Software-based Networking in Railway Systems

Mariana Macedo de Faria Rodrigues Cruz

Abstract—Roadside and Railway networking systems are critical infrastructures that must support fast, reliable and low delay communications. Technologies still used in those infrastructures—such as GSM-Railway (GSM-R), evolving into LTE-Railway (LTE-R) in the case of railways—are becoming more complex, yet more flexible, and evolving to “software defined” architectures. The technologies presented and explored in this work are expected to change the future of these types of critical systems. The main goal of this work is to study the key benefits of using the Software Defined Networking (SDN) model to control the next generation railways/roadside networking infrastructures. The safety, security and correctness properties of SDN controllers in high availability railway/roadside networks will be analysed, with the focus on railway networks for compliance with the European Rail Traffic Management System (ERTMS)/European Train Control System (ETCS) specifications, and in the context of a real project being deployed in the Portuguese Railways by Thales Portugal. From the analysis of the project requirements and the selected network equipment, it was possible to evaluate and propose adequate methods to automatically derive network re-configuration strategies, namely in case of failure events—e.g., preventing packet loss affecting vital railway traffic signalling procedures—in order to reduce field intervention and complexity in those infrastructures.

Index Terms—Software Defined Networking (SDN), Network Functions Virtualization (NFV), Railway Networks, Roadside Networks, Open Network Operating System (ONOS) Controller, LTE-Railway (LTE-R).

✦

1 INTRODUCTION

EACH day, the advancement of technology is a reality, with computer networks rapidly evolving in size, complexity and capabilities. This rapid development covers not only industrial networks, but also other special purpose types, such as for railway or roadside networks, which are the main focus of this work, that intends to study their improvement in the light of new architectural models such as Software Defined Networking (SDN). Both railway and roadside communication networks bring a lot of complexity accompanied by a variety of critical and important features that influence the whole system and are essential for the good functioning of large metropolitan areas and smart cities. However, some of the technologies on which, traditionally, those types of networks are based, although still quite reliable, are becoming more and more complex and out-dated, so the adoption of SDN and Network Functions Virtualization (NFV) models may streamline and simplify their design, deployment and implementation processes. More importantly, in the technical perspective, these types of networks deal every day with citizens, almost 24/7, ensuring that they provide their services safely, reliably and in the best way possible, the mentioned aspects must be the main concerns for their implementation. From the human perspective, the typical specialized work of a network operations engineer is increasingly being revolutionized (and replaced), with the introduction of SDN and NFV technologies, as other software development oriented technicians, with the minimal capabilities and minimum knowledge of those technologies, become also able to perform most basic network operations tasks. So, it is also important to study and understand how those technologies work and what benefits they can bring to real life projects and to daily Operations, in order to keep up with this technological ”boom”.

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1.1 Motivation

Technologies such as SDN or NFV are not yet widely adopted for railway or roadside networks infrastructures, mostly because the change would be a real challenge, specially due to the fact that those infrastructures are complex, and deal with millions of people and critical systems that have a huge impact (in case of malfunction) on the every day life. With regard to road networks, the implementation and adoption of SDN, although technologically similar to railway networks, is of a different nature, as their focus is more on vehicle automation and the implementation of autonomous driving than in traffic management (in railways) and vehicle control (of trains), and there are actually SDN projects focused on the mentioned aspects for road networks. With regard to railway networks, critical systems such as signaling, centralized control of traffic and vehicles, including speed control, telecommunications (voice and data), among others, would benefit with the adoption of cutting edge technologies such as SDN, much more than in the roadside case, mainly because railway networks are more challenging due to the complexity and importance involved in their types of critical systems. Railway networks have special needs and requirements, such as End-To-End (E2E) delays lower than 0.5s, or Error rates less than 1%/h; support adequate bitrates for large numbers of video streams (namely for surveillance and traffic control); and fast and efficient (desirably automated) network recovery time, which must be met, in the best possible way, by the design of their architecture and the careful selection of technologies for their implementation and operation (including provisioning and configuration). Therefore, in the case of their possible evolution to SDN-based architectures, those requirements must be met. As such, one of the objectives of the work described in this document is to study the technologies, standards and solutions related and/or applicable to roadside and railway networks, namely the recent/emerging technologies such as SDN and NFV. Another objective is of practical nature, in order to understand and evaluate if and how the integration of these technologies is viable and if they really bring advantages to these very important and critical systems, namely in a real project for railway network. This work was possible due to the support of Thales Portugal, which is involved in the implementation of Portuguese roadside and railway communications networks. Therefore, although the company is involved in the deployment of a real roadside project, it has been decided to focus the study in the railway network project.

2 BACKGROUND

Both railway and roadside networks are complex infrastructures that deal with the provision of critical services, where human lives and/or important infrastructures depend on the success of information transmission.

2.1 Roadside Communications Networks

There are several infrastructures that are still poorly served, with respect to communications networks, such as suburban roads, highways and other road services, since there are still many challenges and factors that influence the performance and existence of those infrastructures, such as the high speed movement of vehicles, or their longitudinal nature. It has become a huge concern to have good and reliable communication systems, especially in modern highways. Emerging roadside networks, or vehicular networks are expected to contribute to improving traffic efficiency and road environment, but due to the fact that vehicle network demands are challenging, it is sometimes hard to establish solutions to meet the expectations [1]. The backbone infrastructure of roadside networks can be divided into three possible categories:

1) Wired Backbone Infrastructure: In [2] the authors thought about the possibility to replace the road communication network systems with an “Integrated IP/optical network” allowing it to be also used as a backbone network platform for Vehicle to Roadside (V2R) communications. Since most highways generally do not integrate many communication network systems into their infrastructures, adopting

the wired backbone solution may lead to a lot of wasted time and high capital costs [2].

2) Wireless Backbone Infrastructure: There are certain types of direct communications, like V2R and Vehicle to Vehicle (V2V) that cannot handle voice communications and Internet services that other technologies such as cellular networks, i.e., Global System for Mobile Communications (GSM), General Packet Radio Service (GPRS), Universal Mobile Telecommunication System (UMTS), and Long Term Evolution (LTE) can provide. So, the efficiency of known wireless solutions for backbone infrastructure is not enough to meet the requirements of vehicular communications [2]
3) Hybrid Backbone Infrastructure: The authors in [2] could not find a solution for the cooperation of the previous types of communications, but state that their combination would be an added advantage, because they would provide a reliable communication for the roadside network.

The backbone infrastructure has to correspond to demands of several applications. These demands are mostly determined through Quality Of Service (QoS) parameters. In roadside communications systems, both wired and wireless interfaces are needed to respond to different requests. Since it is necessary to have a broad bandwidth, the optical fibre acts as the backbone of the communication system. Currently, long-range roadside wired communication systems are mainly based on optical fibers and coaxial cables. In some cases, long-distance point-to-point broadband radio links are also used [3].

2.2 Railway Communications Networks

Rail communications services have many needs and requirements that differ not only from those of commercial communications networks, but also from those of Public Protection and Disaster Relief (PPDR) systems (which normally include the Railway infrastructures as critical due to the significant impact they may have in case of disaster). Bandwidth requirements for operational rail communications (i.e., communications to ensure that rail functions safely and reliably) were traditionally quite low, with no expectation to grow significantly once implemented, and distinct from passenger entertainment services. The early train-to-ground communication systems, such as Private Mobile Radio (PMR), were operated using Terrestrial Trunked Radio (TETRA) to carry mainly voice operations and narrow band data services. TETRA was operated in the range of 420-470 MHz band, at Ultra High Frequency (UHF). However, due to the limitation in bandwidth and the excessive use of UHF spectrum, PMR has migrated to higher bandwidth digital system GSM-Railway (GSM-R) [4]. The first train command-control and train-to-ground communication international standard was the European Rail Traffic Management System (ERTMS), that defines two very important elements, the European Train Control System (ETCS) and the GSM-R. GSM-R must meet severe requirements for the availability and performance of radio services [5]. Table 1 lists the main QoS requirements for the existing GSM-R system. ETCS and GSM-R form the ERTMS to carry both signaling information and voice communication, so GSM-R currently provides communication between the ETCS elements. However, even at that time the ERTMS selected GSM for its wireless mobile communications, it was clear that it could not fulfil all the requirements necessary for an efficient railway service, even with the specific extensions for railway (GSM-R) included in the system specification. With this limitation, it ended up reducing the availability of the railway infrastructure, which is why GSM-R will become an unreliable railway technology in the future [7], [8], to be succeeded by the LTE-Railway (LTE-R), an adaptation of the 4G LTE communications network, dedicated for

Table 1
QoS parameters for GSM-R (ETCS). [6]

QoS Parameters	**Demand Value**
Call setup time	$\leq$ 10s (100%)
Connection establish failure probability	$\leq$ 1% (100%)
End-To-End delay	$<$ 0.5s (99%)
Error rate	$<$ 1%/h (100%)

railway services, enabling high-speed wireless voice and data communications inside trains, from the train to the ground, and from train to train [8].

2.3 Software Defined Networks

Software Defined Networking (SDN) brought the idea of decoupling the Control Plane from the Data Plane and allowing the control of the network to be made through a logically centralized controller.SDN offers three fundamental attributes which make great contributions and not just on security level: the logically centralized intelligence, programmability and abstraction of the whole network [9]. SDN is all about making an "abstraction" of the network, allowing to see it as a "whole system", in order to make optimal decisions (on routes, on flows, on policies, etc.). The essential concept in SDN is moving the control software off the network device into a compute resource located centrally, enabling the efficient network traffic control while the data plane is used for data forwarding, so the SDN significantly simplifies network management, and offers a programmable and flexible network architecture [10]. SDN has three areas of focus: abstractions of distributed state, forwarding, and configuration.

- *Distributed state abstraction:* shields the programmer from the reality of a network full of machines, each one with its own state, working in a collaborative environment and allowing a global network view.
- *Forwarding abstraction:* allows the programmer to specify forwarding behaviours without the knowledge of vendor-specific hardware.
- *Configuration abstraction:* allows the goals of the overall network to be achieved without loosing the details of how to implement them in the physical network.

One of the big advantages of a SDN-based network is the fact that it can take advantage of two important features: the variety of applications capable of providing a good network programming capability, and the possibility of decoupling the control of the infrastructure trough the use of controllers [11].

2.3.1 Southbound Protocols

To make possible the communication between the controller and the network devices several protocols are being developed. One is the OpenFlow protocol that defines the communication between the controller and the OpenFlow-based switch and the specific messages and formats exchanged between controller (control plane) and device (data plane), in order to obtain and manage their resources. They do this by exchanging OpenFlow specific messages, named controller-to-switch messages [11]. In a typical SDN network, OpenFlow switches connect to each other and with end-user devices, usually sources or destinations of the flows present in the network. Every OpenFlow switch has its own implemented Flow tables with entries (Matching functions and Actions) for packet processing. The SDN controller modifies the entries in the Flow tables of the switches, so that all incoming packets in a port matching a condition are associated with an action, e.g., to be dropped, or to be forwarded by the switch to an out port. If the switch has no matching rule for a certain packet, then sends it to the controller allowing it to program a new rule in the switch Flow tables.

2.3.2 SDN Controllers

As described earlier, the controller—by having a view of the network as a whole—can track the network topology, learning it through the existence of switches (SDN devices) and end-user devices. It can also implement policy decisions and control all SDN devices present in the infrastructure through the Northbound Application Programming Interface (API), the interface responsible for the communication between the controller and the applications. The core functions of the controller are device and topology discovery and tracking, flow management, device management and statistics tracking [12]. Considering that the types of networks we will address in this project, i.e., large scale networks, having in their basis the high velocity of trains or vehicles, with critical requirements, the Open Network Operating System (ONOS) controller seem to be better suited, not just for its possible domains of application but also due to the support of the documentation.

2.3.3 Network Functions Virtualization

SDN and NFV are independent, meaning that with their partnership they can complement each other. Unlike SDN, NFV uses IT virtualisation technology to decouple network functions from dedicated, often proprietary, hardware devices [13]. With the use of NFV is now possible to reduce implementation and support costs, due to the fact that with the use of virtualized elements the need to acquire physical equipment or specific services and its insertion in the network was obliterated. SDN moved from supporting packet routing to implementing more complex functions that are better suited to roadside/railway networks, and through this partnership between SDN and NFV it is now possible to reach the desired efficiency, flexibility and scalability, keeping the simplicity already involved in this type of services [14].

2.3.4 Controller clustering

In SDN the controller is considered the potential Single Point of Failure (SPOF) of the network. Therefore, it is very important to ensure that if the controller fails, the network remains functional and that, consequently, no equipment changes its behavior due to its failure. And how is this done? Through the use of a second controller or even separating the network in different domains where each one has its own controller. This is so-called a distributed ONOS implementation, with the use of a ONOS cluster, allowing for example to configure a load balancing strategy to make a distributed decision, reducing the decision delay caused by network transmission [15], or even to prevent against Distributed-Denial-of-Service (DDoS) attacks [16]. In this work the implementation of ONOS will be made using a single controller, a unique centralized component will provide the global view of the network. Of course, this will bring several challenges and a probable failure of the system, so an approach of using more than one controller and configure a distributed controller topology will be presented in Section 4.

3 PROPOSED ARCHITECTURE

Having in mind that the railway system has specific elements and is a much critical system, the Railway Project was considered to be a lot more interesting to study than the Roadside Project, that is why the focus of this work ended up more on the implementation of SDN technologies for Railway types of infrastructures. In order to provide flexibility and adaptability to the railway communications network, the application level should be independent of the access technologies in use (3G, 4G, etc.) to permit different types of development. The SDN-based architecture proposed for the Infraestruturas de Portugal (IP) railway communications network and solution, illustrated in high-level in Figure 1, must therefore respect, and should improve the key requirements, in order to present all the benefits that a SDN implementation in a network can bring. For this work, one section of the project was chosen, the "Ovar-Gaia" section, as it presents more details of its implementation and also because it has a greater number of equipment, thus making possible to demonstrate the network dimension with greater precision. The main scope of the project corresponds to the following:

- *Signaling:* command, control and supervision systems for railway traffic including automation of level crossings.
- *Telecommunications:* telecommunications systems to support railway operations.
- *Speed Control:* systems that transmit information about the status of the signaling and the speed allowed by the infrastructure to the trains.
- *Centralized Command at Operational Command Centers (CCOs):* command and remote control of signaling installations, from the CCOs.

Explaining the current network architecture a little better, there are two network infrastructures for communications. One consists of a ring of industrial switches from Hirschmann (HR), Model RS30. The other consisting of Alcatel-Lucent Omniswitch (ALU-OS) and

Nokia switches and routers, all hybrid (supporting SDN mode). The current architecture considers the creation of a Multi Protocol Label Switching (MPLS) network that will have to be present at all railway stations on this network section, providing Ethernet interfaces for critical services, which, for reasons of confidentiality, the connections to the network cannot be shown. The Nokia IP/MPLS technology, where Virtual Private LAN Service (VPLS), Ethernet 'Pipe' Services (e-PIPE) (an implementation of Ethernet Virtual Leased Lines)) and Circuit 'Pipe' Emulation Services (c-PIPE) services are available, among others, is also responsible for Routing (Layer 3) on the network. In turn, the IP technology network of the manufacturer Alcatel-Lucent (ALU) implements the functionality of Routing (Layer 3) and Switching (Layer 2), while the manufacturer Hirschmann only implements the functionality Switching (Layer 2). SDN and/or NFV provide new ways to conceive networks and services and, in the railway domain, the progressive introduction of softwarization of services can make next generation railway systems highly flexible and re-configurable [17]. The idea is to deploy at each place general purpose IT resources that can host a number of Virtual Machines (VMs) or Containers, dynamically created by an orchestrator, placed at a Central Point, to support the required services, e.g., Virtual Network Functions (VNFs). In turn, the SDN network equipment (e.g., a Layer 2 switch) can be programmed by the SDN controller to direct to each VM only the specific traffic flows. This approach can put together two technologies that are crucial for network softwarization, SDN and NFV [17]. The architecture can be logically divided into three architectural components: core network, access network, and access functions.

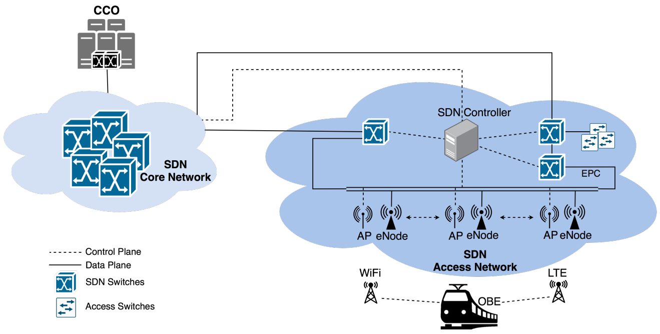


Figure 1. High-level SDN architecture for the railway communications network.

4 IMPLEMENTATION

We proposed to perform a proof of concept of the architecture in order to either confirm and prove that the objectives are achievable, and the benefits it may bring to real projects of Thales Portugal, or just the opposite, i.e., that, however effective the studied solution might be, it would not eventually bring benefits when compared the solutions already implemented. For the Demonstration phase a possible scenario was designed in order to show what are the advantages of using SDN in railway networks, with the objective of evaluating the performance of the proposed architecture when certain critical network events occur, typical of railway networks, like the crash of a link in the core network or even a link overload. The main goals of using SDN in a network is the fact that it brings **programmability**, meaning that it provides links between the application control and network control layers to optimize application performance, increase visibility, and **application awareness**, allowing also the network to automatically react to the dynamic requirements of workloads, and providing a **global control view**. Additionally, the network control systems have a global view of current network conditions in order to improve local actions of individual network nodes on how to treat traffic streams of a particular application. Figure 2 represents the demonstration test bed used for the tests. In that scenario the wireless networks were recreated using a SDN-based WiFi network emulator (https://mininet-wifi.github.io) that can emulate and perform functions of SDN and OpenFlow (OF)-Access Point (AP)- WiFi. The controller is ONOS, that provides scalability, high performance and high availability, specially for the core network. In the data plane, the core network consists of four OF switches (CCO1, Contumil connected to Campanhã and Espinho, Livração connected to Ermesinde). Using SDN, the MPLS can be easily replaced by flows [18], [19], [20]. The access network or the equipment present in physical stations, is represented by ten OF switches. The Campanhã site, is considered to be a central interconnect point of the network, providing also connectivity to a Datacenter, designed with a spine-lead topology, with Top of Rack (TOR) switches on the leafs and multiple switches on the spine. The Campanhã site also interconnects the wireless APs, serving mobile users and trains On Board Units (OBUs). Some switches have hosts connected so it is possible to simulate railway components connected to each station's Local Area Network (LAN). Both OF switches and OF-APs will be controlled by the ONOS controller and provide an OpenFlow compatible implementation. The WiFi stations (mobile, trains) and fixed hosts in LANs have no OF support, so the controller will only see them as end hosts. The SDN controller is ONOS version 2.3.0 (https://wiki.onosproject.org/display/ONOS/Downloads), created in a build VM in VirtualBox named *onos* running Ubuntu 18.04, 64-bit Desktop. ONOS is a leading open source SDN controller for building next-generation SDN/NFV solutions, allowing to create new network applications without the need to alter the data plane systems [21]. The topology for the Demonstration scenarios, was created in Mininet, a simulation framework, using ONOS as a remote controller. Figure 3 corresponds to that topology, but now "discovered" and presented in the ONOS Graphical User Interface (GUI).

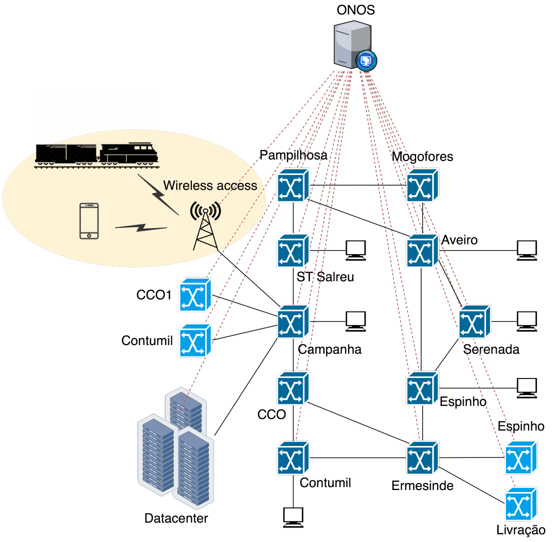
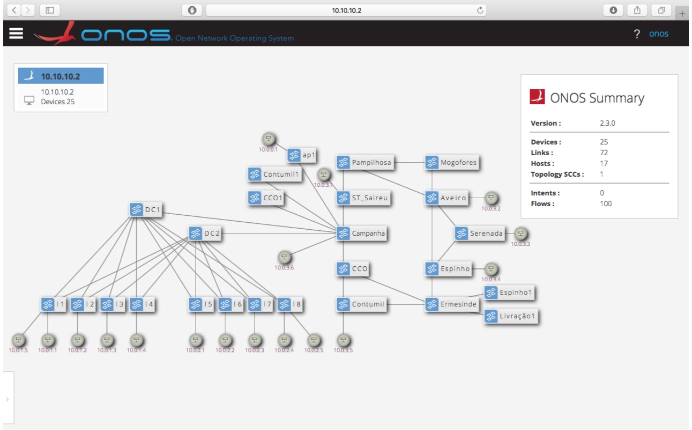


Figure 2. Diagram of the Demonstrator Test Bed of the IP project.



ONOS Summary

Version : 2.3.0

Devices : 25
Links : 72
Hosts : 17
Topology SCCs : 1

Intents : 0
Flows : 100

Figure 3. ONOS GUI, showing the Topology of the Demonstration scenario.

5 DEMONSTRATION

Railway communication network infrastructures have characteristic applications or network aspects that need to meet very specific requirements. For the Demonstration, the tests will focus on the links capacities, by trying to replicate the specifications of the equipments being deployed in the real project, and in terms of link and connection types.

5.1 Use cases

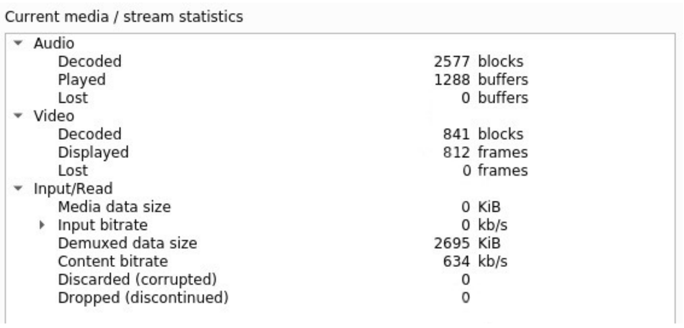
Three typical Use Case scenarios were designed in order to evaluate the behaviour and performance of the proposed architecture: Video Surveillance, Link Failures in the Core network, and Fault Tolerance of the network. IP-based Closed-Circuit Television (CCTV) systems are the defining factor in the success of modern train surveillance systems. The camera must allow a video stream with a High Definition (HD) resolution of 1920x1080 pixels and coded in High Efficiency Video Coding (H.265/HEVC) [22]. For the test scenarios we will use the VLC media player [23], a free and open source framework that plays most multimedia files, and various streaming protocols, in order to measure the instant data rate of the communication, allowing to set up multimedia streams and taking advantage of the SDN configuration. The tests will be performed with Real Time Streaming Protocol (RTSP) protocol, using Transmission Control Protocol (TCP) to maintain an end-to-end connection [24]. Video surveillance services are usually present in railway stations, that is why a streaming video server was placed in our scenario running in the wifi station and a end host as a client. The maximum E2E delay of a user data block in GSM-R is 500 ms. So, in case of a link failure in the network, the tolerated path recovery delay is bounded by that value. As such, and for our SDN test scenario, it is expected that the flow recovery delays would be even much lower than 500ms. The Ping tool will be used to test if a particular host is reachable across the network, this will be used to gather link and flows statistics. It is very important for railway communications networks to be designed with fault tolerance in perspective and redundant mechanisms in order to prevent crashes of critical services or longer unavailability. With the use of SDN, the control of the networking devices is performed by the controller, and so, it is also very important to ensure that the controller is not the Single Point of Failure of the infrastructure. Controllers such as ONOS are designed as a distributed SDN operating system, and configured typically as high-availability clusters, providing fault-tolerance and resilience when individual controller instances fail [25].

6 EVALUATION

Evaluation was performed with the proposed architecture, using the emulation scenario previously described, for the three Use Cases of Video surveillance, recovery from Link Failure and Fault Tolerance (in terms of Controller failure).

6.1 Use Case: Video surveillance

A video with HD resolution of 1920x1080 pixels encoded in H.265, was streamed from the wifi station, by means of a VLC video server. After analysing the traffic generated during the streaming, we measure an uplink data rate of around 634kbps and no frames were lost, as illustrated in Figure 4. The video despite being HD 1080p was encoded with low bitrate (less than 1Mbps), which is quite normal in surveillance cameras, as the stream has only temporal variations (people entering) and not very spatial (the background is almost always the same). The most important aspect was the fact that the transmission was made without loss and without apparent delay.



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Current media / stream statistics
▾ Audio
      Decoded                              2577 blocks
      Played                               1288 buffers
      Lost                                    0 buffers
▾ Video
      Decoded                               841 blocks
      Displayed                             812 frames
      Lost                                    0 frames
▾ Input/Read
      Media data size                         0 KiB
    ▸ Input bitrate                           0 kb/s
      Demuxed data size                    2695 KiB
      Content bitrate                       634 kb/s
      Discarded (corrupted)                   0
      Dropped (discontinued)                  0
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Figure 4. Media statistics of the Streaming session.

6.2 Use case: Recovery from link failure

To test the performance of the controller when a link fails, a link between two switches was changed to down. Two tests were made to test the performance of the network. In the first test, although the controller takes some time to understand that the topology changed due to occurrence of a network event and compute new path, it can be observed that when the link fails the ping echo replies increases from around 1ms to 33.6ms, and immediately back to around 1ms, now the path is going through a new link. The second test is made when the original link is back to up state and the path is changed again to the original link, we can conclude that the path changed because the ping increases to 21.5ms, only in that moment, after the increase its back to around 1ms. In both situations the controller was very efficient to compute the alternative path and the E2E delay did not get higher than 50ms.

6.3 Use case: Controller failure

Physically-distributed SDN controllers are mainly used in large-scale SDN networks for scalability, performance and reliability reasons. A explored cluster hypothesis to demonstrate the importance of implementing a distributed controller is demonstrated. For this experiment Docker was used to run images corresponding to both Atomix and ONOS nodes. Two Atomix containers and two ONOS containers were created in order to assure network reliability and fault tolerance. The idea is to separate network applications and services. The same Mininet topology was once again created, but this time with no wifi and radio network to simplify the deployment of the infrastructure. After that, two created ONOS instances were used to separate network parts. This way the amount of data/flows and packets handled by each controller is decreased, and so the overall performance will surely be better.

7 CONCLUSION

After analyzing and understanding how technologies like roadside and railway networks work it is possible to verify that they are getting old, very quickly, and have a lot of constraints concerning connection, routing performance, interference of other networks, high velocity and others. So, the need to evolve and use technologies like SDN and NFV is huge, because they can easily streamline and optimize this type of infrastructures, and that is what we proposed to explore with this project. There are already a lot of works and researches in this area but in all the solutions the scope is very relative and not very specific. That is due to the fact that we are dealing with critical systems, involved in the day to day of our society, and also that there are lives at stake, and so, assuring the safety of the population is mandatory. So this kind of revolutionary technology should only be put into operation when it is possible to ensure that they are stable enough and reliable. Our belief is that they will revolutionize not only the area of transportation but also the technological world in general due to all of the advantages they bring. This document presented the research aimed at understanding the mentioned technologies, and a study on the utilization of SDN technologies, NFV and associated frameworks with a focus in Railway communications networks, in the context of a project being deployed in Portuguese Railways that arose from the partnership between Thales Portugal and Infraestruturas de Portugal. A possible railway network architecture was designed based on the project carried out by Thales Portugal, which allowed a demonstrator implementation to be created as close to real life as possible in order to ensure that the conditions and requirements expected in the project were in fact fulfilled. It was possible to perceive through the results obtained that when having a controller, in the case of a network event, like a link failure, the end to end delay is not greater than 50ms, and the expected E2E delay in GSM-R must be less or equal to 500ms, so is a very important result to take into account when adopting SDN in this type of networks. Regarding the transmission of streams or the data transfer rate on the network is quite significant, through the transmission and simulation of a HD video stream it was possible to observe that it remained at an average of around 634kbps of data rate uplink, which, again, is a point to favor using SDN. Regarding technologies for network recovery or even increasing the network in terms of equipments or links, the process is very streamlined due to the fact that the SDN is prepared for these situations and is able to do it in the best and fastest way possible. It is then possible to conclude that SDN and NFV are able to effectively meet all expectations and that their implementation only brings benefits to networks like railway, both in terms of performance as well as safety and reliability.

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