Railway Smart Meters

Thesis Research Plan

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Contents

List of Figures

List of Tables

Acronyms

AC	Alternating Current
AMR	Automatic Meter-Reading system
CEBD	Compiled Energy Billing Data-sets
DC	Direct Current
DCS	Data Collecting System
DHS	Data Handling System
DSS	Decision Support System
DSSS	Direct Sequence Spread Spectrum
FEM	Finite Element Method
EMI	Electromagnetic Interference
EETC	Energy-efficient Train Control
EETT	Energy-Efficient Train Timetabling
EMF	Energy Measurement Function
EMS	Energy Measurement System
ERA	European Union Agency for Railways
EU	European Union
GMSK	Gaussian Minimum Shift Keying
GPS	Global Position System
GSM	Global System for Mobile communications
GTO	Gate Turn-off Thyristors
ICT	Information and Communication Technology
IGBT	Insulated Gate Bipolar Transistors
IP	Internet Protocol
IP3	Innovation Program 3
ISM	Industrial, Scientific and Medical
KPI	Key Performance Indicators
LAN	Local Area Network
LC	Inductor-Capacitor
LTE	Long-Term Evolution
MAC	Medium Access Control
MDMS	Meter Data Management System
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
PLC	Power Line Communication
QoS	Quality of Service
PHY	Physical Layer
RTS	Railway Transportation System
RUs	Railway Undertakings
S2R	Shift2Rail
SG	Smart Grid
SMD	Smart Metering Demonstrator
TCMS	Train Communication & Management System
TSIs	Technical Specifications for Interoperability
VSC	Voltage Source Converter
WLAN	Wireless LAN
WSN	Wireless Sensor Networks

CHAPTER 1

Introduction

1.1 Context and motivation of PhD

The railway system is responsible for 1.3% of entire European energy consumption, [1]. The debate on energy efficiency in railways is a well-discussed topic due to its impact on the global energy consumption.

The energy efficiency analysis and management requires a detailed mapping of the energy consumption/generation in the railway system. This detailed mapping of the energy flows should include, not only the rolling stock level but also the traction substations and the auxiliary services. The knowledge of all the load curves permits load prevision, peak shaving and energy cost optimization for the entirely of the railway system.

1.2 Shift2Rail Framework

This work is supported by the iRail PhD program – Innovation in Railway Systems and Technologies whose objectives are aligned with the Shift2Rail (S2R) objectives, [2], which are:

- 1. Cutting the life-cycle cost of railway transport by, at least, 50%;
- 2. Doubling the railway capacity;
- 3. Increasing the reliability and punctuality by 50%, at least.

Complementary, the time target goals are the establishment of a framework, by 2020, for a European multimodal transport system for the passenger rail, freight and for the urban mobility. By 2030 is expected to triple the length of the existing high-speed passenger rail network, 30% of the road freight over 300 km should shift to rail or waterborne transport and achieve a CO2-free city logistics in major urban centers. By 2050, the medium-distance passenger transport should go by rail and high-speed rail, with the connection of all core network airports to the high-speed railway network. On the freight is expected to have all seaports connected to the rail freight transport system and on the urban mobility, the "conventionally-fueled" cars will not have place in cities by 2050, [2].

The S2R carries five innovation programmes, as presented in figure 1.1. Framed on the S2R Innovation Programme 3 (IP3) with the focus on the "Cost efficient and reliable infrastructure", it is proposed the development of a Smart Metering Demonstrator (SMD) that achieves a detailed monitoring and supervision of various energy flows on the premises of embracing the entire RTS.

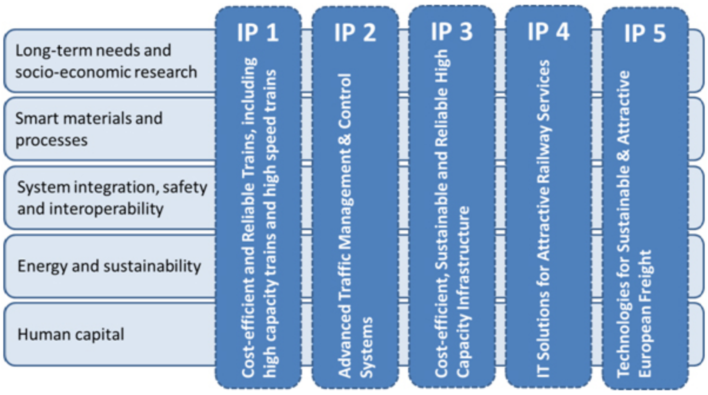

Figure 1.1: Shif2Rail Innovation Programs.

The purpose of any energy management strategy is to build the dynamics of every loads and generators of the power system. This should be performed based on an extensive knowledge of every energy flows. This way, the SMD is required to propose and validate a standard metering architecture that involves the coordination of every measurement performed either in on-board and in ground. In advance, energy data analysis should be provided based on relevant stored data.

1.3 Preliminary state of the art

This section will cover a summary of the state of the art that supports this PhD.

Based on the state of the art, current metering systems focus on rolling stock on-board energy meters for energy billing purposes only, being located close to the pantograph, [2]. A possible advancement beyond the state of the art is the expansion of the measurement system at railway system level, making it a distributed on-board and track-side measurements, thus achieving detailed mappings.

Other issue shown in the state of the art is the intrusion level of currently used metering systems, that in a way, became a critical subsystem of the rolling stock but also requires a relatively long implementation, [2]. An advance beyond the state of the art is a solution based on non-intrusive technology. More detailed simulation models in conjunction with field measurements is included on the methodology to be investigated.

A specific challenge and requirements of this research is the development of non-intrusive WSN in the railway environment. It is intended that this technology should be based on an open system and open interfaces for the data collection, aggregation and analysis. Issues like metering redundancy, outlier detection, fault tolerance and communication reliability, should be considered during the research. In addition, it is expected the design and specification of a set of user applications. Those applications are focused in the energy analysis process, with the aim of providing more information and detailed knowledge. This detailed knowledge will be useful in a decision support system related with, in e.g., eco-driving strategies, timetable planning and preventive maintenance.

1.4 Document structure

This document is divided in 5 chapters, each of them incorporating the relevant subsections to present the subjects mentioned.

Table 1.1: Document structure

Chapter	**Title**
1	Introduction
2	Objectives and Contributions
3	Literature Review
4	Methodology and Work Plan
5	Preliminary Work

CHAPTER 2

Objectives and Contributions

2.1 Objectives

Nowadays, the need for increasing of the energy efficiency in the RTS is a relevant topic. We can see two ways to increase the energy efficiency: (1) we act in the construction of new trains, with the usage of the most energy efficiency technologies or (2) we adapt the current operation of RTS to better use the resources available. On a higher level, this work will contribute for the increase of energy efficiency in the RTS operation, with the optimization of the resources available.

Currently there is a lack of knowledge on the RTS energy flow, which results in poor operation of this system. The decisions taken in the train operation have lack of information from field infrastructure, in both the existence of such information and in terms of quality of the information. Nowadays, we have present trains that does not have available, for the operation point of view, the information on power flow. In recent years, European Union (EU) has promoted the implementation of automatic metering systems in train operations, mainly for billing purposes. However, even with this EU regulation, the periodicity of available data is around 5 minutes, which can put into question the quality of the information.

To have the knowledge necessary to take actions towards the better operation of the RTS, we have to obtain the information of energy usage from the field. This work is focused on collecting information from the field of operation and make it available, in a centralized database (for knowledge extraction mechanisms). To collect information, we have to perform measurements of the energy related variables.

To conclude, the objectives can be synthesized in the following two points:

- Research on **railway energy models**, and **development/implementation of a metering system** for railway power flow monitoring. This is expected to be based on a non-intrusive self-powered sensor node inserted into train power system.
- Research on **communication network models** for a RTS wireless network with **validation through simulation frameworks**. **Development and implementation** of RTS wireless network to store the energy information data of railway into central database.

2.2 Contributions

The expected contributions will be divided in two major areas: (1) the energy measurement and information generation of the sensor nodes and (2) the energy information transmission and storage into centralized database.

On the energy measurement and information generation of the sensor nodes, two contributions can be considered as follows:

- **New energy metering architecture**, according to some specifications such as the usage of a non-intrusive approach. This architecture will generate energy information about the power flow of the railway system.
- **Accurate estimation of power flow** into catenary, based on on-board measurements. The available parameters will be: (1) the RMS voltage, current and apparent power, (2) the instantaneous active power, reactive power, power factor and frequency, and (3) the cumulative energy consumptions in terms of kVAh, kVARh and KWh.

Regarding the energy information transmission and storage into centralized database, the following contributions are expected:

- **Availability of measured data** from trains where currently limited/inexistent energy measurement is performed.
- Data-rate increase of energy measurements, which will result on direct **increase on the quality of information of energy**. This increase will overcome the 5-minute data-rate that currently are used in energy meters.

A further contribution can be the avoidance of broadband real-time/continuous communication (such as Long-Term Evolution (LTE)), with the direct cost reduction of information transmission of energy RTS data.

CHAPTER 3

Literature Review

3.1 Power system of Railway Transportation System

In this section is started the literature review of this document, with the coverage of the power system of RTS. This system is reported in 2013 to transport 6.4% transport modal share of people and 8.7% transport modal share of goods, [1]. With high influence in the transportation of goods and people in the last century, this system had substantial technological enhancements. Currently we have a RTS with substantial differences in the supply system.

In subsection 3.1.1 is presented an overview on European railway electrical supply systems. Later on, in subsection 3.1.2, a comparison between different catenary supply systems is presented and in subsection 3.1.3 is presented a comparison of the power system architecture of trains. A further detail on train electrical components is presented in subsection 3.1.4.

This section is supported on the chapter 5 of the work of [3]. Further reading of this book chapter is recommended.

3.1.1 Overview of Existing European Railway Power Systems

Back to the 19th century, the steam turbine was the main propulsion system for the trains. Later on, electric and diesel propulsion systems were adopted. In recent years occurred a massive introduction of power converters based on Insulated Gate Bipolar Transistors (IGBT), which allowed an increase of energy efficiency (allowing, for example, regenerative breaking and reduction of power losses in traction motors).

Due to this evolution, different topologies of the railway system exists nowadays. In table 3.1, different catenary topologies are visible which results in different power systems for RTS.

Across the Europe, RTS depends on different types of electrification systems, as it is illustrated in figure 3.1.

3.1.2 Railway Power Supply System

Similarly to the electrical grid, where a broad area of loads must be supplied, the railway power system must be capable of maintaining trains running in a broad area. The energy is supplied to the railway system through traction substations, similarly to the generation units of the electrical grid.

These traction substations ensure the interface between the electrical grid and the railway system, being responsible of supplying the distribution line of the railway system - or catenary.

Table 3.1: Catenary topology and vehicle characteristics of different railway vehicles. Adapted from [3].

	Catenary topology		**Vehicle characteristics**	
	DC supply	**AC supply**	**Power**	**Top speed**
Tram	600V DC, 750V DC, 900V DC	-	150–300kW	50–70km/h
Metro	750V DC, 1500V DC	-	350kW–1MW	80km/h
Train	750V DC, 1500V DC, 3000V DC	15kV AC (16.7Hz) and 25kV AC (50Hz)	200kW–8MW	120–350km/h
Locomotive	750V DC, 1500V DC, 3000V DC	15kV AC (16.7Hz) and 25kV AC (50Hz)	500kW–8MW	100–200km/h

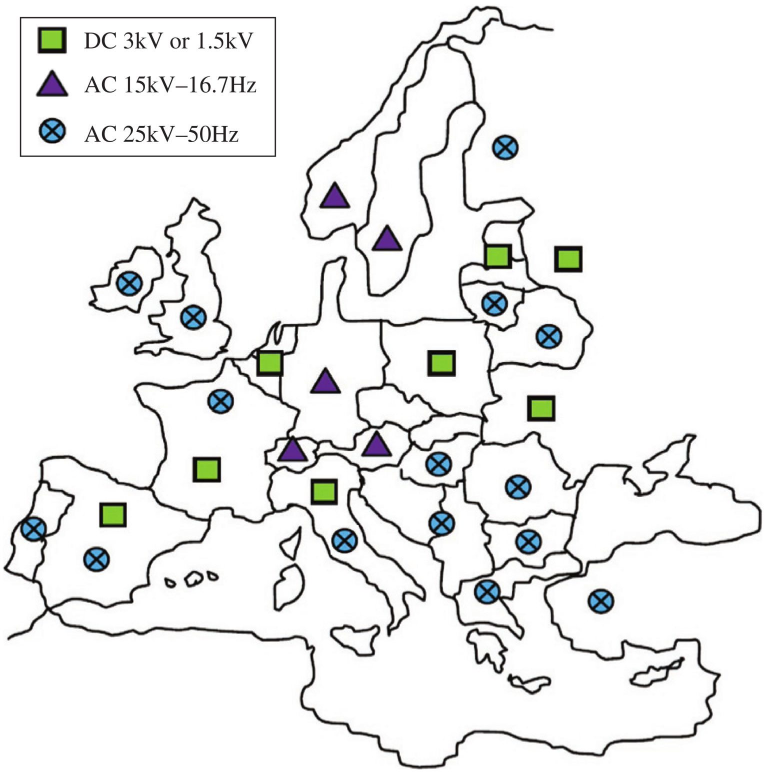

Figure 3.1: Railway main-line power supply systems in Europe. Adapted from [3].

As previously referred, the catenary can be divided in three main topologies:

- **DC supply system**

The DC supply system depends on rectifier converters (controlled or uncontrolled) and this railway power supply topology requires several traction substations, towards the reduction of power losses in catenary due to the high value of the electric current. In figure 3.2 is presented the supply architecture of such lines.

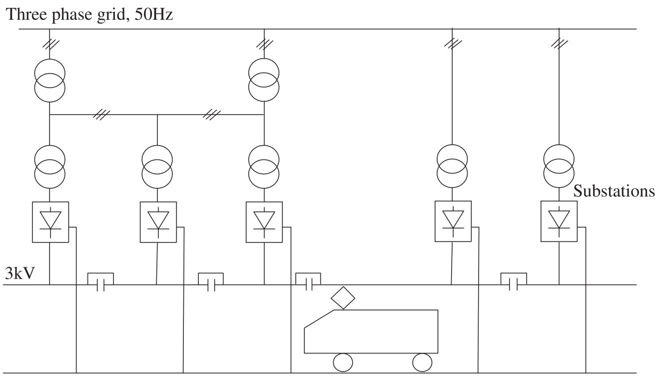

Figure 3.2: DC supply system architecture. Adapted from [3].

- **AC 50Hz (or 60Hz) supply system**
  With AC catenaries, low frequency single-phase on-board transformer is required to step down the catenary voltage (25 kV or 15 kV) to the rectifier operating voltage (the rectifier is a single-phase voltage source converter, usually with bi-directional power flow).

On the traction substation, a special setup of power transformers avoids the usage of complete power converters. In figure 3.3 is presented the substation setup to supply a single-phase 50 Hz catenary.

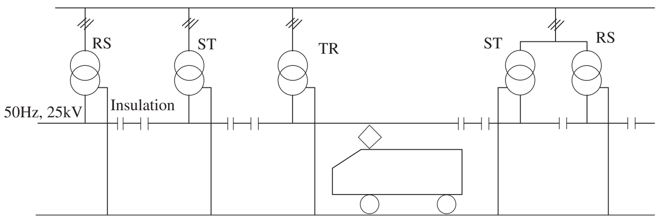

Figure 3.3: 50 Hz 25 kV supply system. Adapted from [3].

- **AC 16.7 Hz supply systems**
  An alternative setup is presented in figure 3.4 where a single-phase 16.7 Hz supply voltage is generated with a complete power converter.

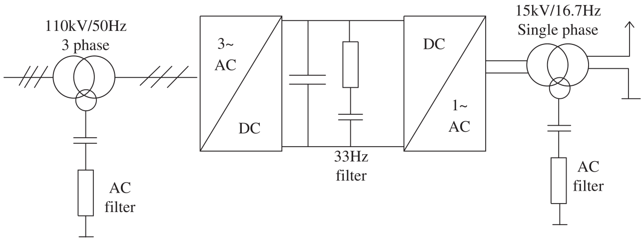

Figure 3.4: 16.7 Hz 15 kV supply system. Adapted from [3].

3.1.3 Train Power Supply System

In this subsection, three types of powering in trains are presented. The first two requires a catenary to supply the train and the third are dependent on on-board energy generation (using diesel internal combustion engine).

- **DC supply system**

  The DC catenary allows an almost direct connection between train power traction and inverter DC bus, as represented in figure 3.5.

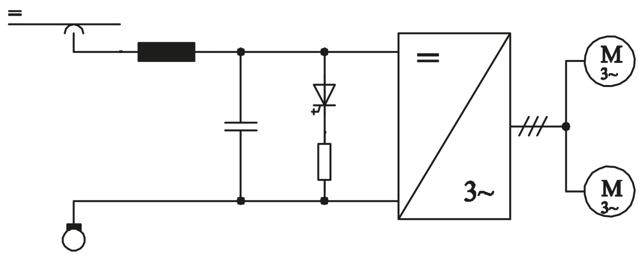

Figure 3.5: Train internal power circuit of a DC supply system.
Adapted from [4].

- **AC supply system**

  As previously presented, the catenary voltages can be either AC or DC. On the AC catenaries, a single phase transformer and a rectifier is needed to create a DC bus for traction power converters, as presented in figure 3.6.

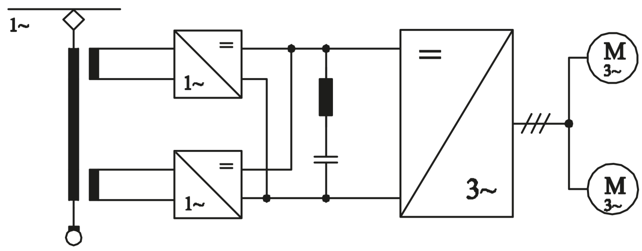

Figure 3.6: Train internal power circuit of a AC supply system.
Adapted from [4].

- **Diesel-electric supply system**

  An important market share in railway traction is occupied by diesel trains. This type of traction allows the avoidance of catenaries as the power source. The internal power circuit of those trains is presented in figure 3.7.

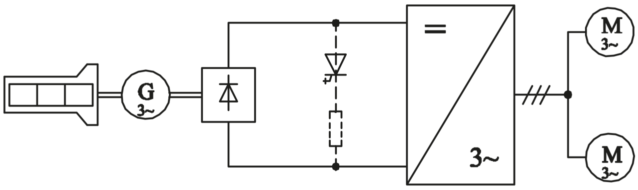

Figure 3.7: Train internal power circuit of a Diesel electric locomotive with alternator. Adapted from [4].

3.1.4 Train Power Components

In figure 3.8, the train power components are illustrated. Further description of each of the main components of train internal power circuitry is listed in bellow.

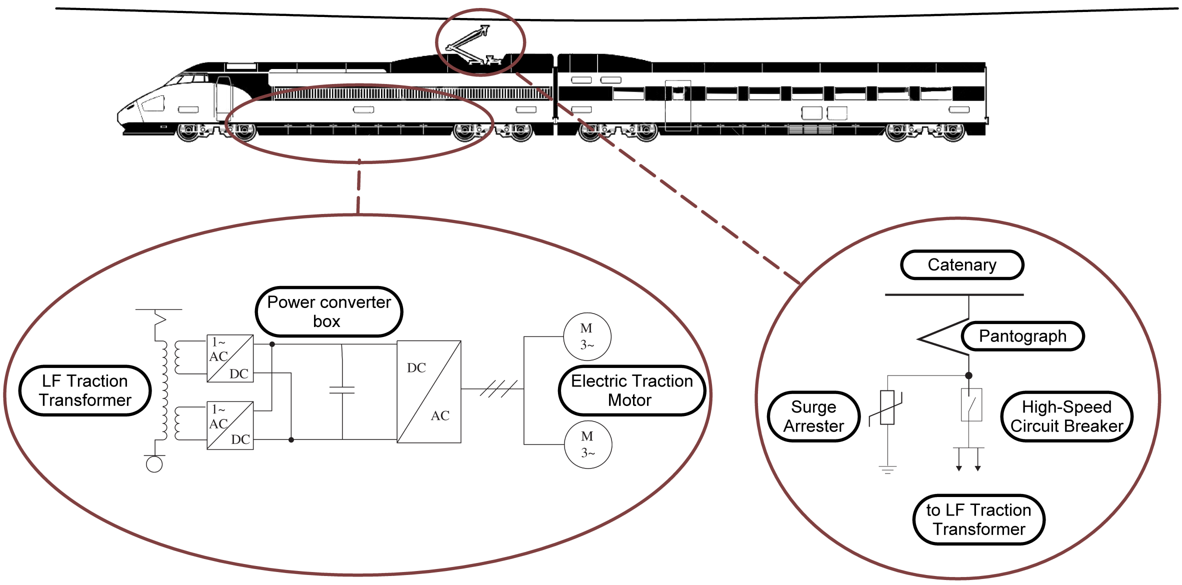

Figure 3.8: Train Power Components.

1. Pantograph
The pantograph is a device capable of maintain an electrical contact between train and catenary while in motion.

2. Surge Arrester
This equipment ensures over-voltage protection of train internal circuit, against external events (such as lightings) or internal events (switching faults)

3. High-speed Circuit Breaker
This device allows the safe interruption of high current faults.

4. Low frequency Traction Transformer
The traction transformer reduces the alternate voltage of the catenary to be compliant with the voltage level of the power semiconductor box.

5. Input LC Filter
The main objective is to improve the power quality of the energy supply with the reduction of harmonic distortion (with the absorption of high frequency harmonics and injection of low frequency ones).

6. Filter Inductor and DC-link Capacitor
The filter inductor and DC-link capacitor are part of the power converter box. These devices are responsible for the filtration of the DC waveforms.

7. Power Semiconductors
The power semiconductor devices are present in train power conditioning and they act as on-off switches. The power conditioning is responsible for the conversion between alternate and continuous electrical waveforms, as they are needed for the interface between traction transformer (AC) and the electric traction motors (AC). The relevant technologies are the Gate Turn-off Thyristors (GTO) and the IGBT.

8. Braking Resistor
Avoid the occurrence of dangerous DC-link voltages (in particular, if the main AC grid does not support absorption of the braking generated energy, the excess of energy is burnt into resistors)

9. Power Converter Box
Includes the power semiconductors (in power inverter arrangement) and cooling media.

10. Electric Traction Motor
Enables mechanical propulsion. The most common technology is the squirrel cage induction motor.

3.2 Energy Sensors

In this section is covered the theory behind energy sensors as well as the technologies used. In subsection 3.2.1 is started the presentation of the electric energy. Further on, in subsection 3.2.2 is covered the energy transducers and in subsection 3.2.3 is presented the challenges and requirements of energy measurement in RTS.

3.2.1 Electric Energy Overview

Energy in form of electricity is the major traction player on the RTS. Complementary to the Diesel, this form of energy is distributed along with the rails in catenaries. As presented in previous section, there are two major ways of rail electrification: AC or DC.

When a train is connected to a DC transmission line, it is possible to exchange energy from and to the catenary, complying to the Kirchhoff's circuit laws. The catenary is considered as a node that has multiple bi-directional power flow elements, specifically, trains and traction substations.

On AC transmission lines, the power flow is directly related to the relation between the voltage and current waveforms, as presented in figures 3.9 and 3.10.

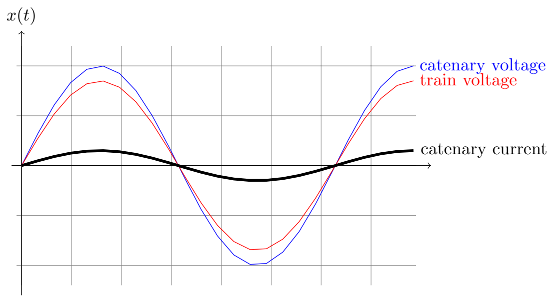

Figure 3.9: Waveforms in traction mode.

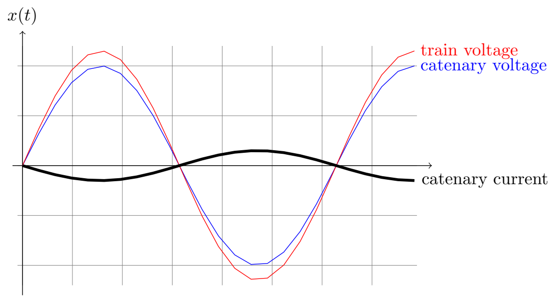

Figure 3.10: Waveforms in generation mode.

The energy calculation depends on the voltage and currents measured in the catenary. This function present in train energy meters evaluates the voltage and currents and generates the active, reactive and power factor information of the train. In figure 3.11 is presented an example of the energy information 1h operation of HX_D1B locomotive.

3.2.2 Current transducers and voltage transducers

According to Pallàs-Areny and Webster (2012), a transducer is a device capable to convert different physical signal forms, [6]. In the scope of energy measurements, current and voltage transducers are employed. These devices convert the field energy waveforms into a voltage (or current) waveform capable of be acquired by a processing unit (such as a microcontroller, programmable logic controller, etc.).

Dalessandro et al. (2007) identifies multiple different physical effects associated to the current sensors as following, [7]:

Magnetic coupling Using the knowledge of transformers, it is possible to perform isolated current measurements. The current transformers are widely used in energy measurement and are based on the magnetic coupling concept, with a ferromagnetic core. With the

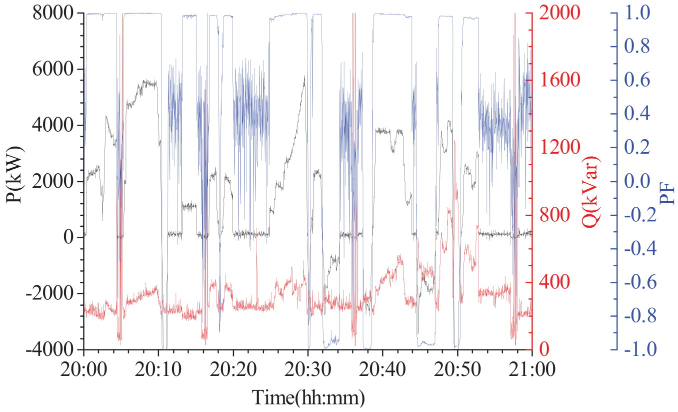

Figure 3.11: 1h waveforms of active power (black), reactive power (red) and power factor (blue) of HX_D1B locomotive. Adapted from [5].

same magnetic coupling principle, the Rogowski coil is a helix wound around a non-magnetic torus and uses the magnetic coupling physical effect to measure the current, as the integrative of the induced voltage on coil terminals;

Magneto resistance The anisotropic magneto-resistive current sensors uses a magneto-resistive sensing element (composed of a nickel iron alloy) to measure the magnetic field induced by a current on a conductor;

Faraday induction Fiber optic current sensors relies on Faraday effect to integrate the magnetic field along the closest path. The magnetic field will cause a magnetooptic phase shift of the light waves and this phase shift is measured with a technique known as fiber gyroscopes;

Hall Effect Similarly to magneto-resistive current sensors, the hall effect sensors uses a sensing element to measure the magnetic field in the air-gap of a magnetic circuit. For AC-only current measurement, no compensation of the flux in the magnetic core is made. The implementation of "Zero flux" compensation avoids the saturation of the magnetic core. This active compensation allows the measurement of currents with DC component.

The voltage transducers depend of an indirect measurement of the electric field. In particular, the principle is the combination of the current measurement in a known load (or resistor), connected to the terminals of the circuit intended to be measured and using the principles previously presented. In figures 3.12 and 3.13 are presented two transducers used for energy measurement in RTS.

Figure 3.12: 25 kV current transformer. Adapted from www.railware.it

Figure 3.13: 25 kV voltage transformer. Adapted from www.railware.it

3.2.3 Energy measurement in RTS

Currently, the European Commission requires the implementation of mechanisms in RTS for energy liberalization, where the Railway Undertakings (RUs) can purchase energy from suppliers of their choice, [8].

The impact of such requirement is the liberalization of the energy market, which brings new challenges in the railway sector. In practical, on-board energy metering is important to make energy savings visible and to allocate the profits of these savings to the respective RUs.

As an example, EcoS energy meter for railway, presented in figure 3.14, identifies the following requirements to comply with:

EN 50463 standard [9] This standard defines the architecture of the Energy Measurement System. It is composed by two blocks: (1) the Energy Measurement Function, responsible for the measurement of voltage and current and for the calculation of the energy and (2) the Data Handling System, that joins the timestamp and the GPS location to the energy data. In section *3.4: Smart Metering*, the components of this standard are better described;

EN 50155 standard [10] This standard defines the aspects of temperature, humidity, shock, vibration, and other parameters that covers electronic equipment used on rolling stock for railway applications;

AC and DC measurement channels The energy meter comply with multiple catenary topologies;

Multiple Connectivity EcoS uses WiFi, Ethernet and 2G/3G/4G. In addiction it is used the localization and time sync from Global Position System (GPS) and Train Communication & Management System (TCMS);

Multiple access and customization EcoS implements web interface and a SoftPLC for expansions and customizations.

Figure 3.14: EcoS railway energy meter. Adapted from railware.it

3.2.4 Energy measurement function

With the compliment of the EN50463 standard, the EcoS energy meter performs the energy calculations as presented in figure 3.15.

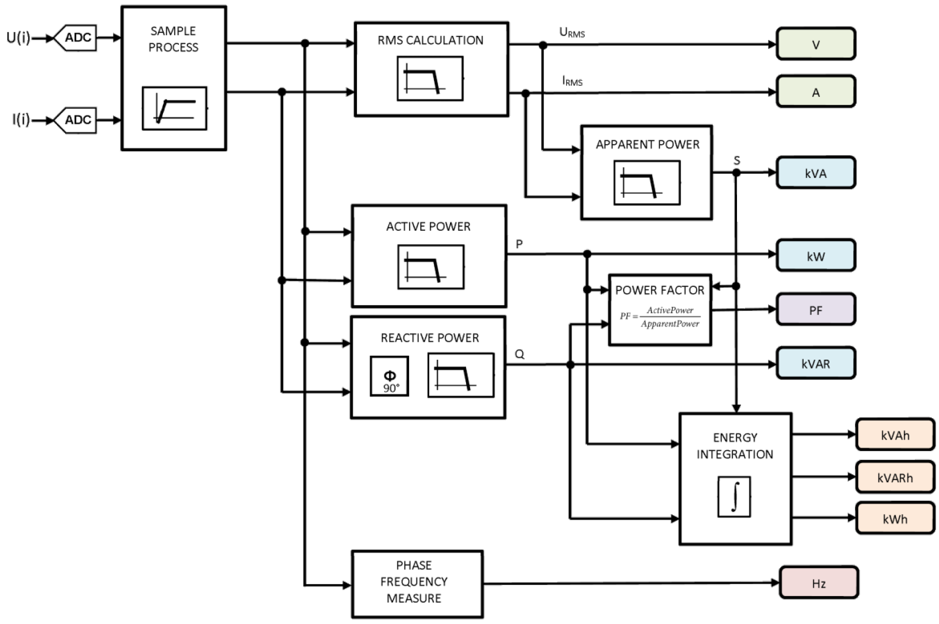

Figure 3.15: EcoS power calculation function. Adapted from railware.it

3.3 Wireless networks

In this section, communication networks are presented, with special attention to wireless technologies. An historic overview is presented in 3.3.1 to illustrate the relevant milestones to achieve nowadays communication networks. In 3.3.2 and 3.3.3 are presented the current solutions for wireless communication. The evaluation of wireless networks is presented in 3.3.4 and 3.3.5, first with the presentation of the KPI and then with the identification of the simulators and emulators.

3.3.1 Network technologies – historic overview

The beginning of modern communication systems is marked with the expansion of the telegraph, having an important milestone happening in 1858 with the first communication between USA and UK. Since then, the telephone has emerged and widely used; the wireless communication was successfully established in 1901 and, decades later, worldwide communication had the support of satellite communication systems.

One important area of communications is the computer networks, and in particular, the internet where it is used in several aspect of business (such as advertising, production, shipping, planning, billing, and accounting, [11]). In 1980 the Internet was a research project involving few dozen sites and currently the Internet is an important part of people's communication.

Currently, a computer network is well organized, having a well-structured Internet Protocol (IP) that defines how data passes through layers, as represented in figure 3.16.

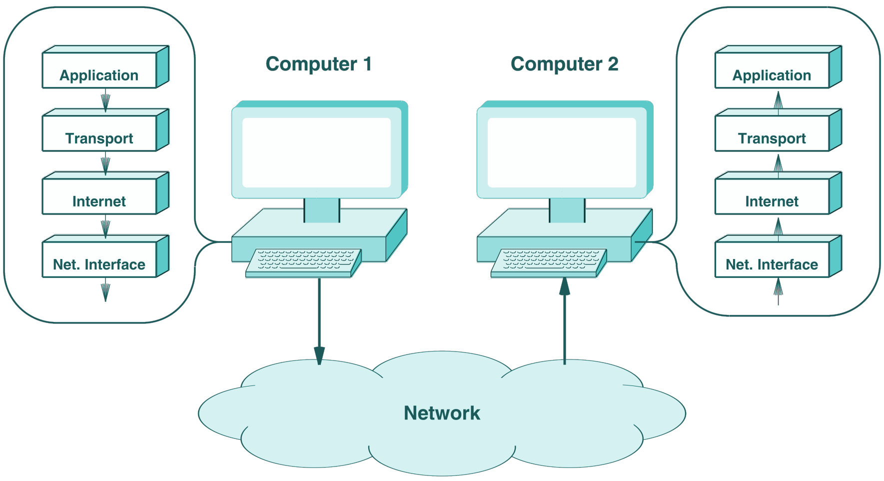

Figure 3.16: Representation of data flow in a computer network. Adapted from [11].

3.3.2 Current Wireless technologies and standards

The following sections will cover the wireless communications in smart metering systems, starting with the low-rate and low-power communications applied on smart meters and ending with the high-rate communications (and consequently higher costs and power than low rate communications). With the increasing on demand for higher bandwidth, broadband technologies such as mobile WiMAX, IEEE 802.16e and broadband Power Line Communication (PLC) are expected to be considered and used in newer installations, [12].

3.3.2.1 IEEE 802.11 (Wireless LAN (WLAN) or Wi-Fi)

IEEE 802.11 is the standard for the information exchange between systems and for the telecommunications. The coverage area of this technology is on local and metropolitan area networks (LANs and MANs). The specific requirements are on the Medium Access Control and on Physical Layer. The most popular versions of this standard is the IEEE 802.11b and IEEE 802.11g, that differs in the modulation technique (Direct Sequence Spread Spectrum (DSSS) technique versus Orthogonal Frequency Division Multiplexing (OFDM) modulation technique). The data rates are, respectively, 11 Mbps and 54 Mbps, [13, 14].

3.3.2.2 IEEE 802.15.4 (ZigBee)

The standard IEEE 802.15.4 imposes conditions in the physical layer and media access control focusing on low-rate (up to 300 kHz) wireless personal area networks. Developed by the Zigbee Alliance and covering the specifications of the IEEE 802.15.4 on the physical layer and the medium access control, Zigbee is a commonly used for low power wireless communication technology. It operates on the Industrial, Scientific and Medical (ISM) bands of 868 MHz, 915 MHz and 2.4 GHz adopting DSSS, [13].

3.3.2.3 DASH7

On the low-rate field of research, an alternative to Zigbee is the DASH7. Using the ISO/IEC 18000-7 standard to support this wireless sensor network technology, DASH7 is developed to reach active Radio Frequency Identification Devices (RFIDs) and operates at 433MHz band. The advantage is the typical range of 250m (could achieve 5 km) and has a typical and maximum data rates of 28 kbps and 200 kbps, being in this specifically designed for Smart Grid and for applications in Smart Energy.

3.3.2.4 6LoWPAN

This IETF development group promotes specifications for the usage of IPv6 on IEEE 802.15.4 networks. It allows the connection between low-power devices to IP networks, with the usage of fragmentation and compression of messages. In conclusion, 6LoWPAN creates an adaptation layer between the IEEE 802.15.4 and IPv6.

3.3.2.5 Wibree

This wireless communication technology is designed for low power consumption and short-range communication. It is designed to work with Bluetooth and, the Bluetooth-Wibree depends on the existing Bluetooth RF and allows ultra-low power consumption.

3.3.2.6 Industrial Wireless Communications: WirelessHART and ISA100.11a

Launched by HART Communication Foundation in September of 2007, WirelessHART is an open wireless communication standard designated specifically for the process measurement and control applications, [15]. This standard is specifically designed to comply with industrial requirements, such as stricter timing requirement, higher security concern, immunity to harsher interferences and obstacles and enough scalability to be used in large process control systems.

Similarly, ISA100.11a aims to provide secure and reliable wireless communication for noncritical monitoring and control applications, [16].

3.3.2.7 IEEE 802.16 (WiMAX)

On the field of the broadband wireless communication there is the Worldwide Interoperability for Microwave Access (WiMAX) under the IEEE 802.16 standard. It is specifically developed aiming the point-to-multipoint communications being applied in fixed and mobile applications and it has data rates up to 70 Mbps over a distance of 50 km. Framed into the smart grid systems, this communication technology is considered as a solution for high data rate communication link to be applied at the backbone of the utilities, [13].

3.3.2.8 Broadband communications: GSM/GPRS and LTE/LTE-Advanced

Operating at 900 MHz and 1800 MHz, the Global System for Mobile communications (GSM) is the most used cellular network all over the world. The modulation technique is the Gaussian Minimum Shift Keying (GMSK) and it achieves transfer rates up to 270 kbps. Its architecture consists of four components: the Operation Support Substation, the Network Switching Substation, the Base Station Subsystem and the Mobile handset. Due to its level of development around the world being present in remote locations, this advantage makes this an interesting technology to be applied in Smart Grid (SG) applications, [13].

LTE is a recent standard for wireless technology that allows high data rates with high capacity and low latency and with a good Quality of Service (QoS). The improved version of this technology, the LTE-Advanced, admit higher capacity with expanded peak data rate of 1 Gbps for the downlink and 500 Mbps for the uplink, obtained on the increase of the spectral efficiency, higher number of active subscribers connected at the same time, and better performance at cell edges, [12]. This technology, for the smart metering environment where the high bandwidth and good QoS are mandatory at some communication points.

3.3.3 Protocols and standards

In computer networks, a protocol is a set of rules that ensure a communication of specific set of information between two machines. A standard is a document that specifies several aspects of something that has the overwhelming agreement and support of an entity (the standards making body). In the networking area, several protocols are supported by standards. In this section is presented some of the protocols that ensure a coherent communication among the sensor networks.

3.3.3.1 IEEE 802.15

The standard family defines the topologies and network roles. In particular, it defines the physical (frequency and channels, spectrum handling, modulation and bit rate) and Medium Access Control (MAC) (packet formats, operational modes, timing aspects, topologies) layers of the Open Systems Interconnection (OSI) model, [17].

Standard	Description	Initial Release / Revision Date	Amendments
IEEE 802.15.1 (Bluetooth)	MAC and PHY Layer Specifications for Wireless Personal Area Networks (WPANs)	2002 / 2005	Bluetooth Core Configuration v4.0 and Bluetooth Low Energy (2009)
IEEE 802.15.2	Coexistence of Wireless Personal Area Networks With Other Wireless Devices Operating in Unlicensed Frequency Bands	2003	In hibernation since 2011.
IEEE 802.15.3	MAC and PHY Layer Specifications for High Rate Wireless Personal Area Networks (HR-WPANs)	2003	802.15.3b (2006): Amendment to MAC Sublayer 802.15.3c (2009): Millimeter-wave-based Alternative Physical Layer Extension
IEEE 802.15.4	MAC and PHY Layer Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)	2003 /2006/ 2011	802.15.4.a (2007): PHY Layer Extension to Chirp Spectrum Techniques and UWB systems 802.15.4c (2009): Alternative PHY Extension to support one or more of the Chinese 314-316 MHz, 430-434 MHz, and 779-787 MHz bands 802.15.4d (2009): Alternative PHY Layer Extension to support the Japanese 950 MHz bands 802.15.4e (2012): Amendment 1: MAC sub-layer 802.15.4f (2012): Active Radio Frequency Identification (RFID) System PHY 802.15.4j (2013) – Alternative PHY Extension to support Medical Body Area Network (MBAN) services operating in the 2360-2400 MHz band
IEEE 802.15.5	Mesh Topology Capability in Wireless Personal Area Networks	2009	-
IEEE 802.15.6	Wireless Body Area Networks	2012	-

Figure 3.17: Members of the 802.15 family. Adapted from [18] lecture presentation slides.

Based on figure 3.17, the 802.15.4 is the standard that defines the Physical Layer (PHY) and MAC layers for low rate wireless personal area networks. It supports **full-function devices** (device capable of being the network coordinator or simple node and can have implemented complex network functionalities) and **reduced-function device** (limited devices with low-bandwidth limitations and limited or no-network intelligence). The possible network topologies are the following:

Star — Each device in the network communicates with the full-function device network coordinator;

Peer-to-peer — All devices communicate with each other (if they are in the communication range). Sufficiently flexible to implement more complex topologies such as multi-hoping, cluster trees and mesh topologies;

Multi-hopping — This is a technique that allows the usage of two or more wireless nodes to convey data from a source to a destination;

Cluster trees Topology to reduce the routing complexity where each node knows its parent node and all its child nodes. It has always only one single path between two nodes.

Wireless mesh This technique allows data to be propagated along a path by hopping from node to node until it reaches its destination.

3.3.3.2 802.15.4-based wireless standards

Radmand et al. (2010) presents a comparison of wireless sensor standards for industrial applications, [19]. In figure 3.18 is present the overall schema of the wireless standards.

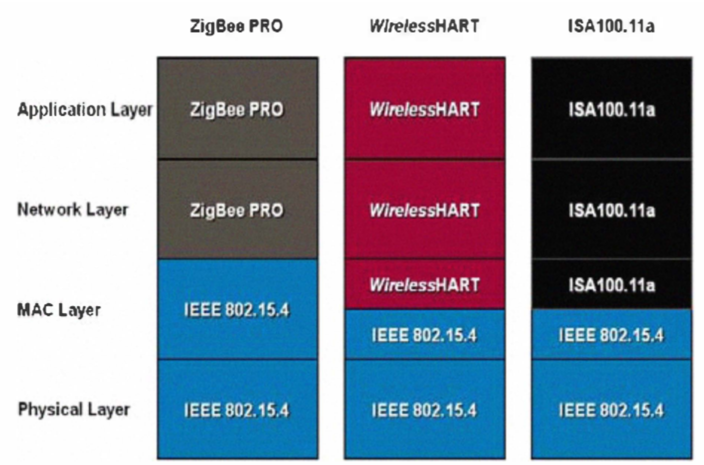

Figure 3.18: Overall schema of wireless standards. Adapted from [19].

3.3.4 Communication KPI

According to Radmand et al. (2010), it is identified the following "Industrial Requirements" for the WSN's, [19]:

Reliability — Reliability is a measurement of the transmission accuracy, in percentage, that evaluates the amount of data that reach its destination. This measurement uses the properties of data communication, acknowledge-based usually.

Latency — Latency is the measurement of the time delay and is defined as the time that a data packet takes to be transmitted from the source to the destination. The latency is directly related to the link quality and a high latency link is result of a link with high signal-to-noise ratio.

Sensor Data Update Rates — This KPI is not directly related with the communication link. However, the update rate of the sensor data affects the power consumption due to the increase of the processing effort. In a SYNC-based update rate, this KPI is related to the frequency of the SYNC event.

Wireless Transmission Range — This KPI is the maximum distance that a communication link supports the data transfer with a given reliability and in specific conditions (indoor/outdoor; line-of-sight (LOS)).

Power consumption — The power consumption is a measurement of the combination of the computational effort of the nodes and the transmission effort. It is directly related with the update rate as well as with the link quality and, if it exists, the routing activity in each node.

3.3.5 Network Simulators and Network Emulators

In this subsection is covered the network simulators. The usage of network simulators allows the modeling of various scenarios of real environment. However, pure network simulators avoid the interaction with real environment, which leads space for network emulators, as a hybrid method to combine simulation capabilities with hardware and software components of real networks. Therefore, in this subsection is referred the simulators that allows integration with hardware and software network components, to have an overview on the network emulators.

In figure 3.19 is presented the framework on the mechanisms to evaluate the performance of networks.

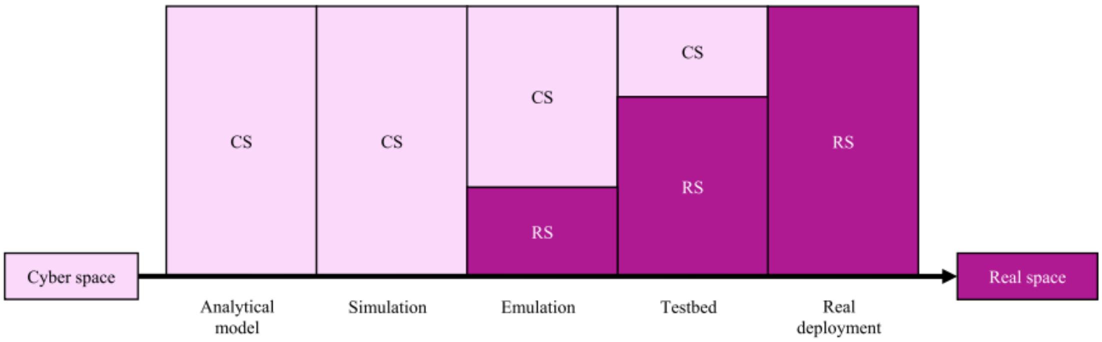

Figure 3.19: Simulation & emulation framework.

An extensive review on simulation tools, made by [20], is presented as following:

NS-2 (network simulator-2) Object orientated discrete event simulator tool, based on two languages (C++ and OTcl).

NS-3 (network simulator-3) Written in pure C++, this simulator has been extensively explored in the literature with various modules like 802.15.4, 6LoWPAN and RPL available. With the usage of ns-3 in emulation mode, the implementation of real testbeds can be validated since it is possible to generate repeatable experimental results, with the usage of real-world network environment that includes all of the ns-3 tracing, logging, visualization and statistics gathering tools.

OMNET++ This simulator is based in C++ in the basic modules and uses Network DEscription (.NED) scripts to connect and assemble the simulation basic modules.

J-Sim JavaSim Simulator has been developed in Java and it has several advantages to carry out large scale WSN simulations.

Mannasim Is based on NS-2 to perform WSN simulations.

SensorSim Similarly to Mannasim, this is a framework for WSN based on NS-2 simulator. However, currently it is not available to the public.

NRL Sensorsim This extension to NS-2 simulator is focused on WSN, similarly to SensorSim and Mannasim frameworks. Currently, it is no longer in development and does not have support.

NCTUns 6.0 On the field of network emulators, this software has the main advantage of using the real world Linux TCP/IP stack and implements almost every IEEE network standards. Last release was on 2010.

SSFNet Java simulator designed especially for WSN's. Last release in 2004.

GloMoSim Non-commercial simulator (the commercial version is *"QualNet"*) designed for wireless and wired network systems.

QualNet 7.0 + EXata 5 Considered one of the most advanced simulator platform these days, QualNet enables a high fidelity virtual model of network, with an advanced GUI. It has a free academic version.

sQualNet Simulator Is an extension of QualNet for sensor network specific models.

OPNET Modeler Suite Is a powerful collection with an interactive GUI to build network scenarios. It has a free academic edition.

SENSE Is a powerful sensor network simulator and emulator.

DRMSim Is a Java-based software that enables large-scale network simulation.

NetSim Is a simulator designed for protocol modeling, network research and development and defense applications.

UWSim This simulator is designed for marine robotics research.

Visual Sense This modeling and simulation software is designed for wireless and WSN applications, as an extension of Ptolemy II.

Viptos Is an interface/bridge between TinyOS and Ptolemy II.

PTOLEMY II Is an open source simulation software, based on Java and with actor-oriented design (where actors are software components, have a concurrent execution and communicate via interconnected ports)

SENS This specific framework for WSN's simulator and emulator that uses a simplified sensor model.

SHAWN Is a customizable sensor network simulator focused on the simulation of the effect caused by a phenomenon (not the phenomenon itself) with scalability and support for extremely large networks. According to SHAWN development repository, last contribution was on 2013.

SIDnet-SWANS This Java-based simulator was made to provide a simulation and proof-of-concept platform for application of WSN's. Latest version was released in 2011.

WSim/Worldsens Simulator/WSNet Simulator This simulator states for being an event-driven simulator for large scale wireless networks. Latest version was released in 2009.

WSN Localization Simulator This is a WSN location simulator stating for being easy, scalable and extendable to many/different localization schemes. It was released in 2013.

NetTopo Simulator This framework is an open source simulator designed in Java. Its main objective is to analyze various algorithms in WSN's.

SIDH Is a Java-based simulator focused on the simulation of thousands of sensor nodes.

PROWLER The Probabilistic Wireless Sensor Network Simulator is a framework that runs under Matlab and is focused to TinyOS applications.

Matlab/Simulink With extensive usage by the research community, Matlab and Simulink software provides resourceful toolboxes for simulation of communication networks, being possible to build a complete WSN model system.

PiccSIM This simulation platform uses Matlab/Simuling and NS-2 for networked control systems (in particular wireless)

LabVIEW Various toolboxes to simulate WSN's are available with LabVIEW.

3.3.5.1 Evaluation of network tools

In the previous list, several tools for the evaluation of network performance was presented. Special attention is given for the tools that has large support either for implementation of several network technologies (wired and wireless) and, with this requirement, the following network simulators will be considered for further research:

- NS-3;
- OMNET++;
- QualNet 7.0 + EXata 5;
- MatLab Simulink;

3.4 Smart metering

In this section, special attention is given to smart metering. The smart grid framework is presented to justify the need for smart meters and then, an overview on the features of metering systems is presented. This section is concluded with the presentation of the metering systems in railways.

3.4.1 Smart grids and the need for smart meters

Smart Grids improves the functionality and concept of traditional electrical grids by obtaining the grid component's data using Information and Communication Technology (ICT). Such grids benefit the reliability and the efficiency of the system with the usage of the acquired data, [12].

Although the smart meters do not have an effective definition, those devices are composed by an electronic box and a communication link, [21]. A smart meter is responsible for measuring the energy-related parameters and the user consumption with a given time interval. All those measurements are then transmitted upon a communication network to the utility or to other player with the responsibility of using the meter data. The information obtained from the data is shared with consumer-side devices, to inform the end-users on their related costs and energy usage, [22].

Smart meters implement a bidirectional communication on top of Automatic Meter-Reading system (AMR). They are inherent to smart grid systems.

Similarly to the evolution of electricity meters, the utility grid has evolved from a centralized production and control perspective to a distributed one. The conventional electrical grid is a network with a transmission link connecting power producers and end-user consumers. The control and distribution of electrical power is made in a centralized way. With the increase of power demand, increase of complexity and having more and more decentralized power generation, a migration to the smart grid framework is required, [23].

3.4.2 Features of smart meters and metering systems

A smart metering system combines several controlling devices, an extensive number of sensors for measuring the parameters and devices responsible for the transferring of the data and the commands. The detection of unauthorized consumption due to electrical energy theft and the improvement of the energy in the distribution are other advantages of smart meters. These devices acts as a gateway by having a communication interface protocol to the database stored by the utility company, [23].

The design of an ideal smart grid has to focus on prediction, adaptability and reliability points. Moreover, it requires to cover the demand adjustment, the load handling, flexibility and sustainability and it should incorporate advanced services. In advance, an end to end control capability has to be ensured as well as finding the optimal cost and asses, increase the quality of energy and quality of service. Another features of smart grids are the automatic restoration and self-healing, being all the previously presented features of the smart grids highly dependent of the role of the smart meters, [12].

Smart-meter types are also distinguished based on features like data-storage, communication type and connection with the energy supplier. The data storage capability allows data to be stored in the meter, being transferred after a few days or weeks to the Meter Data Management System (MDMS) of the utility. Compensations for some power quality deficiencies can be also considered; therefore, the future meters should be also capable of register certain basic power quality characteristics. In advance, the design of rate and tariffs of electricity providers determine the requirements such as the period of meter intervals or the temporal resolution (commonly ranging from 15 min to 1 h). During those intervals, the production and consumption of active and reactive power is mandatory to be separately measured, [22].

3.4.3 Metering systems in railways

Towards an increase of interoperability of the rail system within the Community [8], the Directive 2008/57/EC specifies the need of Technical Specifications for Interoperability (TSIs), presenting essential requirements in which each rail subsystem should meet to ensure the interoperability of the railway system within the EU. Those TSIs are of the responsibility of European Union Agency for Railways (ERA) and are listed as following:

- Locomotives and passenger rolling stock - 1302/2014;
- Noise - 1304/2014;
- Wagons - 321/2013;
- Infrastructure - 1299/2014/EU;
- Energy - 1301/2014;
- Control command and signaling - 2012/88/EU;
- Persons with reduced mobility - 1300/2014/EU;
- Safety in railway tunnels - 1303/2014;
- Operation and traffic management - 2015/995/EU;
- Telematics applications for freight service - 1305/2014/EU;
- Telematics applications for passenger service - 454/2011;

On the energy field and with the purpose of implementing on-ground energy Data Collecting System (DCS), technical specifications for interoperability relating to the 'energy' subsystem of the rail system in EU are specified in the commission regulation No 1301/2014, [24].

The On-Board energy measurement systems are pointed in Appendix D of commission regulation No 1302/2014 [25]. This regulation appendix presents the requirements for such energy measurement system. The general architecture is defined as following:

- **Energy Measurement Function (EMF)**, measuring the voltage and current, calculating the energy and producing energy data;
- **Data Handling System (DHS)**, producing compiled energy billing data sets for energy billing purposes, by merging data from the EMF with time data and geographical position, and storing it to be sent to on-ground DCS by a communication system;
- **On-board location function**, giving geographical position of the traction unit. Contrary to fixed installation revenue meters, train meters must have the knowledge of time and geographical position [26];

Figure 3.20 presents the general overview of the on-board energy measurement system.

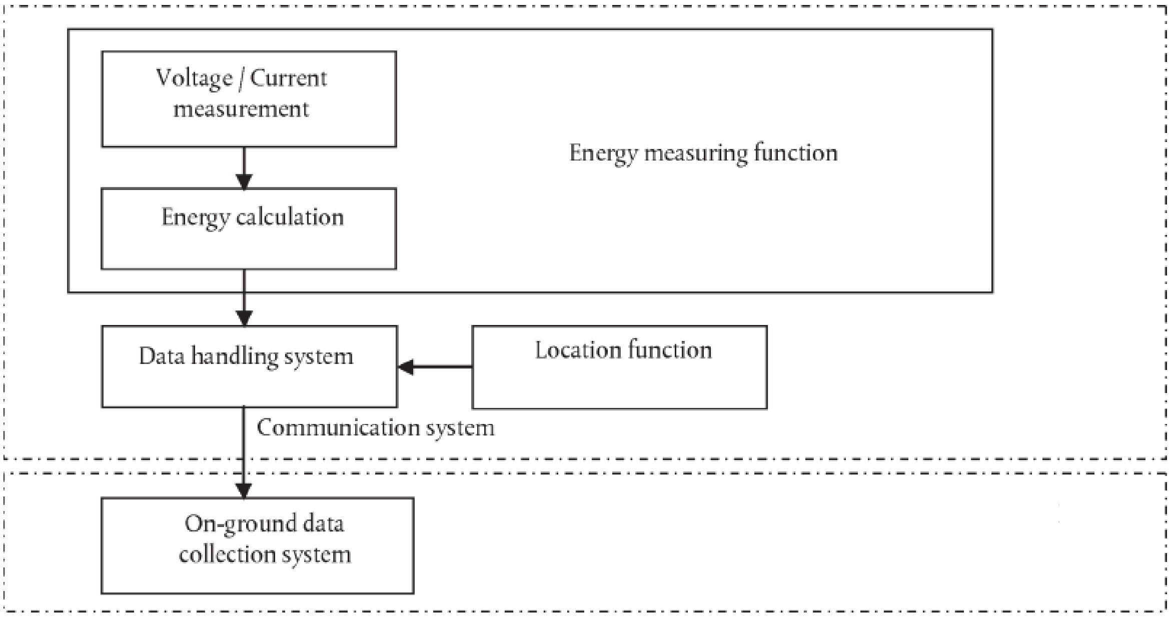

Figure 3.20: Functions, data flow and regulation scope of on-board energy measurement system.

As global requirements, all active and reactive energy should be measured, the measurement equipment should be rated to match the traction unit current and voltage rating, the system should be protected from intrusion, and finally, the loss of power in the measurement system should not affect the data stored in EMS.

Complementary to the previously presented system requirements, each component of the energy measurement system has specific requirements as listed as following:

Energy Measurement Function (EMF) Has specific metrological requirements to specify the accuracy of the sensors and it has the requirement of having the reference period of 5 minutes defined by the UTC clock time (shorter measuring period is allowed in the case that the data is aggregated into 5-minute time reference period);

Data Handling System (DHS) Should compile the data (without corrupting them), using the same time reference as EMF. This system should store compiled data of, at least, 60 days' continuous work and should have an alternative method of accessing the data. Finally, this system should produce Compiled Energy Billing Data-sets (CEBD) by including an EMS identification number, a timestamp, a location data and the consumed/regenerated active and reactive energy.

Location function Has specific location requirements to define the latitude and longitude, as well as an accuracy of 250m and the location data information should have the same timestamp.

On-board to ground communication The specification related to interface protocols and transferred data format are an open point.

Santschi and Braun (2015) identifies the EN 50463 that should be considered to the certification of EMS on on-board trains, [26]. This standard is divided in 5 areas as presented in figure 3.21.

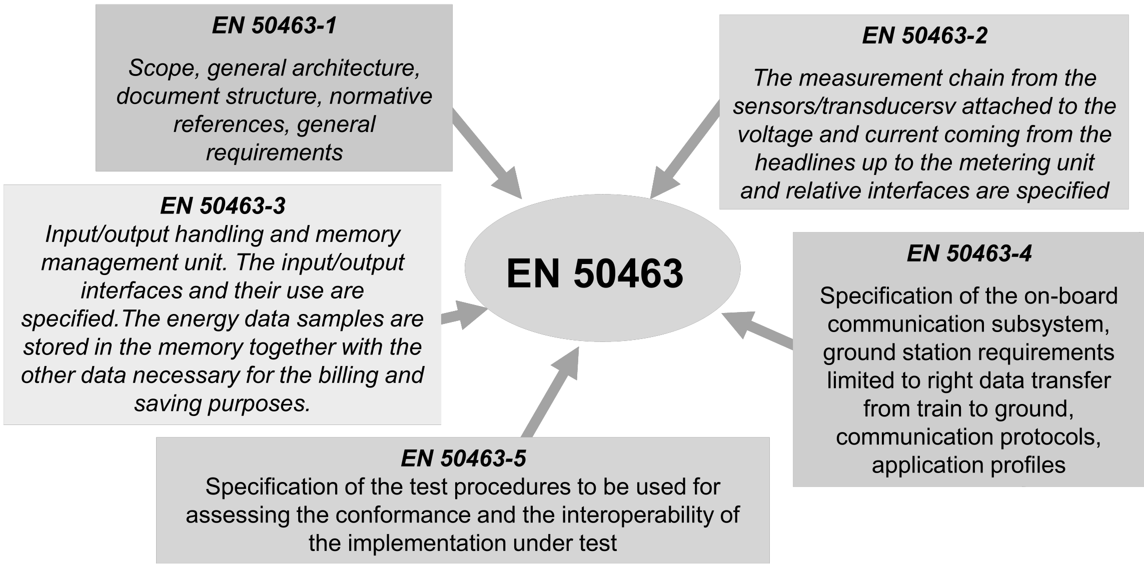

Figure 3.21: Structure of EMS EN 50463 standard. Adapted from [27]

3.5 Decision Support Systems

In previous chapters we have presented the RTS and the means to acquire energy information of such system. In this chapter is presented the possible generation of knowledge that can help to feedback the RTS in a DSS.

In subsection 3.5.1 is presented the framework that supports the DSS. In further subsections are presented some DSS that contributes to the increase of energy efficiency in railways.

3.5.1 The information and knowledge as the base of DSS

At a lower level of a data acquisition system, the measurements of needed variables are performed. Combined, this raw data supports the generation of information. In the field of energy data acquisition system, the information is the combination of the voltage/current electric measurements and non-electric data (such as location, timestamp, etc.).

This information can be stored in databases and, with this accumulated information, it is possible to extract knowledge on the energy flow in RTS. This knowledge is the base of DSS. For instance, a railway operator that has the knowledge that a particular action results in energy efficiency increase/decrease can actively contribute to a better usage of RTS resources.

The DSS can be used in other areas rather than energy efficiency. Several DSS are used for various areas of RTS operation, either for immediate and long-term decision support. As examples, the literature presents the works on traffic control support and dynamic rescheduling [28, 29], crew planning [30], strategic railway capacity planning [31] and track maintenance and renewable management [32].

In the scope of this work, special attention will be given to DSS that contribute to the increase of energy efficiency. In order to decrease the energy consumption, Scheepmaker et al. (2017) identifies two ways: (1) the Energy-efficient Train Control (EETC) or eco-driving, that uses the least amount of energy for a given timetable and (2) the Energy-Efficient Train Timetabling (EETT), that constructs the timetable with the objective of reducing the energy consumption, [33].

3.5.2 Eco-driving – driving assistant

This type of DSS is directly related to the decrease of energy consumption. This topic is inserted in the field of operational research and is based on the optimal control theory, where the train optimal control is derived from Pontryagin's maximum principle, [34]. In synthesis, the determination of optimal speed profile will define the best traction regimes for each condition. The traction regimes are presented in figure 3.22 and described as following:

- Acceleration with maximum available traction force;
- Cruising, as the traction regime that keeps the velocity constant;
- Coasting, where the free train movement due to inertia defines the traction regime;
- Full braking, used to reduce the train to a desired speed or fully stop the train, and a moment where the energy can be regenerated;

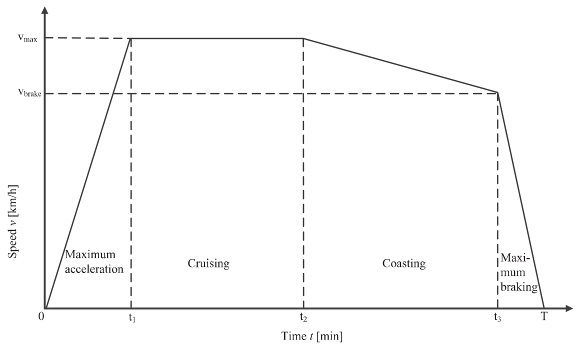

Figure 3.22: Optimal traction regimes. Adapted from [33].

3.5.3 Timetable scheduling

Similarly to Eco-driving DSS, in this type of DSS is addressed the minimization of the energy consumption, with three research streams in the literature: (1) the usage of the total running time of a train as a variable, (2) the optimal distribution of running time supplements over successive train runs and (3) the synchronization of the timetables to maximize the usage of regenerated braking energy, [33].

3.6 Issues and problems in WSN

An important contribution of a wireless sensor network in the railway system is the availability of useful knowledge about energy consumption to the decision support systems.

Therefore, such acquisition systems are required to provide accurate data regardless of the quality of the acquisition sensors, Electromagnetic Interference (EMI), sensor supply fluctuations, among other error sources.

Through computational algorithms, the increase of communication reliability and fault tolerance is possible. Those computational algorithms detect outliers or, in the scope of this PhD, detect erroneous data that will disturb the outcomes of decision support systems.

3.6.1 Outlier and outlier detection

Outlier detection is a computational task to detect and retrieve information from erroneous data values. The definition is usually close to anomaly detection or deviation detection.

Branch et al. (2006) identifies outlier detection as an essential step to either suppress or amplify outliers and precedes most data analysis routine, [35]. Abid et al. (2016) points the need of detecting aberrant data and sensors within an WSN, [36]. Zhuang and Chen (2006) extends the outlier definition to the case where the outliers are introduced in sensing queries and in sensing data analysis, [37].

In the scope of the PhD, an outlier is a data value or a data instance that do not represent the correct consumption status.

The threshold of what is an outlier or not (or a value that do represent the correct consumption status or not) is given by the output of the subsystem that is immediately after the acquisition of consumption status subsystem, the decision support subsystem, gave a correct output or not. Figure 3.23 illustrates the integration of the consumption acquisition subsystems with the decision support subsystem.

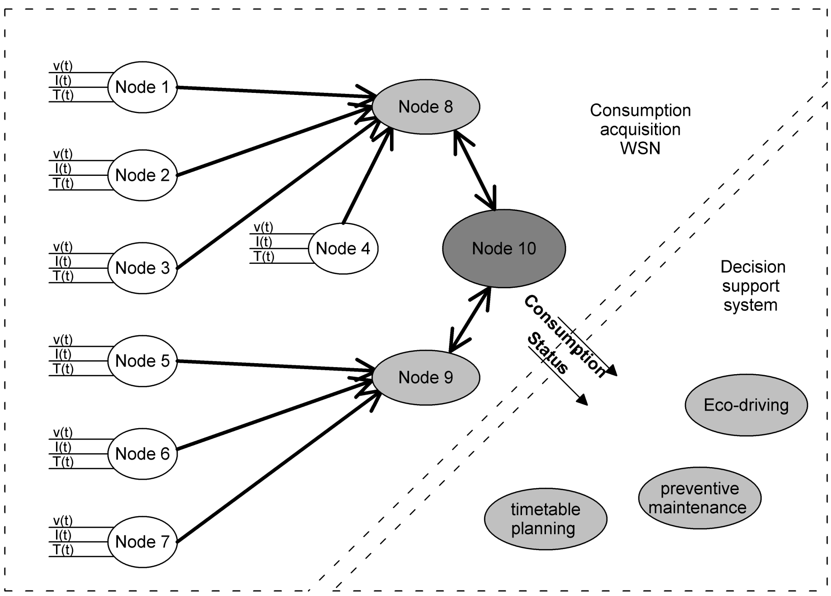

Figure 3.23: Integration of the WSN with a decision support system.

Without an outlier detection mechanism, the decision support subsystem may have the following outputs:

Input deviation from real value lower than a threshold The Decision Support Subsystem output is in accordance to the real consumption conditions.

Input deviation from real value greater than a threshold The Decision Support Subsystem output is not in accordance to the real consumption conditions.

The problem of taking decisions based on wrong considerations of the consumption status is that it may lead to loss in desirable efficiency or increase of costs.

Let us consider a simple and hypothetical example where the DSS will provide an output towards suggesting an action in preventive maintenance based on the usage of a component. Considering that the usage of the component is depending on the counting of situations that the component is working above the nominal conditions. Without an outlier detection mechanism, the outliers will induce the DSS in counting situations of overcharge of the component, where the measurement is not related to working nominal conditions but is related to external influences, such as EMI or temperature. The output of DSS may suggest a preventive maintenance on a component that is working in proper conditions.

To conclude, with an outlier detection mechanism in the consumption acquisition subsystem the decision support subsystem may know if the value of consumption is an outlier or not and, with that information, the DSS output will be more accurate with the real conditions of operation.

3.6.2 Literature review of Outlier detection in WSN

WSN has been widely used in several applications in several domains such as industrial, scientific, medical and others. Those applications have been supported by the advances in wireless technologies as well as in the evolution of microcontroller technologies, with enhanced processing capabilities associated with reduced energy consumption.

3.6.2.1 Motivation

Rajasegarar et al. (2007) points an important motivation for the inclusion of computational algorithms, i.e. outlier detection algorithms, to reduce the transmission of erroneous data, since in WSNs, the majority of the energy consumption occurs in radio communication, [38]. In particular, they present the case of Sensoria sensors and Berkeley motes, where the energy consumption in communication exceeds, in ranges from 1000 to 10000, the energy consumption of computation.

Thus, this raises a research opportunity to reduce the communication usage of μCs, by adding processing features, where the small increase in the computation will significantly reduce the energy consumption in the transmission. These processing features are, among others, the outlier detection algorithms.

On the field of the quality of the data acquired by WSN, the motivation of detecting outliers in data acquired from WSN has been extensively presented in the literature. The need for acquire data from harsh or "highly dynamic" environments as well as the need to validate and extract knowledge from the acquired data are one of the main points in the motivation to study the outlier detection in WSN, [39–42].

3.6.2.2 Research areas

Zhang et al. identifies the outlier detection research areas in three domains, [39] :

- Intrusion detection: Situation caused by malicious attacks, where the detection techniques are query-driven techniques;

- Fault detection: Situation where the data suffer from noise and errors and where the detection techniques are data-driven ones;

- Event detection: Situation caused by the occurrence of one atomic or multiple events and where the majority of the research has been developed due to its complexity.

Based on the division of this three domains, the upcoming research is intended to be focused on the event detection and fault detection techniques. Specifically, the main goal for this research will be the event detection algorithms.

3.6.2.3 Challenges

The challenges of outlier detection in WSNs are related to the quality of the acquisition of the sensors, the reliability of the modules in terms of energy or environmental susceptibility, and the communication requirements and restrictions.

Zhang et al. lists the challenges as the following, [39]:

- Resource constraints;
- High communication costs;
- Distributed streaming data;
- Dynamic network topology,
  frequent communication failures,
  mobility and heterogeneity of nodes;
- Large-scale deployment;
- Identifier outlier sources;

Branch et al. (2006) identifies an important challenge, where the probability of occurrence of outlier events are extremely small, [35]. Other authors identify the large amount of data as the main challenge for outlier detection in WSN, [36, 43]. In addition, some studies highlights the inexpensive and low fidelity sensors as the main reason for the error generation and the main challenge is identified on the distributed streaming data among a large amount of sensors, [37]. Another challenge is pointed to be the processing of data from sensors that generate continuously data, that is uncertain and unreliable, [41].

To conclude, the main challenge will be the usage of inexpensive and low fidelity sensors that will be affected by the rush railway environment. Complementary, the main challenge of using outlier detection mechanisms in the railway WSN is the balance between the detection accuracy and the influence that undetected data-instances will induce in other subsystems (in particular in decision support systems dependent on data from the WSN). In addition, the detection accuracy is directly related with the memory usage, computational requirements, communication overhead, etc.

3.6.3 Taxonomy of Outlier Detection Techniques

The study of detection techniques requires a well-defined taxonomy framework that addresses the related work on the different areas. This taxonomy is well defined and solid in the literature, where the works of Zhang et al. (2010) and Chandola et al. (2009) reflect a similar approach on presenting a taxonomy for outlier detection techniques, [39, 40].

In the following sections, a coverage in relevant techniques is presented:

- Classification based techniques.
    - Bayesian Networks
    - Rule-based techniques
    - Support Vector Machines
- Statistical based techniques.
    - Parametric — Gaussian based
    - Non-parametric — Histogram based
    - Non-parametric — Kernel function based
- Nearest Neighbor-based techniques.
    - Using distance
    - Using relative density
- Clustering based techniques.
- Spectral Decomposition based techniques.

CHAPTER 4

Methodology and Work Plan

This chapter presents the methodology that is intended to be adopted in the development of this PhD thesis. Based on the methodology and expected contributions, a work plan for the upcoming years is presented.

In section 4.1 is presented an overview of the architecture of proposed work. In sections 4.2 and 4.3, the methodology and expected contributions are detailed. In section 4.4 is presented the workplan.

4.1 Architecture of proposed work

Framed in this PhD work, a smart metering system can be divided in four major areas, as represented in figure 4.1. On lower level, the needed data is **measured** (such as voltages, currents and so on). Based on this measurements, **information** can be obtained (such as power, energy, power factor, GPS location). This information can be stored in databases and, a further step is on the analysis of this information towards obtaining **knowledge** that can be used in a **Decision Support System** (DSS).

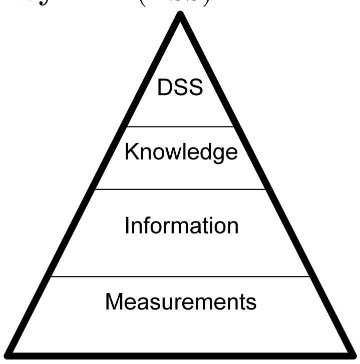

Figure 4.1: Overall functional architecture of a smart metering system.

This work will focus on the two lower levels of the smart metering system pyramid. Therefore, the energy data must be acquired, processed, transmitted and stored in a centralized database, as represented in figure 4.2.

A distributed sensor network to perform the acquisition of the energy measurements in each of the transformer's secondary windings is, at this moment, of advanced interest. For the acquisition part, a non-intrusive self-powered sensor node will be considered. The processing part depends on an accurate knowledge of the modeling parameters of the catenary and the traction transformer, which depends on train GPS location and power flow conditions. It is

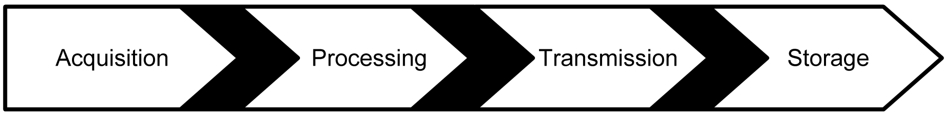

Figure 4.2: Data flow of measurement-information layers.

expected that each of the sensor node contributes to this processing part. These two parts are further detailed in the methodology and expected contributions of section 4.2.

The transmission of the generated information to a centralized storage is further detailed in section 4.3. Several models will be considered for accurate simulation of such transmission network. The overall architecture of the system is presented in figure 4.3.

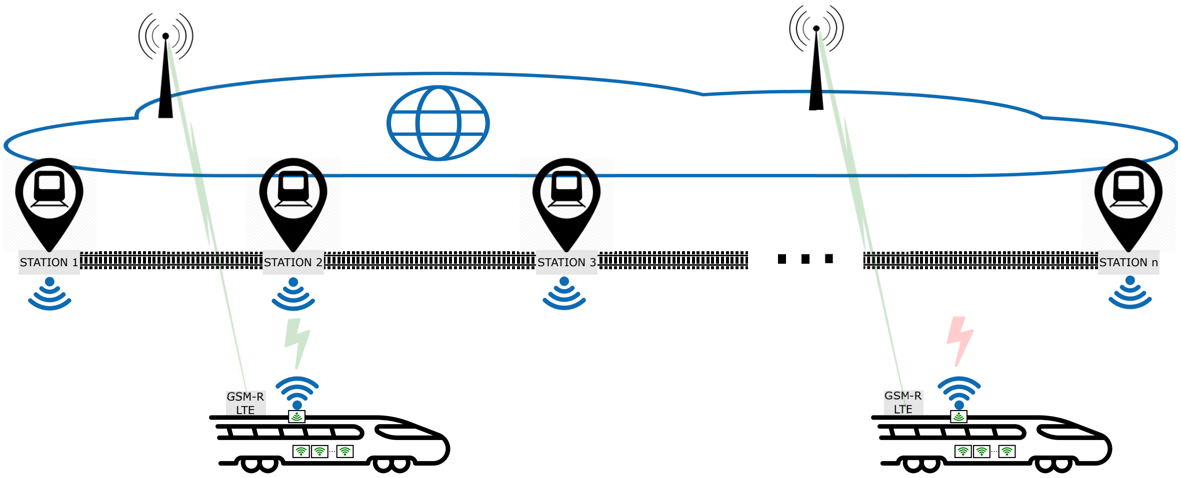

Figure 4.3: Architecture of proposed work.

4.2 Non-intrusive self-powered sensor node

4.2.1 Purpose

The purpose of this section is to cover the acquisition and processing parts of the data-flow presented previously. As a starting point, a non-intrusive and self-powered sensor node allows the measurement of AC currents in all transformer secondary windings, as illustrated in figure 4.4. This figure is based on the 3400 series train topology of *Comboios de Portugal* (CP) used in urban services.

Based on the field measurements, a data concentrator will receive the current and voltage measurements from each sensor node. This data concentrator generates information based on the needed estimations and the acquisition of GPS location, as proposed by the European Commission regulation No 1301/2014. For each time-stamp, the active and reactive power is calculated and transmitted together with the geographical position.

In the scope of Shift2Rail, is expected to develop a smart metering system for RTS. Assuming that a non-intrusive measurement system is of extreme interest, this proposal of a non-intrusive and self-powered sensor node goes along the goals of Shif2Rail.

On the field of measurement, non-intrusive technical solutions have been used for several years for current measurement, such as hall-effect current sensors, rogowsky probes or current transformers. For self-powering purposes, some studies on using current transformers for energy harvesting has been proposed in the literature, [44–48].

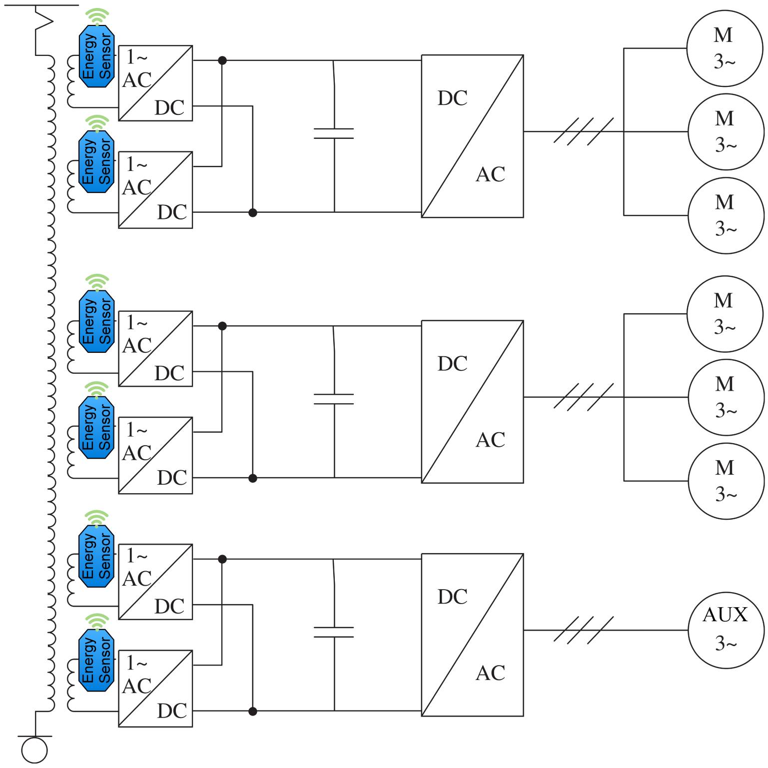

Figure 4.4: Power architecture of case-study train.

4.2.2 Methodology

The methodology is divided into two parts. The first part will be related to the processing of the data generated by the sensor nodes and the second part is the definition of the sensor itself.

As a starting point of the methodology, it is expected to work on the **development of models using simulation frameworks** similar to the ones presented in figure 4.5. The modeling of such architecture allows the evaluation of the power contribution of a train, at a certain instant, to the power injected to the catenary. This methodology will contribute to **simulation and implementation of processing algorithms** in the train data concentrator that, based on the measurement of AC secondary winding's voltages and currents, will generate the accurate value of the energy injected in the catenary by the traction substation. The expected result will be the comparison and validation of the energy injected into the catenary (retrieved from the traction substation meter) and the estimated energy (as the outcome of this part of work).

In this second part of the methodology, or the acquisition part, the sensor will be defined and validated. As a first step in the methodology, using Ansys or similar Finit Element Method (FEM) software, the **current and electric field of one winding will be simulated**. With the results of this simulation, the current and voltage sensors will be evaluated. In a further step, **real experiments on low voltage test-bench** will test the proposed sensor node.

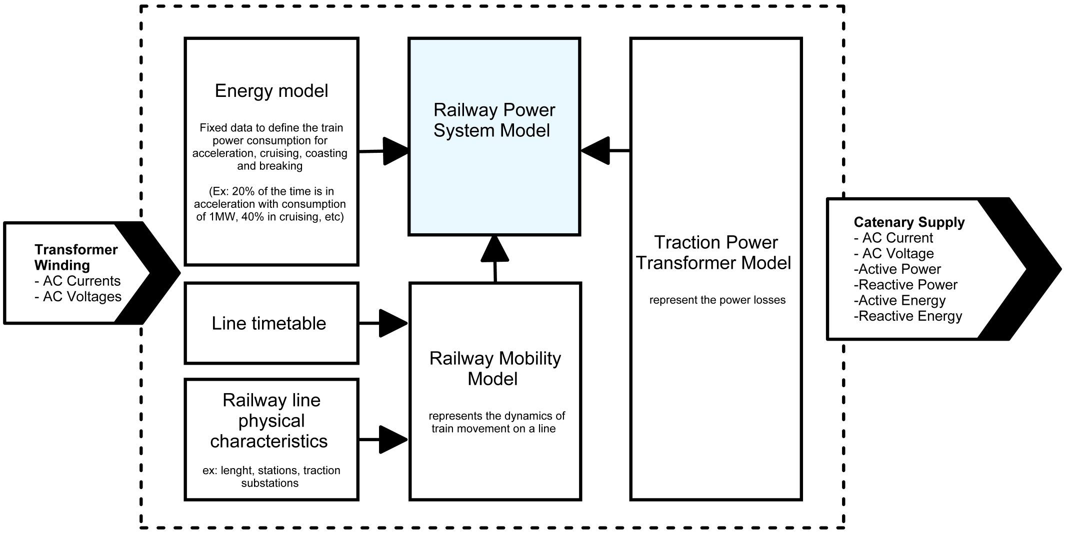

Figure 4.5: Models needed for simulation.

4.2.3 Simulation tools and frameworks

Pilo et al. (2000) identifies the need of two tools for the simulation of railway power lines: (1) the simulator for the railway line and (2) an electrical system simulator, [49]. Based on that, Almagro and Marano (2017) use the simulation tool **OpenDSS** with the Python integration for the simulation of the railway power lines, [50]. A further study on OpenDSS shows enough documentation and recent updates (march 2017) with the possible integration with VBA Excel, MatLAB and Python scripts.

Mathworks suggests also the usage of **MatLAB and Simulink** for rail electrical systems modeling. Similarly, **Ansys** products are suggested for the simulation of railway power systems as well as **PSIM**. The three previously presented products are also flexible to work in co-simulation, with the advantage of choosing the best software for the most straightforward application.

4.2.4 Contributions

On the energy measurement and information generation of the sensor nodes, two contributions can be considered as follows:

- **New energy metering architecture**, according to some specifications such as the usage of a non-intrusive approach. This architecture will generate energy information about the power flow of the railway system.
- **Accurate estimation of power flow** into catenary, based on on-board measurements. The available parameters will be: (1) the RMS voltage, current and apparent power,

(2) the instantaneous active power, reactive power, power factor and frequency, and (3) the cumulative energy consumptions in terms of kVAh, kVARh and KWh.

4.3 RTS wireless network

4.3.1 Purpose

The main purpose of the RTS wireless network is to transmit energy measurements and information generated by the nodes to a centralized storage server.

As a lower level and as previously presented, each train has current sensors as nodes and a data concentrator. Between nodes and data concentrator, AC voltage and current measurements must be exchanged. At this level, the relevant issue will be the presence of EMI, that will affect the communication link.

Between train data concentrator and ground-level, the train movement should be considered to better comply with the purpose of transmission the information generated at trains to the centralized storage server.

Further modeling and simulation of a WSN for energy measurement of RTS rolling stock will be made.

4.3.2 Methodology

The methodology for this part will include the **modeling and simulation** of network blocks similar to the ones presented in figure 4.6. An accurate modeling and simulation will define the more appropriate network technologies to implement in this RTS network. The simulation will be performed in a NS-3 simulator or similar. The **results** of such simulation will define the max data-rate of the sensor nodes as well as the nodes energy consumption required for the information transmission.

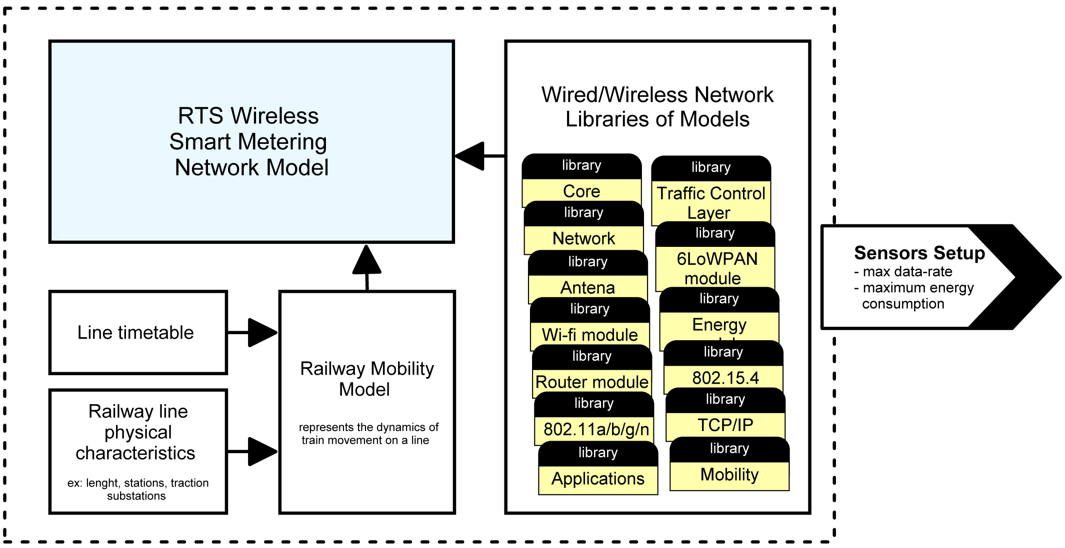

Figure 4.6: Models needed for simulation.

4.3.3 Simulation tools and frameworks

Several simulators/emulators were presented in the literature review chapter. From those, special attention is given to the NS-3 simulator and the MatLAB/Simulink tool.

4.3.4 Contributions

Regarding the energy information transmission and storage into centralized database, the following contributions are expected:

- **Availability of measured data** from trains where currently limited/inexistent energy measurement is performed.
- Data-rate increase of energy measurements, which will result on direct **increase on the quality of information of energy**. This increase will overcome the 5-minute data-rate that currently are used in energy meters.

A further contribution can be the reduction of the dependence of broadband real-time/continuous communication (such as LTE), with the direct cost reduction of information transmission of energy RTS data.

4.4 Work plan

Based on the before-mentioned objectives, an annual planning for future developments was built for the next three years. The work plan is presented in Table 4.1.

Secondary tasks of the work plan are the deliverables for the iRail PhD program and for the FCT institution, which occurs at end of academic year.

Table 4.1: Thesis work plan

Year	**Semester**	**Task**		**Milestone**
1	1st	Train power model development	Simulation of traction power transformer	
			Simulation of train power system	
		RTS energy model development	Integration with real case-study	
	2nd		Simulation of railway power system	
			Algorithm implementation	
		Energy measurement system: node development	Hardware development of Energy Measurement Node	
2	1st		Results acquisition: test bench validation of Energy Measurement Node	Publication(s): Energy Measurement Node
		RTS wireless smart metering network model development	Model simulation	
			Integration with real case-study	
	2nd		System integration with energy measurement nodes	Publication(s): RTS wireless smart metering network
		System integration	Development of energy data storage system;	
			System integration: RTS wireless smart metering network	
3	1st		Results acquisition: Railway Smart Meter	Publication(s): Railway Smart Meter
	2nd	Thesis Delivery	Document writing	
				Thesis Delivery
			Public Presentation	Public Presentation

CHAPTER 5

Preliminary Work

5.1 Implementation of a point-to-point communication between a moving train and a station

For this preliminary work, two network simulators were evaluated: the NS-3 and the OMNeT++. The approach of performing the evaluation of two network simulators allows, at this planning stage, to increase the knowledge on such simulators.

In figure 5.1 is presented the train mobility model of the case-study: Porto-Caíde railway line operated by *Comboios de Portugal* (CP). This example, the simulator receives the GPS coordinates of the line path and generates the mobility model. In this example, the train velocity is constant, without having in consideration the train stopping in stations. Future work will consider the velocity curves presented in subsection 3.5.3: *"Eco-driving – driving assistant"*.

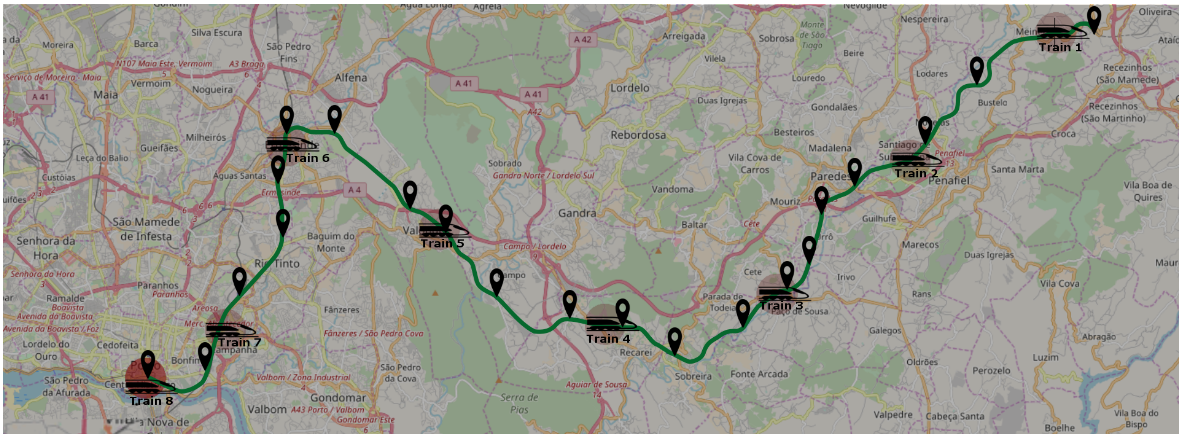

Figure 5.1: Porto-Caíde railway line: simulation using OMNeT++ network simulator.

The output of this mobility model will be, in the future, a file with the distances of each communication link, for each time-stamp. In this scope, each communication link will be the distance between each train and each of the train stations.

This output of the mobility model will be used by the network simulator to perform the simulation of the network link, that have this variable distance. To perform such simulation, the work of [51] using the OMNeT++ simulator supports a vehicle communication with 802.11p standard. However, in this preliminary work, the NS-3 network simulator was tested. In figure 5.2 is illustrated the interaction of both software simulators.

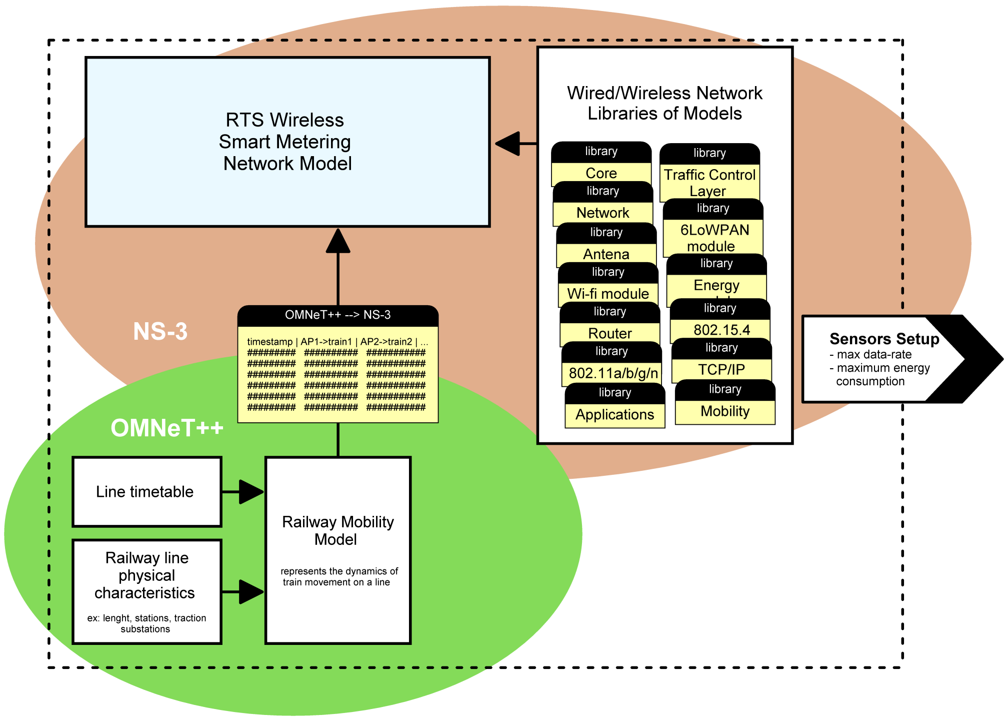

Figure 5.2: Simulator layers: proposed solution using OMNeT++ and NS-3.

The simulation case-study for the NS-3 simulator was defined as a moving node at constant speed of 1 m/s that crosses a stationary node. In figure 5.3 is illustrated the different data-rates of different 802.11 network standards for the moving node that starts 200 meters away from the stationary node, crosses it and stops 200 meters away.

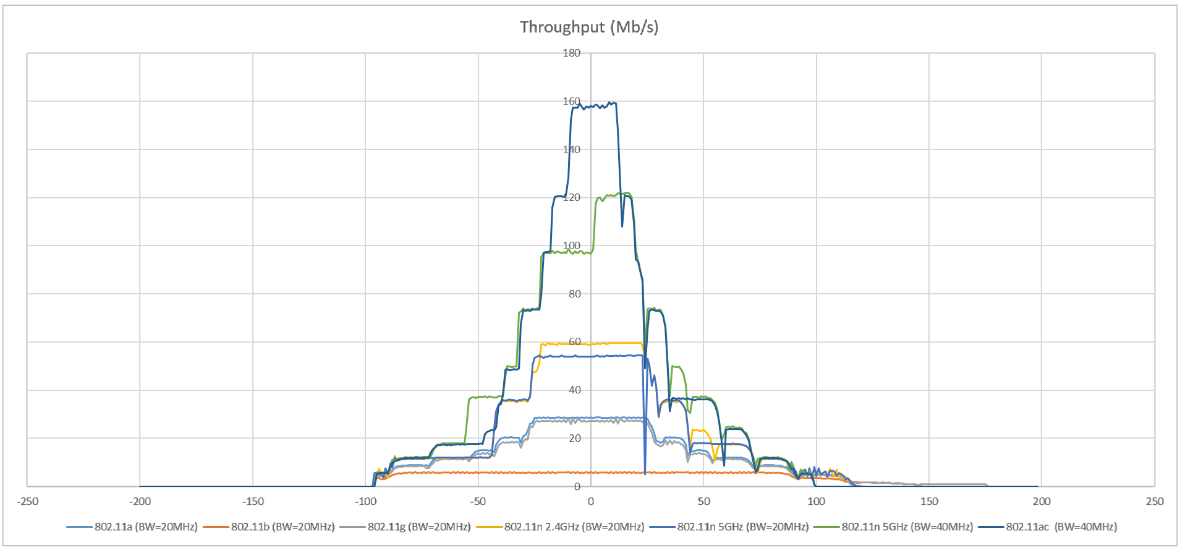

Figure 5.3: Evaluation of moving node for different 802.11 network standards.

5.1.1 Conclusions and future work

With this preliminary work, a first approach to create a communication scenario was presented. The case study for this scenario was a set of moving trains in Porto-Caíde railway line, each of them with a constant speed of 12m/s (calculated to comply with the timetable) and scheduled to departure from origin station 10 minutes apart.

With the OMNeT++ simulator, this scenario was simulated. Future work will comply with the variable speed of trains, with the consideration of stopping in stations. The expected output will be, for each existing communication link, the distance at each time between a train and a stationary node. This allows further evaluation of the throughput using an adequate simulator.

In the second part of this preliminary work, the scenario was set to be a moving node between two points at fixed speed and having a stationary node in the middle. This allows the evaluation of the throughput for different 802.11 standards. With the NS-3 simulator, this scenario was implemented and tested. The results prove that this preliminary work will support the throughput evaluation of each communication link between the train and every base stations near the railway line of case study.

5.2 Evaluation of the non-intrusive voltage sensor

A critical issue that can be identified is the measurement of voltage waveforms using a non-intrusive approach. The work of [48] presents a possible non-intrusive voltage measurement for energy meters. In this work is referred that, for the authors knowledge, there is no commercially available non-intrusive sensor for voltage measurement in low-voltage wires (230-400 VAC). Despite that, some studies are proposed in the literature for extra/high-voltage monitoring systems based on a capacitive cell.

Based on the solution of [48], a voltage sensor was implemented and tested, as presented in figure 5.4, with the equivalent circuit in 5.5.

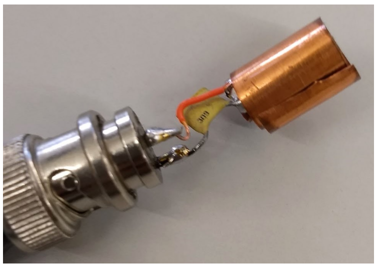

Figure 5.4: Photo of implemented non-intrusive voltage sensor.

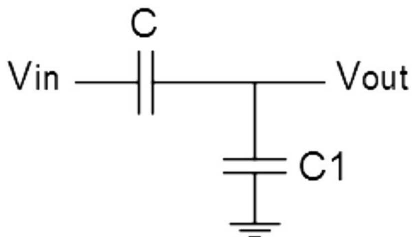

Figure 5.5: Equivalent circuit of non-intrusive voltage sensor.

To evaluate this sensor, two tests was performed: one with normal conditions of the grid, and other near a Voltage Source Converter (VSC), respectively in figure 5.6 and 5.7.

In ideal conditions, the voltage in the sensor is given by $V_{out} = (\frac{C}{C+C1})V_{in}$. By having in consideration the impedance of the oscilloscope, the voltage in the sensor suffers a phase shift which is visible in both figures. In addition, with a combination of measurements and simulations, the values of C1 and C was obtained with a value of 3.9 nF and 3.2 pF respectively

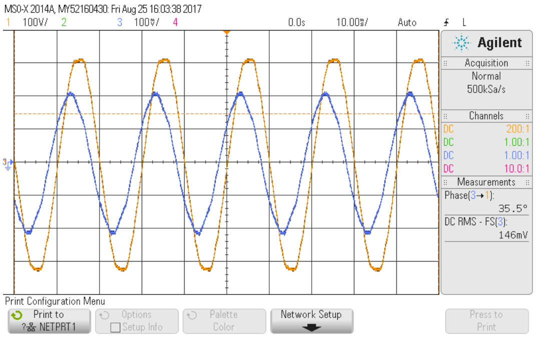

Figure 5.6: Waveforms of acquired and sensed voltages in normal conditions: (orange) AC main voltage and (blue) voltage in sensor.

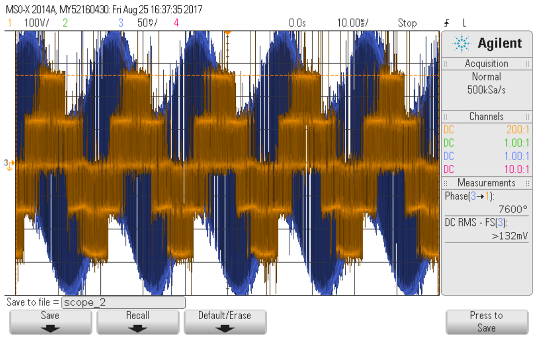

Figure 5.7: Waveforms of acquired and sensed voltages in inverter: (orange) AC main voltage and (blue) voltage in sensor.

(considering that C1 is measured in the coaxial cable terminals and that the oscilloscope has a 1 MΩ and 11 pF equivalent internal circuit).

The VSC is connected to the grid with a low-frequency transformer, which results in a line-to-line voltage of 200V (RMS) in the VSC, [52].

The purpose of this preliminary work is to evaluate if this solution presented in the state of the art is feasible to be implemented in an environment with huge amount of noise. At first evaluation the answer is negative, due to the need of extra work to estimate the voltage using the blue waveform of figure 5.7.

If it is possible to extract the voltage waveform, this can be considered as a **contribution to the field of voltage measurement** in noisy environments, and in particular, in the railway environment.

A second part of this preliminary work is the extraction of information from the sensor, in particular the phase of the voltage. To achieve this goal, a simple conditioning circuit made to amplify the voltage level of sensor to full range of μC ADC. The μC used was an Infineon XMC4500 and is responsible for the digital processing. In figure 5.8 is illustrated the architecture for signal conditioning and digital processing.

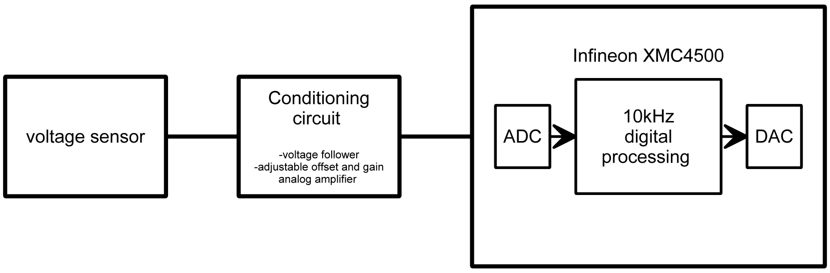

Figure 5.8: Signal conditioning and digital processing architecture.

The digital processing is based on the flowchart of figure 5.9. The 50Hz digital filter is the first chain in the digital processing of the signal; the offset elimination algorithm finds the DC value of the input 50Hz signal and generates an output without offset. The quadrature signal generation generates a signal with 20/4ms delay.

The angle of the signal is then generated, as presented in figure 5.10 where there is no

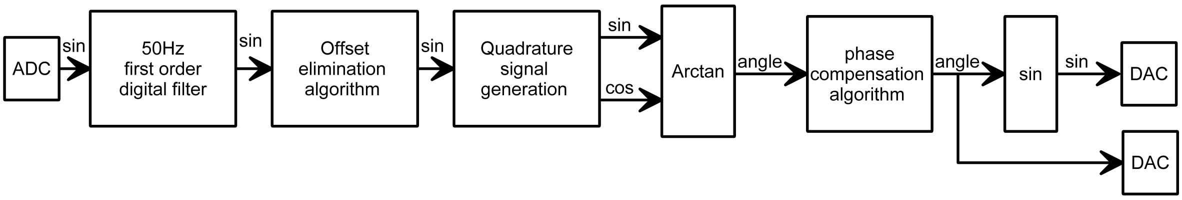

Figure 5.9: Signal conditioning and digital processing architecture.

phase compensation and the output of the phase estimation (in pink waveform) has a phase deviation around 10 degrees, compared with the line voltage (in orange waveform). In blue waveform is presented the estimated angle of voltage.

Complementary, in figure 5.11, the phase was compensated which resulted in an accurate estimation of the voltage phase, with a phase error around 1 degree.

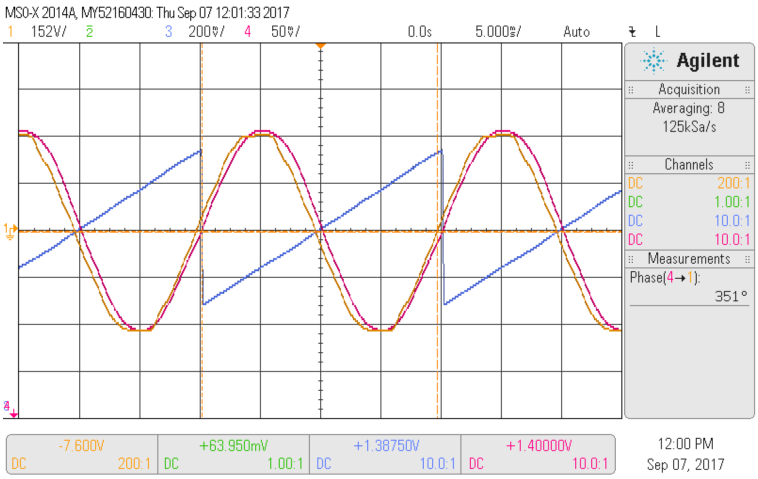

Figure 5.10: Waveforms of AC voltage (orange), estimated voltage (pink) and estimated phase angle (blue) without phase compensation.

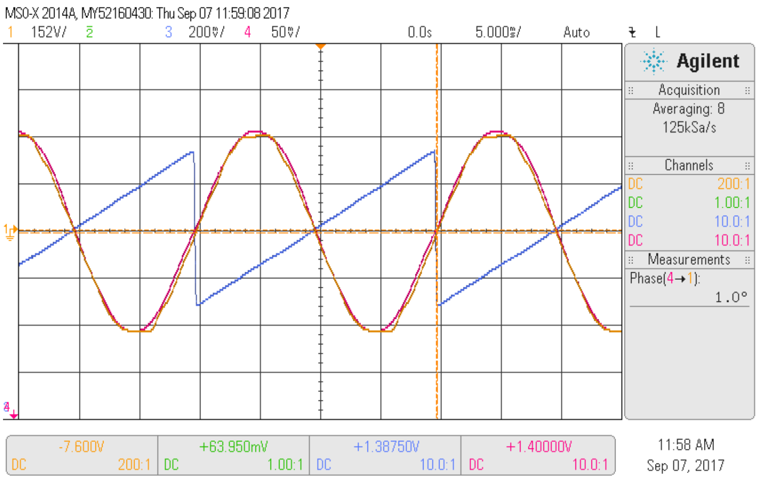

Figure 5.11: Waveforms of AC voltage (orange), estimated voltage (pink) and estimated phase angle (blue) with phase compensation.

5.2.1 Conclusions and future work

The work presented in literature that support these experimental results is feasible. **The voltage phase can be estimated with accuracy of around 1 degree**;

For the future work, the following steps are identified:

- The conditioning signal must support the dynamics of the switching frequency of the VSC. In one way, the bandwidth of the conditioning circuit must support the switching frequency dynamics; Complementarily, this conditioning circuit must adapt the voltage, using a programmable gain and offset amplifier, to better use the full-scale of the ADC.
- The execution time was measured and is around 50% of the total available execution time (of 100us). Future work will promote the optimization of the time execution.
- Further future work will be the estimation of the voltage angle (of fundamental harmonic) of a VSC connected to a low-frequency transformer. The methodology to fulfill this estimation must be evaluated.
- As presented previously in the methodology chapter, the simulation of the sensor module must be performed to evaluate the application of this sensor to the train environment.

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