Inatel

Dissertação de Mestrado

Transport Communications Systems - Modeling Railway Vehicle Networks

Rita de Cássia Duarte Leles

Maio/2022

Transport communication systems – Modeling Railway Vehicle Networks

Rita de Cássia Duarte Leles

Dissertação apresentada ao Instituto Nacional de Telecomunicações, como parte dos requisitos para obtenção do Título de Mestre em Telecomunicações.

ORIENTADOR: Prof. Dr. José Marcos Câmara Brito
COORIENTADOR: Prof. Dr. Joel José Puga Coelho Rodrigues

Santa Rita do Sapucaí 2022

Leles, Rita de Cássia Duarte
L539t
Transport communications systems – modeling railway vehicle networks. / Rita de Cássia Duarte. – Santa Rita do Sapucaí, 2022.
74 p.

Orientador: Prof. Dr. José Marcos C. Brito / Prof. Dr. Joel José Puga Coelho Rodrigues.
Dissertação de Mestrado em Telecomunicações – Instituto Nacional de Telecomunicações – INATEL.
Inclui bibliografia.

1. Redes de Comunicação 2. Ferroviárias 3. Internet das Coisas 4. Redes veiculares 5. Redes sem fio 6. Mestrado em Telecomunicações. I. Brito, José Marcos C. II. Rodrigues, Joel José Puga Coelho III. Instituto Nacional de Telecomunicações – INATEL. IV. Título.

CDU 621.39

Ficha Catalográfica elaborada pelo Bibliotecário da Instituição
CRB6-2718 – Paulo Eduardo de Almeida

Transport communication system – Modeling Railway Vehicle Networks

Dissertação apresentada ao Instituto Nacional de Telecomunicações – Inatel, como parte dos requisitos para obtenção do Título de Mestre em Telecomunicações.

Trabalho aprovado em 05/05/2022 pela comissão julgadora:

Prof. Dr. José Marcos Câmara Brito

Orientador – Inatel

Prof. Dr. Francisco José da Silva e Silva

Universidade Federal do Maranhão

Prof. Dr. Samuel Baraldi Mafra

Instituto Nacional de Telecomunicações - Inatel

Prof. Dr. José Marcos Câmara Brito

Coordenador do Curso de Mestrado

Santa Rita do Sapucaí-MG – Brasil

2022

“Simplicity is the ultimate sophistication”.

Da Vinci, Leonardo (1519).

Dedication

ACKNOWLEDGMENTS

First, I want to thank God for achieving this realization.

Thanks to my friends Thiale Moura and Paulo José Loureiro who always received me with great affection in Santa Rita do Sapucaí, where I traveled from São Paulo every weekend to study. It was a long and beautiful journey with my friends.

Thanks to my supervisor Prof. Dr. Joel José Puga Coelho Rodrigues, whose patience made me make the most of my work, of his moments of repression that he always ended up teaching, and that often inspired confidence in the execution of the work. Thanks for the knowledge, dialogues, trust, and guidance that was certainly the most valuable.

Thanks to my final supervisor Prof. Dr. José Marcos Câmara Brito, that receive me with total cooperation and enthusiasm, taking me to a final stage of my work.

Thanks to Gisele Moreira dos Santos, from the academic records service and Aline do Couto Pereira Vieira, from the financial administrative center. They were extraordinary people throughout the master's period.

I thank the National Institute of Telecommunications - Inatel, for the support in this paper, as well as all professors for the precious teachings. Specially Prof. Dr. Antônio Marcos Alberti, I really enjoyed your classes, a person with a disruptive mind, my inspiration.

I thank my friends Odair Piccin, Elvira Diogo, Kellow Pardini, Aline Aires, Jorge Roberto Carneiro, Élcio Carlos do Rosário, Flavia Patricia da Silva, Danielly Bravin, Julia Dainezi Fernandes, Marília Bontempo e Evandro César Vilas Boas. In particular, my appreciation for Mauro Alexandre Amaro da Cruz, an extraordinary person who always supported me during this journey.

I thank my family, who was always present in my life, specially to my father and big friend José Luiz Duarte, who rests with God.

ABSTRACT

Networks in the context of railways solutions are networks that support train-ground communications and are destined to support applications of operational and commercial nature from rail operators. The minimum requirements for data communication on the rail network can be mapped through existing and consolidated applications. With recent advances in network technologies, especially on the Internet of Things scenario, numerous possibilities for new applications and business are emerging. However, they can also bring unpredictable risks due to their innovative nature and considering that rail service beyond cargo transport also involves the transportation of passengers, it requires safe applications that can guarantee especially the passenger's life. It is necessary to advance the lines of research in all subjects so that these new emerging technologies are implemented with a certain level of maturity. That way, it is necessary to research the requirements for railways networks concerning typical services and possible changes in actual requirements in the function of implementing emerging technologies. Focusing on Vehicular Networks for Railways, this Master Dissertation is a case study that uses typical data collected, from which points of improvement are mapped for the development of new technologies, thus supporting the deployment of emerging technologies.

Keywords

Railways networks, Internet of Things, IoT, Data Communication System, Vehicular Networks, Cybersecurity, Wireless networks, Railways applications.

RESUMO

As redes no contexto da solução ferroviária são redes que apoiam as comunicações ferroviárias e são destinadas a apoiar aplicações de natureza operacional e comercial por parte dos operadores ferroviários. Os requisitos mínimos para comunicação de dados na rede ferroviária podem ser mapeados por meio de aplicações existentes e consolidadas. Com os recentes avanços nas tecnologias de rede, especialmente no cenário da Internet das Coisas, inúmeras possibilidades para novas aplicações e negócios estão surgindo, mas também podem trazer riscos imprevisíveis devido à sua natureza inovadora, e considerando que o serviço ferroviário além do transporte de carga também envolve o transporte de passageiros, requer aplicações seguras que possam garantir especialmente a vida do passageiro. É necessário avançar as linhas de pesquisa em todas as disciplinas para que essas novas tecnologias emergentes sejam implementadas com um certo nível de maturidade. Dessa forma, é necessário pesquisar os requisitos para a rede ferroviária em relação aos serviços típicos e possíveis mudanças nos requisitos reais em função da implementação de tecnologias emergentes. Com foco em Redes Veiculares para Ferrovias, esta Dissertação de Mestrado é um estudo de caso que utiliza dados típicos coletados, a partir dos quais são mapeados pontos de melhoria para o desenvolvimento de novas tecnologias, apoiando assim a implantação de tecnologias emergentes.

Palavras Chave

Redes Ferroviárias, Internet das Coisas, IoT, Sistemas de comunicação de dados, RedesVeiculares, Ciber segurança, Redes sem fio, Aplicações ferroviárias.

Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

4G	Fourth Generation
AC	Alternate Current
ALPHA	Adaptive and Lightweight Protocol for both Hop-by-hop and end-to end Authentications
BD	Big Data
CBTC	Communication-Based Train Control
CCTV	Closed Circuit TV
COTS	Commercial-Off-The-Shelf
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EMS	Electromagnetic Susceptibility
ESG	Electrical Smart Grids
ETSI	European Telecommunications Standards Institute
GSM-R	Global System for Mobile Communications – Railway
HSR	High Speed Railways
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
LTE	Long Term Evolution
LTE-M	LTE Cat-M1 or Long Term Evolution (4G)

RRID	Rail Radio Intrusion Detection System
OCC	Operational Control Center
PIS	Passenger Information Systems
QoS	Quality of Service
TD-LTE	Long Term Evolution – with Time Division
TETRA	TErrestrial Trunked Radio
Wi-Fi	Wireless Fidelity

Chapter 1: Introduction

1.1. Motivation

The use of network technologies to implement data communication systems in Railway transportation infrastructure and services today is essential. Railways have been investing in new technologies, particularly in recent years. Techniques in Railway Networks (Networks that provide train-ground communications) are emerging every day and becoming a great opportunity in Internet of Things (IoT) scenarios [1].

With the growth of smart cities concepts, where the rail sector is inserted, a transformation in this segment based on the evolution of IoT-based technologies has also started automatically. Traditional systems for Railways operate today with networks wired-based and radio-based communication, but in fact, intelligent infrastructure and the Internet of Things will take this to another level, with even more technical resources available to assist and manage the systems.

Vehicular Networks in the context of Railway, responsible for train-ground communication, nowadays represents three essential types of data communication systems: Safety-Related Applications (which are responsible for the safe movement of trains), non-Safety or Operational Applications (operational services, including services for operators or stakeholders without safety implications, like Closed Circuit TV (CCTV), passenger information, remote maintenance, and sensing) and Passengers Application (to providing Internet access to onboard passengers) [2].

New concepts aligned with the advancement of the internet of things have extended to the rail sector, and a very strong one has been to treat mobility as a service, and thus a remodeling of the existing service is needed as this new service it is fully connected to the internet and interfaces with many other external services.

The network technologies have contributed to the evolution of the railway systems, bringing about significant changes in the operation of these services. For example, the driverless technology already implemented in several countries, including Brazil, proves that each time the railway operators are looking for a form of autonomous operation, or with as little human intervention as possible, and more safely.

1.2. Problem definition

With the emergence of disruptive technologies, such as the Internet of Things, systems redesign often happens to implement new systems models and applications based on emerging technology.

At the moment of transition of technology, for example to the railway sector, a study of the minimum requirements necessary to meet specific needs is necessary, based on the knowledge acquired through existing technologies, so that new technologies can be securely implemented and add solutions to existing problems not yet covered by the previous technology.

This is the moment when the redesign thinking stage takes place, where the modeling of new rail vehicle networks is studied giving space to new implementations and technologies, opening the opportunity to solve known problems and improve the capacity of systems.

The way wireless technologies are used in railways does not perform enough, with problems in implementation considering the harsh rail environment and limited services. Clearly there is potential to explore more services.

This dissertation starts from an existing application and points out items that must be rethought and improved, in the context of this moment of technological transition based on the Internet of Things.

1.3. Objectives

The main objective of this work is to research and map the requirements (aspects) for the railways' applications related to train-ground communication networks and possible changes in the real solutions supporting the implementation of emerging technologies with a high level of maturity, using studies based on existing applications.

To attain this main objective, the following partial objectives were defined:

- Mapping requirements based on existing technologies;
- Present case studies, based on actual data collected;
- Indicate improvement points based on the case studies presented in this dissertation.

1.4. Main Contributions

Data collected in a real environment are analyzed and compared with key aspects pointed to prove that there are gaps that need to be improved, thus demonstrating, through these gaps, points of improvement for emergent IoT technologies.

1.5. Publications

During this research work, the following scientific paper was published:

[1] R. D. C. D. Leles, J. J. P. C. Rodrigues, I. W. Woungang, R. A. L. Rabelo and V. Furtado, "Railways Networks - Challenges for IoT Underground Wireless Communications," 2018 IEEE 10th Latin-American Conference on Communications (IEEE LATINCOM 2018), Guadalajara, Mexico, November 14-16, 2018, pp. 1-6, DOI: 10.1109/LATINCOM.2018.8613203.

1.6. Thesis statement

The choice of the development work with mapping requirements (aspects) in terms of Railways Networks is a highly important factor in obtaining a good quality of Service in train-ground communication systems, given the complexity and the technological diversity technologies involved in this kind of system.

An assessment of train-ground communication based on the aspects analysis of typical applications can substantially contribute to support that important design decision; that way, any technology that satisfies the requirements can be chosen. Also, it can contribute to emergent technologies in terms of mapping minimal requirements to attend the specific performance. Another hand, disruptive technologies, for example, the Internet of Things, can bring innovative scenarios where aspects need to be formulated to satisfy the railways' applications.

1.7. Document organization

The remainder of this dissertation is organized as follows. Chapter 2 provides an overview of the Railway Network Context. Chapter 3 proposes mapping the requirements based on existing technologies. Chapter 4 presents results analysis, where all data collected are compared with proposed requirements, pointing possible gaps that need improvements. Chapter 5 concludes the dissertation, displaying invaluable learned lessons, main conclusions, and suggestions for further studies.

Chapter 2: Railway Network Context

In this chapter, a characterization of the railway environment is first made, and a standard wireless network architecture is presented, which is generally used to meet the communication needs of the railway system. Then the impact that the Internet of Things has on these rail networks is described, in addition to a literature review presenting the works related to the theme.

2.1 Railway Network Characterization

Rail transport is a type of displacement that occurs by rail, dedicated to the transport of people and cargo. Records indicate that this means of transport is one of the oldest, and its emergence is directly linked to the First Industrial Revolution, a historical event that took place in Europe in the late 18th and early 19th centuries.

Rail transport for the transportation of cargo has its widespread use on all continents, and its use is strongly used to transport iron ore, soybeans, sugar, coal, corn, soybean meal, diesel oil, cellulose, steel products, etc. Rail transport for the transport of people is widely used on all continents, forming a set of public transport networks, generally integrating with the other available means of transport, such as buses, cars, and airplanes, generating a big urban mobility system.

Regarding the railway network in Brazil, they are fundamental resources for the flow of ores and soybeans, which are the main commodities in the country. A study by IBGE (Brazilian Institute of Geography and Statistics) indicated that 21.1% of the total cargo transported in the country uses the railway modal. Whereas, in countries like the United States, this transport represents about 50% of the cargo transport. Specifically, in the Brazil scenario, there is a very strong indication, on the part of the Government, of investment interest for the expansion of this type of modal, with investments funded by the Federal Government and with private investment partnerships, which obviously drives research and developments for the sector.

The sector has undergone a real technological transformation over the years in the way in which they are operated since it started in a rudimentary way, and like all other modes, it incorporated the use of telecommunications networks for its operation and maintenance services. As a form of modern rail network operation and management, operators use various networks systems/technologies for railway applications. There are numerous technologies across countries, according to each local regulation. Within telecommunications network technologies, wireless networks for rail services are widely used, and today are growing their applications.

In this dissertation, the focus will be on wireless networks that support the operation of railway networks. It will be demonstrated how this construction is currently, as well as the points that must be improved, considering the fundamental characteristics of the applications directed to the railway networks. These characteristics, especially those aimed at passenger transport, demand strict requirements for reliability, availability, and security.

In general, radio communication for rail operations is considered "mission-critical" for general train operations and for emergency management of trains. In addition, railway radiocommunication systems have a long-life cycle and are applications with industrial use characteristics due to the required robustness. Enhanced rail traffic management, passenger safety, and security are operations that depend on today's telecommunications systems, specifically based on rail networks. Through these networks, train control, voice sending, command, operational information, as well as monitoring data between onboard radio equipment and related radio infrastructure located along the trackside, are performed. To date, narrowband and broadband wireless technologies are used to support rail services.

A generic architecture of the components used by wireless networks that support railway applications is schematically represented in Figure 1. The main elements of the rail network may consist of onboard radio equipment, trackside radio, and network infrastructure (the core network, based on fiber optics).

Physically, the full trackside coverage by the radiofrequency signal is achieved positioning the radios, the way the good signal level is continuous along the track.

Operationally, each network is selected by the onboard radio application, and generally are used as Client/Access Point applications, where onboard radios are configured as clients from trackside Access Point radio that is connected in a Server application (usually the network is configured as a client/server application). The onboard radio connects with trackside radios to access the core network, which connects them to management elements, from which they send and receive information, as presented in Figure 1.

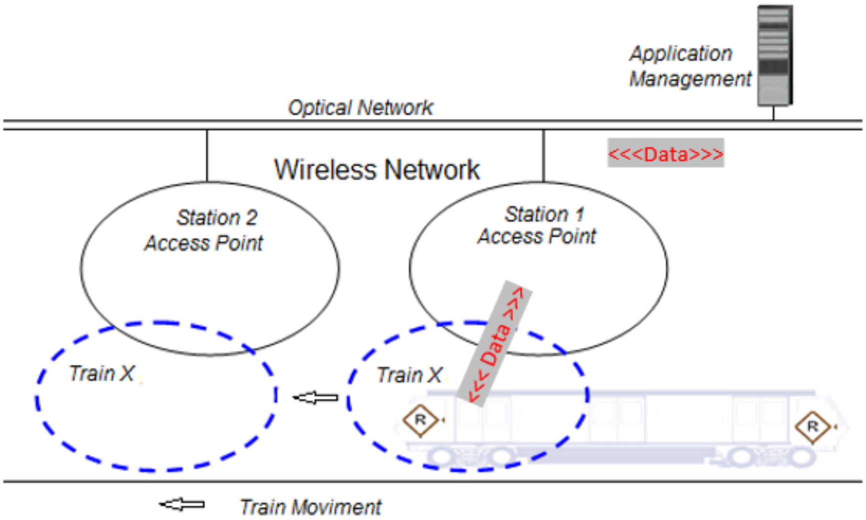

Figure 1 – *Schematic wireless and optical rail network.*

These trackside radios are always connected to an optical backbone that takes all the information to the Control Center, where the managers of these applications are generally centralized. This is the characterization of the railway networks with respect to the physical devices that form the architecture of the network.

Another aspect to take into consideration is the environmental characteristics, which are very specific for this application. The railway environment is usually open areas or tunnel areas (mainly for metro service applications), as illustrated in Figure 2 and Figure 3.

Figure 2 – *Open area trackside environment.*

Figure 3 – *Tunnel area trackside environment.*

Each of these types of environments has its characteristic and specific difficulty in the implantation of the system, since regarding the implantation in open areas, the propagation of the radio signal can become difficult because of physical obstacles, external interferences when close to the urban areas, inclement weather, etc. On the other hand, when it comes to tunnel area, propagation conditions become more complicated by physical obstacles, curves, little physical space of propagation when the tunnel is narrow, where the train itself can cause interference or cause reflections on the signal, which is being propagated by the radios. Another issue to note is that many metro applications work with trains powered by overhead lines, which makes the environment extremely noisy and susceptible to electromagnetic interference.

Even with regard to the physical characteristics of the environment, there are very specific requirements, as the railway environment is very hostile in terms of dust, humidity, temperature variations, and especially vibration, both for onboard equipment, which is subject to internal vibration at which causes a series of problems, such as mechanical wear and tear on friction parts, problems in cable connections, among others, as well as equipment installed at the edge of the track, which is susceptible to sudden currents of air, with the passage of trains. Due to these reasons, the equipment for railway applications must have industrial characteristics, which are more hardware-intensive equipment, since they have a degree of IP protection (protection against dust and water) and always meet specific railway mechanical standards of vibration and shock.

Another question to be addressed is the issue of the infrastructure needed to implement the railway systems, especially the power supply required. Currently, the infrastructure is very heavy, with a very large amount of cabling distributed along the trackside connecting the equipment to the power and network cable systems. This makes systems more difficult to deploy in terms of design, cost, and execution time, as well as more complex maintenance after deployment. And this feature becomes even more relevant in rail cargo applications, where the track has a very long extension and generally passes through remote locations where infrastructure installation becomes complicated (see Figure 3, on the left side, the detail of the trays needed to accommodate the necessary cable infrastructure).

Main railways systems that require network support, according to this characterization, are Signaling of trains and Control Systems and Passengers systems. A simplified architecture, in operational terms, is shown in Figure 4.

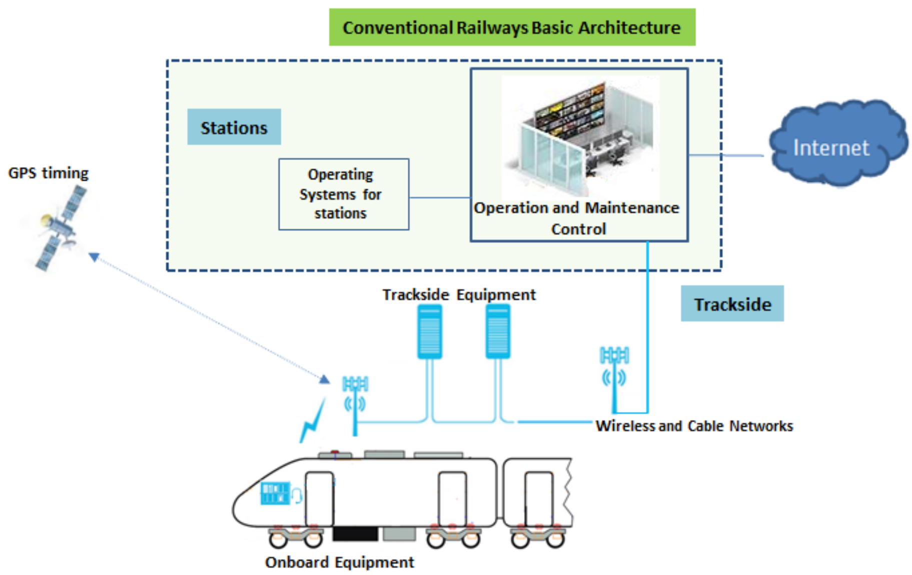

Figure 4 – *Conventional Railways Basic Architecture.*

Through this typical architecture, all rail systems are connected and monitored by service operators. These systems are operated with multi-system centralized at the Operation and Maintenance Control, which allows operational employees monitoring in real-time. Services like signaling and control, passenger information, closed-circuit television, infrastructure management, power distribution for system, and train control systems are managed.

However, all this conventional architecture is going through a moment of technological transition, motivated in large part by the emergence of the Internet of Things, where questions about the improvement of railway operations are the subject of studies [3], as well as for all other modes of transport, given that some authors place the transport area as one of the pillars of the so-called Smart Cities.

When a moment of transition like this is reached, studies and modeling by specialists are essential to map the deficiencies of current systems and indicate points of improvement, so that studies of new technologies can be implemented, bringing important corrections, innovations and, consequently, technological modernization of the sector.

With the specific objective of indicating points of improvement in the existing wireless communications systems, within this rail context, it is necessary to understand the impact caused by new technologies on the existing systems, which will be a guide to understand the trends, so the researchers can make its developments in line with the technical possibilities and with the expectations of the major operators in the sector.

Next section presents, in detail, the impacts that Internet of Things and emerging technologies are affecting the sector and intrinsically the themes that are guiding these changes.

2.2 The impact of Internet of Things in Railways Networks

In the last few years, the IoT has gained all attention in the world. Academy and all sectors of industry are discussing, deploying, and developing all applications based on these concepts. But what is the definition of IoT?

Some definitions can be found in the literature, but in fact, the Internet of Things concept was proposed in 1999 by Kevin Ashton; he has mentioned, “The Internet of Things has the potential to change the world, just as the Internet did. Maybe even more so” [4]. Today, the term Internet of Things means the advanced connection of devices, systems, and services. It goes beyond the traditional machine-to-machine M2M concept and encompasses a wide variety of protocols, domains, and applications [5].

Internet, today, is the backbone of virtual communication worldwide. The next upcoming form of communication that uses the Internet as the underlying technology is The Internet of Things (IoT) [6].

However, when this term came up, the goal was to describe the connection of all objects or things over the Internet, and these things represent electrical or electronic devices of different sizes and features connected to the Internet. With the exponential advancement of these innovations, this term did not seem to be enough to describe all forms of connections; other terms, such as Internet of Everything (IoE) and Internet of Nano Things (IoNT), are emerging in the scientific world [7]. Concerning Nano Things connected, it is quite understandable, as it would never be possible to achieve ubiquitous computing [8] by just connecting devices or objects to the internet. A smaller and perhaps even imperceptible ecosystem must be achieved and connected before the real concepts of ubiquity are reached.

Within everyday infrastructure, the Internet of Things has really begun to impact all "things", but globally, transforming all connected things into a true cooperative ecosystem. This concept has extended to full services and sectors. Thus, broader concepts such as Smart Cities have emerged, and therefore, all structural services contained in smart cities, such as Smart Health and Smart Transportation.

Smart transport is a component of Smart Cities [9]. The railway's segment, an example of many other sectors, has been impacted with IoT disruptive technologies. Transportation vehicles, including trains, are being prepared for making driving simple while ensuring passenger's journey safe and useful by externally as well as internally incorporating all the relevant technology sophistications.

Trains are increasingly becoming a trendsetting platform for ubiquitous infotainment and entertainment. Today's trains are connected, and their important components are being sensor attached, facilitating them for remote monitoring, diagnosis, control, repairing, and maintenance [10].

Smart transports are gaining a lot of market, and researchers are gearing up to bring in disruptive and ecologic transformative for next-generation smart vehicles that have less carbon footprint for cargo and passengers segment.

Now, the railway industry is in a position where it can exploit the opportunities created by the IIoT (Industrial Internet of Things) [11], enabling communication technologies under the paradigm of Railway Internet of Things [12].

In practice, IoT begins to contribute with optimization and improving solutions for existing systems and services, and emerging technologies will certainly innovate all things since the manufacture of trains, until its main services for cargo and passengers, the networks that provide train-ground communications, and of course, nowadays becoming a great opportunity in new development and integrated technologies.

Concerning current railways networks, in a simplified and correlated way, the main components that construct an end-to-end rail network are demonstrated according to the schematic block shown in Figure 5.

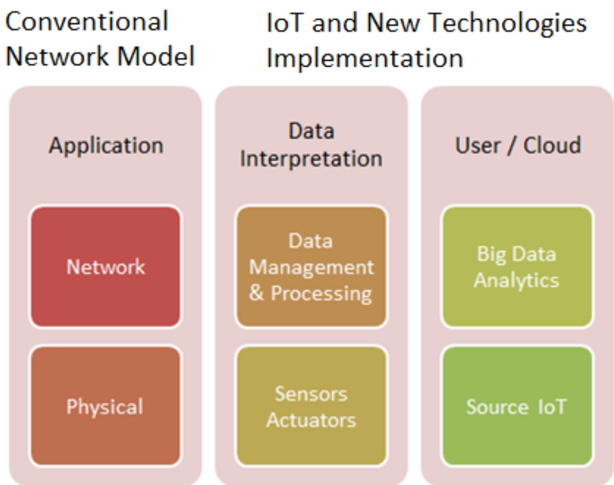

Figure 5 – *Components to railway networks – schematic block.*

Within this current framework, IoT has contributed in a way to implant innovations in each of these blocks but also has contributed in a global way to insert this small structure in an integrated global eco-system, inserting this small structure in a context greater than Smart Transportation, which in turn is contained within the Smart City. Thus, the direct impacts of IoT will be analyzed in each of these blocks, beginning the low-level analysis (hardware level), as following described.

Physical - The main themes addressed at the physical block are **Smart Sensorization** and **Smart Actuation**, which deal with what IoT has done for innovation regarding hardware, and in this case, the great novelty revolves around smart objects and sensors [13].

Smart objects, like sensors, also contribute to the railways' maintenance being the actuators and receptors of the physical part. Connected to intelligent networks, they can contribute in an integrated way for more accurate diagnoses and predictive actuations [14]. In addition, they play a key role in collecting data from the real environment, creating this way, the big amount of physical data, being the generator of data so that higher instances can have data to make the necessary decisions. In this field, the contributions are diverse, starting with the optimization of the physical size of the sensing hardware, as well as the various types of data that can be collected.

These are the edge elements of the network, which make the physical connection with the real world, and act both in collecting the data to be analyzed, as well as the final actuation or adjustment, executing the determined adjustments after the analysis of higher instances.

Network - Concerning to middle block, **Data Management & Processing** represents the core network of the system, where the IoT contributions or impacts are principally discussions and proposals of new models of network architectures specific for IoT.

As trains become networked devices, wireless networks can collect different types of data through sensors. Further on, hundreds of sensors built into each train produce a large amount of strategic data to activate more automation. In short, the amount of data generated is expected to grow dramatically in the coming years. This emphasizes the need for high-performance data analysis solutions, implementing Data Management and Processing to conceptualize cognitive services for next-generation trains. This core would function as **Big Data Analytics**, which would receive a large amount of data from the lower layer.

Application – Finally, in the upper block, the applications impacted by IoT are presented. In this block are represented the new applications that are being created due to the evolution of IoT.

With the widespread penetration of promising connectivity technologies, trains are being empowered to have new capabilities through continuous and spontaneous interactions with other track trains, maintenance systems, and so on. With **Cloud/User** connectivity, more efficient services and applications can be made available to rail operators and passengers [15]. In addition to making travel simpler, safer, and more satisfying, in-house trains can be more productive through e-learning, e-commerce, entertainment, and interactive and information systems.

Applications are being created and deposited in cloud application stores to be accessed and used by smartphones and infotainment systems in trains and dashboards to substantially raise the passenger's information and interactions levels.

At the application level, several direct impacts of the IoT on the rail sector can be highlighted, such as: i) Predicting demand and optimizing capacity, assets, and infrastructure; ii) Improving the end-to-end experience for travelers; iii) Increasing operational efficiency while reducing environmental impact, and iv) Ensuring safety and security travel.

Analyzing in an integrated global eco-system, these components of the schematic block are now connected to the external environment to achieve the full integration with external systems, instead of being segregated from external interfaces (before being connected to the internet).

This feature of being connected to the Internet was a breakthrough in terms of rail networks because signaling networks with high-security requirements were never connected to the Internet; they were dedicated networks.

2.3 Literature Review

In this section, a review of the literature based in articles related to the topics discussed will be presented, i.e., the themes topics developed by researchers regarding the main topic of this dissertation. It is very important to make a contextualization in terms of the technologies that are being discussed now to understand the scenario in which the rail networks are inserted.

It is hoped that rail networks being built at this time will provide advanced services due to new technologies that are being incorporated and that are enabling the generation of new applications and integration with external systems. In fact, it is expected in the next steps that the rail networks may work in an adaptive and interactive way with the external environment, through internet connection which adapts to the specific needs identified for the rail segment. So smart decisions can be made, such as increasing or decreasing the training range autonomously, based on external information, or even changing your internal routes of operation automatically when there is a fault detected in some of the trains in circulation, for example. These networks will be interactive to base their decisions on analysis of data collected from various sources, thus making an operation adaptive to moment needs in a dynamic way.

These are characteristics of the differentiated operations that will be deployed in new concepts brought by emerging technologies. Many terms have emerged to designate this new model of rail network and much by the impact of IoT concepts and at the same time to defining specifically this application, such as the **Railways Internet of Things** and **Smart Railways**, for example.

These concepts designate an intelligent network, completely integrated with other modes of external transport through the internet, capable of collecting and managing data from external sources, and in real-time capable of adapting its operation to better suit the demand of the moment.

For this to be possible, the wireless networks that communicate between trains and control centers play a fundamental role. Many articles can be found in current literature with citations to **train-ground communications.** In classical urban Rail, the train-ground communication system mainly uses Wireless Local Networks (WLANs) to realize the transmission of different train-ground communication applications independently. Mainly literature concerning train-to-ground and train-to-train communications [16], [17], [18] can be found (this second basically follows the concept of the Internet of Things, where trains are represented as smart "things" that communicate with each other within an ecosystem).

Since a railway needs a long way of radio coverage, other technologies, which have greater coverage, are also cited as alternatives in the literature to ground-to-train communication, such as Long-Term Evolution (LTE) technology [19], [20]. But, in fact, no one currently technology seems to be totally adequate for rail specific needs. Fundamentally, the technology chosen to perform this communication will depend a lot on the type of environment, whether it will be an open environment, tunnels, or both, and the distance to be covered.

In practical cases, commonly, the same company operates more than one rail or subway line. Because these railways or lines are often built at different times, a train-ground communication system for different rail lines may use equipment from different manufacturers, which will bring integration challenges for management, even, it may result in an emergency brake of train or traffic safety when a train is going across different lines [21]. This requires mobility requirements for communications between different operating environments.

Services transmitted on rail networks are generally geared to the operation and maintenance needs of the system itself, as well as passenger services. Based on these types of operations, there are real needs for the insertion of new technologies that can provide devices that improve rail operations and maintenance services and improve passenger services. There is a large space for application development based on new technologies in this segment and many challenges.

A very important aspect to note is that these networks have very restrictive safety features as they are often geared towards service passenger transport, which requires an extremely high degree of safety [22]. These networks have **Reliability, Availability, Maintainability and Safety** (RAMS) requirements.

The advent of softwarization completely changes the structure of known networks while rethinking rail network design and management, which positively affects the efficiency of service provision and maintenance. **Software-Defined Networking (SDN) and Network Function Virtualization (NFV)** introduce appropriate abstraction techniques for easy and efficient service chain deployment and the use of general-purpose hardware devices. Introducing these rail paradigms is challenging due to their strict service and safety requirements and represents a promising approach that allows for disruptive improvement of management systems and paves the way for state-of-the-art rail control systems [23].

Concerning to new concept of network resource **Virtualization**, many studies are also being developed, mainly to prove the performance improvement, the system **quality of service (QoS),** and the system security performance [24]. Related to resource virtualization, some literature also approaches virtualization as a strong element of systems integration and presents as a positive side the drastic decrease of physical structures, which can contribute significantly to the maintenance and optimization of systems [25].

Proposals for an integrated network virtualization-based train-to-ground communication system for urban rail systems could improve the classic systems currently in operation, such as systems based on Wi-Fi networks, where many radios produce trackside coverage. As a result, there are excessive handoffs between radios as the train moves along the track, proposing a new handoff scheme to support the transfer between virtual networks. The QoS parameter of the application layer of the Signaling system, Passenger Information and CCTV subsystems is used as a measure of performance in transfer design, adding optimization to the existing network model [26].

A railways management system is currently hosted in central technical rooms that centrally manage and supervise trains traffic of different geographical areas. Proposals about the execution of management activities taking advantage of cloud networks instead of storage in centralized servers are discussed [27]. Suggestions to distribute among cloud resources the computational load due to the elaboration of the collected data and the derivation of required commands for trains and actuators.

Observing an IoT scenario, where all "things" are connected to the Internet, the volume of data generated and changed in real-time by these connected devices is immeasurable. In this aspect, data storage and **Cloud computing** network concepts are discussed, and concepts such as Fog networks for applications sensitive to delays are widely considered to meet the needs of rail networks. However, data storage becomes a complex subject because it would be extremely efficient to be able to store only relevant data for the systems. Thus, it saves the network from transmitting unnecessary data to the final storage occupying spaces without practical use. It would be extremely important that these data be treated and classified intelligently.

Increasingly, the challenge of these networks must be incorporating intelligent technologies like **Big Data** capable to store (if it is necessary) this immeasurable amount of data, but also capable to manage this data intelligently, and filter information relevant to end applications, as **Data analytics** for example [28], [29]. However, this pure data collection through Big Data, analyzed through data analytic applications, is just the beginning of something much deeper involving more intelligent decision making by rail systems; more than a simple data crossing, fatally **context-aware** research is also part of it. For example, the implementation of context aware scenarios within different locations within the railway system (i.e., infrastructure elements as well as within the train) is analyzed by [30], [31].

Regarding the main feature of a network where all things are connected to the internet, there is a very pertinent and sensible issue that is the subject of many technical studies, which is related to network security, since rail networks are infrastructures that carry information for vital train operations, much of it related to passenger transport. According to [32], **Cyber-physical security** is a major concern for the new generation of trains; therefore, analyzing vulnerabilities and characteristics of the railway threat landscape, including potential threats, threats agents, and motivations, are questions widely discussed.

For integrated wireless network development, it is necessary to guarantee the interoperability of railway equipment between different manufacturers and integration with legacy systems. Without standardization, it is practically impossible to achieve this goal. The use of open communication standards seems to be a way to follow. However, this point is controversial concerning the security system, as Cyber Security [33]. Due to the incorporation of standard communications protocols and networking devices, the system is vulnerable to cyber-attacks such as viruses, hackers, organized criminals, and state-sponsored groups. Mitigation measures should be in place, including a robust security strategy, collaboration with government departments, and technological, social and procedural countermeasures [34], [35].

Extensive studies on infrastructures from the perspective of cyber security [36] and research has been conducted. This is certainly the most sensitive point when connecting a passenger transport network to the Internet, as they have extremely strict safety requirements. It is necessary to ensure the integrity of messages, preserving the signaling system of interception or interpretation by others. Around the world, cyber security is a firm requirement for railway networks since transport services are frequently a target of attacks by hackers. In this regard, the challenge is creating interoperable networks while ensuring the security and integrity of the data transported from malicious attacks.

The growth of wireless communication technologies as part of railway applications brings, consequently, the increase in studies focusing heavily on improving technologies and verifying their weaknesses, in this way it is possible to find a relationship with studies where practices are applied for dealings related to cyber security. Research demonstrates cybersecurity best practices to help organizations identify, protect, detect, respond and recover to sophisticated insider threats and vulnerabilities [37].

Analyzing at the frequency usage aspect, appropriate recommendations for national regulators who are responsible for **RF spectrum management** are given regarding the regulatory framework for fulfilling IoT device connection survey requirements in various scenarios of their usage. Currently, there is a tendency that IoT will be implemented on a large scale to boost smart city development, therefore, the calculation of spectrum for IoT spectrum is urgently needed [38], and IoT spectrum requirement for smart transportation [39].

The IoT that allows connectivity of network devices embedded with sensors undergoes severe data exchange interference as the unlicensed spectrum band becomes overcrowded. By applying **Cognitive Radio** (CR) capabilities to IoT, a novel cognitive radio IoT (CR-IoT) network arises as a promising solution to tackle the spectrum scarcity problem in conventional IoT networks [40]. Another important question is that **Energy efficiency** in the CR-IoT network must be carefully formulated since the sensor nodes consume significant energy to support CR operations, such as in dynamic spectrum sensing and switching [41].

The implementation of fifth-generation technology is driven many studies. According to [42], cognitive radio and non-orthogonal multiple access are candidate technologies for **5G networks** that can improve spectral efficiency and accommodate a large number of IoT devices. Furthermore, radio frequency (RF) energy harvesting can increase the energy efficiency of IoT networks. RF regulation is nationally important in theory, policy, and practice. Technological advances, innovation, penetration of new technologies, economic and military power are all directly connected to wireless regulation [43].

Finally, the concept of everything as a service, which is a strong technological trend, also migrates into the railway sector, implementing Mobility as a Service (MaaS), which in the view of operators is the integration of various forms of transport services into a single mobility service accessible on demand. For the user, MaaS can offer added value using a single application to provide access to mobility with a single payment channel instead of multiple ticketing and payment operations.

MaaS is essentially an operating concept that reinforces the need to integrate the railway network with external elements, that is, a concept already presented on an intelligent network capable of collecting and managing data from external sources and, based on data analysis in real time, adapting to momentary demand.

Chapter 3: Mapping the requirements based on existing technologies

This chapter cites the technology chosen for a practical test, briefly describes the test environment as well the setup used, and the typical results collected through the execution of this test setup.

3.1 Technology and standard used

Many network technologies could be chosen to be part of this study; however, the IEEE 802.11.a/b/g Wi-Fi standard, operating at 2.4 and 5 GHz was chosen to demonstrate the characteristics of the typical railway environment and serve as a parameter for the analyzes presented in this dissertation. This technology is widely used in railway applications, both in infrastructure services and providing connections to passengers.

Performing network-based communication in a rail environment using Wi-Fi technology will permit to obtain parameters to compare and map the gaps that need improvement concerning railways networks. Analysis using these parameters will map the basic requirements and points of improvements for the new technologies in rail networks.

The main technical characteristics of the modem used in the experiments are summarized in Table 1.

Table 1 – *Radio Modem technical specifications.*

Item	Specifications
Radio Modem standards	*IEEE 802.11a/b/g/n*
Frequency Operation	2.412 to 2.462 GHz (11 channels)
	5.18 to 5.24 GHz (4 channels)
Transmission Rates	802.11b: 1, 2, 5.5, 11 Mbps
	802.11a/g: 6, 9, 12, 18, 24, 36, 48, 54 Mbps
TX Transmit Power	802.11b: Typ. 23±1.5 dBm @ 1 to 11 Mbps

	802.11g: Typ. 20±1.5 dBm @ 6to 24 Mbps, Typ. 19±1.5 dBm @ 36 Mbps, Typ. 18±1.5 dBm @ 48 Mbps, Typ. 17±1.5 dBm @ 54 Mbps
	802.11a: Typ. 18±1.5 dBm @ 6 to 24 Mbps, Typ. 16±1.5 dBm @ 36 to 48 Mbps, Typ. 15±1.5 dBm @ 54 Mbps
RX Sensibility	*802.11b: -97 dBm @ 1 Mbps, -94 dBm @ 2 Mbps, -92 dBm @ 5.5 Mbps, -90 dBm @ 11 Mbps*
	802.11g: -93 dBm @ 6 Mbps, -91 dBm @ 9 Mbps, -90 dBm @ 12 Mbps, -88 dBm @ 18 Mbps, -84 dBm @ 24 Mbps, -80 dBm @ 36 Mbps, -76 dBm @ 48 Mbps, -74 dBm @ 54 Mbps
	802.11a: -90 dBm @ 6 Mbps, -89 dBm @ 9 Mbps, -89 dBm @ 12 Mbps, -85 dBm @ 18 Mbps, -83 dBm @ 24 Mbps, -79 dBm @ 36 Mbps, -75 dBm @ 48 Mbps, -74 dBm @ 54 Mbps
Default antennas	*2 dual-band omni-directional antennas, 2 dBi*
Mode Operation	*Access Point / Client / Bridge*
Power Consumption	*12 to 48 VDC, 800 mA (max.)*

Table 2 summarizes the standards and certifications obeyed by the Wi-Fi modem used in the measurements.

Table 2 – *Radio Modem Standards and Certifications.*

EMC	EN 61000-6-2/-6-4
EMI	CISPR 32, FCC Part 15B Class B
EMS	IEC 61000-4-2 ESD: Contact: 8 kV; Air: 15 kV IEC 61000-4-3 RS: 80 MHz to 1 GHz: 10 V/m IEC 61000-4-4 EFT: Power: 2 kV; Signal: 1 kV IEC 61000-4-5 Surge: Power: 2 kV; Signal: 2 kV IEC 61000-4-6 CS: 10 V IEC 61000-4-8 PFMF
Radio	EN 300 328, EN 301 489-1/17, EN 301 893, FCC ID SLE-WAPN008, ANATEL, MIC, NCC, RCM, SRRC, WPC, KC
Safety	EN 60950-1, UL 60950-1
Vibration	IEC 60068-2-6

3.2 Typical experiments environment

The railways' environment is very hostile. Nowadays, railways systems have activities with protective standardization bodies and equipment that follow rules that certify safe and secure trains operations. These rules are specific to each country, but, in general, they refer to the same aspects (with different tolerances, sometimes more or less severity depending on the application).

In addition, a significant feature to be observed in the test environment regarding wireless networks is related to the physical construction of the trackside, i.e., if the network will operate in an open area or tunnel, if it has many curves or physical obstacles that make it impossible to direct signal propagation between transmitter and receiver, etc.

For this experiment, specifically, a tunnel region was chosen to avoid external interference, as Wi-Fi networks are massive at these 2.4 and 5GHz frequencies. In this way, the tests could be performed in a more controlled environment.

3.4 Typical Scenario and Setup

In order to cover the trackside with continuous RF signal, achieving good quality levels, a survey is necessary to define the good positions to fix the trackside antennas and fix the onboard antenna for train-track good communication. This survey aims to map the physical and environmental characteristics of the trackside, as well as the levels of different signals captured by the system in each change of environment, for example, transitions between open areas and tunnels, which can alter the propagation characteristics of the radio signal.

To radio coverage, equipment is installed on the platform region (one way), and measures are collected by the onboard radio with trains moving. Many parameters are collected to validate the quality of wireless transmissions, such as RSSI (Received Signal Strength Indication), Packet Loss, Jitter, and Latency. At the same time, physical parameters of the test equipment are observed.

3.4.1 Experiment Setup for a Wi-Fi network

In this experimental scenario, a point-to-point connection is established, where the radio allocated on the platform uses a directional antenna, which is being directed to one side of the track. The radio allocated on the platform is configured as an Access Point, and the radio that is moved along the track is configured as a client of this AP.

Figure 6 schematically presents the positioning of the AP radio on the platform, and the distance traveled by the client radio, which is allocated on board the train. The distance traveled under RF coverage on the track as the train travels, where data is collected, is also presented.

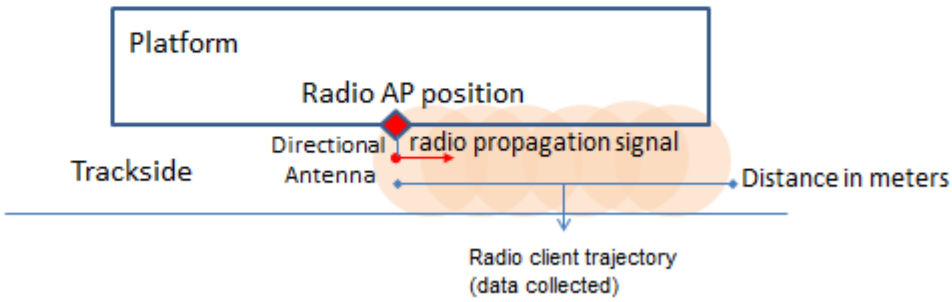

Figure 6 – *Illustration architecture used for Wi-Fi network data collection.*

The technical characteristics of the radios and antenna are described in Section 3.2 – Equipment Description.

3.4 Typical results collected

3.5.1 Wi-Fi Networks collecting data

a. Collecting Network data

Using one Ping Tool (installed in notebook connected in client radio), the Ping Summary window provides basic information such as IP address, packets received/sent/lost, and response time of the required IP address (notebook connected with AP station).

Through this network analysis tool, as shown in Figure 7, it is possible to display the operation in real-time and analyze the statistical results of the communication.

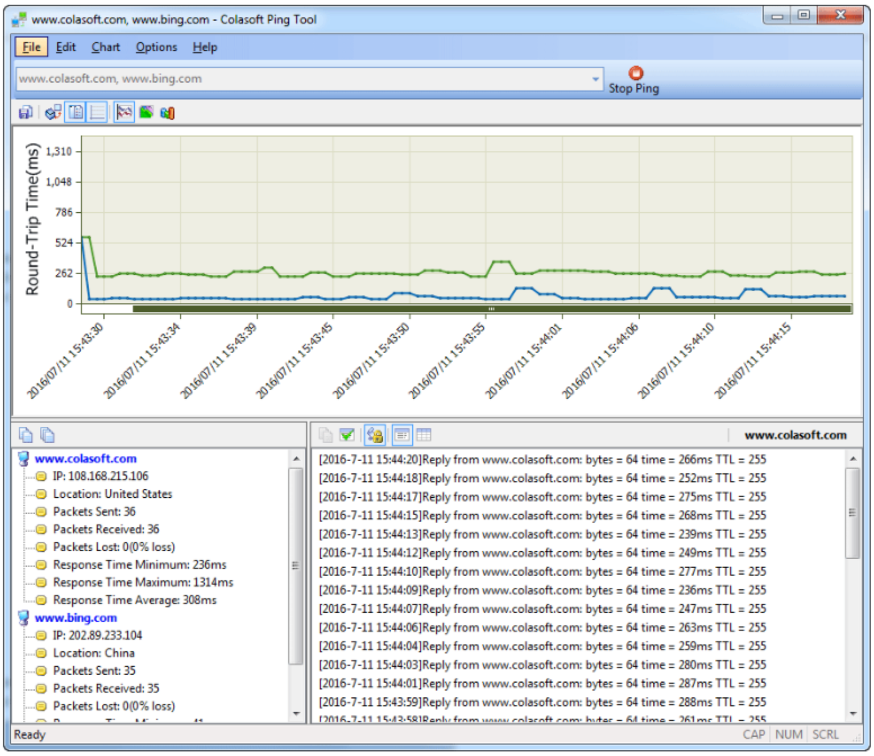

Figure 7 – *Network Ping Tool.*

One point-to-point communication between the radio allocated on a station platform (AP) and the radio moving along the track (Client), as shown in the setup of Figure 6, is established, and the results are obtained and recorded.

b. Collecting Radiofrequency data

Using a wireless network analyzer tool to obtain the RSSI (Received Signal strength indication) in real-time for this point-to-point communication. The results of the measurements are obtained and recorded.

Figure 8 below shows the expected signal levels, expressed in dBm versus the distance traveled in the tunnel by the train (where the client radio is allocated) in meters.

	Signal Intensity	X Tunnel Distances
- 25 to 30 dBm	Excellent signal level, expected intensity for distances very close to the Radio	0 m
-30 to -50 dBm	Levels between -30 and -50 can be considered as an excellent signal level	25 m
-50 to -60 dBm	Good. Signal confidence level	50 m
-60 to -67 dBm	Reliable minimum signal level	75 m
-67 to -70 dBm	Signal level with weak intensity	100 m
-70 to 80 dBm	Unreliable signal strength	Up to 100 m

Figure 8 – *Expected Signal Intensity (dBm) versus distances(m) in reception.*

Through the received signal levels measured at different distances in a typical tunnel environment along the trackside, the following correlation considering Signal Intensity in dBm levels versus Tunnel distances in meters can be considered according to the presented levels. The obtained results are presented in Figure 9.

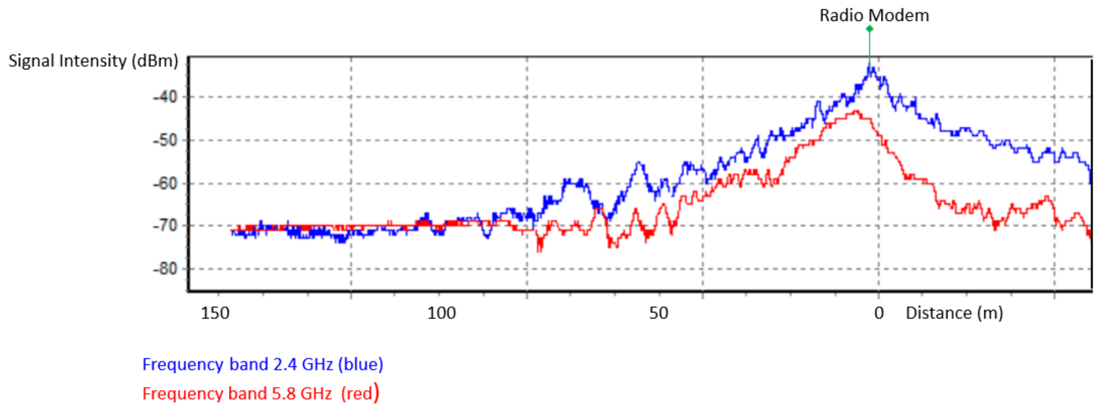

Figure 9 – *Signal Intensity (dBm) in function of Tunnel distances, in meters.*

Figure 9 shows the RSSI collected via the on-board radio while the train moves for the 2.4 GHz frequency in blue and 5 GHz in red. Distance 0 zero is the point where the AP radio is positioned on the platform.

c. Collecting Channels Occupation Data

Using a wireless network analyzer tool, it is possible to obtain the Channel occupation data scan in real-time for Wi-fi channels. The results of the measurements are obtained and recorded.

The quality of communication must be evaluated with real environment experiments since the frequency spectrum allocations are dynamic. One sample or spectrum scan was made in the station, in the moment of setup tests execution collecting typical environment the channels occupation, as shown in Figure 10.

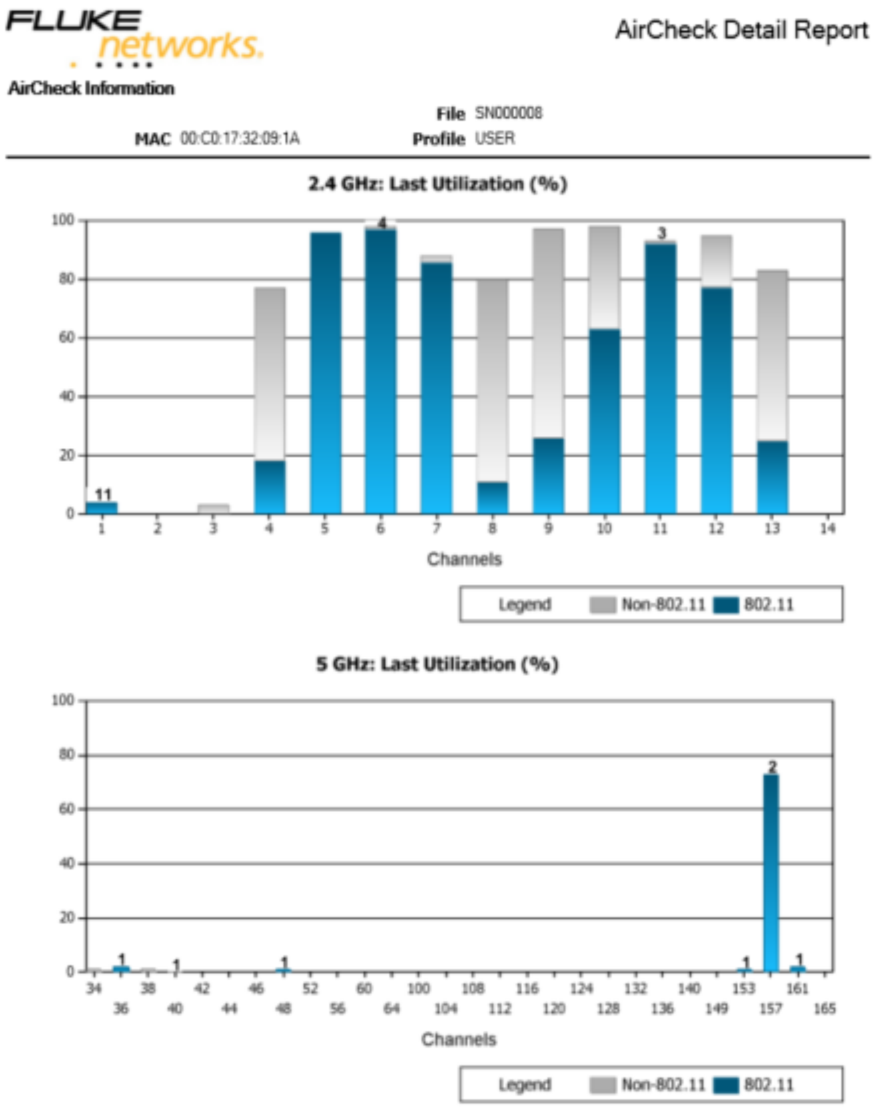

Figure 10 – *Channels occupation.*

The upper graph shows the occupancy of channels within the station for the 2.4 GHz frequency band and the lower graph shows the occupancy of the channels for the 5GHz band.

Chapter 4: Results Analysis

This chapter presents an analysis of the results obtained by running the Test Setup presented in Chapter 3.

4.1 Case study based on actual data collected.

In this chapter, all data collected in a real environment are analyzed and compared with requirements pointed out below to prove that, in a real case, there are gaps that need to be improved, thus demonstrating through these gaps, points of improvement for emergent IoT technologies.

The experiments will be analyzed considering three layers: physical, network and application, as illustrated in Figure 11, demonstrating that new IoT Technologies can bring progress at all layers.

Figure 11 – *Network Fundamental Blocks*.

The points or aspects to be analyzed are described below. Regarding the **Physical** layer, Wi-Fi experiment results can be analyzed from the following perspectives:

Environmental Characteristics – three important environmental characteristics related to the railway must be observed when designing wireless systems.

The first refers to Electromagnetic compatibility, see standards in Table 2, once most trains in operation are powered by high voltage [44], [45]. The environment is extremely dangerous due to the application of high voltage for the main supply of the train, that is, for the supply of the traction components, catenaries, and the supply of the rail itself. Due to the energization of the catenaries or rails, the environment becomes extremely noisy beside the interferences that may arise on systems.

The second characteristic is related to the signal propagation due to the particularities of the physical environment of propagation, formed mainly by tunnels, and when in an open area, great occupation of the frequencies, since other operating systems and users allocated in the surroundings (industrial and residential) also use the spectrum simultaneously [46]. The result may be unwanted interference with the train's wireless communication system.

The third is related to mechanical requirements for the hardware (see Table 2 standards) because onboard equipment is susceptible to constant train vibrations and trackside equipment, as Access Points and antennas installed in the trackside, is susceptible to the air displacement caused by the passage of the train in the tunnel. This requires that onboard and trackside equipment have good mechanical resistance and industrial characteristics. Thermal requirements are another point because this environment contains high dust, humidity, and has very high temperatures, which always hinders equipment operation. The trackside environment is very hostile to hardware. Meet the hardware characteristics makes it possible to increase the product life cycle and the safe operation of the system.

Concerning signal propagation, described as the second important characteristic, the data collected in the tunnel (see Figure 9) shows that at a distance of 100 meters from the access point, reached a signal strength level of -70 dBm at reception (values collected were similar for both frequencies 2.4 GHz and 5.8 GHz, with slightly better performance for the 2.4 GHz frequency). -70 dBm is considered the threshold value for reliable communication; with values above, packet losses affect the quality of the signal at reception (packet loss reaches unacceptable levels for communication).

For the IEEE.802.11.b/g standard, it is described that the theoretical reach in meters in an indoor propagation environment is 35 and 38 meters, respectively, and for an outdoor propagation environment, it is 140 meters. For the IEEE.802.11.a standard, the range in an indoor propagation environment is 35 meters, and for an outdoor environment, it is 120 meters.

Energy Efficiency - To perform this experiment, radios were powered with 48 volts DC power supply, according to radio modem technical specifications (see Table 1). An AC source is required for each radio, and then conversion to DC power supply is done.

Observing Figure 9, which presents signal intensity versus distances covered in tunnels, in 100 meters is received for the radio client in the trackside the signal intensity of -70 dBm. This range can be increased by using a directive antenna in Access Point radio; it can be considered that one Access Point would be needed every 400 or 600 meters in each side of the trackside (depending on the gain of the antenna) for full trackside coverage.

Figure 12 below schematically shows the theoretical positioning of the radios Access Points Wi-Fi along the track (on both sides), so that full RF coverage along the track can be achieved.

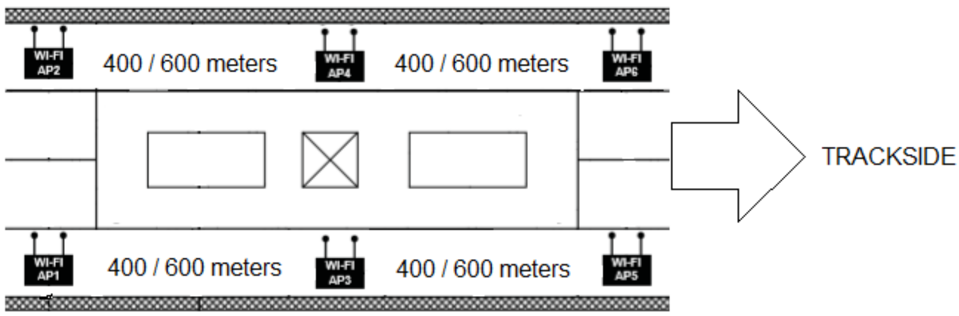

Figure 12 – *Distribution Access Points in trackside for full coverage*.

In a real design condition where hundreds of radios are used for full trackside coverage, it is possible to imagine the number of power supplies and converters needed to power all network devices distributed along the trackside. In addition to radios, the entire wired network is also powered; in other words, the energy consumption required to implement a traditional system is immense, as well as the physical infrastructure of cables that must be implanted in the tracksides to supply all equipment, in addition to the rolling stock itself [47].

Hardware (Virtualization of Physical Resources) – As discussed in this dissertation, the amount of physical equipment needed to provide a continuous wireless network to cover a trackside that reaches kilometers in length will be unthinkable going forward. The amount of hardware needed to generate an infrastructure like this is very large and requires expensive maintenance (see the example of the distribution of access points to cover the trackside in Figure 12). In addition, there is the core network, the backbone, which connects each access equipment to the management elements, a vast network infrastructure accommodated in local technical rooms.

Figure 13 below schematically shows the optical backbone that connects the Access Points radios that are distributed along the track to the Control Center, where the application management systems are normally located.

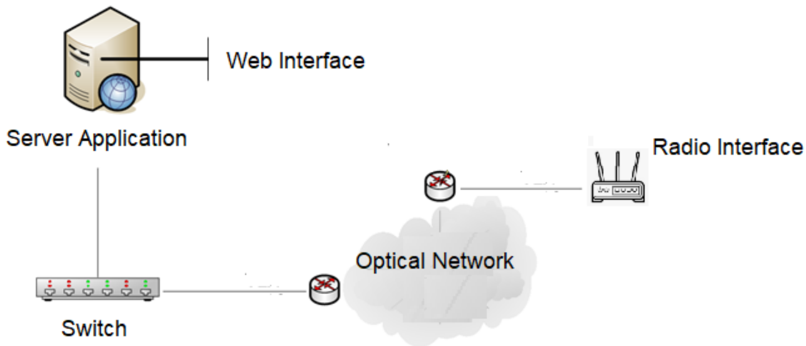

Figure 13 – *Generical backbone to connect radio's network.*

IoT scenario allows discussing several technical themes and how to build new technologies, and the virtualization is a resource widely discussed as a form to optimize networks, for example, decreasing many physical resources and expanding applications concerning networks. The concept behind network function virtualization is to decompose a given network service into a set of functions that can be implemented on commodity hardware through software virtualization techniques.

In practice, this is a constant work of development and systems integration, where, for example, each module (hardware) can take on more functionality eliminating the amount of hardware needed to perform each function and can deploy virtualization of physical resources to use the minimum necessary hardware (functionality implemented in abstract resource).

In this case study, an exponential increase in connected equipment, as envisaged in the IoT concepts, would not be possible with existing hardware concepts, because the existing infrastructure connects the railway operation services and will provide a connection for all users. For this reason, the decrease in physical resources and different forms of power supply has been deeply studied, as this item is directly linked to the advancement and implementation of technologies for IoT.

Two interesting ongoing research topics related to network virtualization are Software Defined Networking (SDN) and Network Function Virtualization (NFV). Software-defined networking can be seen as “the separation of [network] forwarding hardware from the control logic” [48]. Thus, SDN can be viewed as an enabler for network virtualization since it allows functionality to be implemented in the abstract rather than the physical domain [49]. The development of these technologies is related to the necessary improvements for this railway environment.

Regarding the **Network** block of Figure 11, Wi-Fi test results can be analyzed from the following perspectives:

Mobility - Most of the existing urban rail system to train-ground communication is based on Wireless Local Networks (WLAN) technologies. This is a great constraint to use this technology for applications that require mobility; by nature, they were not developed for this purpose.

In ground-to-train communication, the train is the moving element, traveling at speed along a physically variable trackside between tunnels and open areas, where each physical area or environment has a different radio wave propagation. The trackside must receive this radio signal coverage so that the moving train is not disconnected from the network and can transmit and receive all control application data transparently and in real-time.

By analyzing the range of a radio using Wi-Fi technology, it is possible to imagine how many radios will be needed to cover a complete trackside that is kilometers long so as not to leave any uncovered areas (see an example of distribution in Figure 12) and precisely because of this, the successive number of handoffs that the radio installed onboard the train must make on this route [50].

From the beginning of the use of these types of Wi-Fi technologies for rail communication, radio manufacturers for this type of application had many problems with these successive handoffs (because there was a loss of application communication due to network packet losses over handoff time). They had to heavily customize their embedded software to reduce handoff times precisely because these technologies were not suitable for the mobility required.

This fact affected railway networks too much because railway applications are susceptible to delay (because it has safety characteristics), meaning that if applications that control train movements lose communication, the emergency brake of the train is immediately applied before an accident occurs, i.e., the train must not lose communication.

The practical way to address this situation is to provide equipment redundancy to ensure that communication is not lost in any way. However, this involves other issues as more equipment is installed to do this redundancy and the management problem gets worse as there will be a duplicate of equipment and duplicate information to be managed. In addition, all solutions aim to reduce the amount of hardware and not increase it.

In this respect, Wi-Fi solutions seem unsuitable for applications of this nature, as there is a negative point that cannot be circumvented, which is that the physical range of signal coverage on the road is very small in relation to the distances to be covered, even when an antenna with a more gain is used.

Independent Frequency Network – As explained, the choice of Wi-Fi standard specifically for this study is because it is widely the most used and known standard in all types of applications and uses ISM (*Industrial, Scientific & Medical*) band frequencies as operating frequencies.

However, concerning the occupation of the channels, illustrated in Figure 10, it is possible to see that many channels have an occupation of almost 100%, meaning that many channels are already practically saturated using this technology. Even considering that the occupation of the channels occurs dynamically and that this data is only a 'photo' of a specific moment, another item to be analyzed is that a large part of the Access Points is for residential use, i.e., they are applications that make continuous use of the spectrum, they are not applications that make an intermittent use.

On the other hand, as shown in Figure 10, there is a much lower usage in the 5.8 GHz band; it is apparently underutilized.

Two aspects can be seen in relation to the use of frequencies: the shared use with residential applications and the poor distribution of applications in the available frequencies.

Table 3 – *IEEE Comparison Standards 802.11.*

Standard	802.11a	802.11b	802.11g	802.11n	802.11ac	802.11ax
Frequency Bands	5.8 GHz	2.4 GHz	2.4 GHz	2.4 GHz / 5.8 GHz	5 GHz	1-6 GHz
Year Released	1999	1999	2003	2009	2014	2019
Maximum Data Rate	54 Mbps	11 Mbps	54 Mbps	600 Mbps	1.3 Gbps	10-12 Gbps
Maximum Range	400 ft	450 ft	450 ft	825 ft	1000 ft	1000 ft

As shown in Table 3, the new IEEE 802.11 standards already make a better distribution using other spectrum frequencies. However, two aspects must be observed: the first is that the amount of equipment and users that tend to be connecting from now on is exponential, and the second is that users, whether residential or industrial, tend to implement the technologies as they are available on the market. Thus, there is a dependence on the large equipment manufacturers to place these technologies in their product lines and introduce them on a large scale in the market so that the other standards can be adopted, making this distribution better (in addition to this implementation of the standards does not distinguish residential and industrial users).

Regarding rail services specifically, the question of using frequencies used by residential users in their wireless networks is harmful because they are essential services with a high criticality level. When they pass within urban areas they may suffer interference, in addition to extreme cases already registered, when, for example, the railway traces pass nearby prisons, where signal blockers are generally used, impairing the wireless network propagation.

Bandwidth – The increased amount of data transmitted due to the growth of services connected over the network also increases the bandwidth needs in wireless transmission technology. More and more applications on the railways are using real-time data transmission, which always increases this need.

The basic systems that use train ground communications are Communication Based Train Control (CBTC) systems, Passenger Information Systems (PIS), and Closed-Circuit Television (CCTV) systems. In addition, many others are being implemented aiming at internet services for passengers and more specific services for train diagnostics for maintenance and service management [51], [52].

The implementation of these services must meet the demand, considering the need for each line in operation, such as the number of trains running, the number of track equipment and trains to be monitored in real-time, the number of cameras installed in the trains, number of passengers connected, etc.

Table 4 shows one example with typical needs values for each train communication.

Table 4 – *Train Ground Communication Requirement.*

Application	Throughput	Delay	Handoff Latency	Reliability
CBTC	100 kbps	100 ms	100 ms	High
CCTV	8Mbps	500 ms	500 ms	Medium
PIS	4 Mbps	500 ms	500 ms	Low

In this example, a typical minimum value is presented for basic services for the operation of each train. However, this tends to increase according to the number of services implemented. If there is interaction with more equipment on the road and at stations, they can also share this band if there is communication between elements. On a large scale, a train fleet needs this band in real-time.

Verifying at Table 4, it does not seem to demand much of the system the need for a throughput of 12 Mbps per train, but it can be observed in practice that simultaneous connections can occur at the same Access Point, connecting several trains simultaneously to the Control Center, for example, in addition to other elements of the station or track that use these access points, for example mobile devices used by station operators. This test setup considers technologies that reach a maximum of 54 Mbps according to Table 3, for current technologies (802.11.a/g).

Another point to be considered is that due to the different propagation conditions in the tunnel area and the transmission of the moving train this theoretical value is never reached, in practice this value is always lower.

Network Reliability, Availability, and Safety – Network reliability, availability, and safety are fundamentals for rail transport applications. The networks built for these applications must be highly reliable. In the case of metro transport, signaling systems have strict safety requirements (it is the requirement not to harm people, the environment, or any other assets during a system's life cycle). It also needs to have a high availability rate.

Performance and functional requirements for a communications-based train control (CBTC) system are established in the standard IEEE 1474.1-2004. A CBTC system is a continuous, automatic train control system utilizing high-resolution train location determination, independent of track circuits; continuous, high-capacity, bidirectional train-to-wayside data communications; and train-borne and wayside processors capable of implementing automatic train protection (ATP) functions, as well as optional automatic train operation (ATO) and automatic train supervision (ATS) functions. In addition to CBTC functional requirements, this standard also defines headway criteria, system safety criteria, and system availability criteria for a CBTC system. This standard applies to the full range of transit applications, including automated people movers [53]. Consequently, not only can the line capacity be increased, but the level of safety and services offered to customers could be enhanced and improved as well [54].

This standard from IEEE provides typical ranges for some CBTC parameters for general guidance only. Parameter values for a specific application and/or a specific CBTC system design should be established by the authority having jurisdiction and/or the supplier, considering all relevant factors for the specific application.

Table 5 – *Train Ground Communication Requirement.*

Parameter	Typical range
Maximum number of trains that can be processed by a single wayside controller	10 to 40 trains
Resolution of measured train location (i.e., as reported to establish movement authority limits for a following train for ATP purposes)	± 0.25 m to ± 6.25 m (± 10 in to ± 20 ft)
Accuracy of measured train location during normal (non-degraded) operations (i.e., maximum error in reported train location for ATP purposes)	± 5 m to ± 10 m (± 16 ft to ± 33 ft)
Accuracy of measured train location for programmed station stop (ATO) purposes—without platform edge doors	± 0.25 m (± 10 in)
Accuracy of measured train location for programmed station stop (ATO) purposes—with platform edge doors	± 0.05 m (± 2 in)
Resolution of train movement authority limits	± 0.25 m to ± 6.25 m (± 10 in to ± 20 ft)
Resolution of train speed measurement for ATP purposes	± 0.5 km/h to ± 2 km/h (± 0.3 mi/h to ± 1.25 mi/h)
Accuracy of train speed measurement for ATP purposes	± 3 km/h (± 2 mi/h)
Resolution of train speed commands (e.g., civil speed limits)	±0.5 km/h to ± 5 km/h (± 0.3 mi/h to ± 3 mi/h)
Train-to-wayside message communication delays	0.5 s to 2 s (nominal)
Wayside-to-train message communication delays	0.5 s to 2 s (nominal)
Wayside CBTC equipment reaction times	0.07 s to 1 s (nominal)
Train-borne CBTC equipment reaction times	0.07 s to 0.75 s (nominal)
Rollback detection criteria	0.5 m to 2 m (± 20 in to ± 6.5 ft)
Zero speed detection criteria	< 1 km/h to <3 km/h for 2 s (< 0.6 mi/h to < 2 mi/h for 2 s)

According to the data shown and results obtained in Figures 9 and 12, a network that covers the entire trackside is required with acceptable signal levels, and many redundancies are necessary for the construction of a CBTC type system, that is, a system that can meet the requirements defined in railway regulations for train-ground communication, as presented in Table 5.

Open Standard and Cyber Security – IoT technologies have been developed with open standards to connect everything to the Internet, and it would be impossible if proprietary protocols were used. On the other hand, rail networks have been designed segregated and without an Internet connection because they have rigorous safety requirements. In this regard, the big challenge is creating interoperable networks but ensuring the security and integrity of the data transported from malicious attacks.

Figure 10 shows the occupation of the Wi-Fi channels extracted from the test rail environment; it is possible to verify that there are channels that present a very high occupation, especially the channels in the 2.4 GHz band. This is because industrial and residential users share the spectrum with no separation or distinction criteria in this case.

A point to be noted is that the part chosen to perform this test was a tunnel area, that is, an area with little external influence, but when the road is open, this occupation tends to be much higher since all users of the surroundings share the same spectrum.

Network security is a point of much discussion regarding rail applications. Some countries are already discussing laws that mandate rail operators' network security liability, making them responsible for any incidents or accidents in the event of cyber-attacks that could cause damage or, in extreme cases, victimize people.

Rail services are considered essential for the movement of passengers and cargo, it is a fundamental infrastructure service which makes this service very directed to terrorist actions, focus of military actions in war situations, because achieving a service like this is a way directly from causing chaotic or harmful situations.At this point, a big discussion is open, how to ensure the complete security of a network with such strict security criteria using technologies designed to work with open protocols? Industrial networks today are no longer air-gapped and immune from cybersecurity threats. Another issue is that the more the network connects with external elements, the greater the subject of vulnerabilities. Since systems tend increasingly to be integrated with external elements, the negative effect is having to increase much more data protection of systems within the network, especially data from vital operations of the trains, [55] so it is required tools are sophisticated and robust to protect the network. In addition, there is still the issue of user connectivity, which in a way, is also another element to be managed. On the other hand, there are researchers who argue that the use of open protocols would not be a problem, since these open protocols are widely tested and validated by the community.

It is observed that in several countries, the equipment manufacturers in the railway sector are engaged in developing a standardization to guarantee the minimum requirements to be met. However, this discussion does not involve only technical characteristics, which would be quite complicated due to the rapid evolution of the means of attack, which is a dynamic and fast process of evolution, but it also involves the legal characteristics of each country in the regulation dealings and especially punishment against cybercrimes.

Data managing and Big Data - Discussing an IoT scenario, where all "things" will be connected to the Internet, the volume of data generated by these connected devices is immeasurable. In this aspect, data processing, analysis, and storage are discussed, including cloud network concepts. However, data storage becomes a complex issue because it would be highly efficient if the system itself could analyze and store only relevant data for the applications that use the stored data. Thus, it saves the network from transmitting of unnecessary data to the final storage occupying spaces without practical use. It would be extremely important that these data be treated and classified intelligently.

In this case study based on a Wi-Fi network, is demonstrated only a small data collection from an application on a specific train, simulating a communication from this train (to reach the control center through a Wi-Fi network, that connects to the optical backbone) where the application-based management is located. In this central management location where the databases are installed, recording operational data and making them available for consultation by the operators and maintenance teams, it is possible to verify the amount of data when thinking about the system as a whole, with all the elements connected.

Usually, in current applications, SQL or similar databases are used, which store the applications' data and make this data available in the form of queries. However, dealing with this type of bank has many disadvantages since to maintain it is necessary to create automatic bank cleaning routines to delete the oldest data, thus freeing up space for storing new data. Generally, this data is erased based on older record dates, leaving the most current data recorded; that is, they obey a record time window. However, discarding data without verification of relevance or based on a fixed criterion is not the most appropriate way to do this.

A drastic change in this type of network will occur, transferring data from all users for Internet access (infotainment application) and integrating information from many sensors for predictive maintenance applications, a characteristic of the IoT network. The network core should also have a high capacity to process the necessary algorithms and programs (for delay-sensitive applications) and cloud space to store [56].

As data has been increasing explosively due to the development of social networks and cloud computing, there has been a new challenge for storing, processing, and analyzing a large volume of data. A big data platform certainly helps users develop analysis services effectively.

A good example of applications that have grown considerably are real-time video monitoring of passengers and stations and continuous maintenance monitoring applications, which generate an impressive volume of data that needs to be handled in real time. Therefore, a big data analytics platform is needed that effectively supports the management of this massive data and the development of analytics algorithms and services, collaborating with data owners, data scientists and web service developers, especially as CCTV are exponentially growing on transportation's platform.

To ensure operational safety, it is necessary to monitor all equipment that makes up the railway signaling systems. Reviewing the literature, there are studies that investigate the data management status of permanent railway equipment, perform a demand analysis on the exploitation of big data applications and propose a general framework for a permanent railway platform based on the rail data services, as well as researching data cleaning and management mechanisms, full-text recovery, and cold/hot data storage strategies [57].

In this way, prototypes are being studied to offer big data applications that can provide data and support to decision-making for a proper orientation for the maintenance and management of permanent way equipment.

Regarding **Application** block of Figure 11, Wi-Fi test results can be analyzed from the following perspectives:

Quality of service (QoS) - There are Quality of Service (QoS) requirements for different train ground applications. The QoS requirement parameters for wireless railways networks include communication latency, throughput, handover latency, and jitter. These requirements are essentials for rail application (the signaling services of trains) and users' system.

Applications involving the signaling of trains require more restrictive parameters in relation to QoS. According to Table 4, it is possible to observe examples of applications such as CBTC (train signaling application), which requires low delays, low handoff latency and high reliability, compared to other typical systems, as it is an application that has safety parameters involved.

To achieve such QoS parameters, it is necessary to provide a network architecture that makes redundancies (often physical equipment, in addition to systemic configurations) to mitigate failure situations, maintaining the high availability of the system. In terms of hardware, it is usually duplicated in mission-critical systems, such as trackside radios, so that there is no gap in signal coverage on the track, causing a disconnection in the communication with the train. This is a positive point in terms of availability (QoS), but it is a very negative point for maintenance, costs, energy consumption, etc. [58].

In this case study, only a few typical applications for supporting railway operations are presented so it seems simple to exemplify the QoS parameters that must be met. However, one must imagine that a totally disturbing item in terms of multimedia applications supported by networks of next generation requires an unprecedented escalation of capacity and strict quality of service (QoS) in the networks of connected vehicles, especially in passenger rail transport, since passenger Internet connection services, called infotainment, also become part of applications on current rail networks.

Another important point to note is the tendency of all applications to be Web-based, with significant interaction with external elements reached through the Internet interacting with elements of the internal network of the railway application. In this case, the guarantee of Internet QoS must be discussed since many railway applications are very sensitive to delay, especially signaling applications. This discussion also covers other aspects, such as the trend of storing data in the cloud. For example, an application that depends on querying external data stored in the cloud must consider that the application must access this data through an interface to take the necessary actions, and if these QoS parameters are not well adjusted, this may cause problems or even not meet certain types of delay-sensitive applications.

Returning to the discussion on the qualification of essential data for signaling applications, where it is necessary to have a good data management as explained in the previous item, Data Management and Big Data in Smart Networks can provide necessary mechanisms to separate the relevant information for each application, because by the way they will be qualified, accessed or stored, they can effectively help to achieve the adequate QoS for each application. As shown in Table 4, CCTV and PIS applications can support delays five times longer than a CBTC application, for example. In this example, the availability to access CBTC data is more critical than the others, and it is a priority.

4.2 Improvement points based on the case studies presented

According to the points shown in the previous section, it is evident that it is necessary to discuss an improvement within each item.

The points or aspects to be analyzed and improved based on data collected are described below.

Environment Characteristics – One of the railway environment characteristics is an extremely noisy environment due to the use of high voltage in the power supply of trains by the third rail or by overhead lines (catenaries) that distribute high voltage along the track for train movement.

A great example that can be mentioned as an improvement would be devices that make it possible to reduce this noise, which is also a cause of electromagnetic interference in communication systems, especially wireless. Notoriously, some companies already invest in initial projects with renewable energy solutions that, at the same time, can provide energy in a cleaner way and changes in this railway environment regarding this topic.

This is a trend that must be adopted more and more, generating new solutions that, probably in a few years, will modify the railway solutions known today. An initiative that can be cited as an example is the trains of the Coradia iLint fleet, developed by the company Alstom® that uses hydrogen as an energy source for the trains, currently operating in Germany. It is a clean energy concept for railways, with a sustainable solution for non-electrified networks, which operates with lower noise levels, an innovative design that replaces the traditional solution for a passenger transport line. This type of clean technology, which does not use conventionally power generation, automatically contributes to a cleaner environment in terms of electromagnetic emissions from high voltage lines, also reducing the interference of sources of this nature in wireless systems. Another good example that can be mentioned is the Citadis fleet trains, also manufactured by the Alstom® company present in Paris, Barcelona, Melbourne, Rotterdam, Madrid, Casablanca, Jerusalem, Dublin, Nottingham, and Dubai, which are powered by supercapacitors implanted in the soil, which also produce less noise in their electrification process. In this way, a point suggested as improvement is devices that can reduce noise that cause interference in wireless systems, whether they are inside the wireless system or in the components that make up the environment, such as in the devices of trains and rails.

Another characteristic that the railway environment presents is that it has a large part as an underground network (especially those dedicated to passenger transport in urban areas). This makes the environment very complicated for the uniform distribution of the radio frequency signal, mainly due to the physical constitution of the tunnels where the signal tends to suffer a lot of reflections. As can be seen in Figure 14, when the train is positioned inside the tunnel the little space for signal propagation inside the tunnel (generally the tunnels are very tight when the train occupies a section), there is practically not much space left for the free signal propagation outside the train.

Figure 14 – *Train occupying a section of the tunnel*.

Initiatives such as VLC (Visible Light Communications) can be easily identified as improvements when applied to the railway environment [59].

Immediately, it is possible to observe important points that this technology could improve aspects where the network of the setup used in this dissertation has weaknesses, as follows:

a) Distribution of RF coverage: This application makes use of a visible spectrum of frequencies. In this way, it is much easier to visualize the distribution of RF coverage within the tunnels, making it much easier to distribute the signal evenly along the sections.

b) Capacity and better spectrum distribution: When analyzed in terms of capacity, an application of a technology like VLC jumps from 54Mbps (theoretical data from Wi-Fi setup used in this dissertation) to an impressive 20Gbps [60]. Beyond capacity, it also contributes to a better distribution of services using new bands of the spectrum (which is already widely used in some bands like Wi-Fi), as shown in Figure 15.

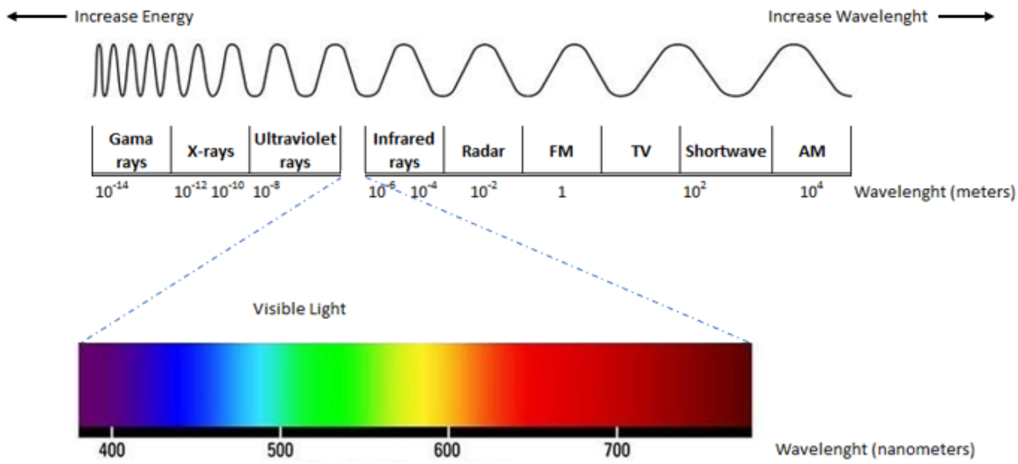

Figure 15 – *The Electromagnetic Spectrum*.

c) Infrastructure Reduction: An implementation like this reduces the amount of physical equipment distributed along the road, which certainly already protects the system from vandalism and improves the issue of system maintenance. Tunnels are usually sanitized with high-power washers, which can damage equipment if they do not have an adequate degree of protection. The smaller the exposed hardware, the longer the system lifecycle will last.

d) Improvement in terms of interference: A negative aspect in relation to wireless applications is the presence of interference, especially in systems that use Wi-Fi, which today shares the spectrum with all types of users, industrial and residential. The use of another technology, finds benefits as it provides new spectrum for transmission, less used by common users, especially residential.

e) Cybersecurity: Once Li-Fi technology is used for this implementation, we can verify that the coverage will be totally restricted to the tunnel area, in this way, the reach of this network outside the tunnel will be practically non-existent. This is an important point for network protection, as it cannot be reached by malicious external users, as the network will be confined within the tunnels.

Discussing a about the hardware part, another point that can be pointed out as an improvement would be the alteration of materials in the construction of the train compositions themselves. The development of less reflective materials (that is, more permissive in terms of penetration for certain frequencies) can help in terms of coverage of radio frequency signals since most of the signals reflected inside the tunnel are due to the direct incidence of the signal on trains; that is, the train itself sometimes acts as an element that spreads the signals that fall on it and consequently causing reflections. With the incorporation of the appropriate materials, the antennas could already be incorporated into the chassis of the train, without the need to install external antennas, as usually is done today, parts of the train could already act as antennas.

The transport industry is constantly studying the application of new lightweight materials for primary structural design. There is an aeronautical trend, where composite materials are now replacing metallic materials in structural and non-structural parts. These initiatives are also accompanied by the railway sector, which can benefit from using new structural materials. By changing the materials of the train's compositions, their weight can be reduced and, as a direct consequence, less energy consumption for moving trains and less CO_2 emissions can be obtained.

Interestingly the practical structural requirements studied for the adoption of composite materials focus on resistance, resistance to collisions and fires, noise and vibration, electromagnetic compatibility, and maintenance. Precisely, if these studies consider electromagnetic compatibility, it would be possible to aggregate in these studies materials to make trains less reflective, thus contributing to the communication systems.

Another point that was described as a characteristic of this railway environment was vibration issue to which onboard equipment is subject. This causes the equipment to suffer successive impacts and vibrations, which reduces the useful life of the equipment and requires industrial characteristics of the onboard hardware.

A point of improvement that could be highlighted is the application of sensors capable of canceling the vibrations on the equipment on board. The suggestion consists of sensors connected to the onboard computer that detects sudden movements and applies an opposite movement of the same intensity to cancel the impact suffered by the hardware (these sensors could act as an absorber system for the onboard hardware). This point of improvement consists of creating devices that cancel or reduce the vibrations suffered by the onboard equipment to extend its useful life. In addition to passenger trains, solutions like this would be of great use for cargo railways where the environment is extremely hostile.

Mobility – With the advent of IoT, the trend of connected mobile devices grows and an improvement point for all network technologies is to be prepared for the mobility of devices.

Thinking about a system prepared for mobility inevitably enters the concept of Smart City. In a connected city the citizens need fast, easily accessible and on-demand means of transport. In a way, it is possible to imagine a mobility system incorporated into the circulating environment, a system that is naturally part of the surrounding environment, as a part of a whole that acts in an integrated manner. Telecommunications networks tend to be the integrating element of this whole, that is, the means by which all things are integrated and interact in an organized manner.

The excessive use of private cars has generated a high level of air pollution, congestion in large cities, poor use of public transport, and often, overcrowding when the network is not designed adequately for the region's population. On the other hand, there is a tendency among younger people not to purchase cars, using alternative means such as applications in general, like Uber® services.

In this way, many opportunities arise and the need to interact with mobile broadband technologies, location detection, and social media, for example, so that the rail system can be integrated through new services and treated like a "service".

Many topics currently being studied can be cited as points of improvement regarding mobility; among them are **Smart Infrastructure**, where cities are developing their new infrastructures using new technologies based on sensors, machine learning, data analysis, and intelligent decision system. Within the rail system, the new networks must be designed with these characteristics, to be part of a participating infrastructure, not only passively, but acting in the environment to which it is inserted, so it will be able to interact and adapt its operations according to the demand of the service.

Another theme that can also be seen as improvement within this context is **Autonomous Driving**. Driverless trains are a reality today. Systems like CBTC operate autonomously or with minimal human interference, making driving easy and safe on the roads. For this system to become increasingly autonomous, many improvements can be implemented, such as communications between trains, Train to Train, Train to Infrastructure through Sensors or Smart Objects, etc.

An improvement that can be mentioned is the **Integration Networks** between operators of the same transport mode, as it is well known that transport is being built to be integrated between them, be it the rail, road and air services. However, observing the railway operators, each one physically builds its network for operation, in isolation, by a train line, for example. This seems to be in the opposite direction if the objective is to make the services act in an integrated manner.

Another point to be included is the **Decentralization of energy systems**, using more and more renewable and more widely available energy sources. Decentralization of energy reduces the demand for urban electricity grids and creates more private and public charging stations. Moreover, since the demand for network coverage is increasing, and in a decentralized way, it is necessary to have a means of energizing it as well; this way, there will be a great contribution to the development of mobility.

Smart mobility regulation can also be cited as a point of improvement, as many cities and governments are introducing laws and regulations that encourage and support the use of mobility applications and new transportation methods. This item includes financial incentives for companies that use clean vehicles, local traffic rules that prioritize public transportation, and integrated urban mobility solutions.

Independent Frequency Network - ISM bands can be used without a license and are subject to a relatively reduced set of operating rules, i.e., do not need a license to operate if the transmit power values are within the set values for low power emissions. Perhaps for this reason, too, having more simplified regulation on the use of frequency spectrum, equipment manufacturers have developed their most commercialized industrial wireless network solutions in these frequency bands.

The big problem is that not only ISM applications are used at these frequencies, but all types of common applications, including the common population, with residential applications of all kinds, which makes the spectrum at these frequencies polluted, especially at 2.4 GHz and 5 GHz.

Another downside is that coexistence of industrial applications with all others increases interference, so many studies and developments are used to strengthen industrial applications against these harmful interferences. In addition, applications using the ISM band, by regulation classified as secondary, may not cause interference in primary, i.e., licensed applications, and in this case, must cease their transmission to ensure the integrity of the primary applications.

Another crucial point to be considered is that with the Coronavirus pandemic, there was a disorderly increase in people working from their homes in a home office regime, and many continued working from home, even after this period. In practically every home, people are connected to a Wi-Fi network working all day. In this way, a situation that was already bad in terms of spectrum pollution becomes unbearable in terms of spectrum sharing with industrial applications that require a certain exclusivity of service.

A point of improvement concerning this issue would be creating a rule for industrial users not to share the spectrum with residential users. In that sense, an amendment to the Regulation on the use of frequencies could be very useful. The generation of mechanisms that can provide industrial users, especially those that have security requirements, for example, passenger transport services, security services, health services, that is, networks that are at the service of public utilities, have their frequencies of operations preserved in some way, or with priority over other non-essential services in case there is a need for sharing. Also, in the case of sharing between services, another point of improvement could be spectrum sharing techniques, which already contained these prioritizations intrinsically, so that it was already possible to identify users and automatically establish these priorities.

Wireless technology (Bandwidth) - The current needs for data transmission, the exponential growth of connected elements, and especially the demand for multimedia application services already automatically makes this item a point of improvement within the railway scenario, which has been following and developing new services based on trends in other sectors. However, the need for everyone will be the same, an increase in the need for bandwidth for high-volume data transmissions, especially multimedia.

Thinking of needs based on current applications, one point of improvement is to generate technologies that allow a higher data rate transmission using less bandwidth, thus optimizing the resources of the transmission medium. This would be a way of optimizing resources as we know them today.

In the book "*Computer Networks and the Internet*" [61], there is an interesting approach in chapter 7.1.3 - "how the internet should evolve to better support multimedia applications", and describes that there are three strands of thinkers, on the one hand, researchers who think that it is necessary to make fundamental changes to the Internet so that applications can explicitly reserve end-to-end bandwidth, so that in this way they can guarantee end-to-end performance. On the other hand, there is a current of researchers who argue that it is not necessary to make any fundamental changes in the best effort service and in the underlying protocols of the Internet, as they defend a more liberal approach, assuming that:

a) As demand increases, ISPs (Internet Service Providers) will expand their networks to serve them.

b) Content distribution networks would duplicate stored content and place it on the edges of the Internet (given that a large fraction of the traffic through the Internet is from stored content, as Web, MP3 or video).

c) In the case of live streaming traffic that is being sent to thousands of simultaneous users, for example, multicast overlay networks can be used, which consists of host users and possibly dedicated servers spread over the Internet. Where, these hosts, the servers and the logical links between them form an overlay network that transmits multicast traffic from the source to millions of users (but unlike IP multicast traffic, in which the multicast function is operated by routers at the IP layer, in this overlay network, multicast occurs at the application layer).

It is also described that there is a third group, which opines for the field of differentiated services (Diffserv), that is, making small changes in the network and transport layers. The idea is to introduce a small number of traffic classes.

In short, points can be improved and in different ways as can be seen in this valid example described above. From the point of view of the first group of thinkers who advocate a fundamental change to guarantee end-to-end bandwidth, a range of possibilities opens. Considering the changes thought by this group tend to be more innovative/radical imagining that to allow applications to make an end-to-end reservation of bandwidth, and for the network to honor those reservations, implies some big changes (even more bringing it to the field of the Internet of Things, where we have massive connections).

Opening the way to create innovative data transmission technologies, a good example may be to use other types of spectra; this may mean providing technologies with greater capacity in terms of bandwidth, such as technologies that use data transmission over visible light, for example.

Network Reliability, Availability, and Safety – Making an analysis from the point of view of Reliability, Availability, and Safety, it is possible to build a wireless network for a railway application and fulfill the requirements set out in the railway signaling standards. The point is that to achieve such parameters using a conventional network, as shown in this dissertation, it is necessary to apply a much redundancy of physical equipment along the road, for example, as shown in Figure 13. It is necessary to make a massive distribution of equipment (access points) along the road, not leaving some points without wireless network coverage. In addition, it is also necessary to provide mechanisms for redundant powering of physical equipment so that there are no power failures causing interruption of services.

Another point that must be observed concerning the wireless network is the interference to which it is subject. As previously mentioned, the increase in the use of wireless networks in the domestic environment becomes harmful to industrial networks that share the same spectrum and thus can cause momentary unavailability in critical services that make use of this technology, directly affecting availability parameters, which is unacceptable for applications with safety requirements involved.

From the point of view of the core network, it is simpler to implement mechanisms that allow increasing availability and reliability through specific configurations that can prioritize certain types of traffic on the network. However, in any case, all good practices in the configurations are conditioned to the high availability of the physical hardware; otherwise, a simple hardware failure can harm the entire network functioning, no matter how good its configuration is.

It is evident that the improvement points related to the physical network, specifically hardware improvements, automatically reflect improvements in the Reliability, Availability, and Safety parameters. This fact does not prevent that improvements in configurations and implementations of new mechanisms against interference from the physical environment can also be applied to increase the availability of the system. The study of mechanisms against interference and noise, is a topic where numerous studies and possibilities in relation to wireless networks.

Quality of service (QoS) – Typically, networks operate on a best-effort basis, so all traffic has the same priority and the same chance of being delivered on time. When congestion occurs, all traffic has an equal chance of being dropped.

Implementing QoS on the wireless network makes performance better and bandwidth utilization more efficient. When QoS is configured on the access point, it is possible to select specific network traffic, prioritize it, and use congestion management and congestion avoidance techniques to provide prioritization. Also, policies are created and implemented in the VLANs configured on the access point. If a network does not use VLANs, QoS policies can be applied to the access point's Ethernet and radio ports.

Under the QoS analysis, it is possible to implement configurations to improve the network performance according to the service to be prioritized. For example, assuming that it is necessary to prioritize voice traffic from the PIS service of a particular train, it is possible configuring QoS for a Voice VLAN on trackside Access Point. In this way, the traffic of voice service to the communication with passenger onboard is prioritized to the detriment of other applications that traffic on the same network.

However, railway signaling services generally use segregated networks precisely because they must reach more restricted availability parameters. Thus, there is a certain discouragement for wireless network designers/architects for railway applications to make signaling networks shared with other services. This becomes a negative point in terms of network integration and optimization, as two distinct physical networks will be needed to meet the needs of basic rail services (some described in Table 4), which can be divided very generally between Safety and non-Safety services.

A point of improvement that can be mentioned directly is the QoS guarantee of a Safety application when sharing resources with non-Safety services in an integrated network. That is, guaranteeing a prioritization of this service over others that share the same network to comply the signaling standards fully.

Open Standard and Cyber Security - The most sensitive theme regarding IoT impacts in the rail sector is precisely the issue of cyber security. Once the rail networks are connected to the Internet, their fleet could be at risk of a cyber-attack. Regarding passenger transport services, the risks are much more significant. Thus, the impacts and importance of safe systems for the future arise since the rail systems, especially the passenger transport systems, are very much targeted by terrorists, motivated by various reasons, trying to expose the systems to catastrophic failures.

Cyber security requires comprehensive solutions to protect networked trains and transport infrastructure. The subject should be studied and developed from various perspectives, such as technical, political, and security. Various efforts from industry, academy, and government can be aggregated to shape current development and make the deployment of new technologies technically safe and regulated.

This is a very complex topic, a vast range of opportunities in new applications arise from this topic, which involves the safe operation of the network, but also applications for tests and simulations of attacks, applications of continuous monitoring of network integrity, and applications for integrity recovery after an attack, vulnerability prediction applications, and so on. In this way, opportunities with algorithms and methods of vulnerability detection, modeling of tools to simulate attacks, establishment of monitoring processes and self-correction of systems, systems recovery tools, and elimination of vulnerabilities are widely promising themes.

As described above, through these citations, this seems to be the topic where most improvements can be made, as so far it does not seem to be mature enough. These can precisely be analyzed as points for improvement, that is, the areas where so far there is not much progress when it comes to this topic.

In this way, all quotes from applications for tests and simulations of attacks, applications of continuous monitoring of network integrity, applications for integrity recovery after attack, vulnerability prediction applications, algorithms and methods of vulnerability detection, modeling of tools to simulate attacks, establishment of monitoring processes and self-correction of systems, systems recovery tools and elimination of vulnerabilities can be highlighted as points for improvement, and in this case, more precisely as points to be developed.

Observing how new networks are being built, the trend of using open standard technologies, that is, that do not use proprietary protocols, enables the integration between networks and services. However, this benefit also has a negative side, which is precisely the creation of certain vulnerabilities, since any developer can have access to the code. In this way, what is a benefit in terms of systems integration, also becomes a problem observed from a cyber security point of view. Artificial intelligence can significantly contribute as a system integrator element regarding security issues. It can add security levels to the systems, acting in an integrated way to the actions of cyber security, since it can act in a predictive way, as if it were acting in a way to anticipate corrective actions or even anticipating vulnerabilities before they can occur, to close these possibilities, as if they were "thrown" ahead. Making an analogy, artificial intelligence would play the role of a firewall with very sophisticated performance characteristics and not just blocking certain access attempts. It would be something capable of operating and taking actions in real-time with more refined techniques for network defense.

Data managing and Big data - Studying the points of improvement that should be implemented in a rail network within the scope of the Data managing and Big Data concerning to Internet of Things scenario, there is an automatic need for intelligent data processing, since there is a tendency for absurd data collection, from systems increasingly monitored in detail. However, this generated information needs to be interpreted and treated to allow for adequate data management and quick and easy availability of important data for applications aimed at network operation and maintenance and commercial/user applications.

It is possible to cite the term currently known as **Data Governance**, which is defined as the collection of processes, roles, policies, standards, and metrics that ensure the effective and efficient use of information in enabling an organization to achieve its goals. Data governance defines who can take what action, upon what data, in what situations, using what methods. Some literature point to this Data governance concept as a basis for Data Management, and it can address important topics such as: **Metadata**, **Data Quality**, **Data Retention,** and **Data Exchange**, which not by chance seem to map some real Data Management needs.

In the current scenario, there is an exponential demand for systems, services and qualified professionals (data scientists, for example). At this point, the concepts of data governance can be cited directly as a point of improvement in terms of Data Management and Big Data, as it can make data processing more effective and efficient through the implementation of its policies, managing data collected through wireless networks or even sensors.

Energy Efficiency - There is enormous potential for the development of technologies related to intelligent networks and systems integration in this area, with emphasis on automation, sensor networks, data collection and analysis software, predictive maintenance, energy efficiency, alternative energy (clean, not polluting, and renewable) sources. A vast subject to be exploiting, companies play a key role in the efficient use of energy resources given the costs of generating energy. Physical equipment needs constant transformations for the future of clean energy generation with renewable sources and the required efficiency. Widely discussed in the research community, it makes this topic practically mandatory for the advancement of any new technology, always thinking of generating the best energy efficiency of its components.

In the railway sector, specifically, there is a gigantic consumption of energy, mainly for the movement of the trains and for all the systems that are part of the trains' signaling, operation and maintenance. While many industry initiatives have sought to improve their energy efficiency, there are many needed changes that can certainly drive new research on energy efficiency and economy, in addition to technologies focused on depollution for the case of alternative and renewable energies.

A point previously discussed in the item of Mobility as the decentralization of energy systems is also relevant as an improvement in this topic, this will make the systems can operate more efficiently, but here, more broadly, the search for new non-polluting energy sources, known as clean energy, also fits.

In terms of systems, it is also necessary to evaluate how the systems consume energy. Three improvements points that can be mentioned: i) the reuse of the energy spent unnecessarily or the development of mechanisms that allow the systems to reuse the energy generated; ii) save energy when not in operation, many equipment individuals already have technology like this, but it is necessary to provide solutions in terms of systems, in an integrated and widely way; iii) generate energy as needed, i.e., generate energy on demand. These are concepts of improvements that can be applied objectively depending on each application; in fact, they are actions that can be implemented in a practical way making the use of energy more efficient.

Virtualization of resources - In this context, many challenges or opportunities are open because, when one physical entity is virtualized, simulations of real environment can be easily glimpsed. Then, physical resource optimization can be achieved, situation corrections or preventive actions can be taken before any damage occurs, among other possibilities.

In terms of software, applications are endless, and one impacting point to note is that rail applications, especially train signaling, have always worked in a segregated way in terms of the network to ensure data security for the system that involves critical levels of safety. This architecture was entirely based on hardware, including duplication of hardware, where redundancies were needed; at this point, a significant paradigm is being broken, with virtualization of physical resources.

Virtualization of physical resources is undoubtedly certainly the near future of the networks, as it seems to be the obvious way to meet the strong trends of decreased hardware utilization. In this way, the virtualization of all possible items can be highlighted as a point of improvement.

Chapter 5: Conclusion and Future Work

5.1. Lessons learned

The redesigning of systems is an exercise in knowing the existing systems, understanding their deficiencies, and designing their points of improvement, which must be continuous. Technologically, the ideal moment to make such changes is when disruptive technologies arise, making possible the innovative technological advance, as is the case of IoT. This dissertation gives an overview of how IoT has impacted the rail sector and some topics of potential exploration by the academic community and the industry itself.

5.2. Main Conclusions

This work contributed to discuss the points that can be improved, when observing a standard application, a railway Wi-Fi network in the way it is usually implemented nowadays. Which has been adapted to meet a connection need for rail applications, but at the same time does not fully meet the need for your type of use. It was exactly, something available to meet a need, but at the same time it could not be customized, thus leaving gaps to be fulfill.

Currently, the technologies of networks are crossing disruption time with the advancement of the Internet of Things. A change in behavior is occurring due to an interaction these people are having with these new technologies, not just good things like easier access like information from the whole world in real time but also bad use from technology that affects Its day by day, like terrorist attacks, for example.

Disruptive technology offers countless possibilities for new business but can also bring unpredictable risks due to its innovative nature. This dissertation brings contributions for these new emerging technologies to be implemented with a certain level of maturity, mapping the requirements (aspects) for the railways' applications related to train-ground communication networks and possible changes in the real solutions.

Objectively:

- Mapped requirements based on existing technologies;
- Presented a case study, and the type of data collected;
- Indicated improvement points based on the case study presented.

This dissertation is an input for new technologies and solutions to be rethought from the point of view of topics subject to improvement, so that when implemented they can efficiently and satisfactorily aggregate the needs of the railway market so that both operators and passengers can enjoy the best benefits that technologies can offer. Understand what the needs of railway applications are and verify if a standard network used today meets these needs.

Contribute also to the development of networks and telecommunications technologies for applications in the railway sector.

5.3. Future works

Some topics can be exploited in depth by academy and industry. In a way, all the topics described as points of improvement may be passive of future studies, either together or alone, once there is a significant correlation between themes.

- Environment Characteristics - Within the characteristics of the rail environment that is quite hostile, develop products that meet these characteristics, with the least amount of hardware possible. Embracing concepts of ubiquitous computing, to circumvent the excessive need to use hardware. Address concepts of Virtualization of resources, to circumvent the excessive need to use hardware.

- Mobility - Explore the changes that can be made, from the point of view of Smart Cities, where mobility is seen as a service. Explore ubiquitous computing concepts within Smart Cities, and their practical applications. Explore the network integration for different rail companies creating global solutions for services interactions in Smart City context.

- Independent Frequency Network - Study possibilities for a rational use of spectrum, where industrial applications do not use spectrum shared with residential applications.

- Wireless technology (Bandwidth) - Discuss bandwidth needs in wireless networks versus implementation of IoT applications in the railway area.

- Network Reliability, Availability, and Safety - Verification of requirements for rail networks versus Internet of Things Rail networks (RIoT).

- Quality of service (QoS) - Explore the improvements that can be made in terms of QoS, as video applications will increasingly demand network resources. Explore how context-aware wireless connectivity techniques can improve QoS in a railway network.

- Open Standard and Cyber Security - Deepen the discussions related to the use of open standards, which is a characteristic of Internet of Things networks versus the vulnerability when analyzed from the cybersecurity aspect. Discuss the characteristics of rail networks and how they can apply cybersecurity best practices. Discuss mechanisms to prevent cyber-attacks on essential service networks.

- Data managing and Big data - Develop concepts related to this topic within the scope of railway networks, where the increase in maintenance and operation data is observed through the application of characteristic sensing techniques on the Internet of Things. Develop algorithms to qualify and process data, especially voice and video captures, for different types of application. Study the correlation of Context-Aware with Data managing and verify how this technique can help in the qualification of the obtained data and distribution for each application.

- Energy Efficiency - Explore Clean Energy related topics within rail applications.

- Virtualization of resources - Develop techniques that embrace ubiquitous computing concepts, to circumvent the excessive need to use hardware. Research the grouping of functions that can be virtualized to reduce the amount of physical equipment to be used on the track by railway signaling systems.

References

[1] R. D. C. D. Leles, J. J. P. C. Rodrigues, I. W. Woungang, R. A. L. Rabel and V. Furtado, "Railways Networks - Challenges for IoT Underground Wireless Communications," 2018 IEEE 10th Latin-American Conference on Communications (LATINCOM), Guadalajara, 2018, pp. 1-6. doi: 10.1109/LATINCOM.2018.8613203.

[2] J. Moreno, J. Riera, L. de Haro and C. Rodriguez, "A survey on future railway radio communications services: challenges and opportunities", *IEEE Communications Magazine*, Vol.53, No.10, pp.62-68, October 2015.

[3] S. Yu, "Research on the Construction of New Urban Rail Transit Management System Based on Cloud Computing Algorithm," *2021 International Conference on Networking, Communications and Information Technology (NetCIT)*, 2021, pp. 139-142, doi: 10.1109/NetCIT54147.2021.00035.

[4] K. Ashton, "That 'internet ofthings' thing in the real world, things matter more than ideas," *RFID Journal*, June 2009.

[5] J. Höller, V. Tsiatsis, C. Mulligan, S. Karnouskos, S. Avesand, D. Boyle: From Machine-to-Machine to the Internet of Things: Introduction to a New Age of Intelligence. *Elsevier*, 2014.

[6] K. Chopra, K. Gupta and A. Lambora, "Future Internet: The Internet of Things-A Literature Review," *2019 International Conference on Machine Learning, Big Data, Cloud and Parallel Computing (COMITCon)*, Faridabad, India, 2019, pp. 135-139. doi: 10.1109/COMITCon.2019.8862269.

[7] M. H. Miraz, M. Ali, P. S. Excell and R. Picking, "A review on Internet of Things (IoT), Internet of Everything (IoE) and Internet of Nano Things (IoNT)," *2015 Internet Technologies and Applications (ITA)*, Wrexham, 2015, pp. 219-224. doi: 10.1109/ITechA.2015.7317398

[8] N. Koshizuka and K. Sakamura, "Ubiquitous ID: Standards for Ubiquitous Computing and the Internet of Things," in *IEEE Pervasive Computing*, vol. 9, no. 4, pp. 98-101, October-December2010. doi: 10.1109/MPRV.2010.87.

[9] Bhagya Nathali Silva, Murad Khan, Kijun Han, “Towards sustainable smart cities: A review of trends, architectures, components, and open challenges in smart cities”, *Sustainable Cities and Society*, Vol. 38, pp. 697-713, 2018 - ISSN 2210-6707, doi: 10.1016/j.scs.2018.01.053.

[10] Z. Hu et al., "An intelligent tension sensor for high speed railway catenary monitoring," *2022 IEEE 2nd International Conference on Power, Electronics and Computer Applications (ICPECA)*, 2022, pp. 500-503, doi: 10.1109/ICPECA53709.2022.9718891.

[11] Hwaiyu Geng, "The Industrial Internet of Things (IIoT)," in *Internet of Things and Data Analytics Handbook*, Wiley, 2017, pp. doi: 10.1002/9781119173601.ch3.

[12] M. Eiza, M. Randles, P. Johnson, N. Shone, J. Pang and A. Bhih, “Rail Internet of Things: An Architectural Platform and Assured Requirements Model”, 15th *IEEE International Conference on Computer and Information Technology (CIT-2015).* pp. 364-370, 26th - 28th October 2015, Liverpool.

[13] R. Raffik, A. Hemanath, S. Hareesh Chandran, V. P. Harshini and R. Raashika, "Sensing Dangers and Threats in Railway Track with Intimation using IoT," *2021 International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA)*, 2021, pp. 1-4, doi: 10.1109/ICAECA52838.2021.9675719.

[14] E. Bernal, M. Spiryagin and C. Cole, "Onboard Condition Monitoring Sensors, Systems and Techniques for Freight Railway Vehicles: A Review," in *IEEE Sensors Journal*, vol. 19, no. 1, pp. 4-24, 1 Jan.1, 2019. doi: 10.1109/JSEN.2018.2875160.

[15] M. Ozturk, A. I. Abubakar, R. N. B. Rais, M. Jaber, S. Hussain and M. A. Imran, "Context-Aware Wireless Connectivity and Processing Unit Optimization for IoT Networks," *in IEEE Internet of Things Journal*, 2022, doi: 10.1109/JIOT.2022.3152381.

[16] H. Song and E. Schnieder, "Availability and Performance Analysis of Train-to-Train Data Communication System," in *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 7, pp. 2786-2795, July 2019.

doi: 10.1109/TITS.2019.2914701.

[17] Q. Zhou, X. Hu, J. Lin and Z. Wu, "Train-to-train Communication Resource Allocation Scheme for Train Control System," *2018 10th International Conference on Communication Software and Networks (ICCSN)*, Chengdu, 2018, pp. 210-214. doi: 10.1109/ICCSN.2018.8488241

[18] Y. Liu and L. Yuan, "Research on Train Control System Based on Train to Train Communication," *2018 International Conference on Intelligent Rail Transportation (ICIRT)*, Singapore, 2018, pp. 1-5. doi:10.1109/ICIRT.2018.8641573.

[19] Changmin Teng, Li Wang and Chaogang Si, "Design and performance tests in different test scenarios based on the TD-LTE train-ground communication system," *2016 2nd IEEE International Conference on Computer and Communications (ICCC)*, Chengdu, 2016, pp. 1575-1579. doi: 10.1109/CompComm.2016.7924966.

[20] F. Wang, L. Zhu and H. Zhao, "Throughput test and analysis in an integrated TD-LTE based train ground communication system," *2016 35th Chinese Control Conference (CCC)*, Chengdu, 2016, pp. 10193-10197. doi: 10.1109/ChiCC.2016.7554968.

[21] Chaogang Si, Changmin Teng and Li Wang, "Design and performance test in an interconnected TD-LTE train-ground communication for urban rail transit system," *2016 IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC)*, Xi'an, 2016, pp. 1734-1737.doi: 10.1109/IMCEC.2016.7867515.

[22] Railway Applications - The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS), *EN 50126/IEC 62278*. Brussels: CENELEC, September 1999.

[23] A. L. Ruscelli ; S. Fichera ; F. Paolucci ; A. Giorgetti ; P. Castoldi ; F. Cugini, "Introducing Network Softwarization in Next-Generation Railway Control Systems" *2019 6th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS),* Cracow, Poland, 2019, pp. 5-7. doi:

10.1109/MTITS.2019.8883348.

[24] L. Zhu, F. R. Yu, T. Tang and B. Ning, "An Integrated Train–Ground Communication System Using Wireless Network Virtualization: Security and Quality of Service Provisioning," *in IEEE Transactions on Vehicular Technology*, vol. 65, no. 12, pp. 9607-9616, Dec. 2016. doi: 10.1109/TVT.2016.2597153.

[25] Fei Wang, Li Zhu and Hongli Zhao, "Virtual resource allocation in a network virtualization based integrated train ground communication system," *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*, Rio de Janeiro, 2016, pp. 2012-2016. doi: 10.1109/ITSC.2016.7795881.

[26] L. Zhu, F. R. Yu, H. Wang, T. Tang and B. Ning, "Handoff performance improvement in a network virtualization based integrated train ground communication system," *2016 IEEE International Conference on Communications (ICC)*, Kuala Lumpur, 2016, pp. 1-5. doi: 10.1109/ICC.2016.7510680.

[27] A. L. Ruscelli, G. Cecchetti and P. Castoldi, "Cloud Networks for ERTMS Railways Systems (Short Paper)," *2016 5th IEEE International Conference on Cloud Networking (Cloudnet)*, Pisa, 2016, pp. 238-241. doi: 10.1109/CloudNet.2016.33.

[28] A. Zarembski, "Some examples of big data in railroad engineering", *IEEE International Conference on Big Data*, pp 96-102, Washington, DC, USA, October 27-30, 2014.

[29] N. Attoh-Okine, "Big Data Challenges in Railway Engineering", *IEEE International Conference on Big Data*, pp 7 - 9, Washington, DC, USA, October 27-30, 2014.

[30] L. Azpilicueta *et al.*, "Context aware scenarios in train transportation environments," *2015 International Conference on Electromagnetics in Advanced Applications (ICEAA)*, Turin, 2015, pp. 755-758. doi: 10.1109/ICEAA.2015.7297216.

[31] P. López-Iturri et al., "Intra-Train Connectivity Analysis to Enable Context

Aware Passenger Environments," *2019 10th International Conference on Information, Intelligence, Systems and Applications (IISA)*, Patras, Greece, 2019, pp. 1-5. doi: 10.1109/IISA.2019.8900730.

[32] M. Rekik, C. Gransart and M. Berbineau, "Cyber-physical Threats and Vulnerabilities Analysis for Train Control and Monitoring Systems," *2018 International Symposium on Networks, Computers and Communications (ISNCC)*, Rome, 2018, pp. 1-6. doi: 10.1109/ISNCC.2018.8531005.

[33] D. Milligan, “Securing a railway control system”, *9th IET International Conference on System Safety and Cyber Security*, pp 1-6, Manchester, United Kingdom, October 15-16, 2014.

[34] M. Bastow, “Cyber security of the railway signalling & control system”, *9th IET International Conference on System Safety and Cyber Security*, Manchester, United Kingdom, pp 1-5, October 15-16, 2014.

[35] Z. Teo, B. Tran, S. Lakshminarayana, W. Temple, B. Chen, R. Tan, D. Yau, “SecureRails: Towards an Open Simulation Platform for Analyzing Cyber-Physical Attacks in Railways”, *IEEE Region 10 Conference (TENCON 2016), Marina Bay Sands*, Singapore, pp. 95-98, November 22-25, 2016.

[36] M. Mylrea, S. N. G. Gourisetti, C. Larimer and C. Noonan, "Insider Threat Cybersecurity Framework Webtool & Methodology: Defending Against Complex Cyber-Physical Threats," *2018 IEEE Security and Privacy Workshops (SPW)*, San Francisco, CA, 2018, pp. 207-216. doi: 10.1109/SPW.2018.00036.

[37] S. Kim, Y. Won, I. Park, Y. Eun and K. Park, "Cyber-Physical Vulnerability Analysis of Communication-Based Train Control," in *IEEE Internet of Things Journal*, vol. 6, no. 4, pp. 6353-6362, Aug. 2019. doi: 10.1109/JIOT.2019.2919066.

[38] E. Babačić, Z. Veljović and M. Pejanović-Đurišić, "Radio-frequency spectrum management in wireless IoT networks," *2017 25th Telecommunication Forum (TELFOR)*, Belgrade, 2017, pp. 1-4. doi: 10.1109/TELFOR.2017.8249279.

[39] D. Kusumawati, D. Setiawan and M. Suryanegara, "Spectrum requirement for IoT services: A case of Jakarta smart city," *2017 IEEE International Conference on*

Communication, Networks and Satellite (Comnetsat), Semarang, 2017, pp. 21-25. doi: 10.1109/COMNETSAT.2017.8263567.

[40] D. Kusumawati, M. Suryanegara and S. Ariyanti, "IoT spectrum requirement for smart transportation," *2017 15th International Conference on Quality in Research (QiR): International Symposium on Electrical and Computer Engineering*, Nusa Dua, 2017, pp. 267-271. doi: 10.1109/QIR.2017.8168494.

[41] J. Adu Ansere, G. Han, H. Wang, C. Choi and C. Wu, "A Reliable Energy Efficient Dynamic Spectrum Sensing for Cognitive Radio IoT Networks," in *IEEE Internet of Things Journal*, vol. 6, no. 4, pp. 6748-6759, Aug. 2019. doi: 10.1109/JIOT.2019.2911109.

[42] B. Alzahrani and W. Ejaz, "Resource Management for Cognitive IoT Systems with RF Energy Harvesting in Smart Cities," in *IEEE Access*, vol. 6, pp. 62717-62727, 2018. doi: 10.1109/ACCESS.2018.2874134.

[43] Haim Mazar (Madjar), "The Radio Frequency Spectrum and Wireless Communications," *in Radio Spectrum Management: Policies, Regulations and Techniques*, Wiley, 2016, pp.1-4. doi: 10.1002/9781118759639.

[44] V. Deniau et al., "Analysis of the Susceptibility of the LoRa Communication Protocol in the Railway Electromagnetic Environment," *2021 XXXIVth General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS)*, 2021, pp. 1-4, doi: 10.23919/URSIGASS51995.2021.9560220.

[45] H. Dabbaghzadeh, A. Falahati and N. Sanandaji, "CBTC Systems Safety Enhancement by Employing an IoT-Based Spread Spectrum Technique," *2021 International Conference on Circuits, Controls and Communications (CCUBE)*, 2021, pp. 1-5, doi: 10.1109/CCUBE53681.2021.9702740.

[46] C. Hu, C. Yang, X. Fang, H. Zhi and L. Hang, "A D2D resource allocation method for IoT network," *2021 IEEE International Conference on Electronic Technology, Communication and Information (ICETCI)*, 2021, pp. 58-62, doi: 10.1109/ICETCI53161.2021.9563426.

[47] H. Wang, Y. Li, H. Zhao and X. Gao, "A novel energy-saving train operation strategy based on particle swarm algorithms," *2021 China Automation Congress*

(CAC), 2021, pp. 985-990, doi: 10.1109/CAC53003.2021.9728530.

[48] B. A. A. Nunes et al., “A Survey of Software-Defined Networking: Past, Present, and Future of Programmable Networks,” *IEEE Communications Surveys Tutorials*, vol. 16, no. 3, pp. 1617–1634, Third 2014.

[49] J. van de Belt, H. Ahmadi and L. E. Doyle, "Defining and Surveying Wireless Link Virtualization and Wireless Network Virtualization," in *IEEE Communications Surveys & Tutorials*, vol. 19, no. 3, pp. 1603-1627, thirdquarter 2017, doi: 10.1109/COMST.2017.2704899.

[50] C. Wu, X. Cai, J. Sheng, Z. Tang, B. Ai and Y. Wang, "Parameter Adaptation and Situation Awareness of LTE-R Handover for High-Speed Railway Communication," *in IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 3, pp. 1767-1781, March 2022, doi: 10.1109/TITS.2020.3026195.

[51] X. Zhou et al., "Deep Reinforcement Learning Coordinated Receiver Beamforming for Millimeter-Wave Train-ground Communications," *in IEEE Transactions on Vehicular Technology*, doi: 10.1109/TVT.2022.3153928.

[52] J. Xu and B. Ai, "When mmWave High-Speed Railway Networks Meet Reconfigurable Intelligent Surface: A Deep Reinforcement Learning Method," *in IEEE Wireless Communications Letters*, vol. 11, no. 3, pp. 533-537, March 2022, doi: 10.1109/LWC.2021.3135602.

[53] IEEE Standard for Communications-Based Train Control (CBTC) "Performance and Functional Requirements," *in IEEE Standard 1474.1-2004* (Revision of IEEE Std 1474.1-1999), vol., no., pp0_1-45 2004, doi: 10.1109/IEEESTD.2004.95746.

[54] R. D. Pascoe and T. N. Eichorn, “What is communication-based train control?” *IEEE Veh. Technol. Mag.*, vol. 4, no. 4, pp. 16–21, Dec. 2009.

[55] G. Copeland and J. McCarthy, "Practical Cybersecurity for Digital Trains," *2019 IEEE 12th International Conference on Global Security, Safety and Sustainability (ICGS3)*, London, United Kingdom, 2019, pp. 212-212. doi: 10.1109/ICGS3.2019.8688036.

[56] H. Zhao, W. Xu, T. Wang, Z. Wang and Z. Cao, "Research on Key Technologies of HSR Intelligent Dispatching based on Cloud-Edge Collaboration," *2021 China Automation Congress (CAC)*, 2021, pp. 426-431, doi: 10.1109/CAC53003.2021.9727640.

[57] Z. Cheng, Y. Wu, T. Li and Z. Zhao, "Research on the Key Technologies of Big Data Based High-speed Railway Permanent Way Data Asset Collection Platform," *2020 IEEE International Conference on Artificial Intelligence and Computer Applications (ICAICA)*, Dalian, China, 2020, pp. 512-516, doi: 10.1109/ICAICA50127.2020.9182429.

[58] J. Yu, R. Wang and J. Wu, "QoS-Driven Resource Optimization for Intelligent Fog Radio Access Network: A Dynamic Power Allocation Perspective," *in IEEE Transactions on Cognitive Communications and Networking*, vol. 8, no. 1, pp. 394-407, March 2022, doi: 10.1109/TCCN.2021.3094209.

[59] C. Verma and C. Selwal, "Visible light communication system (VLC) Using Diversity Technique with 4 QAM OFDM FSO Link," 2018 2nd International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC)I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC), 2018 2nd International Conference on, 2018, pp. 631-635, doi: 10.1109/I-SMAC.2018.8653729.

[60] C. Verma and C. Selwal, "Visible light communication system (VLC) Using Diversity Technique with 4 QAM OFDM FSO Link," *2018 2nd International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC)I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC), 2018 2nd International Conference on*, 2018, pp. 631-635, doi: 10.1109/I-SMAC.2018.8653729.

[61] Kurose, James F., and Keith W. Ross, "Computer Networking: A Top-Down Approach Featuring the Internet" Boston: Addison-Wesley, 2001.