile Ad-hoc NETworks) and CASTALIA for networks of low-power embedded devices (e.g. WSN).
  More details about OMNet++ can be found in [108].

- **SUMO - Simulation in Urban Mobility**: is an open source vehicle mobility simulation software.
  The choice to make the software open source guarantees its constant evolution which now is not limited to being only a traffic simulator, but represents a set of applications able to prepare and manage the simulation. It is designed to simulate a road network of a large city size. This simulation is multi-modal, which means that not only cars are modeled but also the other transport system categories that interact with vehicular environment, such as railway networks,



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OMNeT++/Qtenv (release) - StaticNetworkPaths #0 - omnetpp.ini - /home/user/integration/inet/showcases/visualizer/networkpathactivity
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▸ NetworkPathComplexShowcase (NetworkPathComplexShowca
▸ scheduled-events (omnetpp::cEventHeap)

  ▸ udp (Udp) id=89
  ▸ tcp (Tcp) id=90
  ▸ tn (MessageDispatcher) id=91
  ▾ app[0] (PingApp) id=92
      pingIn (omnetpp::cGate) not connected
      socketIn (omnetpp::cGate) <-- at.out[0]
      socketOut (omnetpp::cGate) --> at.in[0]
      destAddr (omnetpp::cPar) "destination1"
      srcAddr (omnetpp::cPar) ""
      packetSize (omnetpp::cPar) 56B
      sendInterval (omnetpp::cPar) 1s
      hopLimit (omnetpp::cPar) -1
      count (omnetpp::cPar) -1
      startTime (omnetpp::cPar) 0.4s
      stopTime (omnetpp::cPar) -1s
      sleepDuration (omnetpp::cPar) 0s
      continuous (omnetpp::cPar) false
      printPing (omnetpp::cPar) false
      crcMode (omnetpp::cPar) "declared"
      networkProtocol (omnetpp::cPar) ""
      stopOperationExtraTime (omnetpp::cPar) -1s
      stopOperationTimeout (omnetpp::cPar) 2s
      NetworkPathComplexShowcase.source1.app[0].pingR
      NetworkPathComplexShowcase.source1.app[0].pingR
      NetworkPathComplexShowcase.source1.app[0].pingT
      NetworkPathComplexShowcase.source1.app[0].pingT
      NetworkPathComplexShowcase.source1.app[0].numO
      NetworkPathComplexShowcase.source1.app[0].numO
      NetworkPathComplexShowcase.source1.app[0].numL
      NetworkPathComplexShowcase.source1.app[0].numL
    ▸ NetworkPathComplexShowcase.source1.app[0].rtt:his
      NetworkPathComplexShowcase.source1.app[0].rtt:vec

StaticNetworkPaths #0: NetworkPathComplexShowcase
Msg stats: 7 scheduled / 410 existing / 462 created
```

Figure 4.6: Omnet++ simulation environment [109]

motorcycles and so on.

Each vehicle within the network is individually modeled and has its own position and its own instantaneous speed; these values are updated at each simulation step, which lasts one second, according to the previous vehicle with respect to the travel direction and the type of road on which the vehicle is moving. The simulation is defined for discrete time and continuous space.

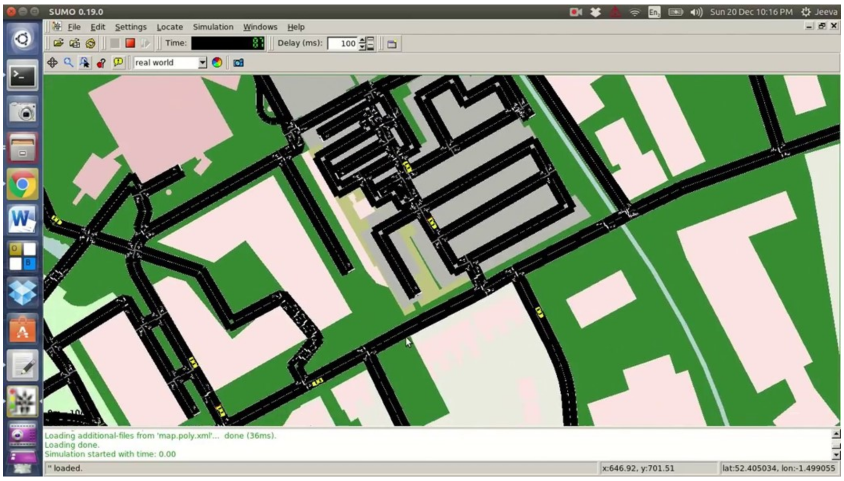
During the simulation the vehicles follow the travel rules that characterize a specific roads, like the direction and speed limits. To perform a simulation the mobility scenario must be firstly created in which the vehicles will be able to travel: the road network including lanes, traffic lights, intersections and other structures useful for representing reality.

To reproduce real traffic environments, through the NETCONVERT module it is possible to import real road networks from different sources, for example OpenStreetMap, and generate scenarios directly usafull by SUMO applications).

Once the operating scenario is created the demand for mobility has to be set, in terms of types and number of vehicles, the possible routes and the list of vehicles that will take part in the simulation.

More details about SUMO can be found in [110].

- **Veins - Vehicles In Network Simulation**: is an open source framework for network simulation that offers a suite of models for vehicular networking. These models are created by an event-driven network simulator (OMNeT ++)



```
Loading additional-files from 'map.poly.xml'...  done (36ms).
Loading done.
Simulation started with time: 0.00
" loaded.
```

Figure 4.7: SUMO simulation environment

in collaboration with a road traffic simulator (SUMO). The other components of Veins take care of setting up, running and monitoring the simulation.

It is designed to be an execution environment for code generated by users (generally an application to be evaluated by means of a simulation). The framework takes care of modeling the lower protocol layers, nodes mobility, setting the simulation, ensuring correct execution and collecting the results during and after the simulation itself.

With Veins, each simulation is performed by running the OMNeT ++ and SUMO simulators in parallel, which are connected to each other via a TCP socket. The protocol for this communication is standardized as the Traffic Control Interface (TraCI) and allows the bidirectional simulation of road and network traffic. The vehicles mobility in SUMO corresponds to the movement of the nodes in an OMNeT ++ simulation: the network nodes can therefore interact with the simulation of the road traffic in progress. With reference to the protocol stacks, fully detailed models of the IEEE 802.11p and IEEE 1609.4 DSRC/WAVE network levels are implemented, including multi-channel operation, access to the QoS channel, noise effects and interference. Specific models are foreseen for the characterization of the radio channel, for antenna specifications and obstacle attenuation, for communication standards, including the european ETSI ITS G5(Artery) for VANET and for cellular networks such as the LTE, as well as traffic management appications like platooning.

More details about Veins can be found in [111].

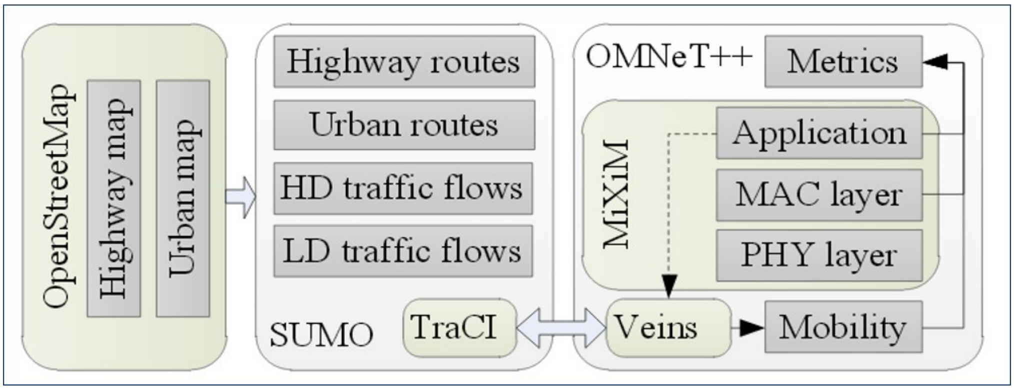


Figure 4.8: Veins framework environment

4.2.4.2 ITS applications and analysis carried out

The following are the research activities carried out in a simulation environment, with regards to performance analysis on short-range vehicle communication technologies and the implementation of smart traffic flow management applications for different operating scenarios:

- **Radio channel congestion analysis**:
  for road safety applications the exchange of awareness messages in the vehicular network, in V2V and V2I communication mode, is fundamental and have to takes place constantly and without loss of information. As the number of vehicles involved in the reference scenario increases, the number of messages exchanged between vehicles and with the network infrastructure increases as well. In presence of a great number of vehicles this massive exchange of awareness messages could lead to a radio channel congestion and the consequent loss of messages. When the network looses those messages, the system safety can not be guaranteed, hence it is crucial to avoid channel overloads.
  Channel load analyzes were carried out through the CBR (Channel Busy Ratio) parameter calculation in a reference scenario represented by a road junction of 300 m x 300 m at the increasing in number of approaching vehicles, up to 105 during 100 seconds, and of transmission rate per time interval up to 50 msg/s for each vehicle.
  For this investigation only cooperative awareness messages (i.e., BSMs) have been considered, with a maximum size of 360 bytes, according to the WAVE standard, at a fixed bitrate of 12 Mbps. As expected, the CBR value has shown to rapidly increase with the number of vehicles and with emission rate, reaching

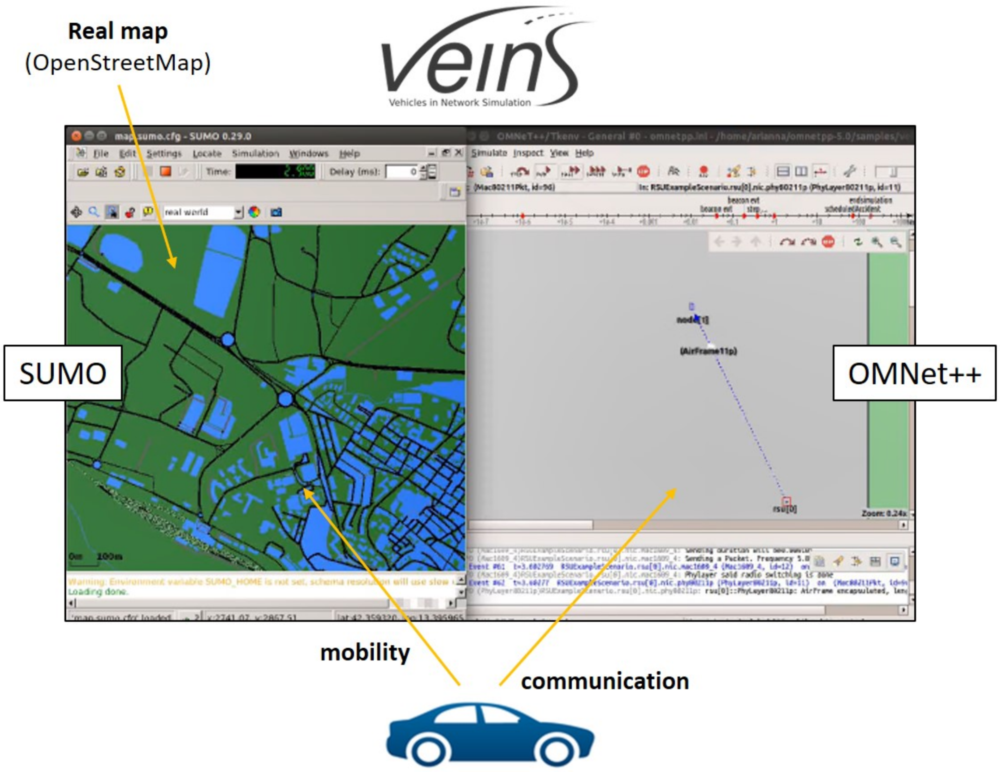


Figure 4.9: Veins - parallel execution of OMNet++ and SUMO

not negligible values also in a quite small area like that under investigation. Vehicular communication, as shown by the use cases proposed below, are useful for improving safety and traffic conditions, but to achieve these results the communication network has to be stable and guarantees functionality in every operating conditions. For this reason, keeping the radio channel congestion levels under control is fundamental: an adequate CBR level guarantees the functionality of the communication system and consequently better conditions of vehicular mobility, such as better conditions of vehicular mobility (e.g. near an intersection) produce a reduction of the radio channel congestion.

- **Management of traffic flows in the presence of car in failure or road accident**:
  a set of tests on applications related to smart management of vehicles was peformed in order to verify the possibility to use vehicular communication to improve the traffic conditions in the event of a road blocked due to an accident or a damaged car. Under these conditions, it is possible to disseminate informa-

tions towards approaching vehicles and force them to choose alternative routes, thus reducing the queues and avoiding risks of further accidents.
A car failure has been simulated at a junction forcing the approaching vehicles to follow specific alternative direction respect to that predefined. By communicating in advance a critical issue on the road, vehicles will be able to change road, thus reducing consumptions, times and accidents risk.
Different tests have been carried out to verify the behavior of vehicles in the absence of vehicular communication and with the activation of the V2X capabilities, as well as specific applications to guarantee priority on specific routes for emergency vehicles.
The results have shown that the vehicular communication introduction contributes to significantly improving of traffic management processes, in terms of reducing resources and preventing potential accidents, as well as supporting emergency management activities.

- **Traffic Lights Optimization with V2I communication**:
  the traffic lights play the key role for the efficient management of vehicular traffic in urban areas, then research activities have been carried out to evaluate the advantages of introducing the vehicular communication technology into their dinamic optimization process. In particular, the possibility of using V2X messages as information source for intelligent traffic lights has been verified, in order to improve the dynamic evolution of the traffic light cycles. To date, some proposed solutions provide for the use of cameras for the optimization of traffic lights, for this reason both the solutions have been implemented through simulations, in a single-cross and double-cross scenario, and the results have been compared in terms of intersection capacity, waiting times of vehicles, arrived/loaded vehicles, queue length and CBR.
  The results showed how the optimization of traffic lights produces an improvement in the management of traffic flows at intersections, and at the same time in the comparison between the V2X-based optimization and the camera-based one; the first one proved to be more robust respect to all the parameters mentioned above, moreover being also less expensive from the maintenance point of view.
  The activities and results related to this application are described in detail in the next section.

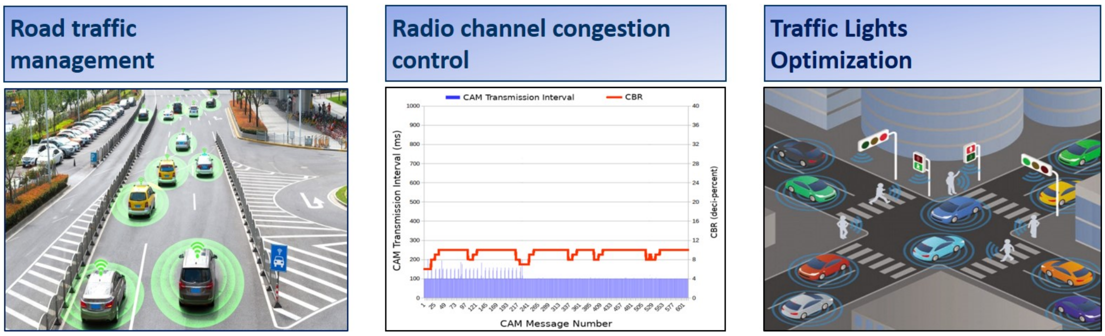


Figure 4.10: ITS application implemented

4.3 A V2I-based solution for traffic lights optimization

4.3.1 State of the art and aims of research activities

The rapid increase of the number of vehicles requires novel approaches and solutions to improve the road network efficiency and reduce critical road situations. Making reference to busy urban environments, the optimization of traffic light cycles represents a key challenge in order to reduce the road traffic congestion and maximize the intersections capacity. Despite the first results dating back to the 70s [112], the current solutions are mainly based on a-priori knowledge of the traffic flows: the number of vehicles approaching to each junction must be known and this flow is supposed to be constant in the time span of a reference period. This assumption is unrealistic and cannot cope with critical situation, such as traffic jams or accidents, that might suddenly change the traffic conditions. Thus the adaptation of the traffic lights control plane to the time-varying traffic conditions at the junctions, is still an open issue.

The usefulness and reliability of V2X communications as information sources for traffic management applications, as well as the channel congestion issues, were investigated and tested in the research activities briefly described in the previous chapter. Some approaches have taken into account the effect of flows variation over time and other intersection characteristics such as saturation flows and lost time [113], [114], [115].

A sequential optimization technique is developed by [113] to minimise the total junction delay for periods of time-varying demand. The analysis [114] can be suitably used for identifying those parameters that have to be determined with high accuracy or explicitly considered in the optimization problems. This is what this work pursues here according to V2I and cameras monitoring. The results of [116] show deep learning can be applied to traffic signal control while emphasizing the huge space of transitional sequences between agent actions. The linear programming model of [117] is based on traffic information provided by real-time sensors installed at each intersection under a basic sensing mechanism in which sensors measure the traffic flow entering every street section at every instant. A more sophisticated signalling scheme is considered by [118], which includes simultaneously signal plan design and signal timing optimization with real-time information on the network dynamics. The model of [119] incorporates flow prediction that may constitutes a follow up of this work. The flow prediction process that estimates the future arrival rates and turning proportions at target intersection based on the available detector information and signal timing plan. [120] investigates the equilibrium problem that arises when signal control parameters of an urban road network are locally optimised and have to be consistent with equilibrium traffic flows. Another way to look at the sensitivity of the problem is via perturbation analysis as in [121]. The advance of the present work with respect to the state of the art relies on the measurement mechanism and inherent data fusion.

Connected vehicles are coming and this will open the way to new approaches for smart infrastructures in the next future, before arrive to a full-autonomus driving, that can react properly relying on real-time data collected from the increasing number of sensors on the field (e.g. cameras, LIDAR, GPS), and for which the vehicular communication can represent a further development element.

Cooperative-Intelligent Transportation Systems (C-ITS) allow each network element to build a model of its surroundings by exchanging messages in V2X communication among them and with the network infrastructure in order to improve the road mobility awareness of network entities. Since these data are periodically transmitted and provide information like the vehicle position, speed and heading they can represents useful sources of information for the optimization of traffic lights.
Today the mainly used technique for junctions monitoring, is the Video Content Analysis (VCA) based on data collected from cameras installed in proximity of the intersection; however this solution is proven to be severely affected by the weather conditions, by the environment complexity and by light conditions.

Whitin these activities the possibility use of vehicular communication to estimate traffic flows at an intersection has investigated, in order to optimize the signalling scheme of traffic lights and overcome the cameras limitations above mentioned. The main contributions of the research activities have been:

- the integration of both a VCA platform and a V2I traffic management application in a simulation environment;
- the comparison between a static and a dynamic management of the signalling scheme, both for the VCA platform and for the V2I communication;
- the verification of the better results obtained with the V2I communication compared to the VCA-based approach.

4.3.2 The traffic light optimization issue

4.3.2.1 The reference model

Considering an intersection with $i = 1, ..., N$ accesses. The reference performance parameter for traffic light optimization is the intersection capacity ξ:

$$\xi = min_i(\xi_i); \xi_i = \frac{s_i g_{Ei}}{f_i t_C} \tag{4.1}$$

where:

- s_i is the saturation flow of the access i, i.e., the maximum number of vehicles that can cross the intersection per unit time;
- g_i, a_i and r_i are the durations of the green, amber, and red signals for the access i; f_i the instantaneous input flow arriving at the access i;
- τ_i is the so-called lost time at the access i, representing the departing inertia of vehicles at the green and amber signals;
- $g_{Ei} = g_i + a_i - \tau_i$ is the so-called effective green;
- $t_C = g_i + a_i + r_i$ the traffic light cycle time.

The light signals are assigned under the constraint of maintaining green to access i' and red to access i'' until their entire durations if i' and i'' may lead to colliding flows. The optimization model consists of the maximization of the intersection capacity under the available $k = 1, ..., K$ traffic light programs with green duration g_k, namely:

$$k^* = arg\ Max_k(min_i(\xi_{i,k})) \tag{4.2}$$

$\xi_{i,k}$ being the capacity of access i under program k: $\xi_{i,k} = \frac{s_i g_{Ei,k}}{f_i t_C}$, $g_{Ei,k}$ being the effective green to access i under program k.

4.3.2.2 Traffic light optimization approach

The reference model for the control algorithm for traffic lights described above is nicely posed mathematically, but it does not cope with measurement of the ξ_i's. In particular, while all the other parameters (s_i, g, E_i, and t_C) can be measured statically and do not vary over time, the instantaneous input flows f_i are subject to variations and in practice must be directly measured by the roadside infrastructure.

The aim of this work was the evaluating the impact of different measurement techniques for the f_i flows on the performance of the control algorithm described above. Specifically, two simulation scenarios based on different measurement techniques have taken into account: cameras and V2I communication based on IEEE 802.11p, used to identify vehicles approaching the intersection, in order to dynamically compute the f_i's and adapt the control algorithm for the traffic light in real-time.

The goal was to highlight the advantages and drawbacks of each measurement technique, to show their comparison in terms of performance analysis in different scenarios and how their accuracy degrades in case of congestion or challenging weather conditions.

The investigation activities are carried out through the Veins framework in a simulation environment using the tools previously described.

4.3.3 The proposed approach

4.3.3.1 Test bench scenarios

Two different operating scenarios have been considered, involving road junctions managed by traffic lights. The first one is a single cross with four branches 100 meters long (Fig.4.11-a), managed by a single traffic light. The second one is a cascade of two crosses, managed by two uncoordinated traffic light systems (Fig.4.11-b). Since the intersection capacity computation above described is based on input flows, the scenario settings provide for the vehicles to travel only one direction without possibility of turning or lane changing, in order to have a totally controlled system from which to unequivocally extract the response parameters. The traffic light systems can operate either in a traditional way, with fixed time for traffic light phases, or according to the optimization method. In detail the optimization method refers to the optimization model previous described, based on traffic flows on intersecting branches, estimated via cameras or through vehicular communications. A single Road Side Unit (RSU) collects and processes data, and provides optimized phases of a single traffic lights system.

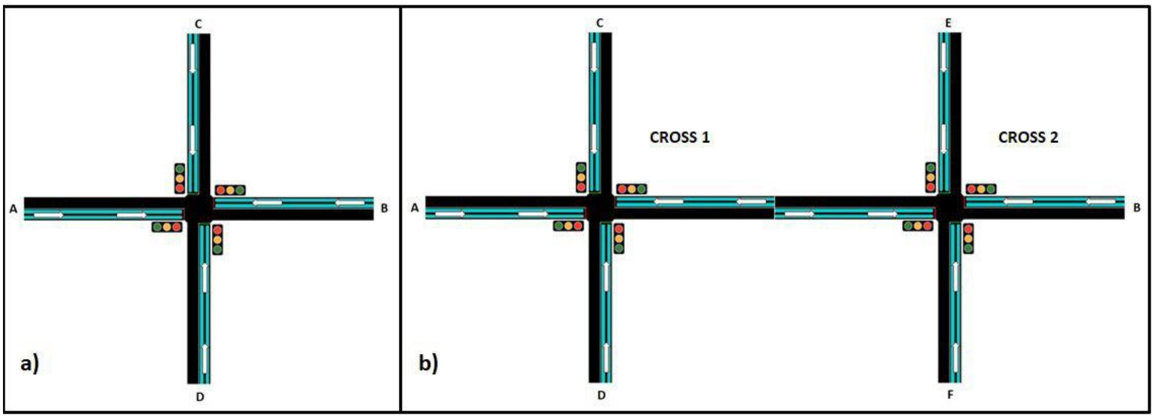


Figure 4.11: Implemented driving scenarios

Tests have been implemented with different road traffic settings, with a number of vehicles entering each branch ranging from 180 to 1080 per hour.

4.3.3.2 Cameras vs V2I

A comparison between performance obtained with two estimation methods have been performed:

- a traditional approach, based on cameras;
- V2I-based approach based on vehicular communication, implemented according to the American WAVE standard.

In both cases, the information are collected and processed by a single RSU.
To simulate cameras the Lane Detector (LD) elements have been used, provided by SUMO, one for each lane. To model the real behavior of cameras detection errors have been introduced, such as no detection or false positives, to simulate critical operating conditions due to failures or extreme weather conditions. Specifically, the modeling of the detection errors has been made according to the real parameters provided by Aitek S.r.l. [122]. To strengthen the system against these problems, redundancy is introduced in terms of number of cameras/LD for each lane. About vehicular communication BSMs are transmitted by vehicles at the default transmission rate of 10 messages per second toward the RSU, which collects them to perform the V2I-based flow estimation.

4.3.3.3 Simulations setup

The IEEE 802.11p technology has been used since the Veins framework provides its stable and consolidated implementation; however, similar results can be obtained also

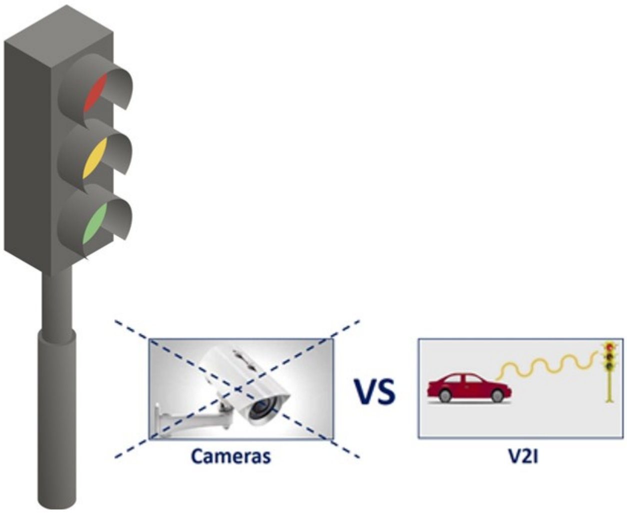


Figure 4.12: Camesa VS V2I communication for traffic light optimization

Table 4.1: Simulation parameters setting

Technology	**Parameter**	**Value**
V2I	Channel bandwidth	10 MHz
V2I	Modulation rate	6 Mbps
V2I	BSM size	150 Bytes
V2I	Default BSM sending interval	100 ms
VCA	Detection rate	94%
VCA	False alert rate	4%
VCA	Information update rate	1 s
Both	Traffic light program update rate	4 s

for the European ETSI ITS standard. Then by using of WAVE protocol stack, in a simulation tests each vehicle periodically broadcasts BSMs (Basic Safety Messages) of 150 Bytes of lenght (SAE J2735-defined range) to surrounding vehicles at a frequency of 10 Hz.

Each transmitted message includes vehicle mobility information (e.g., position, speed, heading and acceleration) and the transmitter ID. Thus, though the BSM dissemination, the RSU collects the required information in order to implement the traffic light optimization logic. Main parameter settings for V2I communication, VCA implementation and traffic light optimization are summarized in Table 4.1. The camera detection rate and false alert rate are the ratio of the vehicles correctly and erroneously detected, respectively. The duration of each simulation was 600 seconds. In order to evaluate the performances of the optimization algorithm, and the optimization technologies for traffic flows estimation, in addiction to the the intersection capacity, the following metrics have also been considered:

- waiting time (seconds): time in which the vehicle speed is below 0.1m/s;
- arrived/loaded vehicles: the ratio of vehicles number that have reached their destination to number of vehicles that were loaded into the simulation within 600 seconds;
- queue length (meters): the length from the junction until the final vehicle in line;

4.3.4 Analysis of results

In the first set of performed tests, a single-intersection scenario was considered with four basic traffic distributions implemented by changing the probability p of vehicle emission per second.

In both the vertical directions (A-B and B-A, Fig.4.11), p is fixed and is equal to 0.05. By contrast, on the horizontal branches, different vehicle densities were simulated, with p ranging from 0.05 up to 0.3 for both directions (D-C and C-D) at the same time. As a benchmark the traffic light logic has considered, without any optimization method. Then, a comparison between the no-optimized case and the optimized logic has been performed, by exploiting and implementing three different traffic detection techniques. In detail four functional scenarios have investigated and compared, respectively based on:

- no-optimized solution;
- camera-based solution without redundancy;
- camera-based solution with redundancy (2 cameras per lane);
- V2I solution.

Numerical results for the single-intersection scenario are shown in Fig.4.13. By results the V2I solution shows to achieve better performances (in terms of arrived/loaded vehicles) compared to the no-optimized traffic light. The Figure also shows that, when the traffic demand is balanced (i.e. when $p = 0.05$), the camera-based solution is heavily affected by false positives and false negatives errors and therefore is unable to outperform the no-optimized case. Even if the redundancy technique copes with this issue (yellow line in Fig. 4.13-a), the V2I-based solution achieves better results,

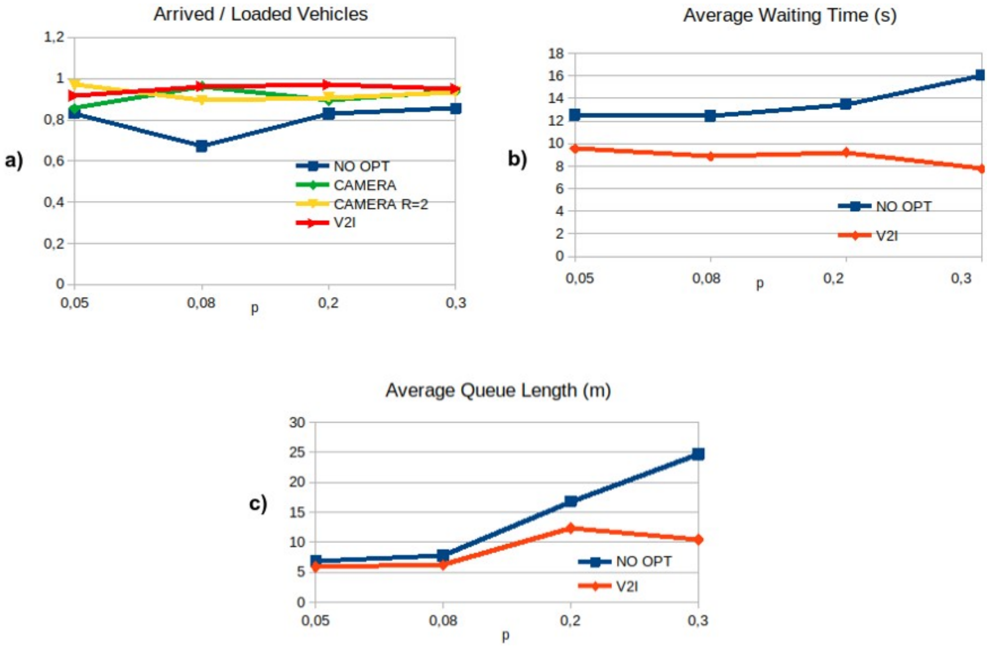


Figure 4.13: Single-cross scenario: simulation results

especially for higher p values (i.e. when the traffic distribution between the two roads, is strongly unbalanced).

In Fig. 4.13-b) the verage waiting results are reported, while those associated to the queue length computation for all the simulated vehicles are shown in Fig. 4.13-c). Also respect to this analysis the more the vehicle density on the horizontal road increases, the more the V2I optimization technique works properly.

For the multi-intersection scenario the numerical results are reported in order to validate the proposed solution in a wider traffic area and discuss the critical points of the optimization model.

Two different traffic demand condition has been considered (as depicted in Fig.4.14):

- a symmetrical distribution with two vertical roads with the same p setting (i.e. with the same vehicle density);
- an asymmetrical traffic distribution with two different p setting at the vertical branches. Specifically, in the symmetrical traffic scenario each vertical direction has a p value equal to 0.05. In the asymmetrical scenario, D-C and C-D vehicular flows have a probability p of 0.05, while E-F and F-E directions have $p = 0.08$.

Like in the previous test, on the horizontal branches, we simulated different vehicle densities, with p ranging from 0.05 up to 0.3.

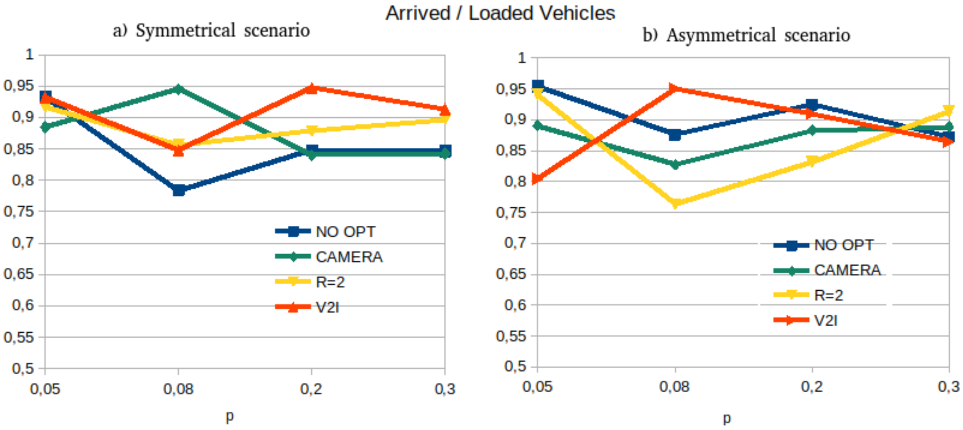


Figure 4.14: Scenario with two intersections: arrived/loaded vehicles ratio for two different traffic flows distributions

Simulation results depicted in Fig.4.14 for the symmetrical case, confirm that the V2I-based solution achieves better performances in terms of arrived/loaded vehicles ratio, when the traffic density on the horizontal road increases (i.e., for $p \geq 0.2$). The same trend is even more evident in Fig.4.15, in terms of the average waiting time. By contrast, in the asymmetrical implementation (Fig.4.14), the V2I-solution does

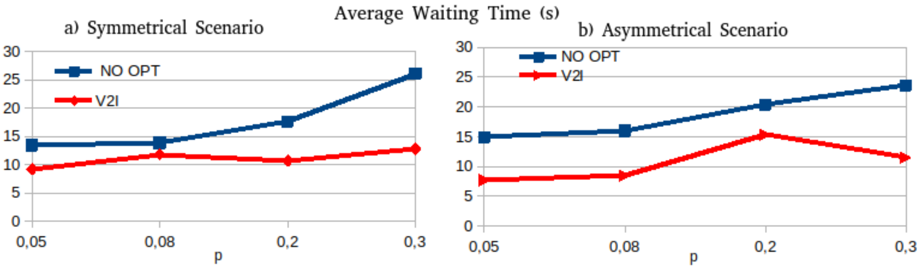


Figure 4.15: Scenario with two intersections: average waiting time for two different traffic flows distributions

not always lead to optimize the arrived/loaded vehicle ratio. Also in Fig.4.15, the compensation of the V2I optimization in terms of average waiting time is a less more competitive when compared with the symmetrical scenario. This weak response is due to the optimization strategy architecture. Since the traffic light logic is optimized for the single intersection, the optimization strategy does not take into account the global traffic behaviour.

Consequently, while the algorithm applied to a particular traffic light optimizes the local intersection capacity, it can lead to the occurrence of unfairness issues by impairing the traffic distribution of a contiguous area. This unfairness condition is highlighted in Fig.4.16: even if the V2I strategy always optimizes the local intersection capacity, the busiest intersection (cross 2) is always penalized when compared to the other (cross 1).

These results demonstrate that the proposed optimization method is not able to improve traffic conditions in complex scenarios where traffic lights do not have a centralized and coordinated high-level optimization system. However, positive results have been obtained regarding the use of vehicular communication as a source of information for optimization, as this solution is immune to errors due to environmental problems and more robust in terms of instantaneous calculation of traffic flows. For the future work, cooperative and centralized optimization techniques will be taken into account to cope with the unfairness issue and must be tested in more complex and congested vehicular networks, in order to characterize the proposed method also in challenging urban environments.

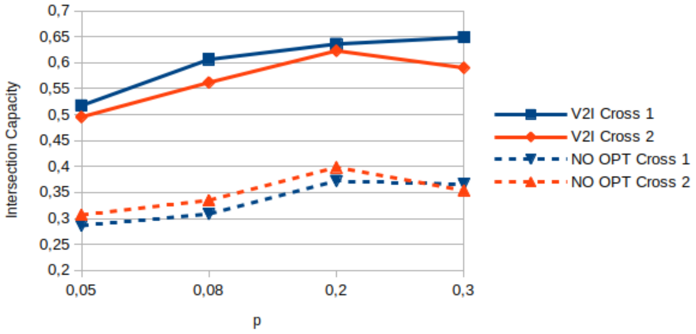


Figure 4.16: Intersection capacity for asymmetrical distribution of traffic flows

4.4 The EMERGE project

4.4.1 The EMERGE project objectives

The EMERGE project aims to design and develop a technological enhancement on the Cooperative Intelligent Transportation Systems (C-ITS) context, with particular emphasis on the accurate and reliable localization of vehicles, a pervasive vehicular communication and the cybersecurity.

The EMERGE project was conceived by the experience gained by the partners in the railway and automotive fields, with the objective of carry out the design, prototyping, implementation and testing of solutions able to support innovative functionalities for mobility of commercial vehicles, through smart equipment and new services and applications.

The project aims specifically to make the commercial vehicle more and more flexible, not only for everyday operations for transport of people and goods, but also as a vehicle ready to operate in emergency situations. The "dialogue" between vehicles involved in emergency situations is essential.

The novelty of the present proposal consists in the possibility of making technologically equipped vehicles immediately available to the rescue units in the management of emergencies, although these vehicles can be normally used in ordinary operating mode for the everyday life. Specifically two reference operating modes are proposed, on the basis of which the equipment supplied will interact differently with the driver:

- *everyday* (e.g. for delivering agencies' couriers): in this condition the vehicle will refer to less stringent constraints with respect to the safety margin, it will carry out its function in accordance with updated traffic information and will process pre-trip planning related to the timings required by the different daily tasks; furthermore, the vehicle will be able to make use of "preferential lanes" for the last mile transport of material at high priority delivery;

- *emergency*: the vehicle becomes a rescue means able to operate in emergency situations (e.g. in a post-earthquake, floods, etc.) in support of rescue teams. In this condition the vehicle will implement advanced functionalities: better performing communications through the combined use of satellite and terrestrial technologies, advanced data management algorithms for the immediacy of information use, augmented reality techniques, possibility of using privileged routes dedicated to rescue vehicles.

The key technological elements of the project are the following: highly accurate satellite location based on multi-constellation satellite receivers (GPS + GALILEO) and augmentation and data fusion algorithms with on-board sensors and cameras; both terrestrial and satellite multi-platform communication; cybersecurity aspects both from the point of view of system design and cyber intelligence.

From the hardware side, the goal is the implementation of architectures for network nodes, of different hierarchical level, and the enhanced equipment of vehicles for communication, localization and data processing. From the software point of view, the objective is the prototyping and validation of systems, algorithms and protocols for smart mobility applications and secure management of inter/intra vehicle communications. User-side solutions will be designed, implemented at prototype level and tested/validated for accurate vehicle localization and multi-platform V2V and V2I communication.

On the infrastructure-side, the project will mainly focus on the design and development of an Edge/Cloud computing architecture to implement applications, based on enhanced machine learning techniques, for collection and elaboration of heterogeneous data from field and the provision of mobility services to users. The EMERGE architecture will have characteristics compatible with the systems currently in use and must be able to evolve towards new protocol paradigms, with particular reference to the 5G technology. All implementation solutions must be robust against all currently known cyber-attacks and those that will be identified in the future through the project activities, with the aim of ensuring the data integrity of localization and navigation, and the confidentiality of sensitive information.

4.4.2 The EMERGE architecture

To support the assisted driving processes towards the autonomous driving goal, each vehicle must be able to determine its position with the maximum accuracy and communicate with the other network nodes in an efficient and secure way, in terms of integrity and confidentiality of information transmitted on the radio channel.

In the EMERGE architecture shown in Fig.4.17, advanced localization systems are designed and implemented that resort on the GPS and GALILEO satellite constellations, as well as augmentation methods and data fusion techniques.

Communication is supported by a multi-platform system, operating with a combination of the following terrestrial technologies: V2X vehicular communication, for both the European (ETSI ITS G5) and the American (WAVE) standards based on the 802.11p protocol, Cellular V2X (C-V2X) based on the 4G (LTE) networks and 5G. To operate in emergency conditions a satellite communication platform, operating in the Ka band, will be used in order to improve the connectivity towards the control centre, and to implement enhanced functions such as the restoration of terrestrial connectivity after the crash of the standard cellular network.

The EMERGE project will design, develop and test the following devices and equipment to be integrated in the commercial vehicles that constitute the fleet for field trials:

- **OBU (On Board Unit)**: for management of the heterogeneous systems and devices to which all the localization and communication units will be connected. The OBU is equipped with a commercial GNSS receiver able to guarantee an autonomous basic localization in the absence of the advanced localization unit.

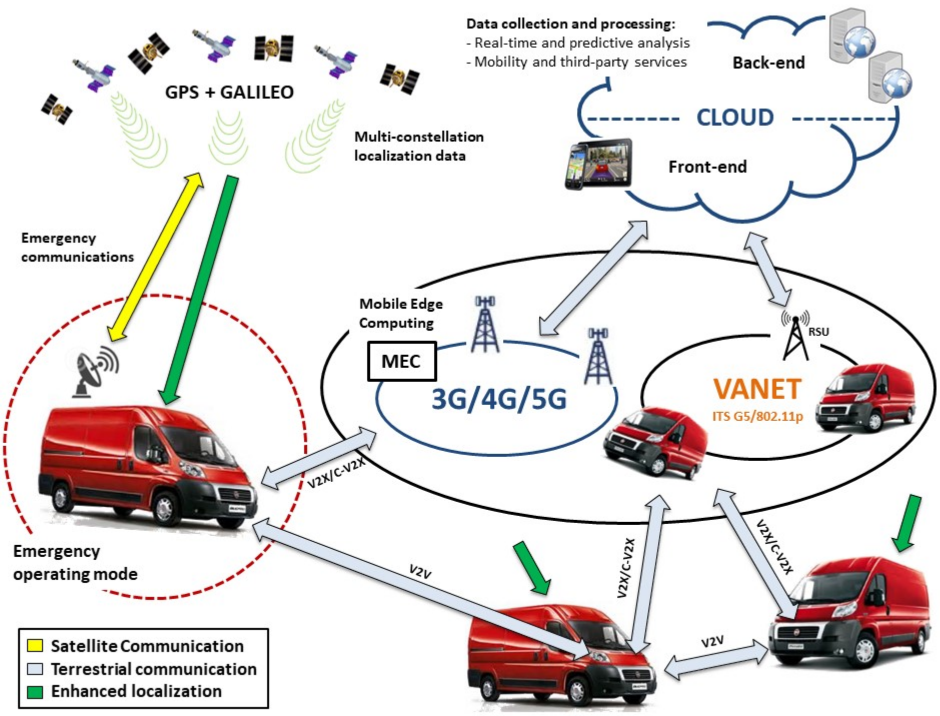


Figure 4.17: EMERGE overall architecture

It includes a CAN Bus interface to the vehicle bus for processing and transmission of data to the cloud. The OBU includes internally two 5G radio modules, one Wi-Fi modules and manages seamless aggregation of links by MPTCP protocol. The SATCOM link is an external input for the OBU.

- **SATCOM**: satellite communication system composed by a fly-away platform and a Satcom-on-the-Move (SOTM) satellite antenna to be installed on the vehicle. In both cases, the communication flows will be anchored to a master antenna, located in the Fucino Space Centre, which will ensure the information exchange between the vehicle and the ground segment.
- **SATNAV**: localization system with a high degree of accuracy and integrity based on the integration and data fusion processes with information provided by a multi-constellation GNSS receiver (GPS + GALILEO), by the vehicle tachymetry and odometry (i.e. the wheel speed extracted from the ABS module), by inertial sensors and additional devices and communication platforms.
- **COMM**: multi-standard terrestrial communication system (V2X, C-V2X, WiFi) based on external radio units connected to the OBU.

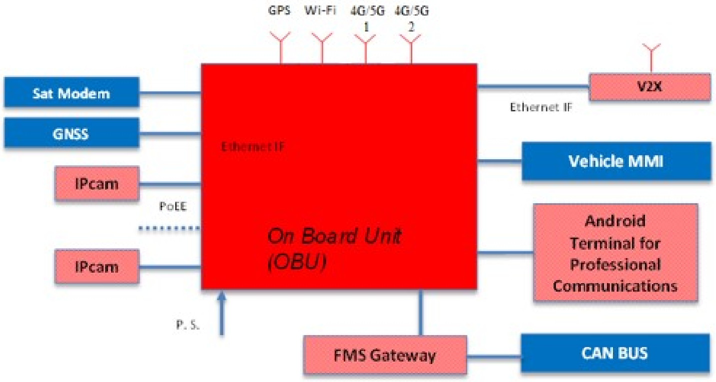


Figure 4.18: Vehicle OBU

- **High resolution IP cameras** (up to six per vehicle) to ensure a 360 degree surveillance of the surrounding environment. They will be useful to produce data flows in order to strengthen the automatic response security systems and provide the control centre with highly accurate video streams on the driving context and the vehicular traffic status in the reference area. IP Cameras are directly connected to OBU via Power over Ethernet links. Video streams are recorded on Solid State disks located on the OBU for post analysis, but live streaming to the centre is enabled whenever required.

The devices and platforms described above make up the full equipment for the emergency vehicle, other eqipment will be composed by subsets of them, starting from the basic one composed by the OBU and the multi-platform terrestrial communication system. On the network infrastructure side a centralized platform based on Edge/Cloud components is envisaged for the provision of mobility services and for localization, as well as the development of smart dynamic and collaborative navigation applications through the collection and storage of heterogeneous data from field. With respect to services at application level, advanced techniques relying on data mining and machine learning will be used to extract useful information from the large amount of recorded data. With reference to communications, the infrastructure component of the EMERGE architecture will be composed by a ground centre able to collect the information flows from all the multi-bearers of the OBUs, and recombine them dynamically for guaranteeing the continuity and quality of the communication and data exchange. An additional Cloud component will allow the management of group professional voice services between the control centre and the vehicles' fleet, also

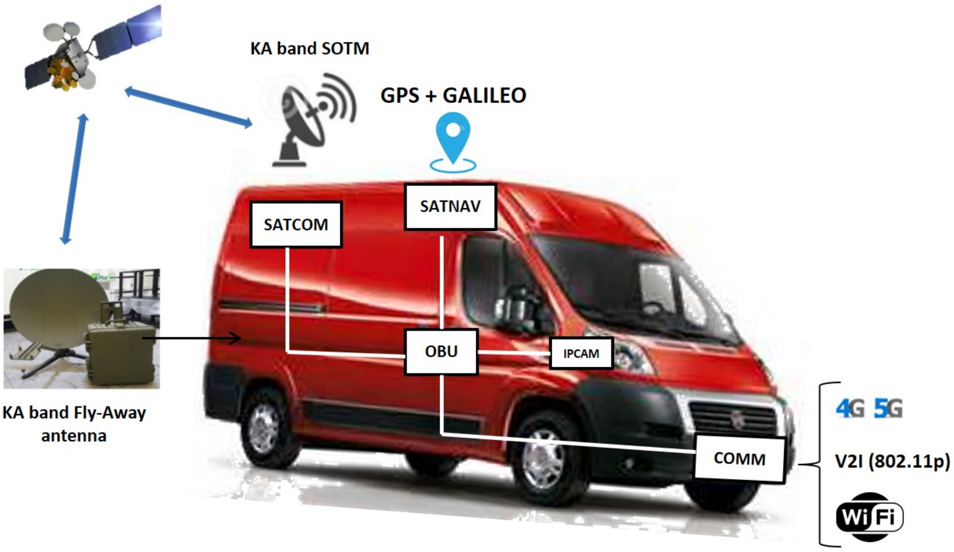


Figure 4.19: Vehicle equipment

providing broadband services for messaging and transferring files and video streams among the group members, in addition to the centralized location of the fleet.

4.4.3 Enabling technologies and proposed solutions

High accuracy localization

The activities will concern the design and implementation of the HW/SW components (i) for vehicles (SATNAV), for the calculation of the accurate position by the on-board devices (ii) for infrastructure in order to provide for navigation services to EMERGE vehicles and GNSS services toward third parties. Furthermore, the prototyping and implementation of advanced localization algorithms will be performed. The on-board navigation module will be based on the location data provided by the satellite GPS-GALILEO multi-constellation, and will be interfaced with the on-board sensors, e.g. via the CAN bus for IMU (Inertial Measurement Unit), speedometer and odometer; and with the multi-platform communication module to implement the data fusion techniques. Prototype design and implementation of localization algorithms based on GNSS (in particular GALILEO with the use of double frequency for the mitigation of local phenomena such as multipath) and additional sensors will be carry out. The use of raw satellite data for supporting the navigation processes is also envisaged. The algorithms will be developed taking into account the requirements for connected and autonomous driving systems and in synergy with railway context applications. Advanced Vehicle Autonomous Integrity Monitoring (AVAIM) for hybrid systems will be also implemented. All the algorithmic solutions will be evaluated and validated in a simulation environment using the VIRGILIO multi-constellation simulator, already validated internationally in the railway context.

Multi-Platform communication

The EMERGE system provides for the combined use of the terrestrial communication technologies currently available, as well as those under experimentation such as 5G, and the satellite communication. To manage the multiplicity of radio flows, communication protocols and the characteristics of the channels used (e.g. the satellite channel with high delay times) we will mainly adopt the MPTCP technique (Multipath TCP). At the same time, possible alternative solutions will be evaluated to ensure adequate QoS for real-time services in emergency operating mode. Since these are IP systems, the scalability is very wide depending only on the expected data traffic, on the number of vehicles and the computing power used. In detail, the V2X vehicle communication network architectures must be defined and developed, in particular for Vehicle-to-Infrastructure, and by considering the protocol architectures of consolidated releases (LTE rel. 13 and 14, ETSI ITS G5, 802.11p), and their evolution in a longer term (5G). An analysis of IP traffic profiles will be performed in relation to the services made available on the communication platform (e.g. diagnostics, video surveillance). Satellite communication will be guaranteed through the development of a SOTM (Satcom On The Move) elliptical antenna to be installed on the vehicle to operate on the Athena Fidus Ka-band space segment for the rendering of value-added services like the Internet access for emergency vehicles. The rapidly evolving agenda for the 5G satellite segment will be considered for upgrading the development plan.

Cybersecurity

The heterogeneous EMERGE architecture requires robustness and reliability against potential cyber-attacks, in order to protect the intra-inter vehicular communication and the integrity of geo-localization information against intrusions. The EMERGE project will carry out the analysis of vulnerabilities and risks of the whole system, taking into consideration the specific operational environment where the system will operate and the technologies used. The approach will follow the ISO 31000 "Risk Management" standard methodology for classifying the potential threats and identifying the necessary countermeasures in order to define the security strategies for the system. This process will be done in an iterative way, in order to establish a minimum set of security measures, both passive and active one (as Intrusion Detection

Systems), which should be deployed. The methodology of risk assessment and threats analysis will be identified for both on-board systems and vehicular communications, then the activities of Vulnerability Assessment (VA) and Penetration Test (PT) will follow. In order to maintain the right level of protection against cyber-attacks, which would compromise the functionalities of the overall system, there is the need for a constant monitoring to identify a new threat during operations. Therefore, this issue will be dealt with and addressed in the EMERGE project through the study of OSint technologies. In order to achieve secure vehicular communications a cryptographic system will be implemented based on Elliptic Curve Cryptography (ECC). In particular, an FPGA-based hardware accelerator for ECC is currently being developed. All the system's functionalities will be developed applying the Secure-By-Design methodology, thanks to which the security aspects are taken into account from the project early stage with the system requirements definition.

4.5 Collaborations and publications

The research activities regarding the V2I-based optimization of traffic lights were carried out within the ***SAFECOP*** project [123].

G. Agosta, S. Chiocchio, E. Cinque, P. Fezzardi, M. Maugelli, A. Persia, M. Pratesi, F. Valentini, "Toward a V2I-based Solution for Traffic Lights Optimization," 11th International Congress on Ultra Modern Telecommunications and Control Systems (ICUMT), Dublin, Ireland, 2019.

The EMERGE project proposal have been realized along with the following partners: **RadioLabs Consortium**, **Leonardo company**, **Telespazio**, **Elital S.r.l.**

A. Neri, F. Rispoli, F. Santucci, M. Pratesi, S. Chiocchio, A. Persia, G. Guidotti, M. Brancati, S. Beco, G. Arista, "EMERGE - Commercial Vehicles and Emerging Technologies for everyday and emergency operations: advanced navigation, advanced communication, advanced," 25th Ka Conference , Sorrento, Italy, 2019.

Other publications and conference contributions:

S. Chiocchio, A. Persia, F. Valentini, E. Cinque, M. Pratesi and F. Santucci, "Integrated Simulation Environments for Vehicular Communications in Cooperative Road

Transportation Systems,” 2018 2nd URSI Atlantic Radio Science Meeting (AT-RASC), Gran Canaria, Spain, 2018, pp. 1-4.

E. Cinque, F. Valentini, M. Pratesi, S. Chiocchio, A. Persia, ”Analysis and Experimental Characterization of Channel Congestion Control in Vehicular Networks,” 2018 IEEE International Symposium on Networks, Computers and Communications (ISNCC), Rome, Italy, Jun 19-21, 2018.

S. Chiocchio, E. Cinque, A. Persia, P. Salvatori, C. Stallo, M. Salvitti, F. Valentini, M. Pratesi, F. Rispoli, A. Neri, F. Santucci, ”A Comprehensive Framework for Next Generation of Cooperative ITSs”, in Proc. of 4th International Forum on Research and Technologies for Society and Industry, Palermo, 10-13 September 2018.

S. Chiocchio, E. Cinque, A. Persia, C. Stallo, M. Pratesi, P. Salvatori, M. Salvitti, F. Rispoli, A. Neri, F. Santucci, ”A Comprehensive Framework for Cooperative Intelligent Transport Systems as the key Enabler of Smart Cities,” 4th Italian Conference on ICT for Smart Cities and Communities, L’Aquila, 19-21 September 2018. (conference presentation).

Chapter 5

Conclusions and future works

Among the research activities described in this document, three transport contexts have been considered and innovative solutions have been proposed to improve safety and efficiency of transport systems compared to the state of the art. For each application domain investigated, an analysis of the state of art has been reported, technological limitation and context issues have been considered together with potential areas of intervention, vision for the next years, and ongoing research and development activities that led us to the design and implementation of the proposed solutions.
This thesis focuses on intelligent transport systems with main focus on communication technologies and architectures, with research and development activities driven by industrial projects. The collaboration with industrial partners offered the possibility to approach the reference contexts and deepen their main technological aspects. At the same time, emphasis is given to the solution of problems related to systems prototyping with a different points of view: high-level design, simulated modeling, hardware description and physical implementation, analysis of the results.

For rail freight transport, a heterogeneous architecture has been presented for constant tracking, real-time diagnostics of trains, as well as efficient management of wagons in parking areas. The proposed solution has been designed at a high level of abstraction through the functional definition of the individual system blocks, and a real testbed was realized using low-cost devices and platforms to test and validate the basic functionalities of the architecture.

In the context of avionics, the ADS-B technology has been approached with particular reference to advanced signal reception techniques, proposed by RTCA. Those techniques are better performing than those currently used and they are necessary to guarantee proper functionality of the surveillance system with high levels of interference.

A simulation environment has been created in Matlab to provide macro-functions for generating ADS-B signals and the conventional replies (interference), modeling of two different RF reception chains based respectively on the logarithmic and linear amplification, implementation of the advanced reception techniques for baseband signals, starting from the preamble detection to the error correction in data field, according to three different decision algorithms.

Through this system, the advanced reception techniques advises by RTCA have been tested and the best performing solution in terms of RF receiver and baseband reception chain has been identified. The resulting solution includes the logarithmic RF stage, the advanced preamble reception chain and the multi-sample decision technique.

Furthermore, the obtained solution has been modeled at RTL level for future implementation on FPGA.

For the vehicular sector, the enabling technologies for connected vehicles have been investigated, with particular reference to technologies and standards for vehicular communications. Different application contexts in which vehicular communication represents a solution that increases the safety and the efficient management of traffic flows have been approached.

All activities were carried out at the simulation level through high-fidelity simulation environments, with which traffic management application were mainly tested (especially for emergency conditions management) and V2I-based solution for traffic lights optimization issues have been investigated.

As for the smart optimization of traffic lights, V2X technology has proven to be more effective than the VCA-based alternative currently used, overcoming the limits relating to errors introduced by environmental factors and producing a dynamic optimization of traffic light cycles able to maximize traffic disposal capacity at intersections. Critical issues have been highlighted in the case of multiple intersections since the optimization model works on the single intersection and is not integrated on the entire system.

Once the main technological aspects for the connected vehicle were investigated, a heterogeneous architecture for the smart management of commercial vehicles able to operate in normal and emergency conditions was proposed through multi-platform equipment for accurate localization and communication, which will also include the use of of the Galileo satellite constellation and the 5G communication technology.

Future works:

Ongoing activities concern the development of a multi bearer and multi technology communication platform, candidate to be an alternative solution to the GSM-R network currently used in the European Rail Traffic Management System (ERTMS), which is becoming obsolete.
The activities of the coming months will lead to the development of this platform, within the Sat4Train project, based on the combined use of satellite communication system and commercial cellular networks.

The HW implementation of the advanced reception architecture for ADS-B systems will be realized on FPGA through VHDL description, in order to test its functionality and compliance with the requirements using real test signals.

With regard to vehicular communication technologies, activities will continue on the smart optimization of traffic lights, with the improvement of the optimization model based on a high-level management of mobility flows, in order to have coordination between traffic lights and then maximize the traffic disposed by the integrated system.
In addition, activities in the EMERGE project will be developed, with research activities carried out both from the point of view of smart vehicle equipment, with multi-platform localization and communication systems, and from the network infrastructure side with a scalable processing and management architecture based on edge/cloud computing. Furthermore, cyber security issues will be addressed, both from the systems design point of view and the cyber intelligence side.

List of Publications

S. Chiocchio, A. Persia, F. Santucci, V. Di Claudio, D. Di Grande, P. Giugliano, G. Guidotti, ”A cloud-based heterogeneous wireless platform for monitoring and management of freight trains,” 2016 8th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), Lisbon, 2016, pp. 263-268. doi: 10.1109/ICUMT.2016.7765368.

S. Chiocchio, A. Persia, F. Santucci, F. Graziosi, M. Faccio, ”Modeling and performance analysis of advanced detection architectures for ADS-B signals in high interference environments,” 2017 32nd International Union of Radio Science General Assembly and Scientific Symposium (URSI GASS), Montreal, 2017.

S. Chiocchio, A. Persia, F. Valentini, E. Cinque, M. Pratesi and F. Santucci, ”Integrated Simulation Environments for Vehicular Communications in Cooperative Road Transportation Systems,” 2018 2nd URSI Atlantic Radio Science Meeting (AT-RASC), Gran Canaria, Spain, 2018, pp. 1-4.

E. Cinque, F. Valentini, M. Pratesi, S. Chiocchio, A. Persia, ”Analysis and Experimental Characterization of Channel Congestion Control in Vehicular Networks,” 2018 IEEE International Symposium on Networks, Computers and Communications (ISNCC), Rome, Italy, Jun 19-21, 2018.

S. Chiocchio, E. Cinque, A. Persia, P. Salvatori, C. Stallo, M. Salvitti, F. Valentini, M. Pratesi, F. Rispoli, A. Neri, F. Santucci, ”A Comprehensive Framework for Next Generation of Cooperative ITSs”, in Proc. of 4th International Forum on Research and Technologies for Society and Industry, Palermo, 10-13 September 2018.

S. Chiocchio, E. Cinque, A. Persia, C. Stallo, M. Pratesi, P. Salvatori, M. Salvitti, F. Rispoli, A. Neri, F. Santucci, ”A Comprehensive Framework for Cooperative Intelligent Transport Systems as the key Enabler of Smart Cities," 4th Italian Conference on ICT for Smart Cities and Communities, L'Aquila, 19-21 September 2018. (conference presentation).

G. Agosta, S. Chiocchio, E. Cinque, P. Fezzardi, M. Maugelli, A. Persia, M. Pratesi, F. Valentini, "Toward a V2I-based Solution for Traffic Lights Optimization," 11th International Congress on Ultra Modern Telecommunications and Control Systems (ICUMT), Dublin, Ireland, 2019.

A. Neri, F. Rispoli, F. Santucci, M. Pratesi, S. Chiocchio, A. Persia, G. Guidotti, M. Brancati, S. Beco, G. Arista, "EMERGE - Commercial Vehicles and Emerging Technologies for everyday and emergency operations: advanced navigation, advanced communication, advanced," 25th Ka Conference , Sorrento, Italy, 2019.

S. Chiocchio, A. Persia, F. Santucci, F. Graziosi, M. Faccio, "Modeling and evaluation of enhanced reception architectures and algorithms for ADS-B signals in high interference environments" (in submission for publication to the Physical Communication journal).

List of Acronyms

3GPP 3rd Generation Partnership Project

A-SMGSC Advanced Surface Movement Guidance and Control System

ACAS Airborne Collision Avoidance System

ACS Advanced Central Sample

ADS-B Automatic Dependent Surveillance - Broadcast

AES Advanced Encryption Standard

ARIB Association of Radio Industries and Businesses

ARM Advanced RISC Machine

ASM Algorithmic State Machine

ATC Air Traffic Control

BER Bit Error Rate

BSM Basic Safety Message

C-ITS Cooperative-Intelligent Transportation System

CAM Cooperative Awareness Message

CBR Channel Busy Ratio

CMOS Complementary Metal-Oxide Semiconductor

COTS Commercial Off-the-Shelf

CRC Cyclic Redundancy Check

CS Central Sample

CU Control Unit

DSRC Dedicated Short Range Communications

ECC Elliptic Curve Cryptography

ECU Engine Control Unit

ES Extended Squitter

ETSI European Telecommunications Standards Institute

FFT Fast Fourier Transform

FPGA Field Programmable Gate Array

FRUIT False Replies Unsynchronized In Time

FSM Finite State Machine

GCU Generic Control Unit

GLONASS GLObal NAvigation Satellite System

GMRS General Packet Radio Service

GNSS Global Navigation Satellite System

GPS Global Positioning System

GSM Global System for Mobile communications

HD High Definition

IATA International Air Transport Association

IEEE Institute of Electrical and Electronics Engineers

IMU Inertial Measurement Unit

IoT Internet of Things

ISM Industrial, Scientific and Medical

ITS Intelligent Transportation Systems

LD Lane Detector

LDM Local Dynamic Map

LE Leading Edge

LIDAR Laser Imaging Detection and Ranging

LR Long Range

LTE Long Term Evolution

M2M Machine to Machine

MAC Medium Access Control

MEC Mobile Edge Computing

MS Multi-Sample

NR New Radio

OBU On Board Unit

OMNet++ Objective Modular Network Testbed in C++

OVS Optical Velocity Sensor

PCU Parking area Control Unit

PPM Pulse Position Modulation

REC Remote Elaboration Center

RPL Reference Power Level

RSU Road Side Unit

RTCA Radio Technical Commission for Aeronautics

RTL Register Tranfer Level

SIM Subscriber Identity Module

SNR Signal-to-Noise Ratio

SOTM Satcom On The Move

SR Short Range

SSR Secondary Surveillance Radar

SUMO Simulation in Urban MObility

TTL Transistor-Transistor Logic

UART Universal Asynchronous Receiver-Transmitter

UAT Universal Access Time

UAV Unmanned Aerial Vehicles

UMTS Universal Mobile Telecommunications System

USB Universal Serial Bus

V2I Vehicle to Infrastructure

V2N Vehicle to Network

V2P Vehicle to Pedestrian

V2V Vehicle to Vehicle

V2X Vehicle to Everithing

VANET Vehicular Ad-hoc NETworks

VCA Video Content Analysis

VDL Very High Datalink

VEINS Vehicles in Network Simulation

VHDL VLSI Hardware Description Language

VP Valid Pulse

VRU Vulnerable Road User

WAVE Wireless Access in Vehicular Environments

WHO World Health Organization

WSN Wireless Sensor Network

Appendix A

HW design of ADS-B receiver

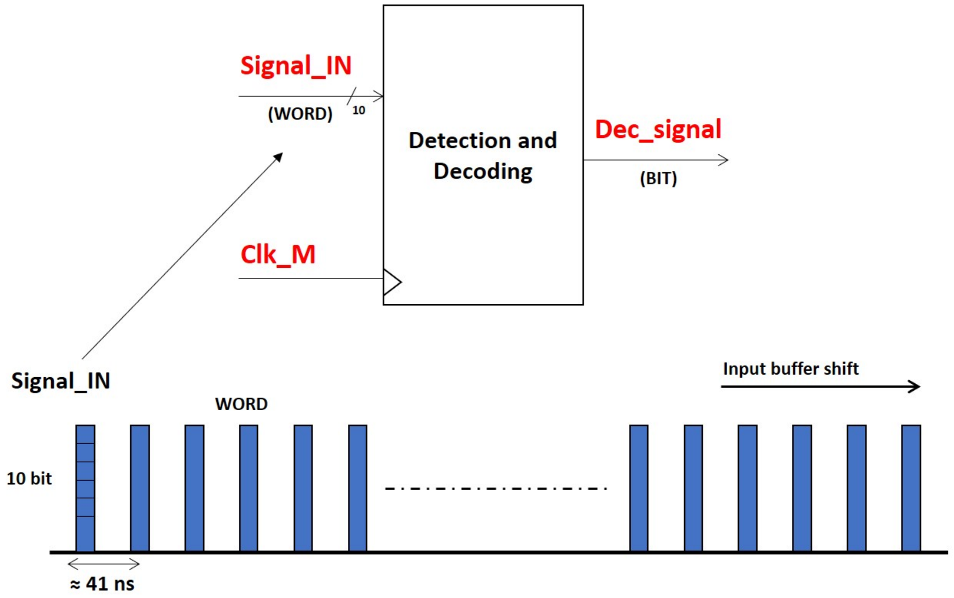


Figure A.1: General system instantiation

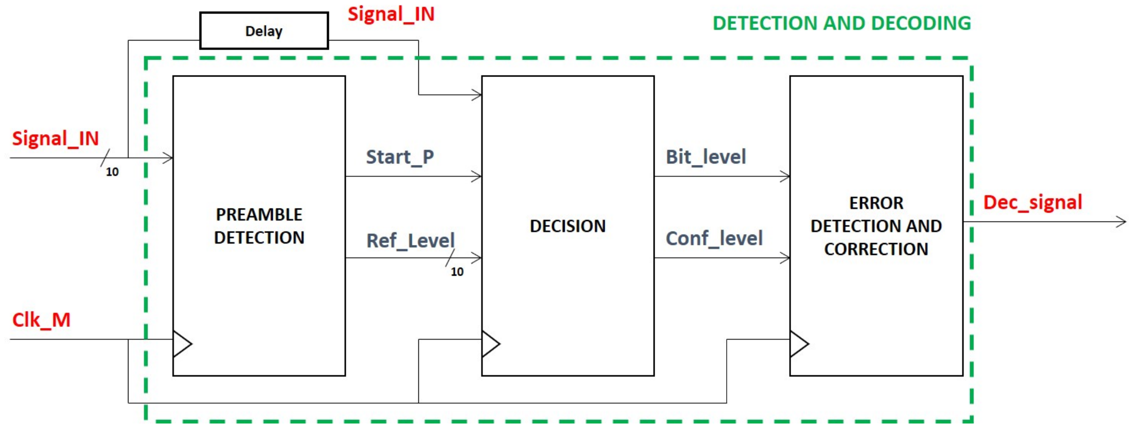


Figure A.2: Main blocks of the Detection/Decoding HW architecture

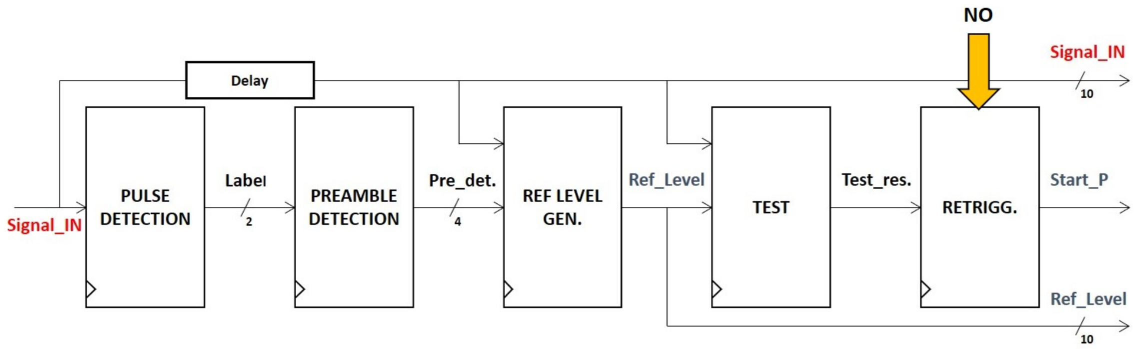


Figure A.3: Preamble detection process

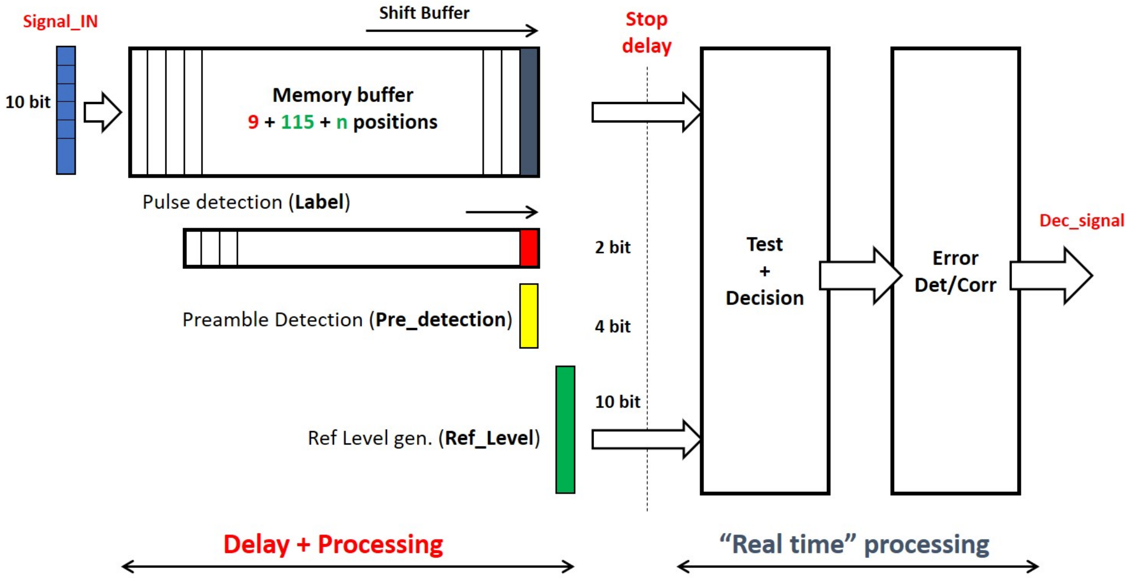
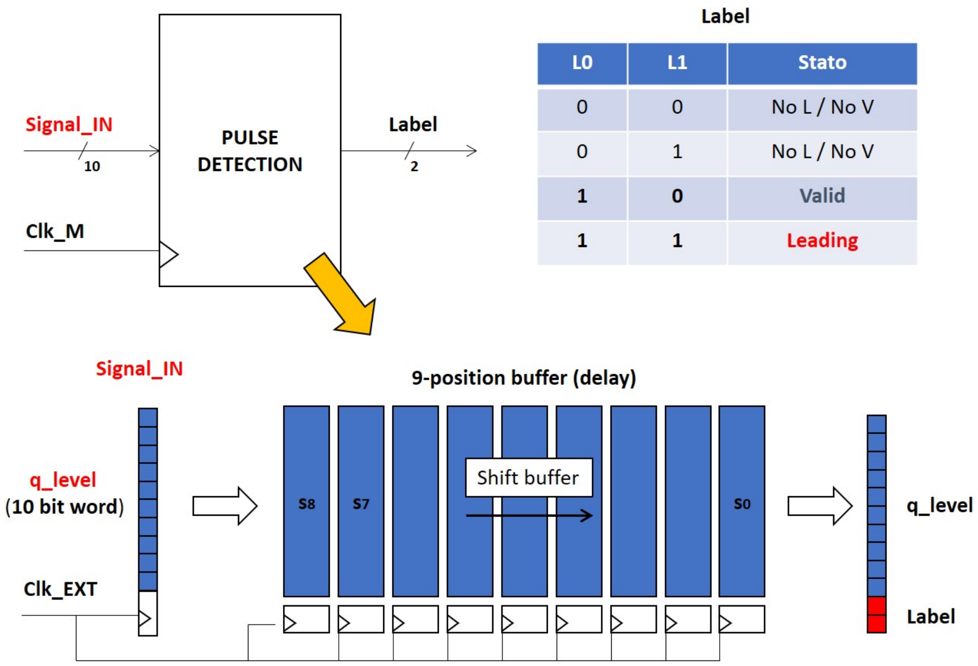


Figure A.4: Preamble detection - Temporal scheme of the system



Label

L0	L1	Stato
0	0	No L / No V
0	1	No L / No V
1	**0**	**Valid**
1	**1**	**Leading**

Figure A.5: Pulse detection - High level description

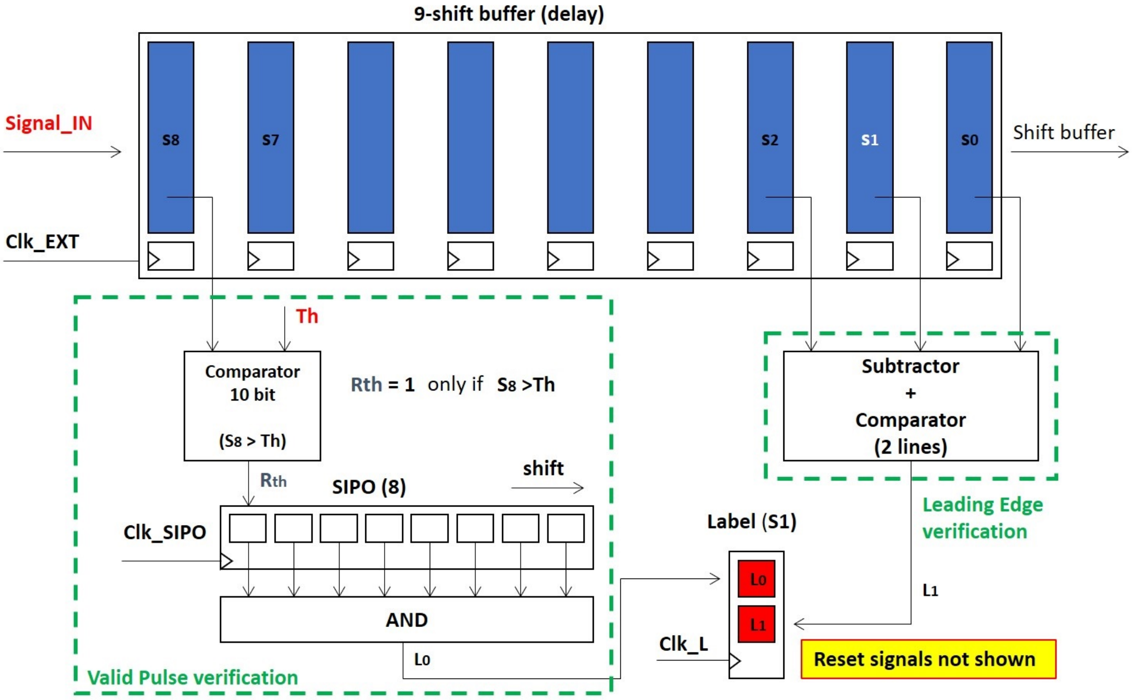
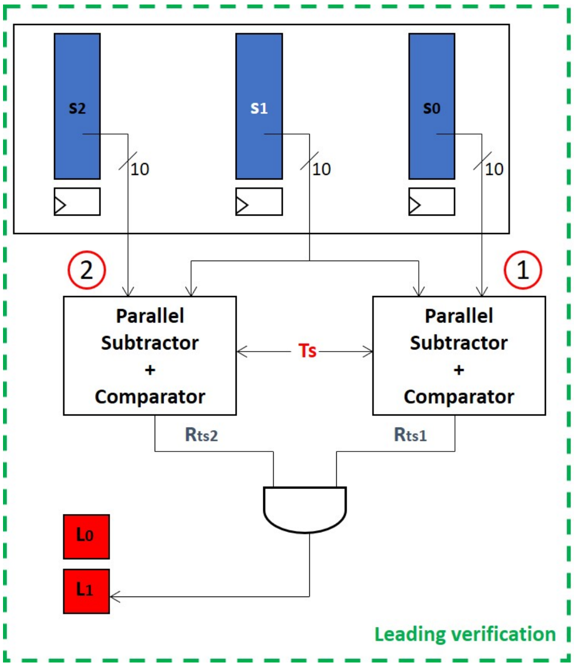


Figure A.6: Pulse detection - VP declaration



Block 1

s(i) – s(i-1) > **Ts** with S(i) = S_1

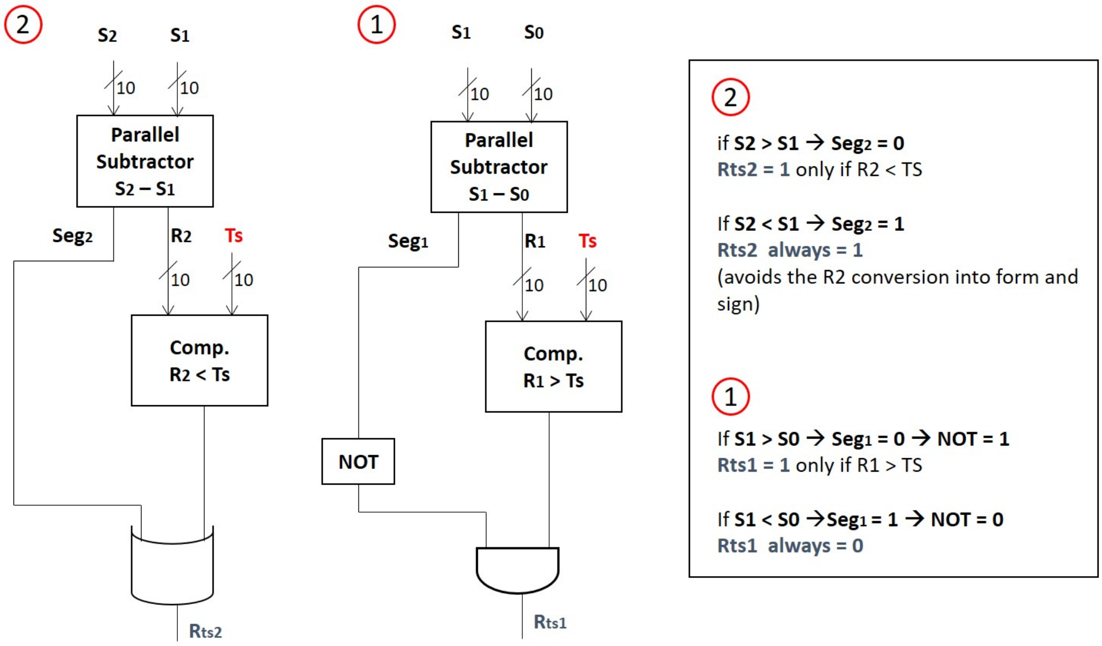
A negative result of subtraction S_1 - S_0 must cancel the result downstream of the comparison
(if S_1 <S_0 → No Leading)

Block 2

s(i+1) – s(i) < **Ts** with S(i) = S_1

A negative result of subtraction S_2 - S_1 must force the positive result downstream of the comparison
(if S_2 <S_1 a negative result is obtained, certainly less than Ts)

Figure A.7: Pulse detection - LE declaration



②

if $S2 > S1 \rightarrow Seg_2 = 0$
$Rts2 = 1$ only if $R2 < TS$

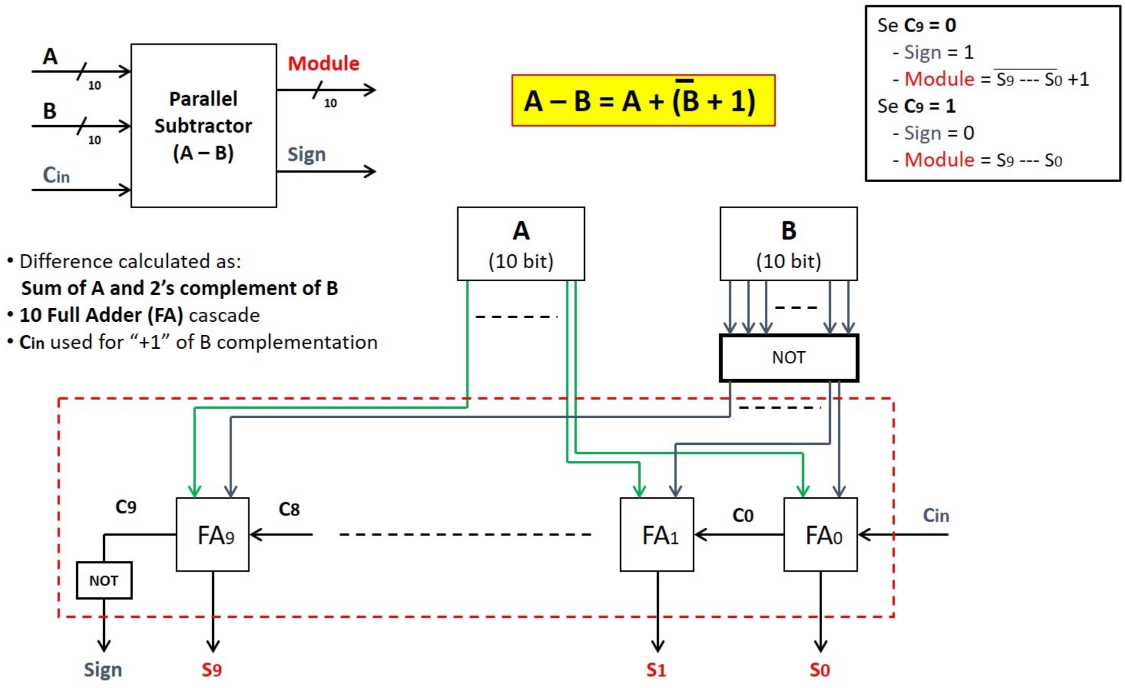
If $S2 < S1 \rightarrow Seg_2 = 1$
Rts2 always = 1
(avoids the R2 conversion into form and sign)

①

If $S1 > S0 \rightarrow Seg_1 = 0 \rightarrow NOT = 1$
$Rts1 = 1$ only if $R1 > TS$

If $S1 < S0 \rightarrow Seg_1 = 1 \rightarrow NOT = 0$
Rts1 always = 0

Figure A.8: Pulse detection - LE declaration: internal blocks detail



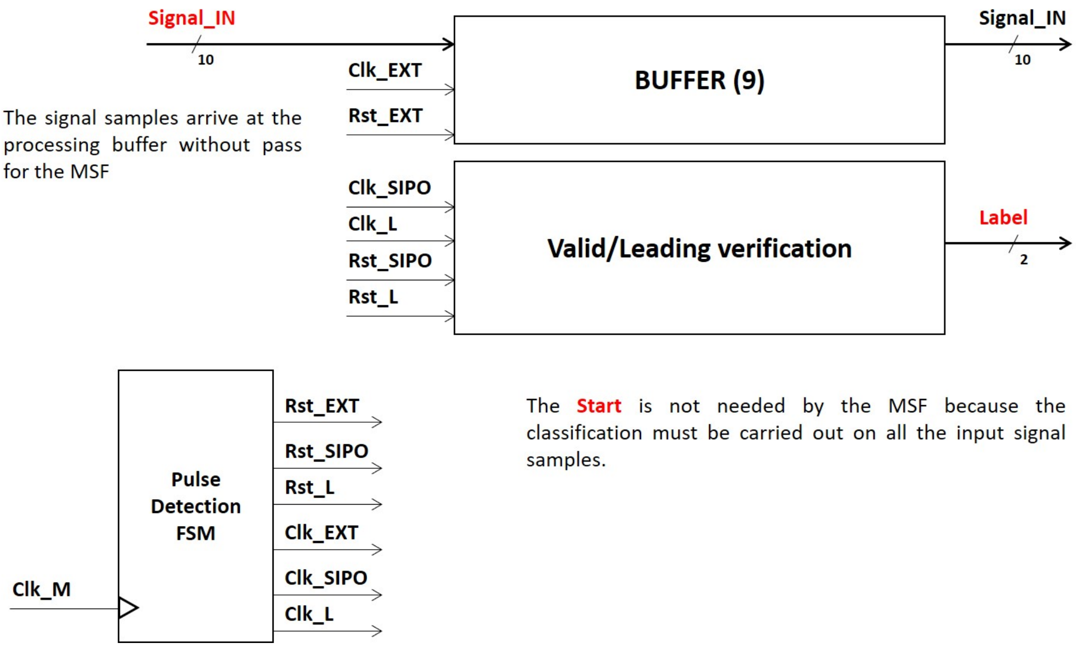
$A - B = A + (\overline{B} + 1)$

Se $C_9 = 0$
- Sign = 1
- Module = $\overline{S_9 \text{ --- } S_0} + 1$

Se $C_9 = 1$
- Sign = 0
- Module = S_9 --- S_0

- Difference calculated as: **Sum of A and 2's complement of B**
- **10 Full Adder (FA)** cascade
- **C_{in}** used for "+1" of B complementation

Figure A.9: Pulse detection - LE declaration: parallel subtractor block



The signal samples arrive at the processing buffer without pass for the MSF

The **Start** is not needed by the MSF because the classification must be carried out on all the input signal samples.

Figure A.10: Pulse detection - LE declaration: FSM

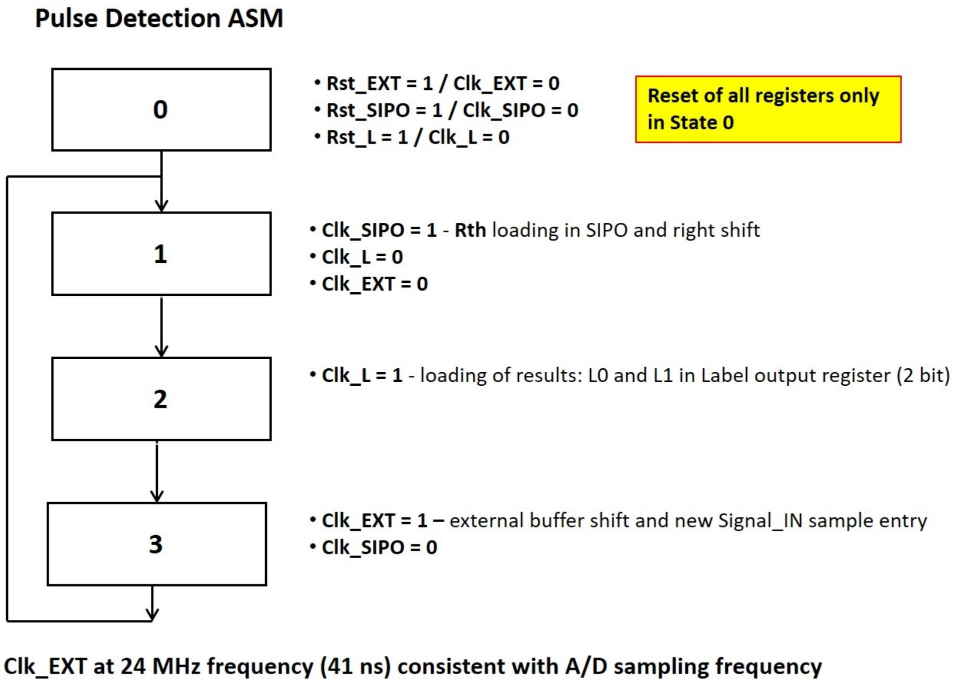


Figure A.11: Pulse detection - LE declaration: ASM

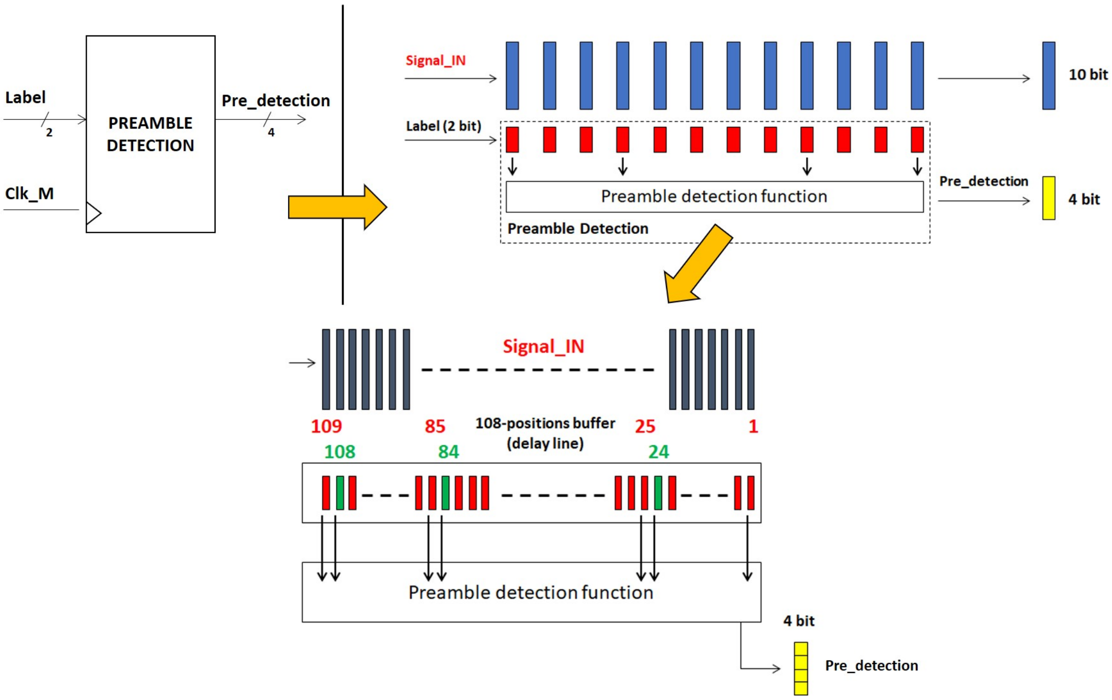
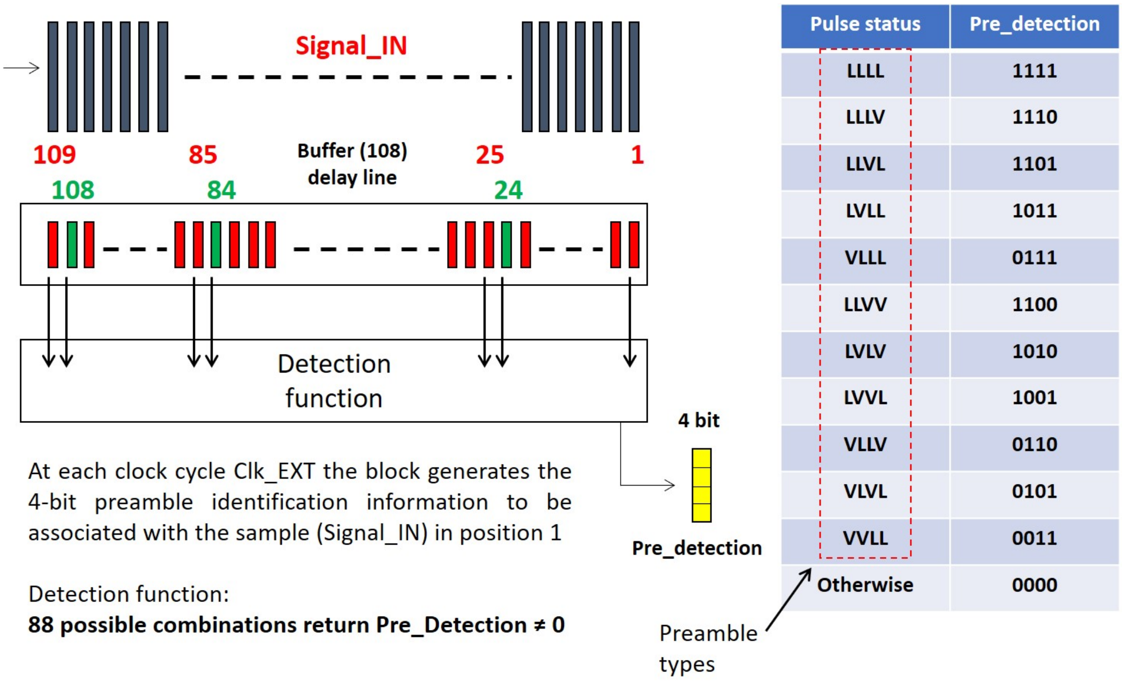


Figure A.12: Preamble pre-detection

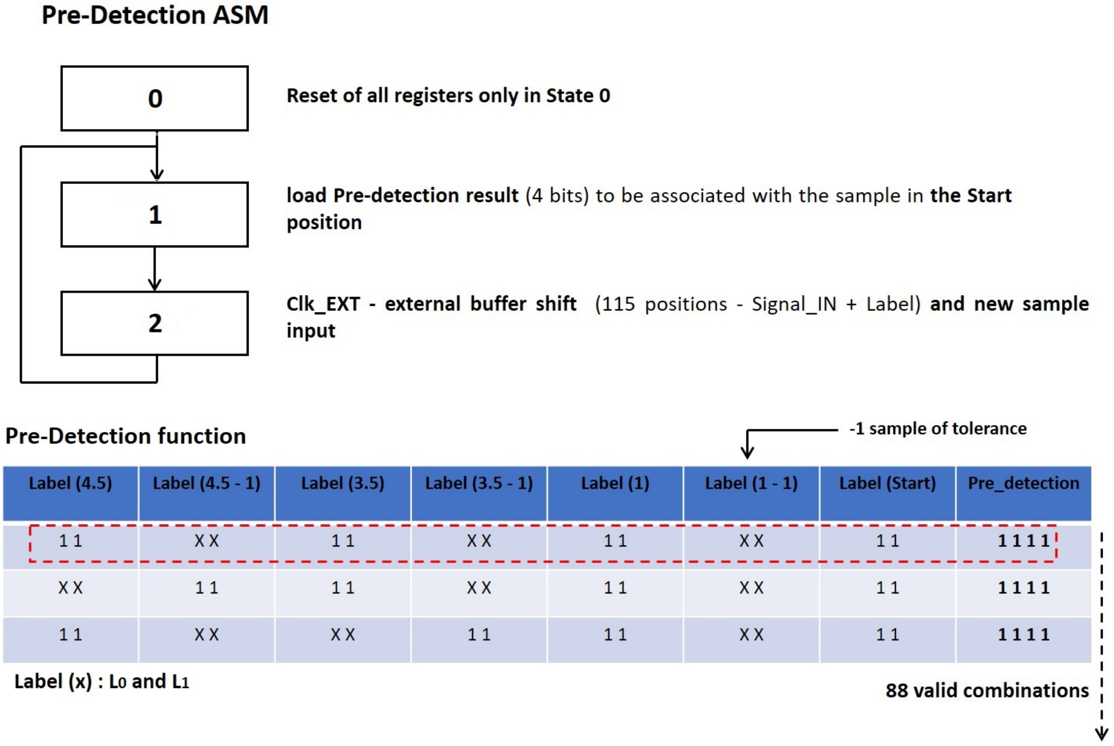


At each clock cycle Clk_EXT the block generates the 4-bit preamble identification information to be associated with the sample (Signal_IN) in position 1

Detection function:
88 possible combinations return Pre_Detection ≠ 0

Pulse status	Pre_detection
LLLL	1111
LLLV	1110
LLVL	1101
LVLL	1011
VLLL	0111
LLVV	1100
LVLV	1010
LVVL	1001
VLLV	0110
VLVL	0101
VVLL	0011
Otherwise	0000

Figure A.13: Preamble pre-detection - Truth table



Reset of all registers only in State 0

load Pre-detection result (4 bits) to be associated with the sample in **the Start position**

Clk_EXT - external buffer shift (115 positions - Signal_IN + Label) **and new sample input**

Label (4.5)	Label (4.5 - 1)	Label (3.5)	Label (3.5 - 1)	Label (1)	Label (1 - 1)	Label (Start)	Pre_detection
1 1	X X	1 1	X X	1 1	X X	1 1	**1 1 1 1**
X X	1 1	1 1	X X	1 1	X X	1 1	**1 1 1 1**
1 1	X X	X X	1 1	1 1	X X	1 1	**1 1 1 1**

Label (x) : L_0 and L_1

88 valid combinations

Figure A.14: Preamble pre-detection - ASM and tolerances for preamble types

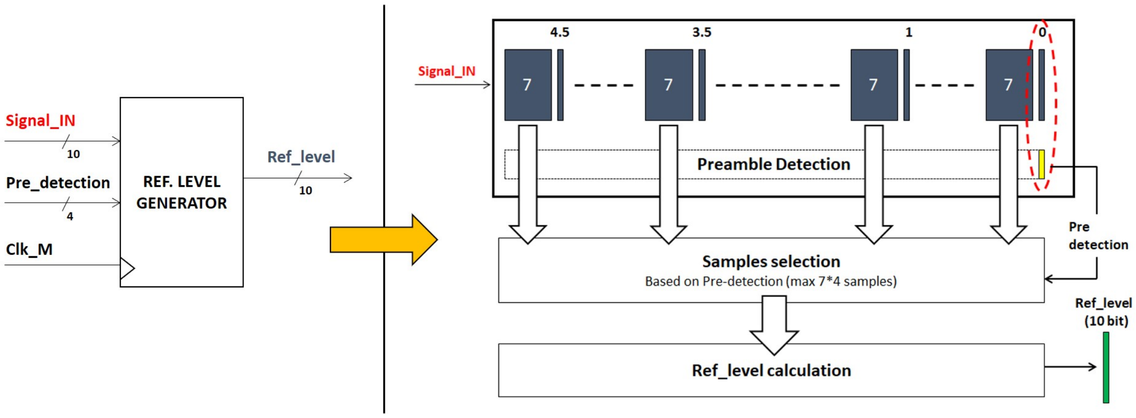
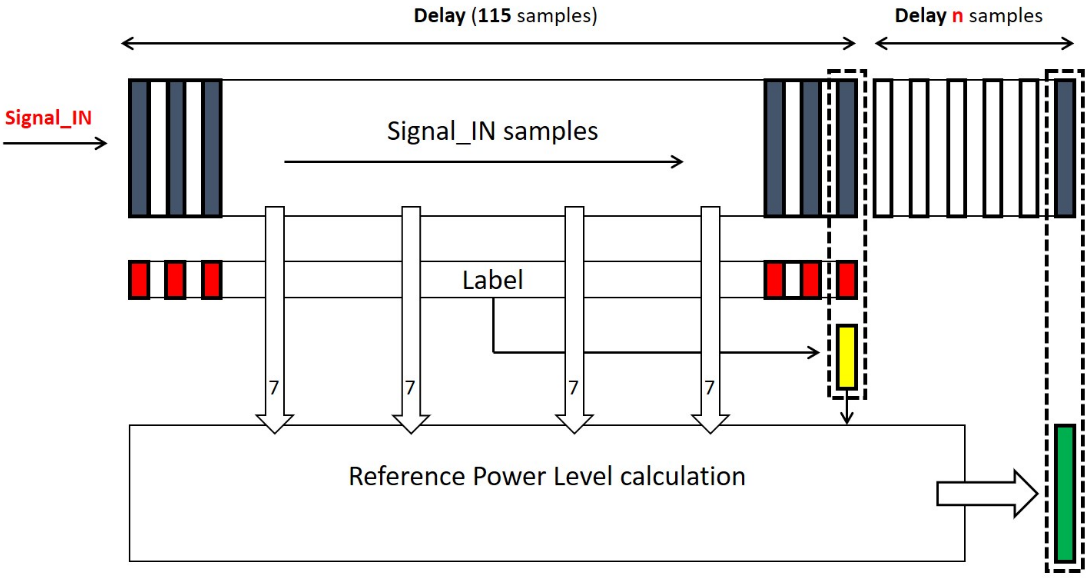
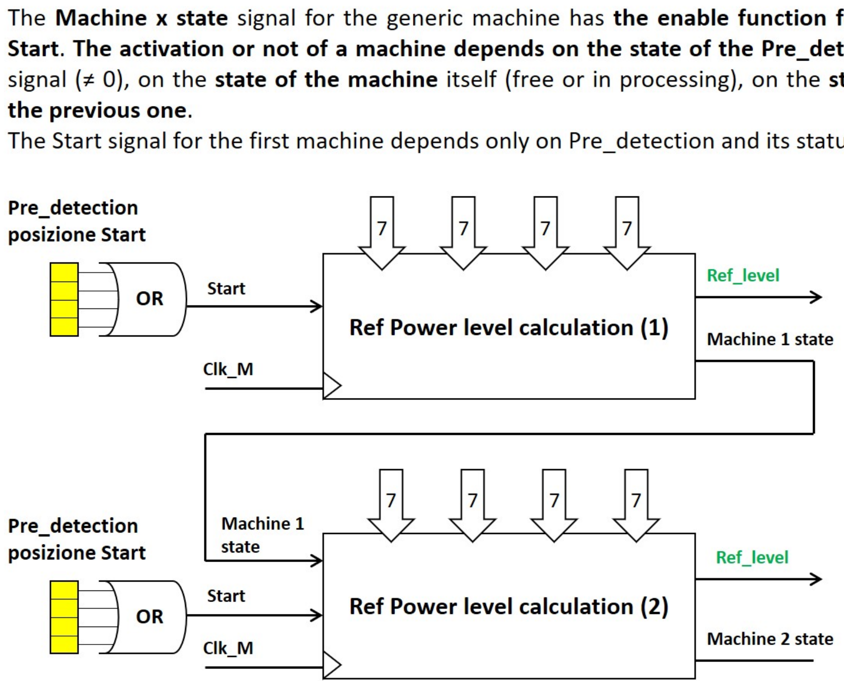


Figure A.15: HW description of the Reference power calculation process



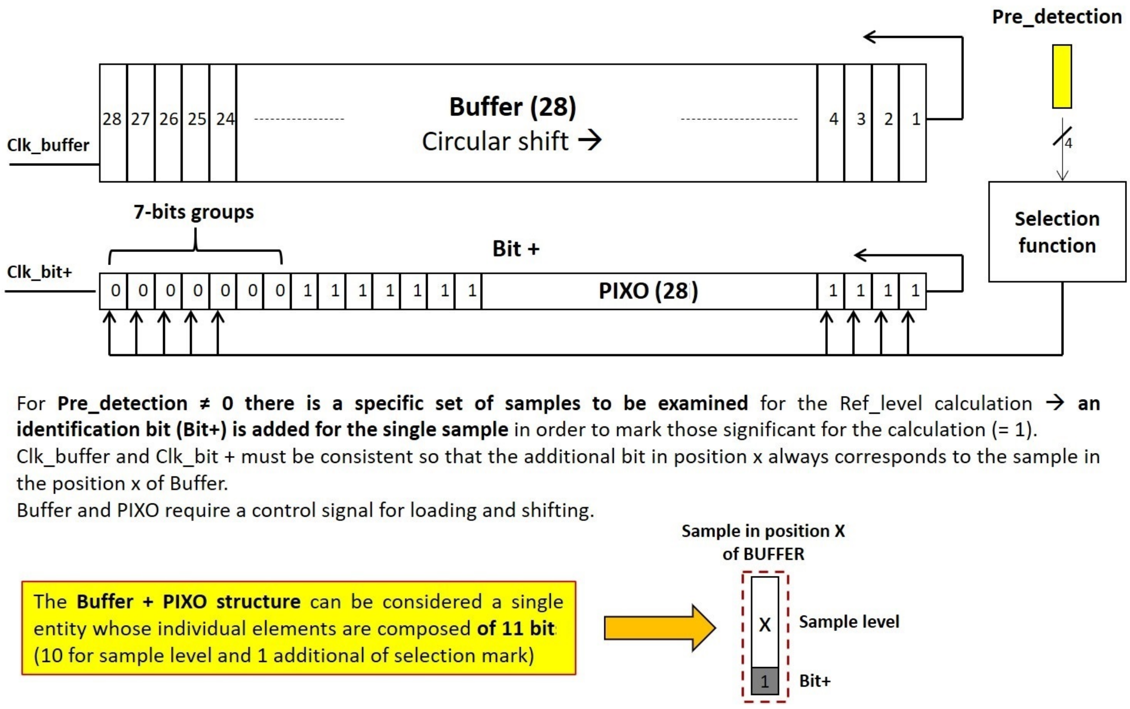
n: delay associated with the the reference power calculation related to the sample in position 0.
The high number of operations leads to the parallelization of the process.

Figure A.16: RPL - Calculation process detail



The **Machine x state** signal for the generic machine has **the enable function for the Start. The activation or not of a machine depends on the state of the Pre_detection** signal (≠ 0), on the **state of the machine** itself (free or in processing), on the **state of the previous one**.
The Start signal for the first machine depends only on Pre_detection and its status.

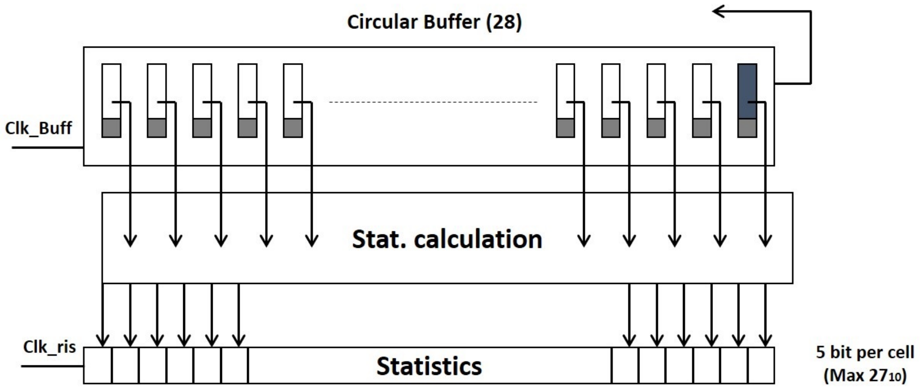
Figure A.17: RPL - Management protocol of parallel lines for calculation



For **Pre_detection ≠ 0 there is a specific set of samples to be examined** for the Ref_level calculation → **an identification bit (Bit+) is added for the single sample** in order to mark those significant for the calculation (= 1).
Clk_buffer and Clk_bit + must be consistent so that the additional bit in position x always corresponds to the sample in the position x of Buffer.
Buffer and PIXO require a control signal for loading and shifting.

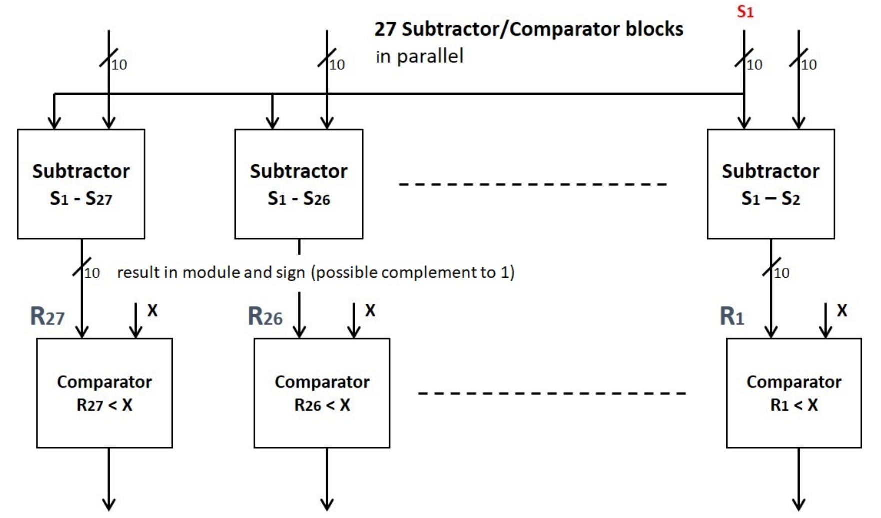
The **Buffer + PIXO structure** can be considered a single entity whose individual elements are composed **of 11 bit** (10 for sample level and 1 additional of selection mark)

Figure A.18: RPL - Samples selection according to the preamble type



At each Clk_Buff cycle the circular shift of the Buffer (28) is performed with the **calculation of the statistic variable associated to the sample in position 1**.
The results of the **27 comparisons per single sample** are stored on a reference register (**memory bench with 28 registers**);
After 28 cycles of Clk_Buff all the results relating to the comparisons between samples **are available**.
The statistics must be calculated by using a set of **28 counters**.

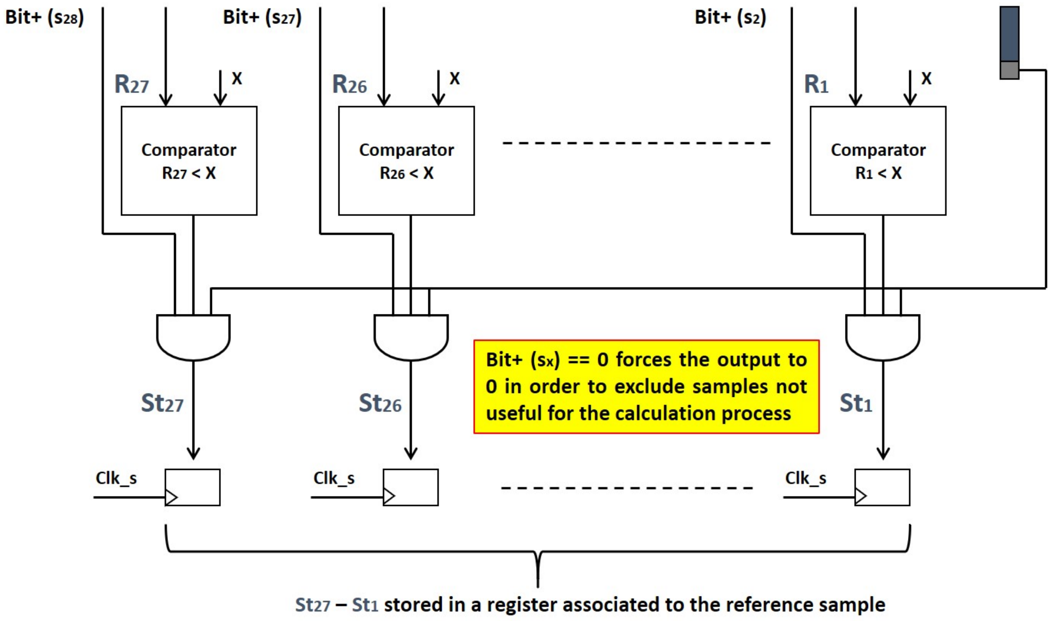
Figure A.19: RPL - Statistics calculation process



In the Clk_Buff interval, the **statistic calculation process concerns the sample in position 1 (S_1)**

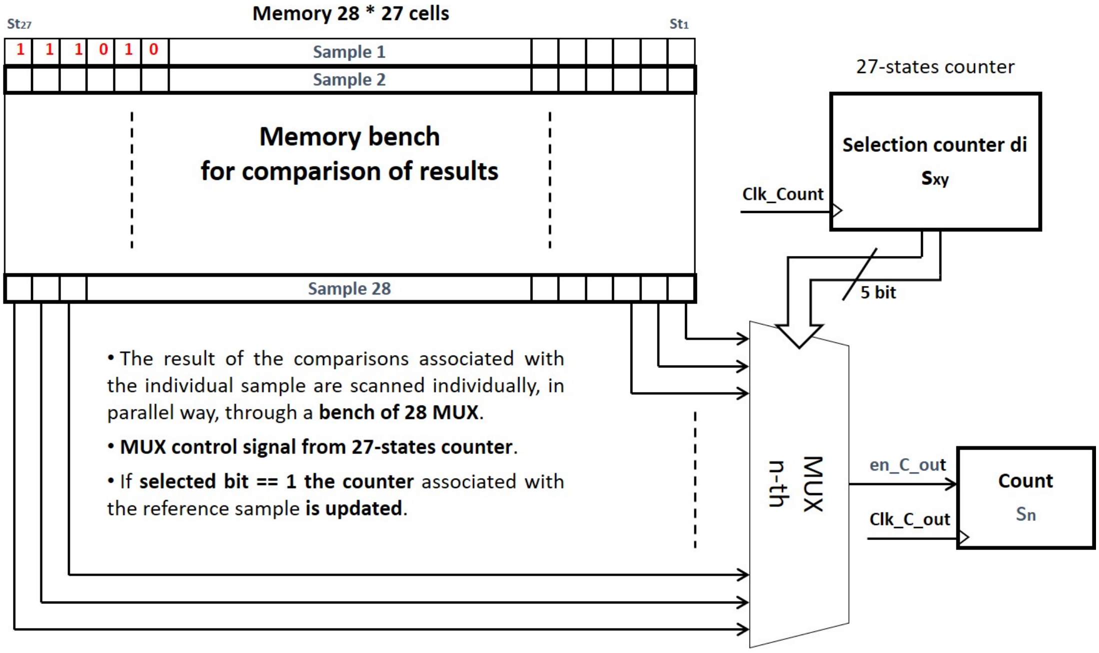
We have to introduce a signal control in order to exclude from the statistics update process those samples with Bit + == 0 → enabling of outputs: S_{27} - S_1 on a Bit + basis

Figure A.20: RPL - Statistics calculation process detail



Bit+ (sx) == 0 forces the output to 0 in order to exclude samples not useful for the calculation process

Figure A.21: RPL - Statistics calculation process: comparison results



- The result of the comparisons associated with the individual sample are scanned individually, in parallel way, through a **bench of 28 MUX**.
- **MUX control signal from 27-states counter**.
- If **selected bit == 1 the counter** associated with the reference sample **is updated**.

Figure A.22: RPL - Statistics calculation process: counter updating

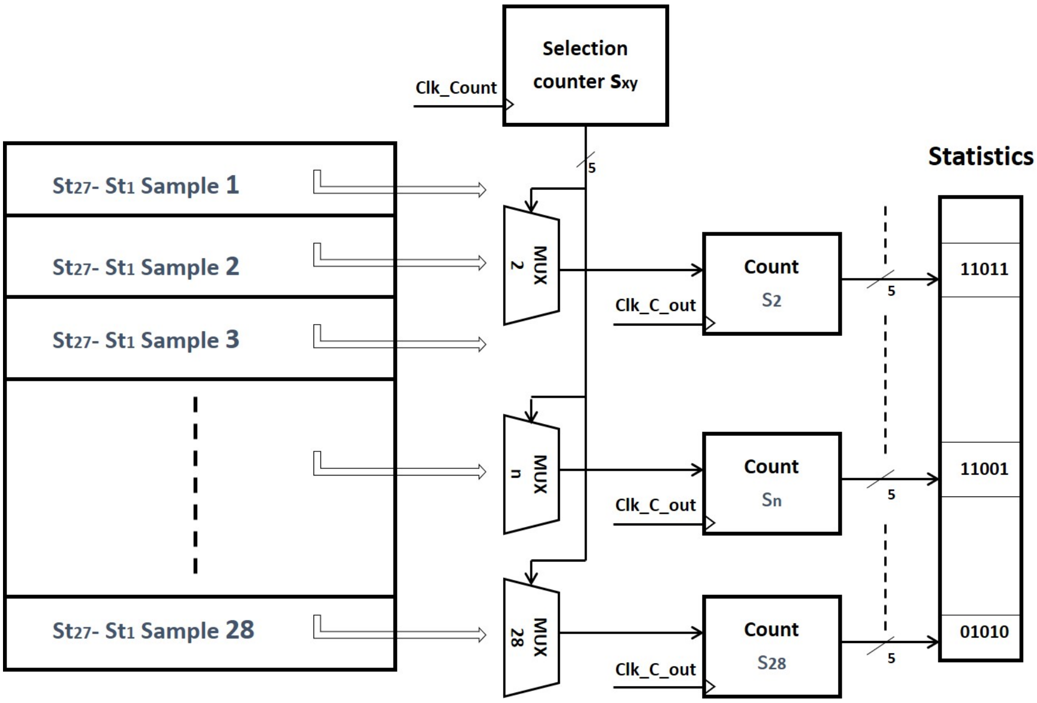
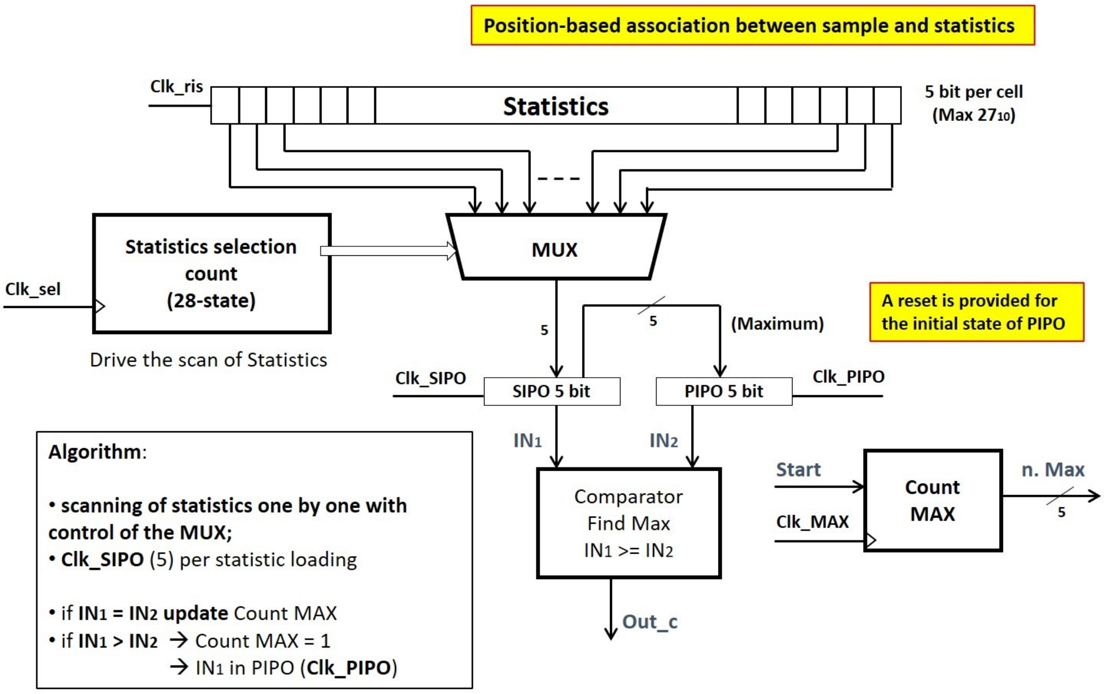


Figure A.23: RPL - Statistics calculation process: parallel lines for count updating



Position-based association between sample and statistics

Drive the scan of Statistics

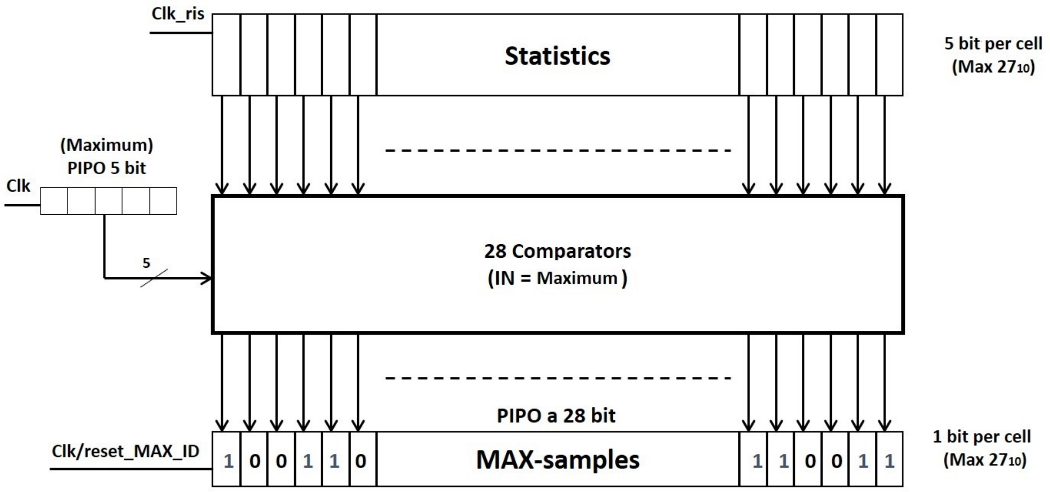
A reset is provided for the initial state of PIPO

Algorithm:

- **scanning of statistics one by one with control of the MUX;**
- **Clk_SIPO** (5) per statistic loading

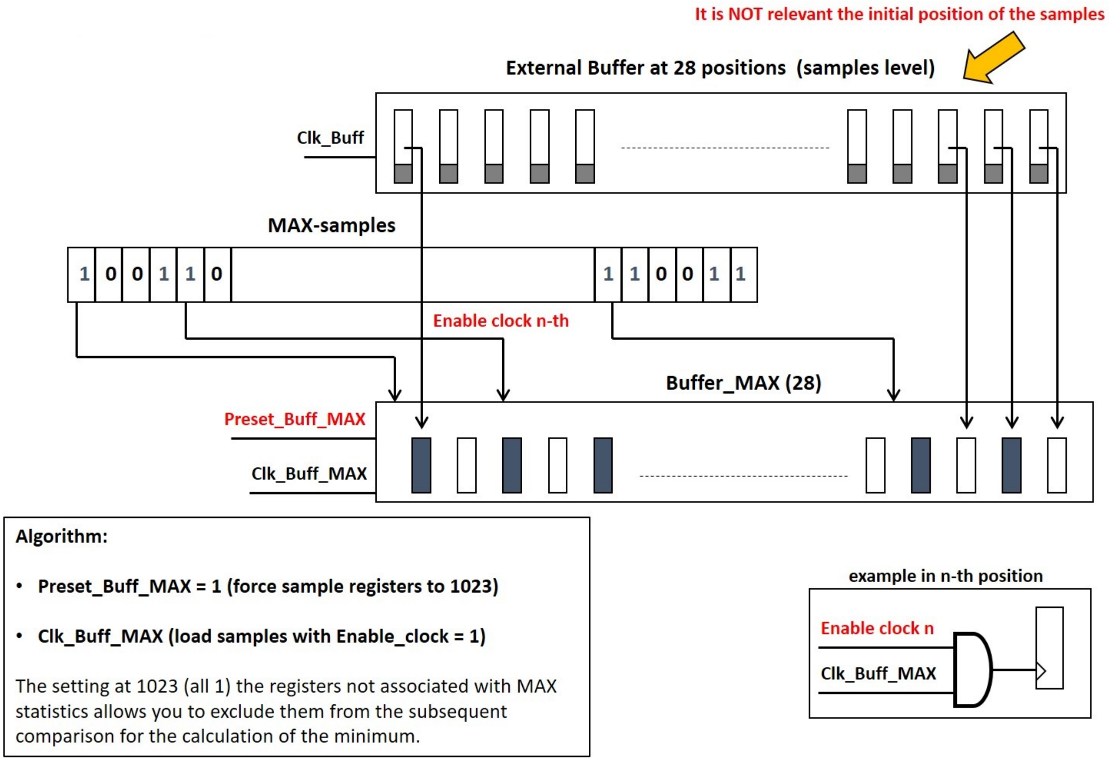
- if **IN_1 = IN_2 update** Count MAX
- if **IN_1 > IN_2** → Count MAX = 1
  → IN_1 in PIPO (**Clk_PIPO**)

Figure A.24: RPL - MAX statistic calculation



MAX-samples buffer is reset at each cycle of Clk_EXT in order to have 1 only at the positions associated with MAX statistic

Figure A.25: RPL - Selection of samples at MAX statistic



Algorithm:

- **Preset_Buff_MAX = 1 (force sample registers to 1023)**
- **Clk_Buff_MAX (load samples with Enable_clock = 1)**

The setting at 1023 (all 1) the registers not associated with MAX statistics allows you to exclude them from the subsequent comparison for the calculation of the minimum.

Figure A.26: RPL - Storage of samples at MAX statistic

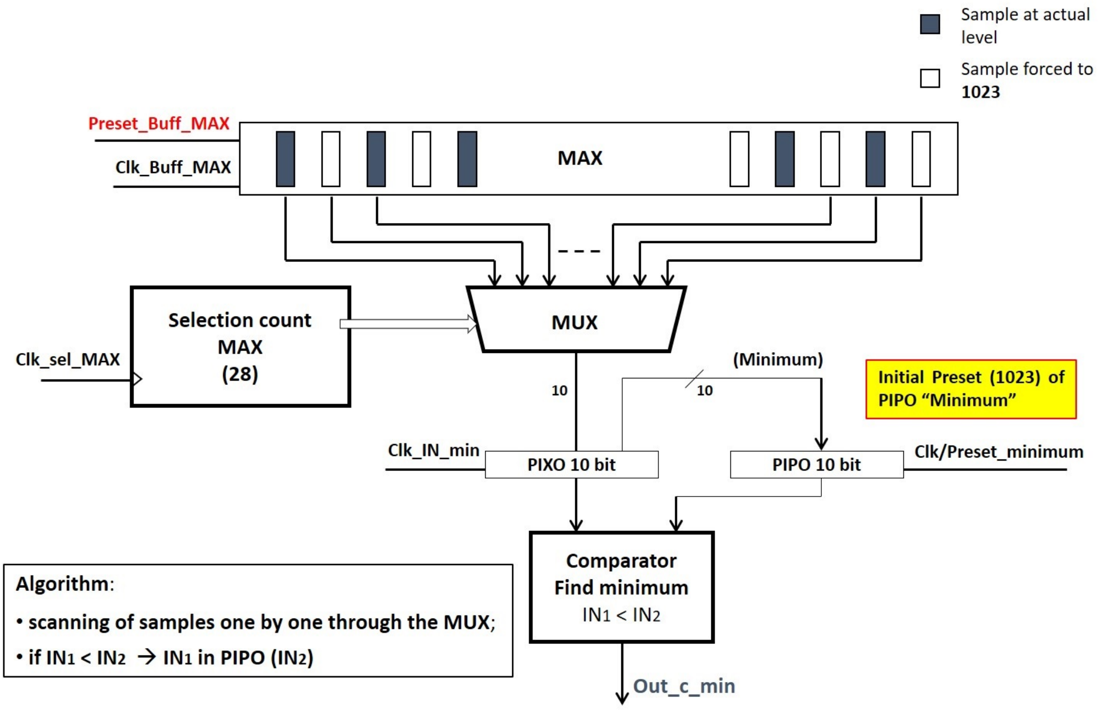


Figure A.27: RPL - Identification of the "minimum"

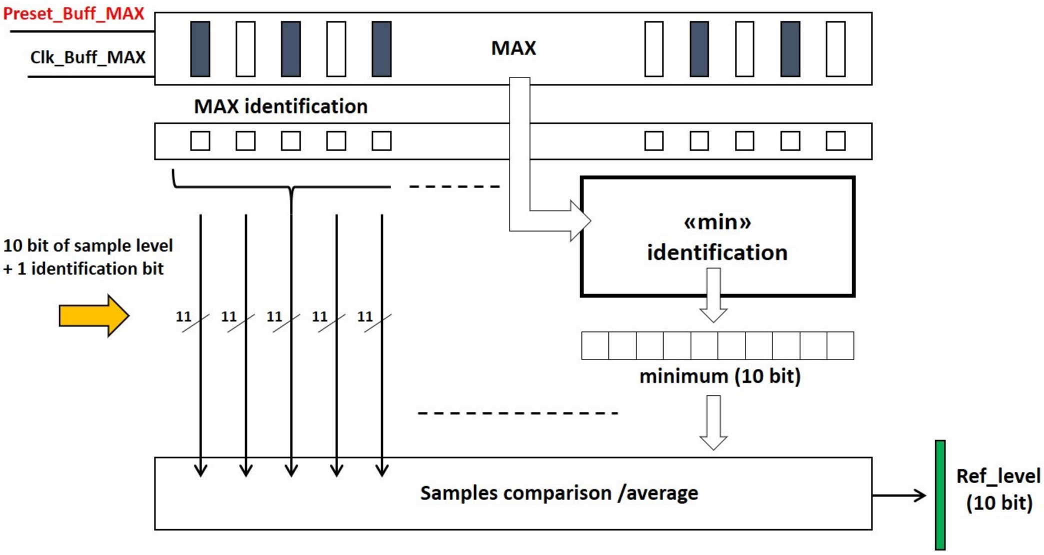


Figure A.28: RPL - Samples comparison and average calculation

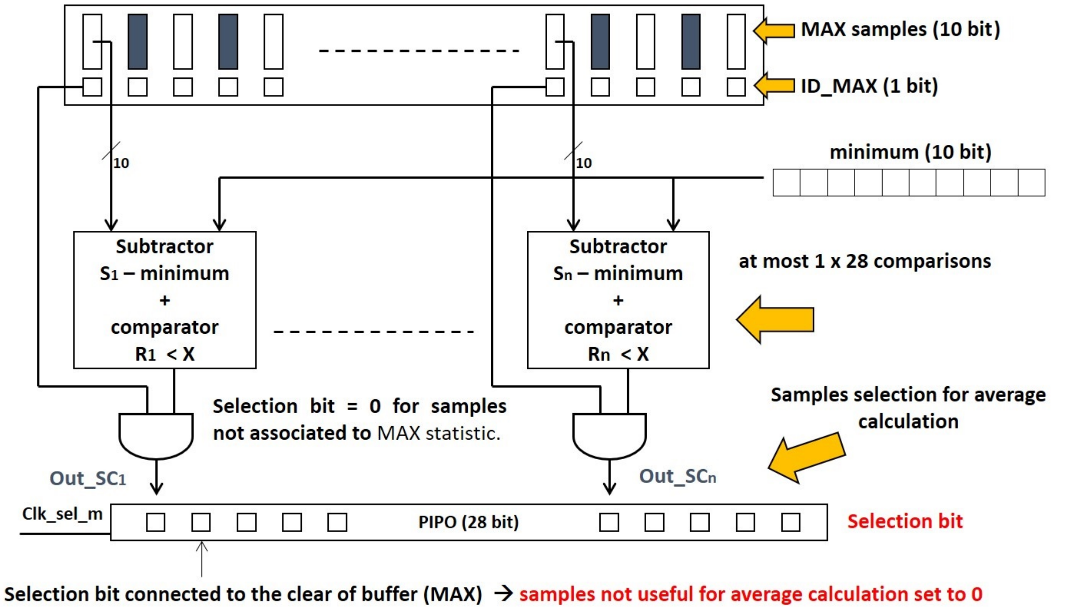


Figure A.29: RPL - Samples selection for average calculation: selection bit

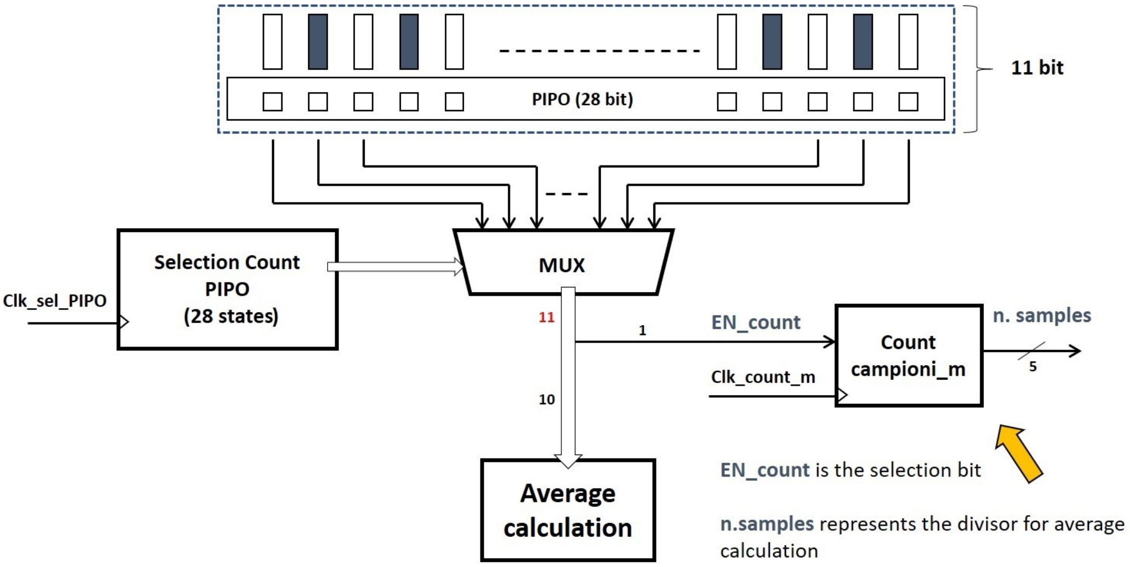
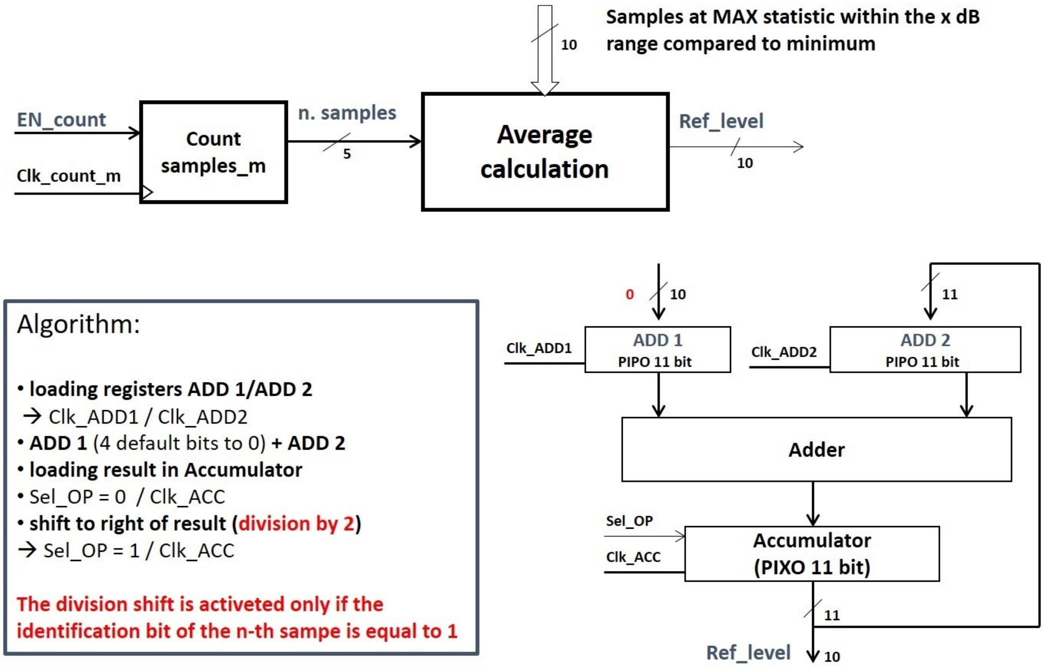


Figure A.30: RPL - Samples selection for average calculation: count updating



Algorithm:

- **loading registers ADD 1/ADD 2**
  → Clk_ADD1 / Clk_ADD2
- **ADD 1** (4 default bits to 0) **+ ADD 2**
- **loading result in Accumulator**
- Sel_OP = 0 / Clk_ACC
- **shift to right of result (division by 2)**
  → Sel_OP = 1 / Clk_ACC

The division shift is activeted only if the identification bit of the n-th sampe is equal to 1

Figure A.31: RPL - Average calculation

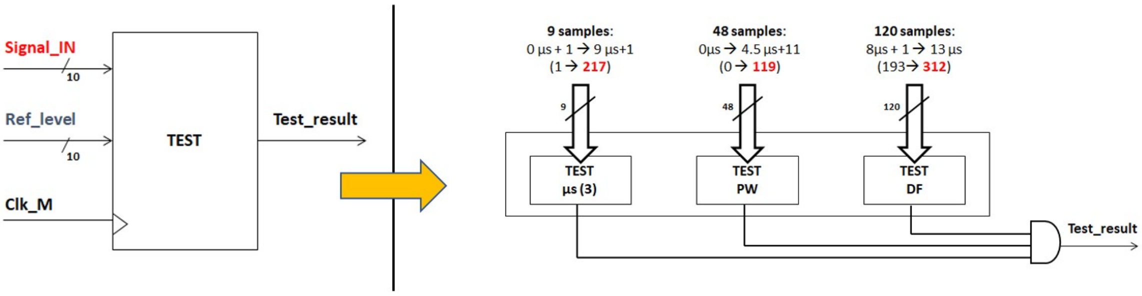


Figure A.32: Preamble tests

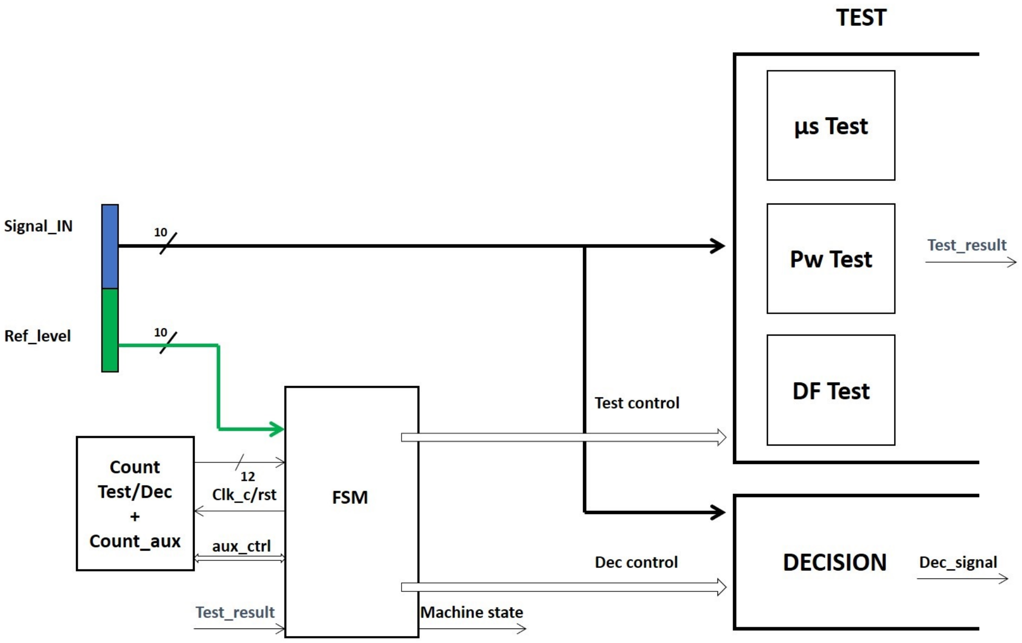


Figure A.33: Preamble tests/Decoding parallel execution

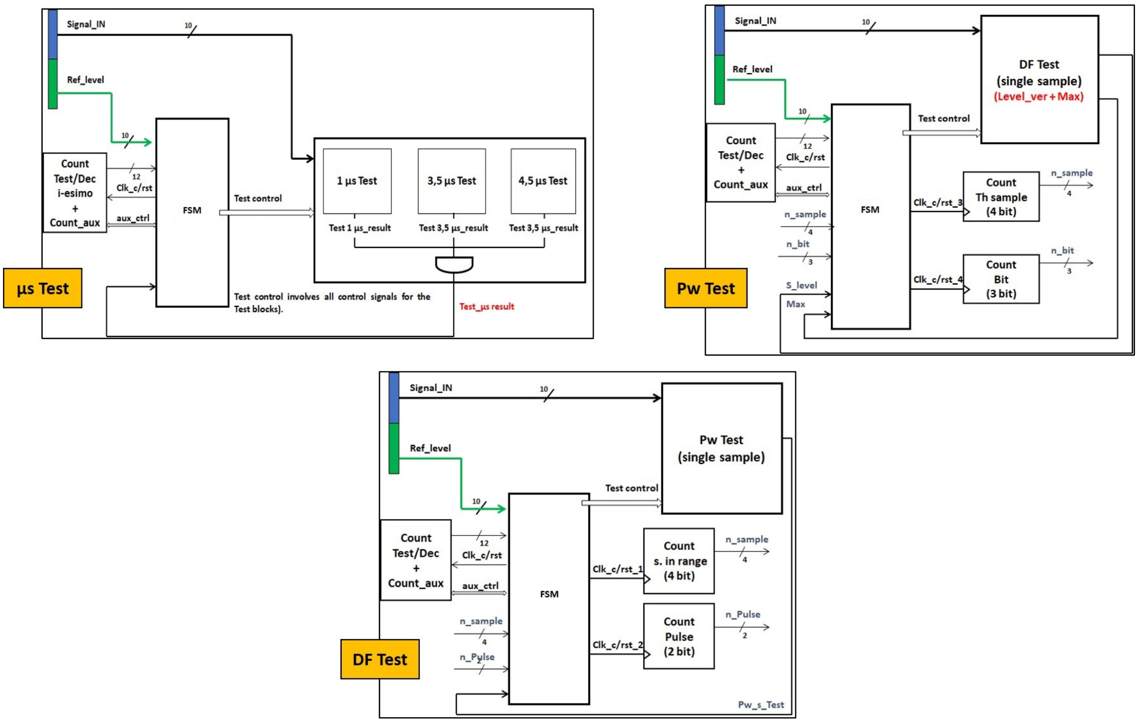


Figure A.34: Preamble tests detail

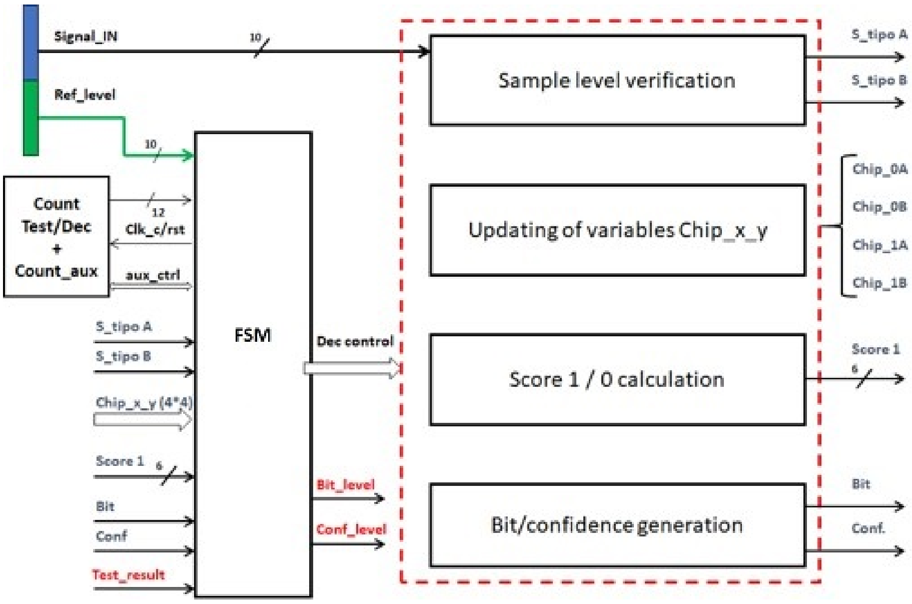


Figure A.35: HW description of MS decoding block

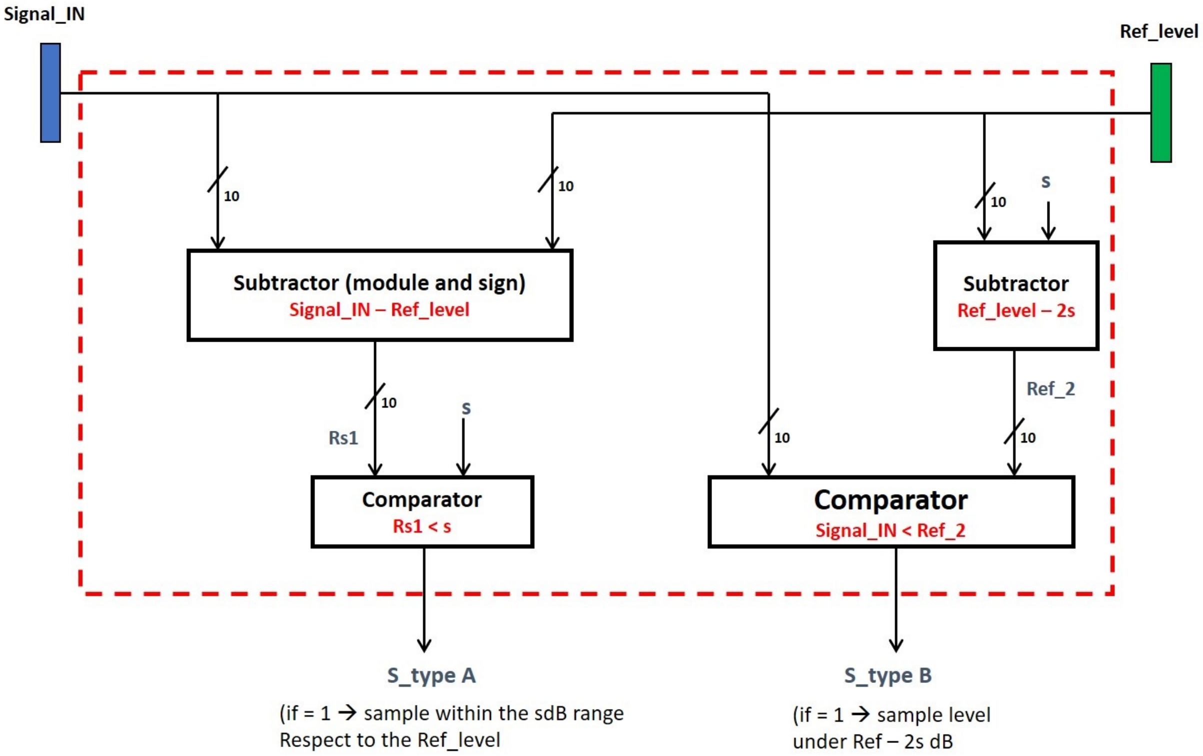


Figure A.36: MS decoding - samples level verification

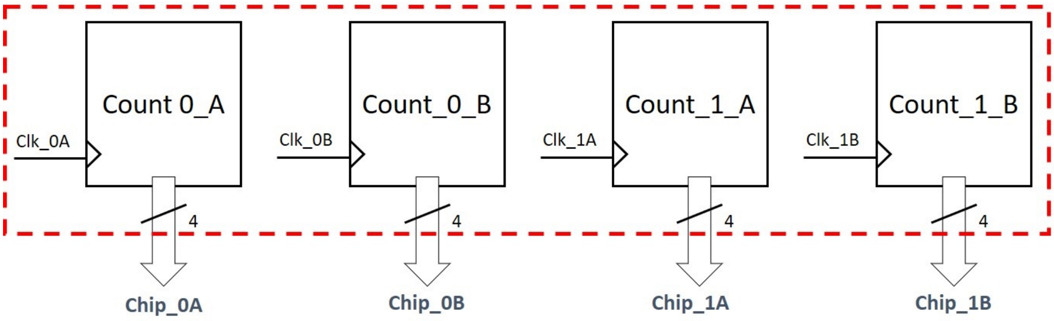


Figure A.37: MS decoding - Chip_x_y update

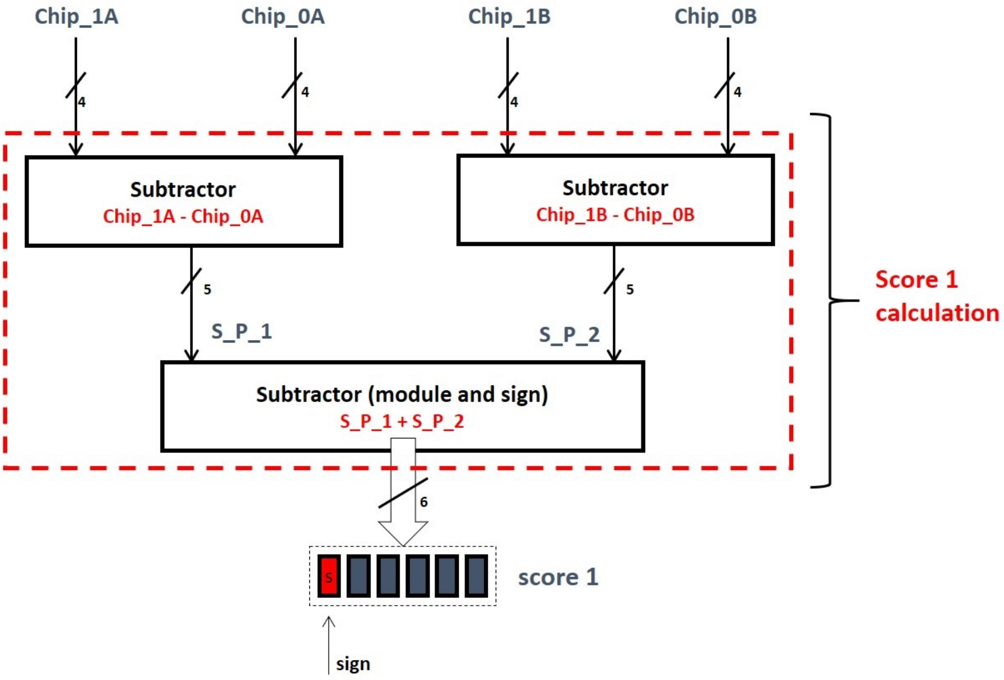

score 1 = score 0 in module but with opposit sign

Figure A.38: MS decoding - Scores calculation

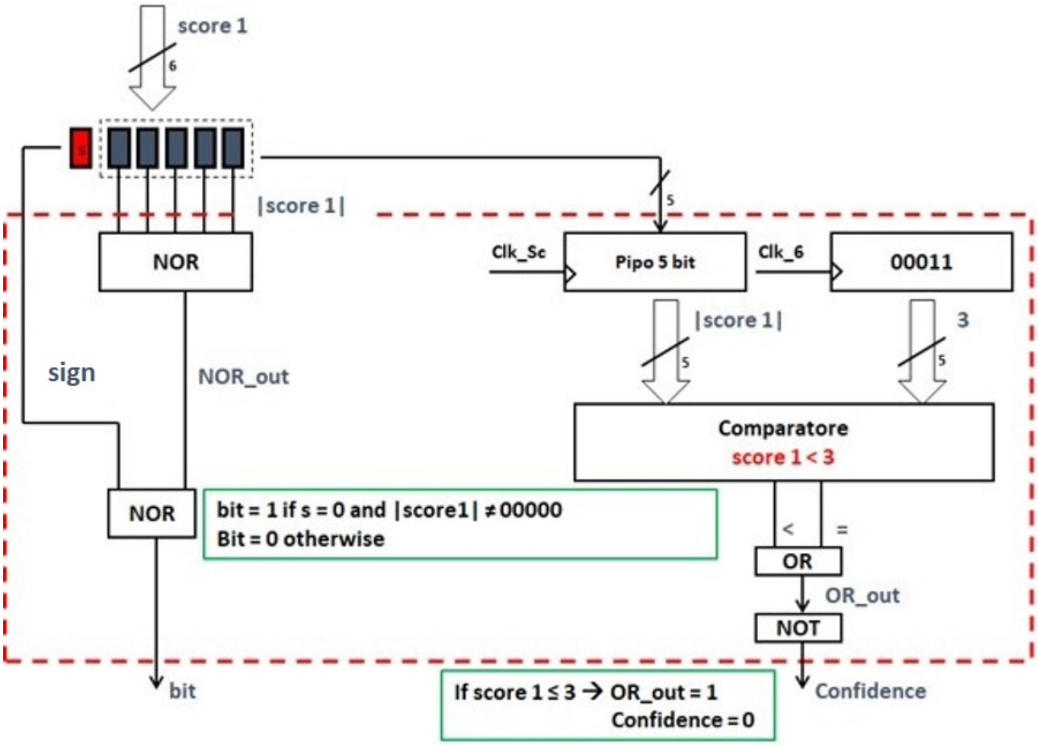


Figure A.39: MS decoding - Bit/Confidence results

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