IN2DREAMS

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D2.2 IN2DREAMS
On-Board Network Architecture and Dimensioning

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Leader/Responsible of this Deliverable: Mir Ghoraishi, pureLiFi Ltd

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Executive Summary

The main objective of WP2 in In2Dreams is to provide a communication platform that will be able to interconnect a growing number of devices (metering devices, sensors and smartphones) located either on-board of trains or at the trackside with the Open Data Management (ODM) platform.

The objective of this deliverable, in the scope of Task 2.2, is to describe the design and development of a heterogeneous network infrastructure comprising Wi-Fi/LiFi/LTE technologies interconnecting the on-board devices (sensors, smartphones etc) with the gateway.

Toward this target, the deliverable starts with describing the communications network architecture, and the technologies which are used in this scenario, i.e. LTE, Wi-Fi, and LiFi. Moreover, free space optics (FSO) is introduced as a candidate for the rollingstock to rollingstock, or rollingstock to the station link. These technologies introduce a high level of heterogeneity to the network as it is shown in the report. Moreover, it is shown that how employing a C-RAN architecture enables coordination of several cells to form super-cells which bring significant benefits in high mobility scenarios.

The proposed architecture to address the challenge of managing and operating the complex heterogeneous infrastructure is via transforming the network to a software defined network (SDN) by virtualizing the network functions. This *softwerization* approach is introduced and management and orchestration framework are discussed.

For the optimization of the network in a cost and energy efficient manner, taking into account the great diversity of requirements introduced by the variety of services, the approach of 'network of queues' is used. This approach used the different KPIs, such as capacity, latency, energy consumption, etc., to optimize network parameters for all physical and virtual network providers.

The details of the LTE and LiFi networks parameters used in this optimization is introduced and generic Wi-Fi parameters are used for the study. These parameters are used to evaluate the proposed infrastructure topology. A realistic scenario for the high-speed train use-case is defined, based on which the network dimensioning analysis has been performed. The results of the analysis, in terms of the required network computational resources and the mobility are presented. From these results it could be understand that traffic offloading to the cloud is beneficial for the portable devices when communication cost is low and the processing load is high. At the same time, it was shown that with the increase of LiFi technology penetration, the mobile cloud computing can be unlocked to a broader range of services. It is also observed that with the increase of service processing requirements, offloading is beneficial for larger mobility and network-to-compute ratios.

Abbreviations and Acronyms

Abbreviation	Description
3GPP	3rd generation partnership project
ACL	Access control list
AP	Access point
ARQ-SR	automatic repeat request selective repeat
BBU	Baseband unit
C-RAN	Cloud radio access network
DHCP	Dynamic host configuration protocol
EPC	Evolved packet core
FDMA	Frequency division multiple access
FSO	Free space optics
Gbps	Giga bits per second
GRC	Gnu Radio Companion
HetNet	Heterogeneous network
HSS	Home subscriber service
IP	Internet protocol
KPI	Key performance indicator
LAN	Local area network
LED	Light emitting diode
LiFi	Light fidelity
LTE	Long term evolution
LTE-R	LTE-railway
LWA	LTE WLAN aggregation
MANO	Management and orchestration
MIMO	Multiple input multiple output
MIPS	Million instruction per second
MME	Mobility management entity
MOP	Multi-objective optimization
NIC	Network interface controller
NFV	Network function virtualization
NFVI	Network function virtualization infrastructure

Abbreviation	Description
3GPP	3rd generation partnership project
ACL	Access control list
AP	Access point
ARQ-SR	automatic repeat request selective repeat
OBU	On-board unit
OFDMA	Orthogonal frequency division multiple access
PNF	Physical network function
OSS	Operation and support system
QoS	Quality of service
RF	Radio frequency
RRH	Remote radio head
SC	Service chaining
SDN	Software defined network
SSID	Service set identifier
TCP	Transmission control protocol
UE	User equipment
VLAN	Virtual local area network
VNF	Virtual network function
VOQ	Virtual output queuing
WDMA	Wavelength division multiple access
Wi-Fi	Wireless firdelity
WLAN	Wireless LAN
WLC	Wireless LAN controller

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1 Introduction

The IN2DREAMS project proposes a dynamically reconfigurable ICT infrastructure to facilitate both the operation and the services supported by the railway network. Despite the recent progress in railway smart metering solutions, the optimality of the grid's ICT network infrastructure remains an unsolved challenge, even when limited to rolling stock monitoring. The same holds for the interoperability between the different heterogeneous segments of the network, which are currently static and unaware of each another.

As a result, Railway System Operators are faced with a number of options for building their ICT networks, but none them enables dynamic reconfiguration of the network according to the operational and business needs and with no clear way to benchmark one solution against the other exist. Therefore, IN2DREAMS aims at proposing a dynamically reconfigurable smart metering system that will improve reliability, ease monitoring and optimise the performance/cost trade-off on the fly.

On the other hand, the explosive growth of mobile internet traffic attributed to the rapidly increasing number of smart devices forces network providers to concurrently support a large variety of applications and services that may need to interact. This introduces the need to transform traditional closed, static and inelastic network infrastructures into open, scalable and elastic ecosystems that can support a large variety of dynamically varying applications and services. This transformation aims to bring new service capabilities to network operators supporting highly variable performance attributes in a cost and energy-efficient manner ensuring, at the same time:

- connectivity for a growing number of very diverse devices, including sensors, rendering devices and actuators, which are often bounded by processing, storage and power constrains.
- high mobility in heterogeneous environments, e.g. in fast moving vehicles such as trains, including densely or sparsely populated areas, supported by very diverse technology deployments. These will need to offer user experience continuity guaranteeing high levels of service availability, e.g. 99.999%.
- support of mission critical services requiring very high reliability, security, global coverage and/or very low latency, which are up to now handled by specific networks [1].

This wide and demanding range of requirements cannot be supported by the current best effort internet or a smooth migration from existing network architectures and technology deployments to next generation solutions. Instead, it requires a paradigm shift to support the upcoming set of services, imposing enormous capacity requirements that exceed 1000 times current bandwidth needs available to 10s of billion end-devices, and demanding enhanced spectral efficiency to enable connectivity of a massive number of devices, in a scalable and sustainable manner. For sustainability purposes, there is a need to reduce the overall power consumption beyond 90% of its current levels, while for improved user experience end-device battery lifetime needs to drastically increase. Given the diversity of end devices and services, a future proof infrastructure needs to adapt to a wide range of service requirements through a flexible architecture offering converged services across heterogeneous technology domains deploying a unified software control [1].

In such environments where user mobility plays a key role, network heterogeneity involves integration of wireless with high-capacity wired network domains interconnecting a large variety of end-devices with compute and storage resources in a flexible and scalable manner. In this context, optical fiber network solutions can facilitate interconnection of distributed data centers (DCs) that can vary in scale, e.g. micro- to regional and mega-DCs, as they provide abundant capacity, long reach transmission capabilities, carrier-grade attributes and energy efficiency. At the same time, spectrum efficient wireless access network technologies such as, Long Term Evolution (LTE) and Wi-Fi, combined with legacy, i.e. 2G, 3G, and emerging technologies as Light Fidelity (LiFi), will allow broader coverage and availability, higher network density and greater connectivity, enabling services such as mobile cloud, machine-to-machine (M2M) communications and the Internet of Things (IoT) [2].

Although these technology solutions can bring significant benefits to network operators and end-users, there are several challenges that need to be addressed before they can be effectively deployed. These include converging heterogeneous network and IT resources integrated seamlessly and overcoming limitations in terms of control and management flexibility. To address these limitations and the associated inefficiencies, novel approaches relying on softwarization of network functionalities have been recently proposed. These enable infrastructure slicing and virtualization that allow physical resources to be shared and accessed remotely on-demand, enabling cost and utilization efficiency through new operational models such as multitenancy. In addition, the development and adoption of suitable algorithms that will jointly allow optimization of business objectives, such as reduced end-to-end energy consumption considering end-device properties and characteristics is expected to play key role in the future [1].

Towards this direction, and in response to needs and requirements for current and future railway system connectivity, IN2DREAMS proposed an advanced communication platform enabling connectivity between a variety of monitoring devices and computational resources through a heterogeneous network infrastructure. This ubiquitous converged infrastructure is expected to integrate an optical metro network with several wireless access network technologies. The proposed infrastructure integrates an advanced optical fiber network solution offering fine (sub-wavelength) switching granularity with a wireless access solution based on LTE, Wi-Fi and LiFi. By appropriately integrating LiFi into the existing radio access network (RAN), traditional technology barriers preventing deployment of mobile cloud applications can be alleviated leading to significant improvements in terms of throughput, data density and latency. Furthermore, by unlocking the visible light spectrum through LiFi and making it available to specific services, e.g. high throughput, RF-interference-free indoor coverage, more efficient utilization of the radio frequency spectrum can be achieved. This infrastructure will interconnect a plethora of monitoring devices and end-users to the OSS. System monitoring will be as non-intrusive as possible as it will be based on advanced signal processing and intelligent learning algorithms.

Heterogeneous networks (HetNet) are among the most promising low-cost approaches to meet the industry's capacity growth needs and deliver a uniform connectivity experience across the coverage areas. HetNet was a term in the mobile communications industry, and its standardization entity, i.e. 3GPP, and specific for its technologies. In its traditional form, a HetNet comprises a group of small cells that support aggressive spectrum spatial reuse coexisting within macrocells. However, in a more general sense, a HetNet can be comprised of any two or more different kind of technologies used for connectivity within the same coverage areas. For instance, in 3GPP, the LTE-Wi-Fi interworking became possible by implementing a modem-level aggregation for superior performance leveraging dual connectivity standardized in Release 12 (R12) [3]. The LTE/WLAN Aggregation (LWA) is another feature of the standard for mobile operators leveraging existing carrier Wi-Fi deployments. A tightly coupled heterogeneous system consists of a common packet scheduler for cellular and WLAN systems, connecting the latter to the mobile core network and achieving the integration between both systems at the lower layers. The user-equipment (UE) still needs to use Wi-Fi security mechanisms, which are time consuming. This was standardized by 3GPP on Release 10 [4]. Alternatively, in a loosely coupled system the heterogeneous wireless networks are not connected directly. Instead, they are connected to the same network. Loose coupling uses the subscriber databases without the need for a user plane interface. To use the Wi-Fi network, the UE first needs to scan for available Wi-Fi APs. It needs to authenticate on the selected AP and then sends or receives data. Figure1 illustrates such an architecture for a rolling stock network.

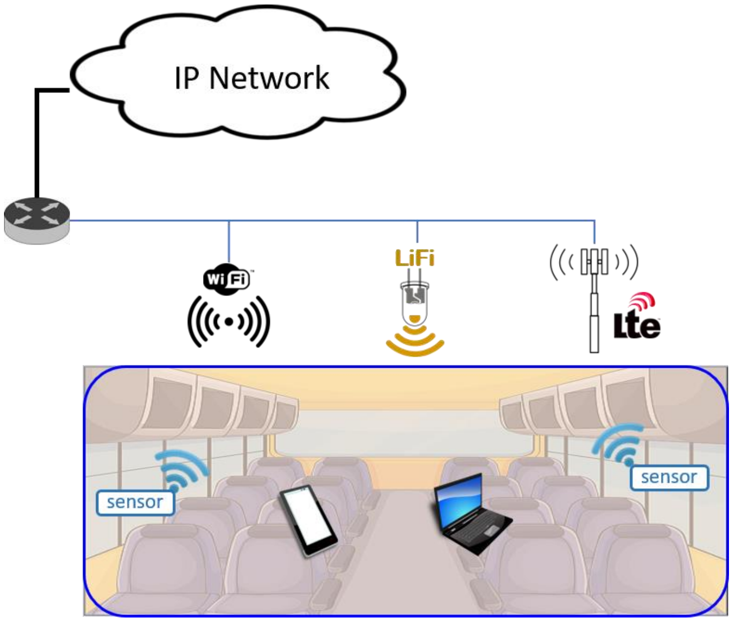

Figure 1 HetNet consisted of LTE, Wi-Fi and LiFi.

This deliverable proposes the multitechnology, HetNet architecture for the railway connectivity, and then provides the optimization analysis by performing network dimensioning simulations. The heterogeneous network scenario considered in this deliverable is comprising of LTE, Wi-Fi and LiFi, while topics on monitoring/maintenance of trackside/ground elements related to the use-cases defined in D2.1 will be addressed in D2.3.

The deliverable also proposes an architecture in accordance to the ETSI Network Function Virtualization (NFV) standard and the Software Defined Networking (SDN) reference architecture that enables orchestration of services with guaranteed quality of service (QoS) [5]. This architecture takes a holistic approach considering, jointly, all network technology domains and computational resources. A description of the required logical functions and their interactions, to efficiently support provisioning of both end-user and mission critical services over the infrastructure is also provided.

Finally, a novel modelling framework has been developed to evaluate the performance of the proposed approach. This includes a multi-objective optimization (MOP) service provisioning model used to study a variety of end-user and mission critical services. The objective of this model is twofold: i) to minimize the operational expenditure of the network in terms of power consumption and, ii) to optimize the operation of the end-devices.

2 Scenario Description and Communication Network Architecture

The proposed network infrastructure deploys of a set of optical and wireless network technologies to interconnect a variety of end-devices and IT resources. The wireless domain comprises cellular LTE, Wi-Fi and LiFi technologies. Free-space-optics (FSO) communications can be used as the backhaul link, i.e. train-to-platform, or rollingstock to rollingstock connections. These technologies exhibit a high degree of heterogeneity as they differ both in terms of operational and performance parameters, including spectrum use, service coverage and reach, physical layer encoding, sharing of the available spectrum by multiple users as well as maximum bit-rate [6].

In order to enhance spectral efficiency, macrocells can be complemented with small cells as they allow higher rates of frequency reuse over carefully designed geographical areas with easy access to the network backbone. In addition to small cells, given that Wi-Fi networks are readily available in almost every public or private area, including most trains rollingstocks, and are easy to install and manage, significant benefits are expected by the joint consideration of Wi-Fi and LTE systems. Additionally, the small cell concept can easily be extended to LiFi to overcome the high interference generated by the close reuse of radio frequency spectrum in heterogeneous networks. A network with multiple optical Access Points (APs) is referred to as an attocells network [6]. Since LiFi operates in the visible light or infrared spectrum, the optical attocells do not interfere with any RF network. Therefore, the optical attocell layer adds data transmission capacity and enhances coverage while existing RF networks are not detrimentally affected. The architecture of each system will be briefly discussed in this section.

2.1 LTE network description

LTE is among the prime wireless access cellular technologies in 4G networks as it is anticipated to offer a theoretical net bit-rate capacity of up to 100 Mbps per macrocell in the downlink and 50 Mbps per macrocell in the uplink if a 20 MHz channel is used. These data rates can be further increased by using Multiple-Input Multiple-Output (MIMO) technology. At the same time, LTE can provide improved QoS characteristics such as low packet transmission delays, fast and seamless handovers supporting high speed vehicular communications scenarios and operation with different bandwidth allocations. LTE can also support a wide range of services and performance metrics in a wide range of environments such as indoor, urban and rural.

Baseband signal processing functionalities in LTE systems are performed by the baseband units (BBU) that are either collocated with the remote radio heads (RRH) or located remotely exploiting the concept of Cloud-RAN (C-RAN) [7]. RRHs are connected to the BBUs through high bandwidth links known as fronthaul.

LTE-railway (LTE-R) is a version of LTE being developed to meet the mission-critical service requirements of railway operators [8]. The network will support both operational and maintenance services on a high-speed commercial railway line operating at speeds of up to 250 km/h. The primary characteristics of LTE – high speed, high security and high-bandwidth capacity – allow it to carry voice and data for train control, on-board video surveillance and infotainment services for passengers on a single IP network. LTE has latency as 10 ms allowing for support of time-sensitive applications and providing quality of service management. It can be deployed in many different frequency bands and has multiple features related to encryption and authentication for security purposes. To avoid frequent handovers and substantial investment for higher base-station density, low-frequency bands, such as 450-470 MHz, 800 MHz, and 1.4 GHz have been widely considered as they are suitable for large area cellular communications [9]. Furthermore, the carrier aggregation capability of LTE will permit the use of different bands to overcome problems of capacity. Standard LTE includes a core network of evolved packet core (EPC), the IP-based EPC supports seamless handovers for both voice and data to cell towers, and each cell will support high data and voice capacity by high-speed packet access. As a candidate for the next-generation communication system for high-speed trains, LTE-R inherits all the important features of LTE and provides an extra radio access system to exchange wireless signals with onboard units (OBUs) and to match high-speed train specific needs. Compared with the public LTE networks, LTE-R has some differences in the architecture, system parameters, network layout, services, and QoS. The preferred parameters of LTE-R are summarized in Table 1 System Parameters of LTEand LTE-R [9], based on the future QoS requirements of high-speed train communications. Note that LTE-R will be configured for reliability more than capacity. The network must be able to operate at 500 km/h in complex railway environments. Therefore, quadrature phase-shift keying (QPSK) modulation is preferred, and the packet number of retransmissions must be reduced as much as possible.

Table 1 System Parameters of LTE and LTE-R [9]

Parameter	LTE	LTE-R
Frequency	800 MHz, 1.8 GHz, 2.6 GHz	450 MHz, 800 MHz, 1.4 GHz, 1.8 GHz
Bandwidth	1.4 MHz - 20 MHz	1.4 MHz – 20 MHz
Modulation	QPSK, M-QAM	QPSK, 16-QAM
Cell range	1 km – 5 km	4 km – 12 km
Cell configuration	Multisector	Single sector
Peak data-rate (DL/UL)	100 Mbps / 50 Mbps	50 Mbps / 20 Mbps
Peak spectral efficiency	16.32 b/s/Hz	2.55 b/s/Hz
Data transmission	Packet switching	Packet switching (UDP data)
Packet retransmission	IP packets	UDP packets
MIMO	2x2, 4x4	2x2
Mobility	Up to 350 kmph	Up to 500 kmph
Handover success rate	>99.5%	>99.9%
Handover procedure	Hard/soft	Soft (no data should be lost)
All IP	Native	Native

2.2 Wi-Fi wireless connectivity for rollingstock

An example of passenger wireless internet access is described in [10]. Both 2.4 GHz and 5 GHz radios are used for passenger device connections, providing the ability to support higher-bandwidth connectivity in the less congested 5GHz frequency range while maintaining backward compatibility for devices that only support 2.4GHz frequencies. The access points are deployed in FlexConnect mode[11], which transports user traffic via a locally-defined virtual local area network (VLAN) on the onboard network. This helps enable access to local resources such as an on-demand entertainment server, and eliminates the potentially inefficient routing of traffic via the centralized Wireless LAN Controller (WLC). All access points are still centrally managed via the WLC. If the tunnel from the WLC to the access point is interrupted, new client connections will not be allowed but existing authorized connections will continue to pass traffic.

The number of access points deployed within a car depends upon several factors, including the physical topology of rail car, the number of passengers expected in the car, whether the passengers predominantly sit or stand, and suitable mounting positions. A minimum of two access points should be planned for most deployments, in order to provide infrastructure redundancy; no more than four access points are typically needed. Each access point is capable of handling up to 75 device connections efficiently.

Multiple services are supported by the onboard wireless infrastructure, with unique SSIDs for each service, providing service separation across the common onboard infrastructure. Each SSID is mapped to a separate VLAN, which is then provided a separate IP subnet by the DHCP server via the onboard gateway. This provides proper service separation and service routing.

Short description on the deployment considerations for the passenger wireless internet access are:

- The passenger wireless internet access SSID is configured to be open, with no authentication required. This reduces any barrier to entry for using the Wi-Fi service.
- When associating to the SSID for the first time, the passenger will be presented with a portal landing page.
- Depending upon the requirements of the rail operator, the passenger may simply have to accept the terms and conditions of use or provide additional information to verify entitlement to use the service, such as a ticket number.
- Another option is to have the passenger install a certificate profile on the device via the rail operator's application, which then grants them secure access to the wireless internet access.

By deploying the onboard access points in FlexConnect mode, passenger traffic from authorized sessions is switched to a locally-defined passenger Wi-Fi VLAN in order to allow for local resource access for services, such as personal device infotainment. In order to maintain security for local service access and to maintain service separation throughout the onboard network, all local service traffic access is through inter-VLAN routing implemented on onboard gateway. This provides a single place for implementing security policies for service access, such as Access Control Lists (ACLs).

2.3 LiFi network architecture and requirements

LiFi (Light Fidelity) is a type of optical wireless communications for which LEDs are used to transmit data wirelessly by changing the light intensity at very fast speeds. At the receiver side, photo detectors are used to convert light intensity fluctuations to an electrical signal [12]. LiFi extends the concept of visible light communication (VLC) to achieve higher data-rates, bidirectional transmission and fully networked optical wireless communications. Moreover, LiFi supports user mobility and multiuser access. The typical range of a LiFi communication link is less than 100 m, and the system supports random user locations within the LiFi coverage region which can be indoors or outdoors. Therefore, a LiFi system is composed of multiple cells and this is also referred to as a LiFi attocell network since the cell sizes can be ultrasmall with radii in the metre region. Figure 2 introduces the concept of a LiFi attocells network.

LiFi attocells allow extremely dense bandwidth reuse due to the inherent properties of light waves [13]. Not only the coverage of each single attocell is very limited, but also walls prevent the system from suffering from cochannel interference between rooms. This precipitates in the need to deploy multiple APs to cover a given space. However, due to the requirement for illumination indoors, the infrastructure already exists, and this type of cell deployment results in the aforementioned very high, practically interference-free bandwidth reuse. A byproduct of this is also a reduction in bandwidth dilution over the area of each AP, which leads to an increase in the capacity available per user. The user data-rate in attocell networks can be improved by up to three orders of magnitude compared to existing femtocell networks [13]. Therefore, LiFi not only benefits from additional free spectrum which is 2600 times larger than the entire radio frequency (RF) spectrum, but it also takes the small cell concept to new levels which are not easily possible in RF. Moreover, communication links are bidirectional, either full-duplex or half-duplex at user data rates greater than 10 Mbps.

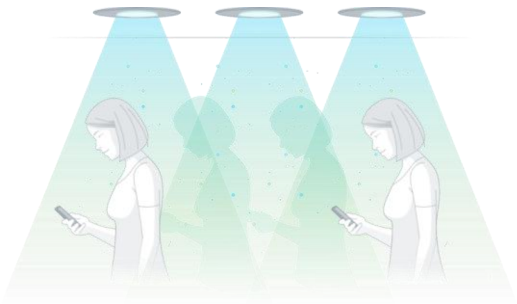

Figure 2 LiFi attocell concept

2.4 FSO network architecture

Free Space Optics (FSO) communications technology has become an ideal solution for modern networks desiring high data rate secure transmission and can fully cover modern communication network requirements between train busses and train stations. An FSO system is a point-to-point technology that uses a laser beam to send data through the atmosphere that can offer full-duplex 2.5 Gbps Gigabit Ethernet throughput. The main advantage of such technology is the high data-rate, that can be achieved with a remarkable low installation and operational cost. Furthermore, FSO systems are license free so they are ideal for locations where radio interference and congestion make installation of radio frequency alternatives impossible. Despite the narrow beamwidth of the laser beam, FSO system can be used for mobile communications due to modern precise tracking techniques, so links between train busses and train stations or even between trains can be easily deployed. Hence FSO provides communication network with high performance, availability and security that will meet the modern and future requirements of communications. Such systems can be easily adapted to the existed networks as they have multiprotocol support and are compatible with all existing protocols.

Concerning the physical layer of the network, Fast Ethernet and Gigabit Ethernet are widely used in every type of modern network in order to transmit electrical or optical signals. FSO systems use Fast Ethernet and Gigabit Ethernet for full-duplex communications supporting the IEEE802.3 standard providing high bit rate up to 2.5 Gbps [14].

The most common channel access method used for FSO is Frequency Division Multiple Access (FDMA). Two types of FDMA that is widely used in FSO systems are the Orthogonal FDMA (OFDMA) and Wavelength Division Multiple access (WDMA) [15]. Both OFDMA and WDMA are suitable for higher bit-rates and at the same they can provide a better bit-error-rate of the communication link. Another access protocol that can be applied in FSO links is the Code Division Multiple Access (CDMA) that requires less dynamic range in contrast to FDMA technique [16].

In the transport layer, transmission control protocol (TCP) that is the most popular reliable transmission protocol for various internet applications, is fully supported by FSO systems [17]. Although FSO systems are deployed under high-error environments, which is because of signal attenuation and disturbances in the free-space channel by air turbulence, precipitation, etc.; that degrade the TCP performance, there are techniques which can be used in order to improve the quality of the network. Such techniques are mainly base on modifying the TCP congestion operation to adapt to the multiple segment loss. Notably, 'automatic repeat request selective repeat' (ARQ-SR) in the link layer can also be applied in order increase the performance of the TCP [18]. ARQ-SR is basically a retransmission scheme which accepts out-of-order frames and buffers them and therefore not only improves the error-rate, but also can avoid unnecessary retransmission of frames. In addition, it has to be mentioned that all modern FSO systems support IPv4 and IPv6 technology. Finally, in the application layer, a typical FSO system provides various modern protocols such as asynchronous transfer mode (ATM), optical carrier 3 (OC3), Synchronous Transport Module level-1 (STM1), Society of Motion Picture and Television Engineers (SMPTE), etc.

Based on these, a communication link that can be used to connect train busses and train stations in order to deploy a modern, fast and secure network is presented in Figure 3. The presented network provides high bit-rate, secure, wireless communications link between train station and train buss, supporting all modern protocols of LTE and 4G systems according to IEEE standards.

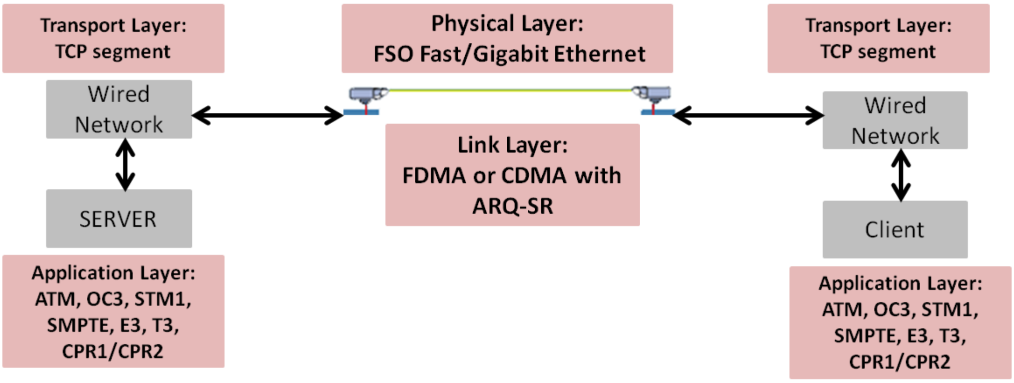

Figure 3 Communication protocol for FSO system

2.5 Cloud-RAN architecture

C-RAN is expected to bring significant benefits in high mobility scenarios as it enables fast coordination and grouping of several cells forming super-cells with a much larger size. To quantify the benefits of centralization in high mobility scenarios, let us consider the case where microcell base-stations are placed 1.2 km apart. For fast moving objects, i.e. trains, with a speed of 300km/h, handovers will be performed every 7s, leading to over-utilization of network resources [19]. However, by clustering several base-stations together handover frequency can be radically reduced.

To support the transport network requirements associated with C-RAN [20], we propose the adoption of an optical transport solution offering high capacity and advanced features including dynamic bandwidth allocation both in the time and frequency domain [21]. Given the technology heterogeneity of the proposed infrastructures, a critical function is interfacing between technology domains including isolation of flows, flexible scheduling schemes QoS differentiation mechanisms and mapping of different QoS classes across different domains. This can be achieved adopting flexible hardware functions that allow hardware repurposing through concepts such as hardware programmability. Hardware programmability can potentially enable dynamic and on demand sharing of resources guaranteeing also the required levels of isolation and security. In this context, programmable Network Interface Controllers (NICs) that are commonly used to bridge different technology domains at the data plane can play a key role. These controllers have a unique ability to provide hardware level performance exploiting software flexibility and can offer not only network processing functions, i.e. packet transactions [21], but also hardware support for a wide variety of communication protocols and mechanisms [22] such as, Virtual Output Queuing (VOQ). As depicted in Figure 4 through VOQ, a single physical buffer traversed by different flows can be divided into several separate queues with guaranteed performance facilitating hardware sharing through e.g., virtualization.

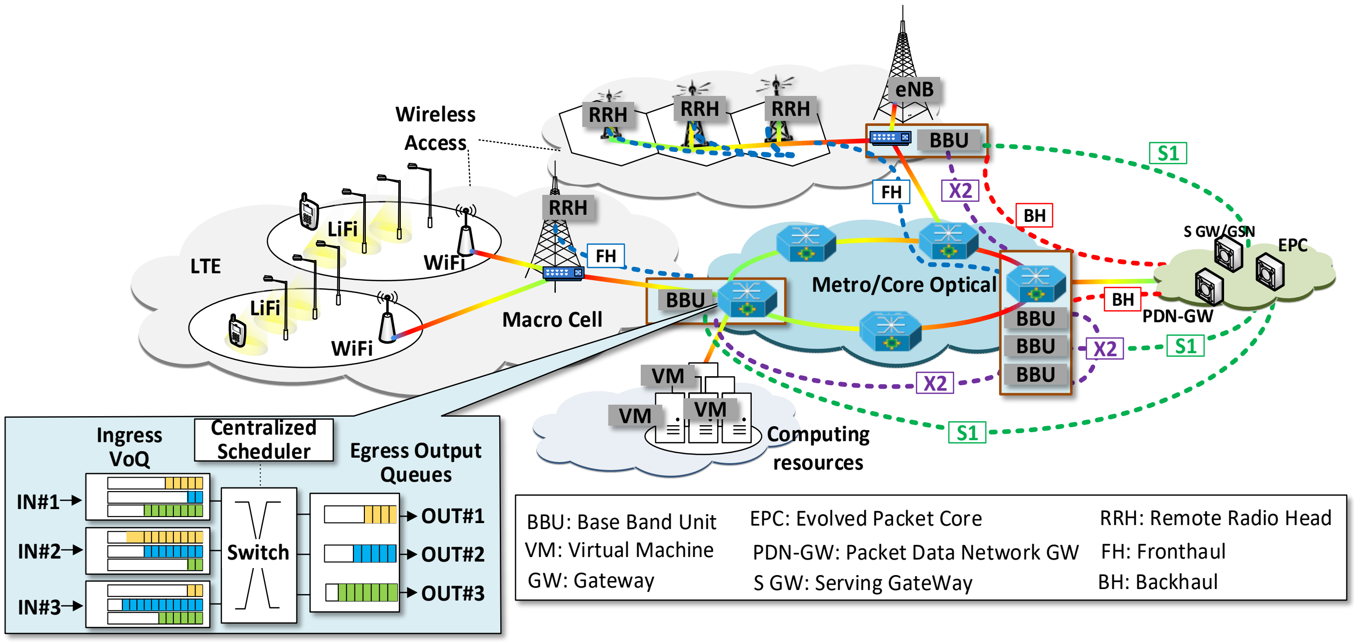

Figure 4 Converged Heterogeneous Network and Compute Infrastructures

3 Network Softwarization: Control and Management

As already discussed, the proposed infrastructure, Figure 4, exhibits a great degree of heterogeneity in terms of technologies. To address the challenge of managing and operating this type of complex heterogeneous infrastructure, the integration of the SDN and NFV approaches is proposed. In SDN, the control plane is decoupled from the data plane and is managed by a logically centralized controller that has a holistic view of the network [5]. In early SDN deployments the data plane implementations only supported packet forwarding related functionalities. However, the advent of new high performing technologies such as LiFi and dynamic optical metro solutions necessitates the execution of much more complex networking functions such as scheduling, network monitoring and management, resource virtualization, isolation, etc. In response to this, SDN controlled programmable hardware infrastructures can now effectively support implementation of these functionalities using high level programming languages.

At the same time, NFV enables the execution of network functions on compute resources by leveraging software virtualization techniques [23]. Through joint SDN and NFV consideration, significant benefits can be achieved, associated with flexible, dynamic and efficient use of the infrastructure resources, simplification of the infrastructure and its management, increased scalability and sustainability as well as provisioning of orchestrated end-to-end services.

Examples of features that enable these benefits include the option to virtualize the separate control plane, using NFV and deploy Virtual Network Functions (VNFs). These are controlled by the SDN controller, to allow on demand resource allocation, able to support dynamically changing workloads [23]. SDN network elements can be treated as VNFs, since they can be implemented as software running on general purpose platforms in virtualized environments. Both SDN and non-SDN models can be supported by SDN network elements. On the other hand, network applications can include SDN controller functions, or interact with SDN controllers and can themselves provide VNFs. Network elements controlled by SDN controllers can also provide Physical Network Functions (PNFs). Service Chaining (SC), combining and orchestrating physical and virtual network functions to support end-to-end service provisioning over heterogeneous environments is considered to be one possible network application.

A typical example of an SDN /NFV architectural framework is illustrated in Figure5 a). It is observed that network function virtualization infrastructures (NFVI) comprising LiFi and Wi-Fi components together with traditional non-virtualized physical infrastructures, e.g. LTE deploying RRHs, are interconnected with the pool of computing resources through SDN based optical network domains. Each Wi-Fi/LiFi administration domain may host multiple SDN data plane elements and expose its own virtualised resources through an SDN controller to the upper layer SDN controllers. In our case, the upper layer as illustrated in Figure 5 a) refers to the optical layer. The hierarchical SDN controller approach adopted can assist in improving network performance and scalability as well as limit reliability issues [23]. In the proposed architecture, the top network controller will manage network resource abstractions exposed by the lower level controllers that are responsible to manage the associated network elements. Orchestration of both computation and network resources is performed by the NFV Orchestrator and can be used for the support of multitenant chains, facilitating virtual infrastructure provider operational models. It is also responsible to interact with third party operations and support systems (OSS).

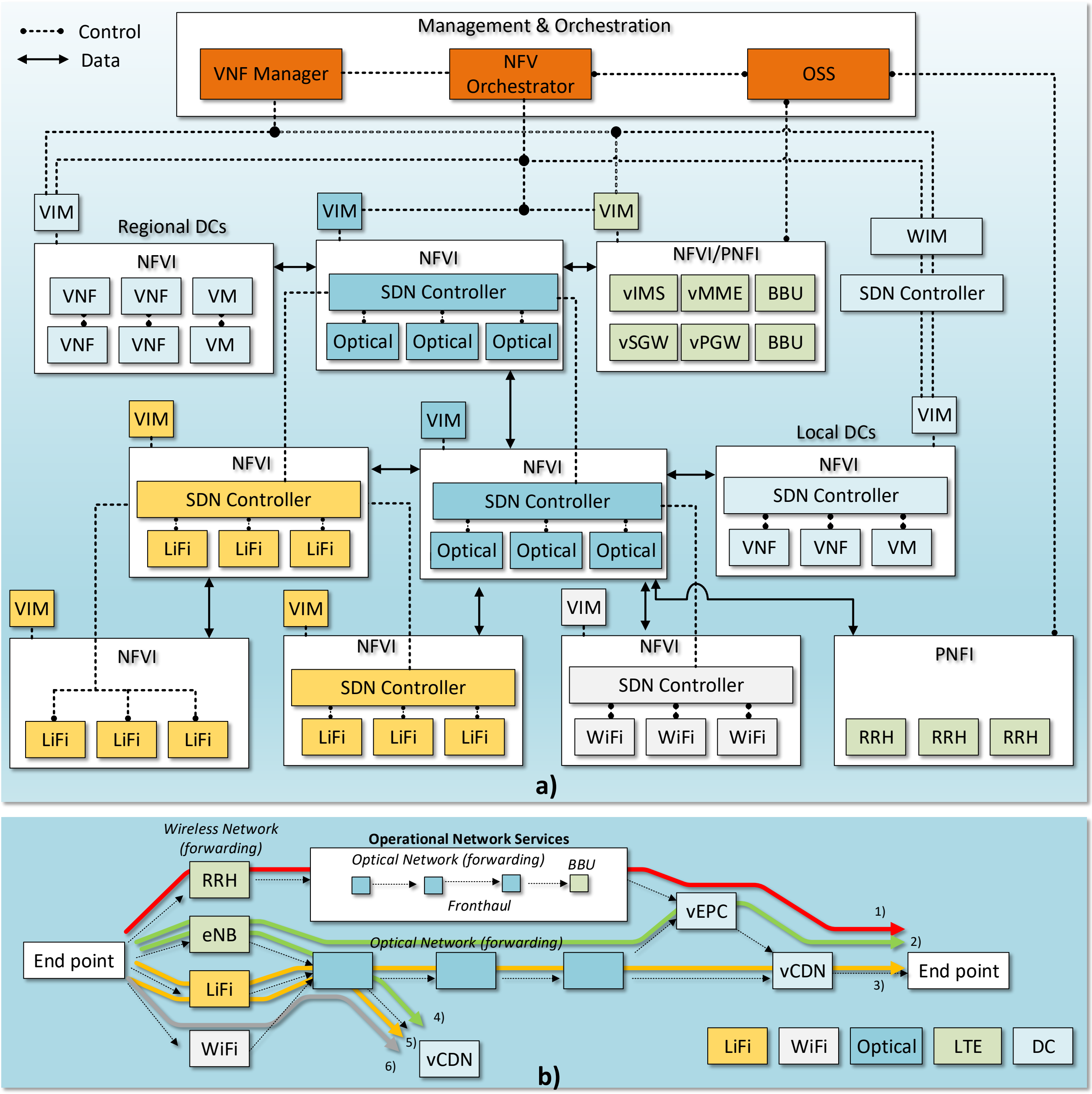

Figure 5 a) Example of an SDN/NFV-based control and management framework for Heterogeneous Network and Compute Infrastructures, b) Service chaining over heterogeneous network infrastructures in support of content delivery services: 1) vCDN over C-RAN, 2) vCDN over LTE, 3) vCDN hosted at remote DCs through LiFi, 4)-6) vCDN hosted at local DCs over LTE, LiFi and Wi-Fi respectively

4 System Specification

In this section first the proposed LiFi network for the rolling stock is introduced, and LiFi system specifications is discussed, and then overview of the Open Air Interface (OAI) as the LTE system used in the analysis is discussed.

4.1 LiFi network architecture and system specification

4.1.1 LiFi network for rolling stock

A proposed LiFi network planning for a typical rollingstock is demonstrated in Figure 6. Each LiFi attocell can cover an area of up to 4 seats in the rolling stock. The full area of the rollingstock can be covered by a network of LiFi APs. Broadband internet coverage and sensors connectivity within the rollingstock is covered by this LiFi attocells network. Each LiFi access point supports multiuser scenario, that is multiple devices and sensors can be connected via each access point to the network simultaneously. Moreover, each AP can be equipped with up to 64 GB internal memory which can be used for contents caching, edge computing, etc., so that the broadband connection is maintained even when the Internet connection is loose or lost. The APs are connected to the network via an ethernet cable and through the gateway. One or two (one at each end) gateways are considered for each rollingstock.

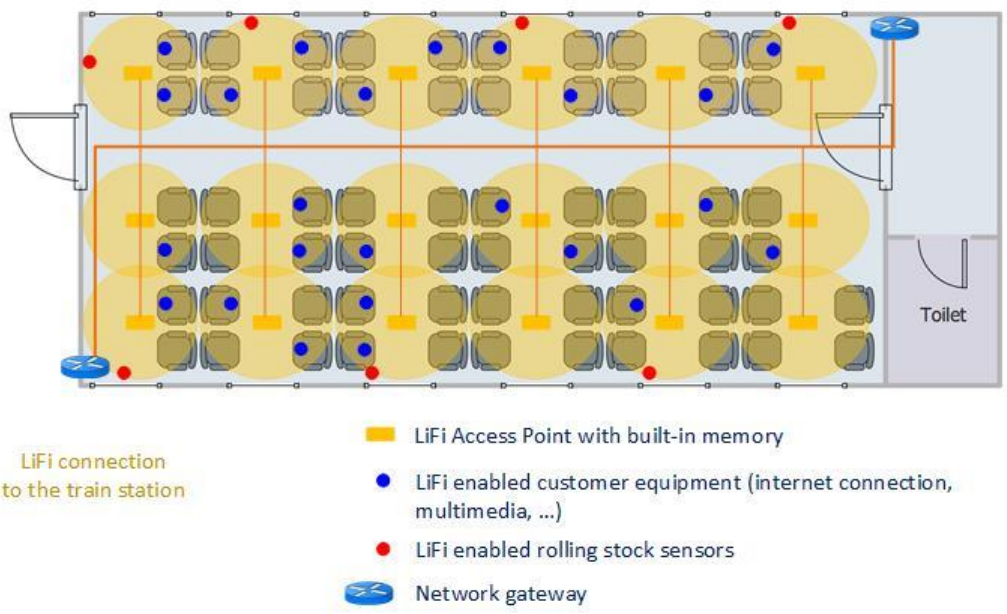

Figure 6 Scenario description: LiFi broadband/IoT coverage within rolling stock

4.1.2 LiFi system specification

LiFi XC, is a pureLiFi product, which consists of a LiFi AP and a LiFi USB-dongle which can be connected to any portable device equipped with USB2.0 port. The AP and USB dongle are presented in Figure 7 and Figure 8. While main performance specifications for LiFi XC system is described in Table 2. The AP is implemented using an embedded Linux device. It has its own ARM CPU, memory and storage. The main purpose is to bridge ethernet connection with LiFi interface implemented using FPGA and analogue front-ends. The interface is connected via USB (hard-wired on the PCB) to the ARM core and managed by mac80211 stack via dedicated Linux driver.

Figure 7: LiFi XC AP

Figure 8: LiFi XC STA

Table 2: System parameters

Parameter	Nominal Value	Unit
Downlink line rate (max)	43	Mbps
Uplink line rate (max)	43	Mbps
Downlink UDP data rate (max)	36	Mbps
Uplink UDP data rate (max)	27	Mbps
Maximum concurrent users	8	-
Minimum operational distance	10	cm
Maximum operational distance	130	cm

The LiFi XC AP system overview is illustrated in Figure 9, while its general physical and operational characteristics are as follows:

- Dimensions: 88 x 88 x 20 mm
- Weight: 200 g
- Operating temperature: 0 – 35°C
- Peak power consumption: 8W
- Power supply: PoE+, uPoE, 27-57 VDC (DC power supply)
- Data interface: 10/100/1000 BASE-T ethernet
- LED light source: TBD
- Status LED indicating AP status

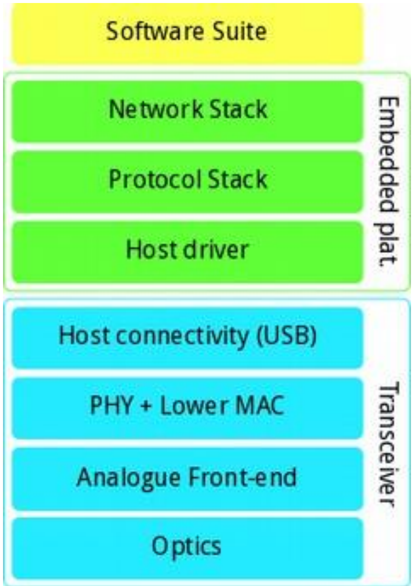

Figure 9: AP system overview

The analogue front-end of the transmitter (LED driver or TX driver) is implemented as a separate module as shown in Figure 9. This module is connected to the AP with a 10-way MicroFit-3.0 cable. General characteristics of LiFi XC Tx driver are as:

- Dimensions: 74 x 55 x 32 mm
- Weight: 124 g
- Operating temperature: 0 – 35°C
- Max power consumption: 4.2W
- Lamp connector: 3 way push inSTA

The LiFi USB dongle (or station (STA)) is a USB network adaptor, that enables the host computer to connect to LiFi networks. It does not contain its own CPU, memory or storage and thus it relies on the host for computing power as well as protocol/network stacks and software suit. The STA architecture is shown in Figure 10, while its general physical and operational characteristics are as:

- Dimensions: 85 x 29.4 x 10.2 mm
- Weight: 42 g
- Operating temperature: 0 – 35°C
- Peak power consumption: 2.5W
- Data interface: USB 2.0
- LED light source: SFH4715AS (850nm), integrated in STA, UL LED

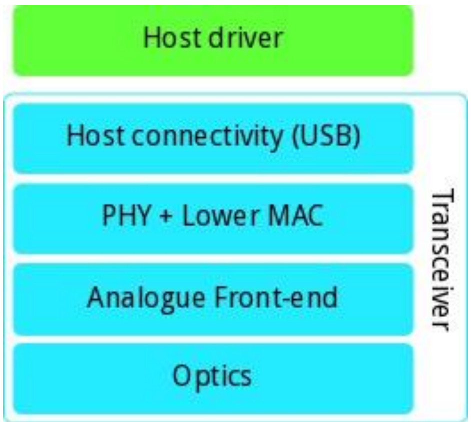

Figure 10: LiFi STA system overview

The LiFi STA (USB dongle) can be connected to any portable device with a USB connection. Figure 11 shows a Microsoft Surface Pro 4 with LiFi connection enabled by an XC USB dongle.

Figure 11: LiFi enabled Tablet using XC USB dongle

The interfaces available on the AP and STA are listed in Table3 and Table 4.

Table 3: List of interfaces on the AP

Interface	Function
10/100/1000 BASE-T ethernet	Network interface Option for power via PoE+ or uPoE
48V DC connector	Power alternative to PoE
10-way Microfit 3.0	Interface with LED driver
DALI interface	Interface to DALI controller where available
0-10V Control	Can be used for LED dimming
Optical interface	STAs connect via optical interface

Table 4: List of interfaces on the STA

Interface	Function
USB 2.0	Laptop connection
Optical interface	To connect to an AP

The physical layer architecture of the LiFi XC system is based on OFDM waveform, which has been used in many high data-rate applications. The choice of OFDM was due to its architectural simplicity, robustness against channel nonflat frequency response, and its spectral efficiency.

For the LiFi XC system, OFDM is chosen as the modulation at 16 MHz bandwidth. The architecture of the transceiver follows standard OFDM system design with specification and parameters illustrated in Figure 12 described as following.

Tx Architecture. The Tx block diagram is shown in Figure 12 (top block). Specific parameters can be listed as:

- Scrambling based on IEEE802.11 standard
- Convolutional Coding at rates 1/2, 2/3 and 3/4
- Bit interleaving based on the IEEE802.11 standard
- Symbol mapping as BPSK, QPSK, 16QAM, and 64QAM, based on the available SNR
- Framing block deals with the pilot insertion (to be used for channel estimation and synchronization) and RF impairment estimation and compensation
- The FFT/IFFT size is 64, and cyclic prefix (CP) of 1/4
- DAC is 12 bits resolution at 260 MSps rate

Rx Architecture. The block diagram of the Rx architecture is illustrated in Figure 12 (bottom), which is basically the inverse of the Tx architecture, while the channel needs to be estimated as well to be used in detection process. The only block to be specified is the ADC as following:

- ADC with 12 bits resolution at 160 MSps rate

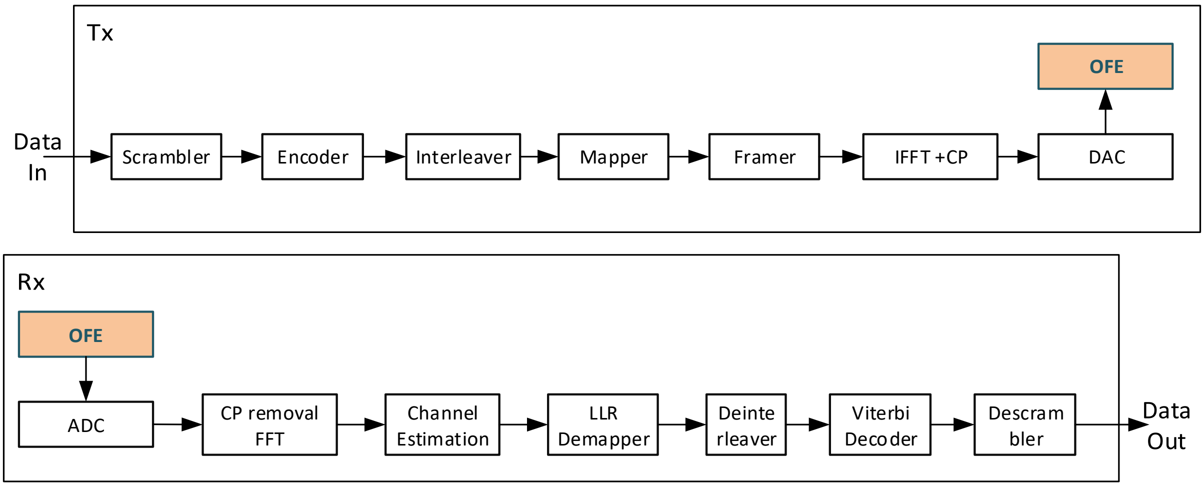

Figure 12. Block diagram of baseband Tx and Rx architectures.

The LiFi XC MAC layer is based on and compatible with 802.11 standard. It is implemented in two parts: Lower MAC and soft MAC.

The lower MAC works as the interface between PHY and upper layers and is implemented in the Mico32 microprocessor on the devices (both the STA and the AP). For the demonstrator a proprietary access algorithm is used with following specifications:

- Full-duplex operation
- Multiuser support
- Handover support
- Retransmissions and rate adaptation handling

The soft MAC is responsible to transfer data between the USB interface and the 802.11 protocol stack. On the AP side, Host APD is used to generate management related packets such as beacons. The soft MAC is implemented in the Host driver.

4.2 LTE system specifications

4.2.1 Softwarized LTE implementation based on OpenAirInterface (OAI)

As mentioned above, IN2DREAMS relies on a multi-technology access network for the interconnection of the sensing devices with the Gateway. In addition to commercially available LTE implemenations, a software RAN solution based on OAI will be also investigated. According to this approach, critical components of the evolved packet core (EPC), as illustrated in Figure 13, including the serving gateway, the mobility management entitity (MME) and the Home Subscriber Server (HSS) are implemented in software and run as independent modules over standard x86

Servers. The LTE APs rely URSP B210 that act as low cost RRHs.

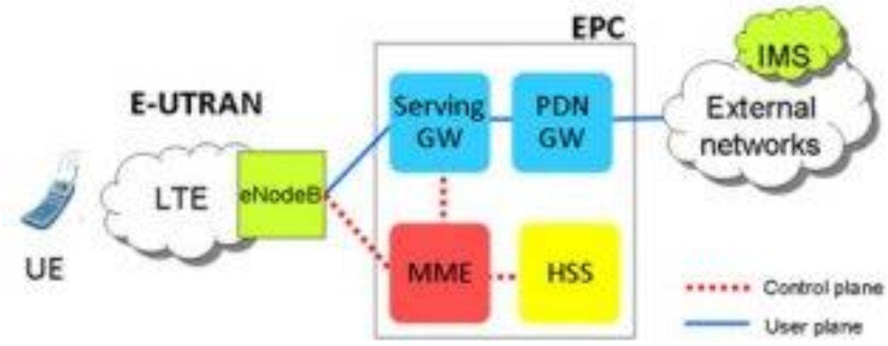

Figure 13: Basic EPC architecture [1]

4.2.2 OAI Deployment

To deploy the softwarized LTE network, a single machine has been used to host the whole EPC protocol stack (MME, HSS, S+G-PW, eNB). The equipment used for experimentation includes:

- A Dell Latitude E7470 notebook with an Intel i7 6600k processor (4 cores), 8 GB DDR4 RAM and an Ubuntu 17.04 operating system
- A USRP B210 board designed by Ettus
- Two antennas
- A Smart CardReader by Alcor
- LTE blank USIMs
- An HTC Desire Eye Smartphone

Experimental Validation: To validate the performance of the LTE platform, the allocated spectrum was first examined. For this purpose, we used Gnu Radio Companion (GRC) that we launched in a separate x86 machine where a second USRP B210 has been attached. For the spectrum analyzer we used the "WX fosphor Sink" block and for the Waterfall sink we used the "QT GUI Waterfall

[1] http://www.3gpp.org/technologies/keywords-acronyms/100-the-evolved-packet-core

Sink" block.

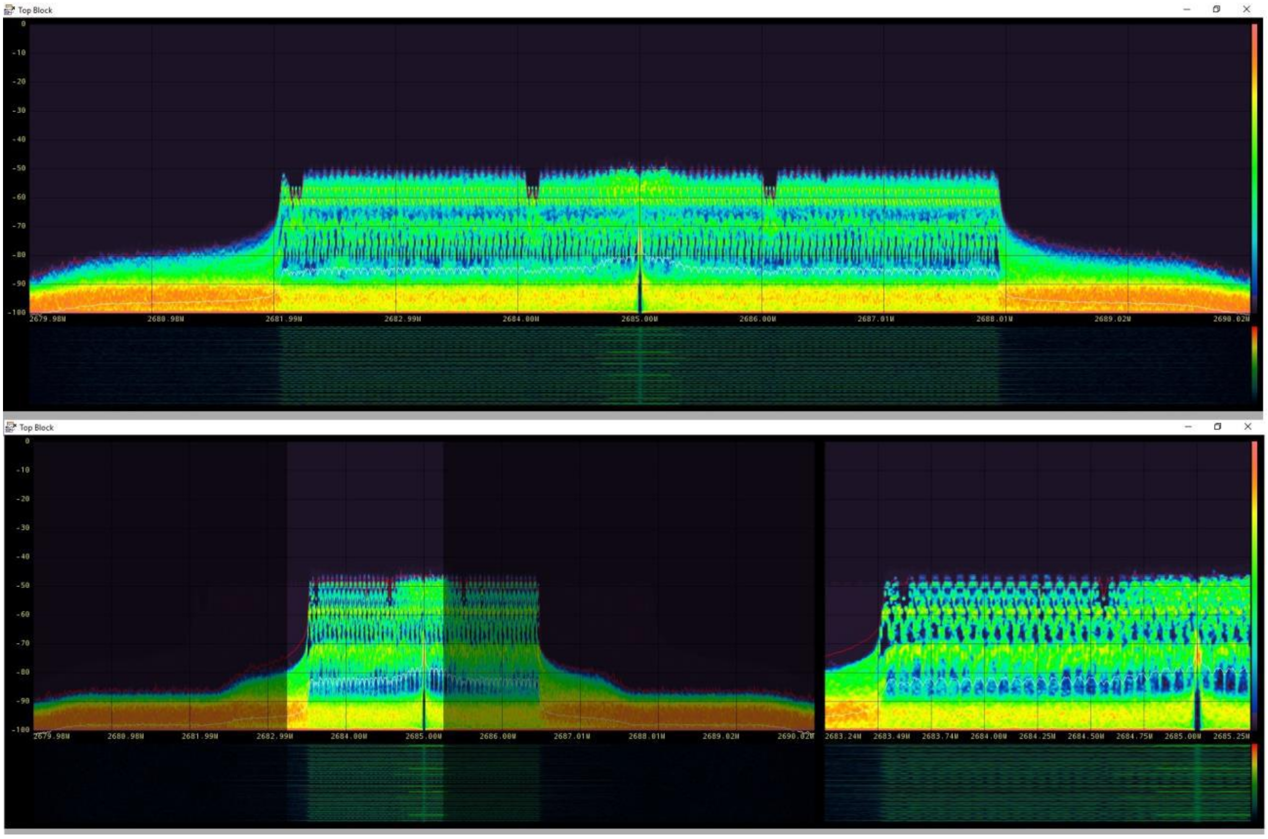

Figure 14 OAI LTE Spectrum with the use of GNU Radio Companion for the 5MHz Configuration

Figure 14 shows the spectrum captured from the second USRP board for a 5MHz LTE configuration with the 25 Physical Resource Blocks. Both the upper and the lower figures show the same spectrum, but the lower one is zoomed. We can clearly see the orthogonal and overlapping OFDM subcarriers in the spectrum. Notice that this figure was captured before connecting the Smartphone to the OAI, so there is no real data transmitted except for the physical channels/signals. We can also see the null subcarriers at regular intervals, where the peaks are considerably lower compared to the other subcarriers. By manipulating the configuration file, we obtain the spectrum for 10 and 20MHz bandwidth, where we can clearly see the spectrum spreading with the increase of the bandwidth. Figure 14-Figure 19 show the utilized LTE resources under various system configurations.

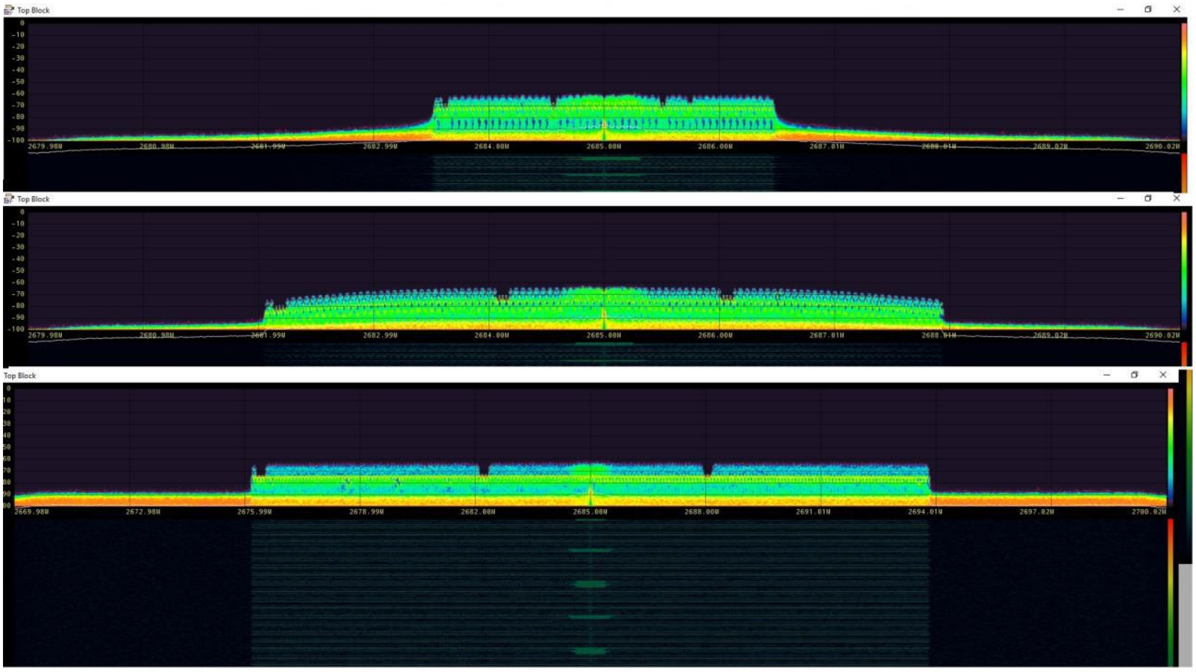

Figure 15: OAI LTE Spectrum at 5MHz, 10MHz and 20MHz Configurations

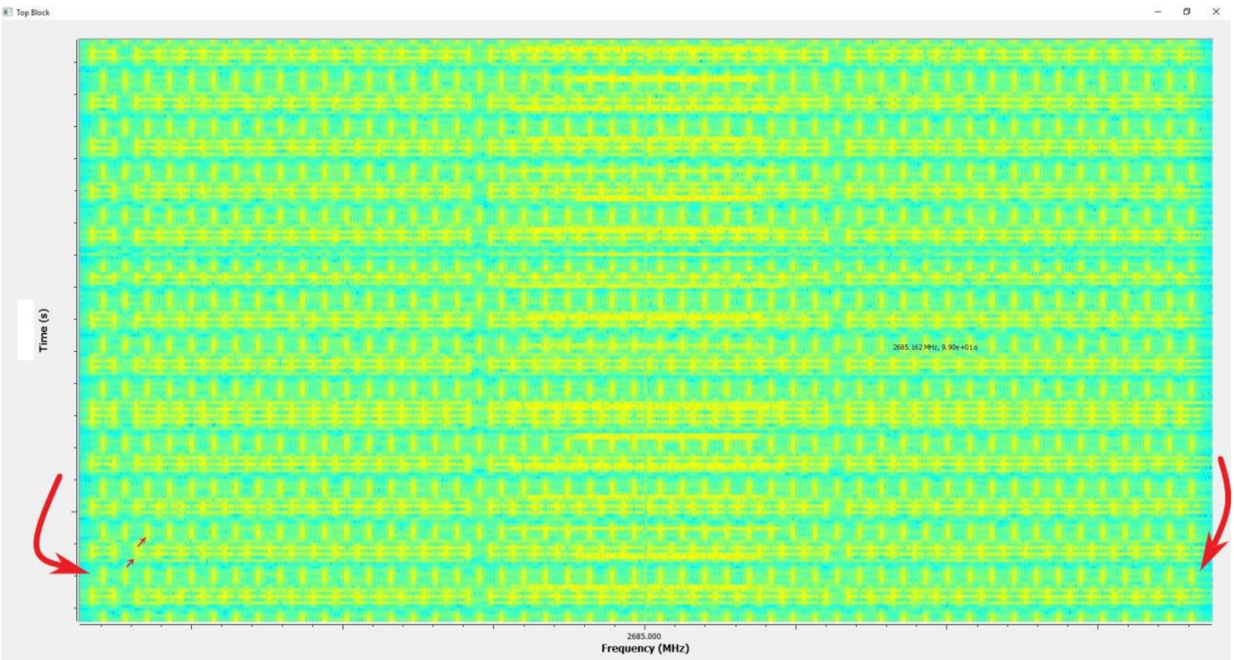

Figure 16: Physical Resource Blocks in LTE

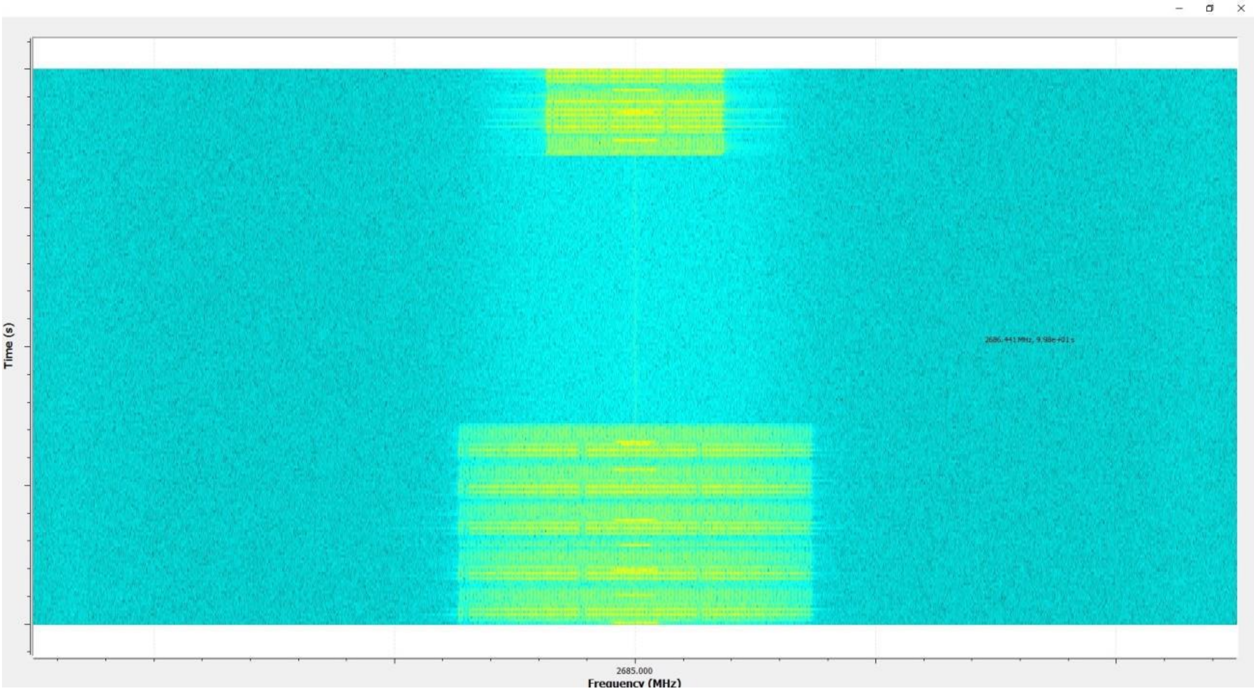

Figure 17: Physical Resource Blocks (PRB) in LTE: top element show PRBs under 5MHz configuration, bottom elements PRBs under 10MHz configuration.

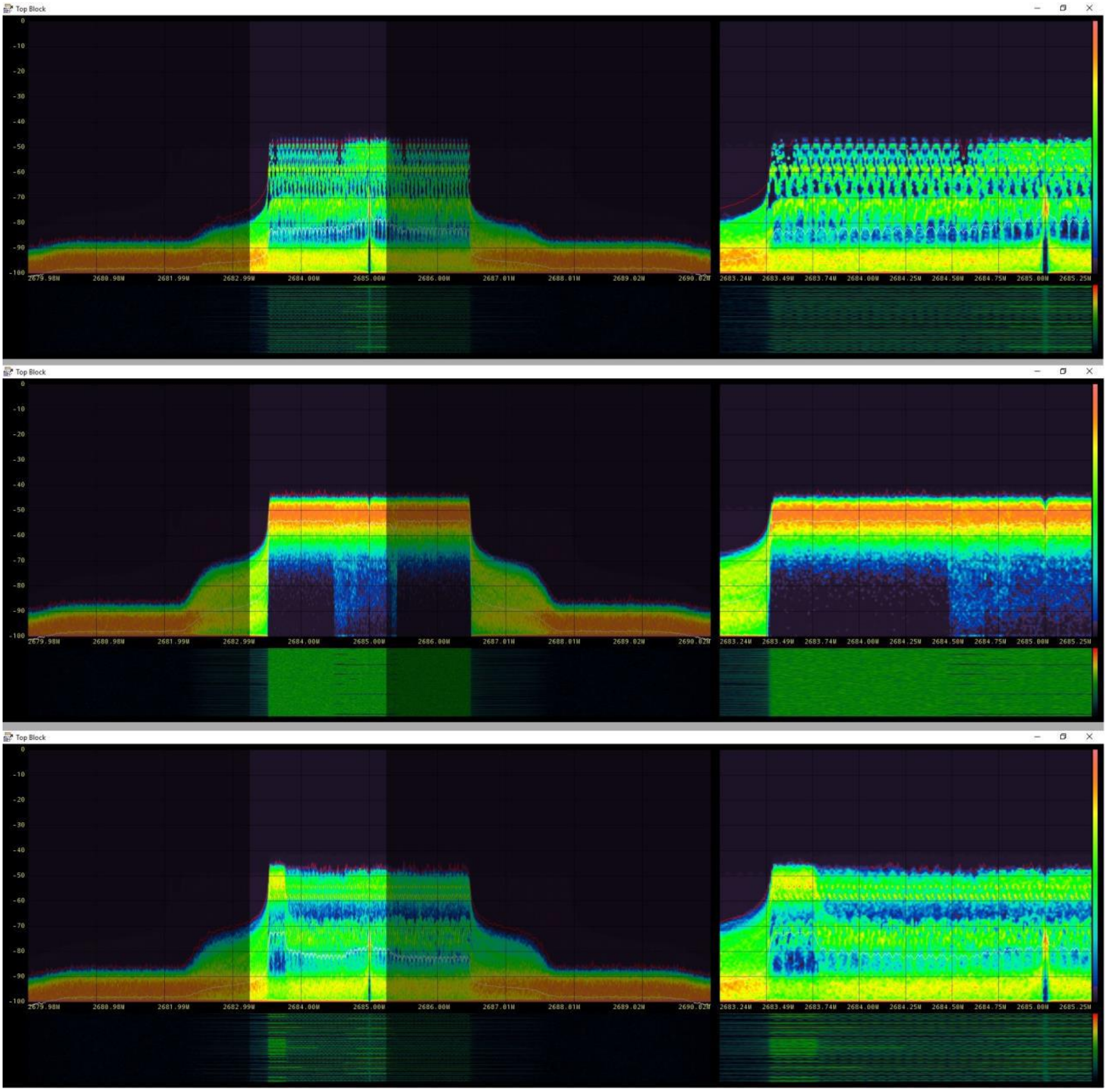

Figure 18: Top figure: Allocated spectrum in Downlink (DL) where we see that the subcarriers are not used. Middle figure: Allocated spectrum under fully utilization in the DL. Bottom figure: Spectrum allocation in the uplink.

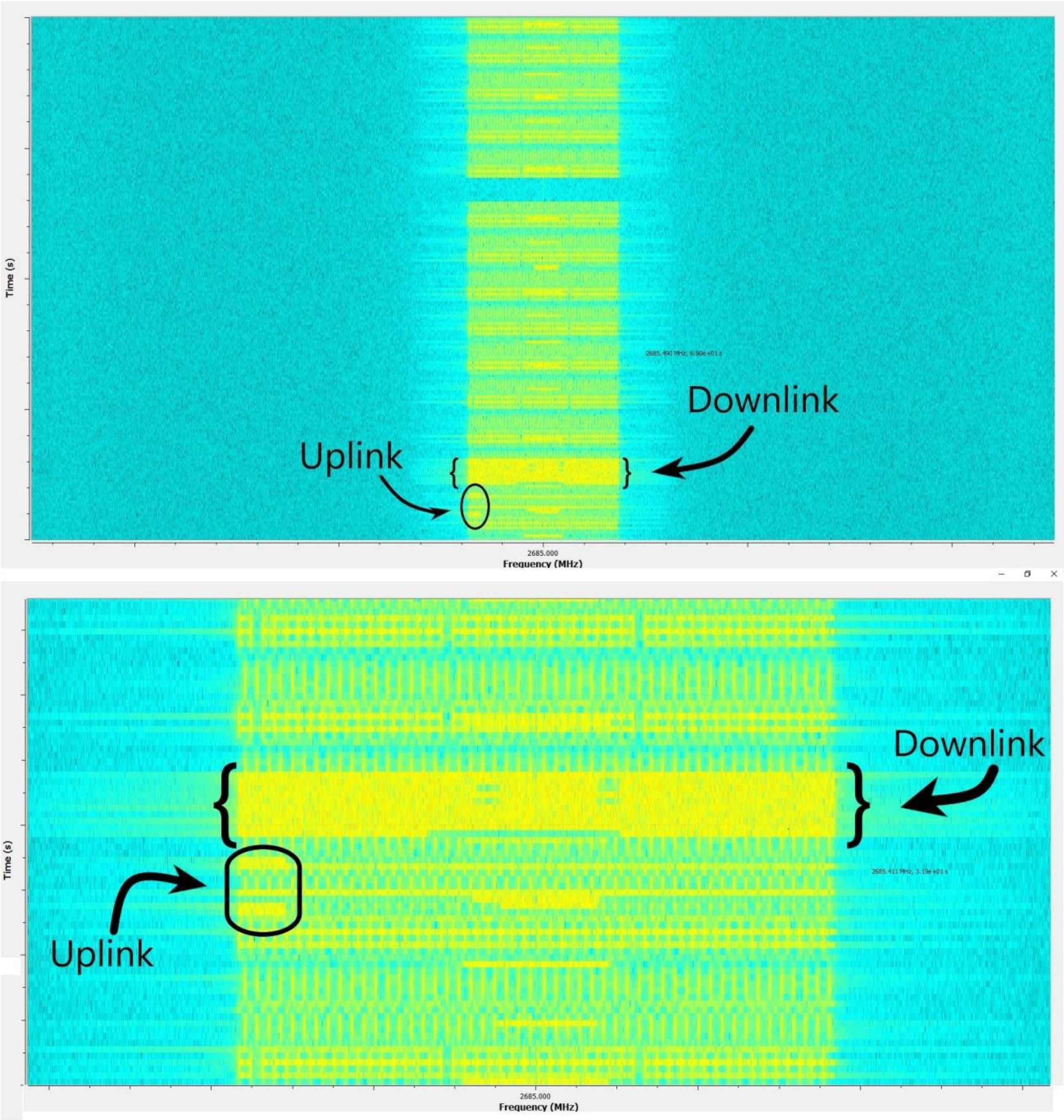

Figure 19: PRB allocation during uplink and downlink transmission.

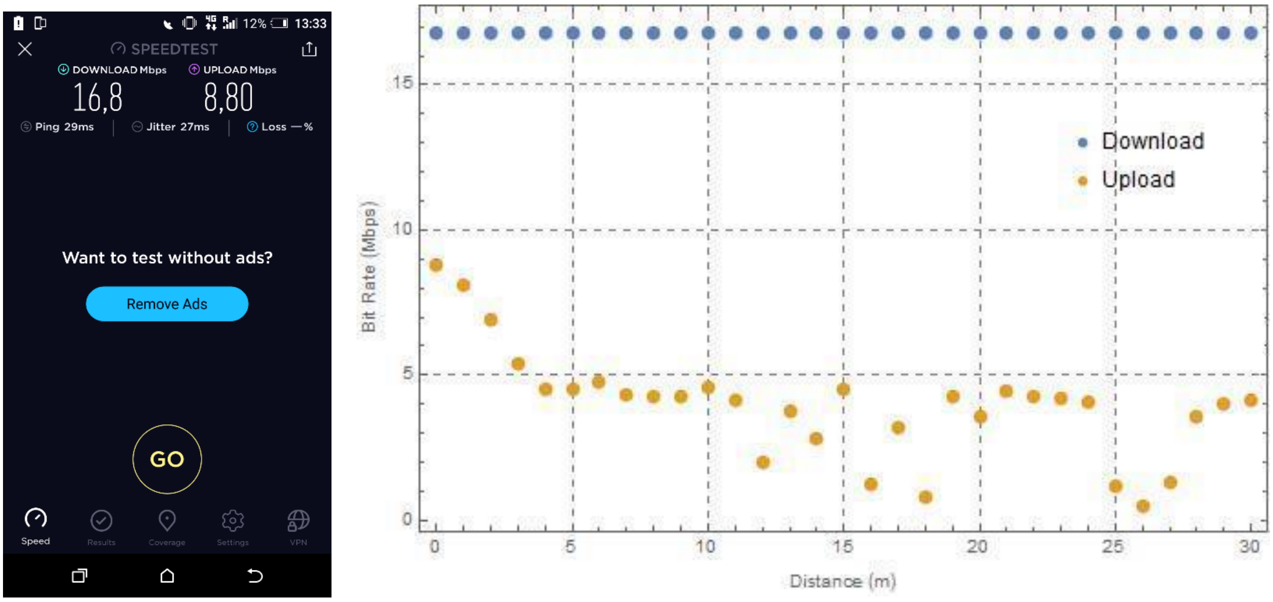

Figure 20: a) LTE speed test for a 5MHz configuration, b) Throughput as a function of distance for UL and DL transmissions.

5 Modelling and Performance Evaluation

5.1 Network of queues modeling approach

To address the great diversity of requirements introduced by the upcoming services in a cost-effective and energy efficient manner, optimal resource assignment considering the unique application and device characteristics is needed. In achieving this goal, the development of intelligent optimization algorithms considering different Key Performance Indicators (KPIs), i.e. capacity, latency, energy consumption, for all physical and virtual network providers can play a key role. In the SDN/NFV architecture, shown in Figure 5, this process is located at the management and orchestration (MANO) layer, offering, to network service providers, suitable tools that can assist in performing a broad range of tasks, including [23]:

- activities related to service chain management, able to Create/Delete/Update network SCs and a set of other relevant network functions
- management of SCs considering virtual and/or physical resources and definition of traffic rules to dictate the selection of the optimal chain out of a set of possible chains
- scale-in/out functionalities such as the, ability to bring up/down multiple network functions on an on-demand basis
- traffic offloading from one forwarding entity to another

- unified orchestration of compute and network elements
- service orchestration with legacy or third-party Operation Support System (OSS)

The combination of these tools facilitates the support of any mix of services, use-cases and applications and can assist in addressing both technical and business challenges anticipated to arise in future network infrastructures. A specific use-case that can be used to highlight the role of these tools is the provisioning of smart metering services in railway environments, deploying a heterogeneous network infrastructure, as shown in Figure 5 b). The objective is, each metering device to transmit its reading to the gateway through the appropriate network technology that maximizes its battery lifetime under QoS constraints.

To provide smart metering services, the orchestrator instantiates different type of VNFs that are deployed and chained together, each having specific processing and bandwidth requirements. Based on the type of wireless access technology, i.e., RRH, eNB, Wi-Fi, LiFi, used to forward data from mobile devices (End-Point A in Figure 5 b)) to the FSO and the on-board gateway. Multiple candidate service chains can be created. To realize each SC, sufficient network bandwidth and processing capacity must be allocated, corresponding to specific physical resources, for the interconnection and deployment of VNFs. VNFs are then processed in the order defined by the corresponding SC. For example, SC1 in Figure 5 b) illustrates the case where a mobile device transmits its measurements to the gateway through an RRH. To realize this, wireless signals received by the RRHs are forwarded over an optical transport network to the BBU pool and then to the DC location. Flow conservation as well as mapping and aggregation/de-aggregation of traffic between different domains should be also satisfied.

Apart from network and capacity constraints, end-to-end delay is an important KPI that needs to be also considered in the analysis. In highly loaded heterogeneous networks, end-to-end delay can be greatly influenced by queuing delays associated with the interfaces. Therefore, applying specific queuing policies and scheduling strategies at these locations is very important. Significant delay benefits can be achieved by instantiating the necessary network functions and reserving the required virtual/physical resources. End-to-end delay can be mathematically modelled through queuing models and the adoption of closed form approximations derived by modeling the different network domains as open, closed and/or mixed queuing networks. An example is illustrated in Figure 21 where a three-dimensional Markov chain is adopted to model the three wireless access technology domains i.e. LTE, LiFi and Wi-Fi. Each dimension of the Markov chains corresponds to a different virtualized wireless access domain with its state space defined as

$\mathcal{S} = \{(i,j,k) | i \leq \mathcal{I}, j \leq \mathcal{J}, k \leq \mathcal{K}\}$,

where i, j and k correspond to the virtualized resources used across the LTE, LiFi and Wi-Fi dimension respectively and (i, j, k) is a feasible state in $\mathcal{S}$. Note that $\mathcal{I}$, $\mathcal{J}$ and $\mathcal{K}$ correspond to the maximum set of resources that can be allocated to a specific provider. A key characteristic of the proposed scheme is that it allows modeling of traffic offloading decisions from one entity to another, i.e. LiFi to Wi-Fi or LTE, as well as modeling of the arrival of a new service request by modifying the corresponding state, i.e. $(i, j, k) \to (i + 1, j, k)$, when a new forwarding decision is applied through the LTE network. The steady state probabilities of the Markov process can be determined in a unique way using the well-known matrix-geometric solution techniques and the corresponding service delay can be determined.

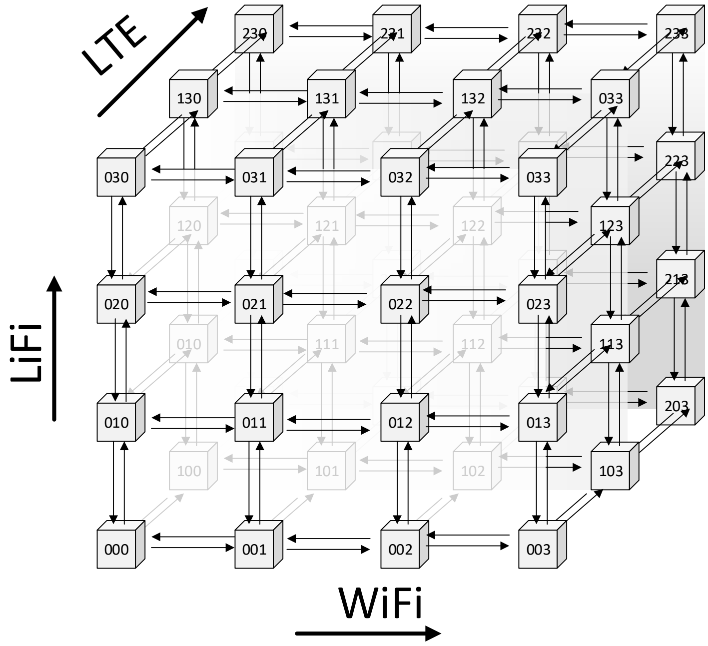

Figure 21 Modelling queuing delays in converged network environments: three-dimensional Markov chain for estimating delays in virtualized wireless access network

Markov chain models can be effectively used to evaluate the performance of domains where statistical independence between arrivals and services exists. Therefore, they can be applied to describe scenarios where virtual resources are realized through isolated physical resources such as different channels, spectrum, wavelengths etc. However, these models cannot be extended to technology domains where common buffers are shared among multiple virtual flows.

An additional consideration to be taken into account during the operation of this type of infrastructures is resilience. To ensure resilience, the Markov chain model shown in Figure 21 is extended to cover the case of failure of LTE, LiFi or Wi-Fi APs. The key idea behind the proposed protection scheme is that in case of failure of an AP, services are redirected to the remaining operational APs. The overall process is modeled through the Markov Chain shown in Figure 22. As previously described, under normal operational conditions users are served by all APs. However, in case of failure of LTE, LiFi or LTE demands are served by the other APs. For example, assuming that the system is in state (i, j, k), in case of LTE failure the i service flows of the LTE AP will be redirected to the Wi-Fi AP and the new state of the system will be $(0, j, k + i)$. Similarly, in case of failure of LiFi the new state of the system will be $(i + j, 0, k)$. The failed AP can be either repaired after a predefined interval or remain out of operation. In case of failure of another AP, all demands will be served by a single access technology. Finally, an immediate repair is scheduled in case of failure of all APs.

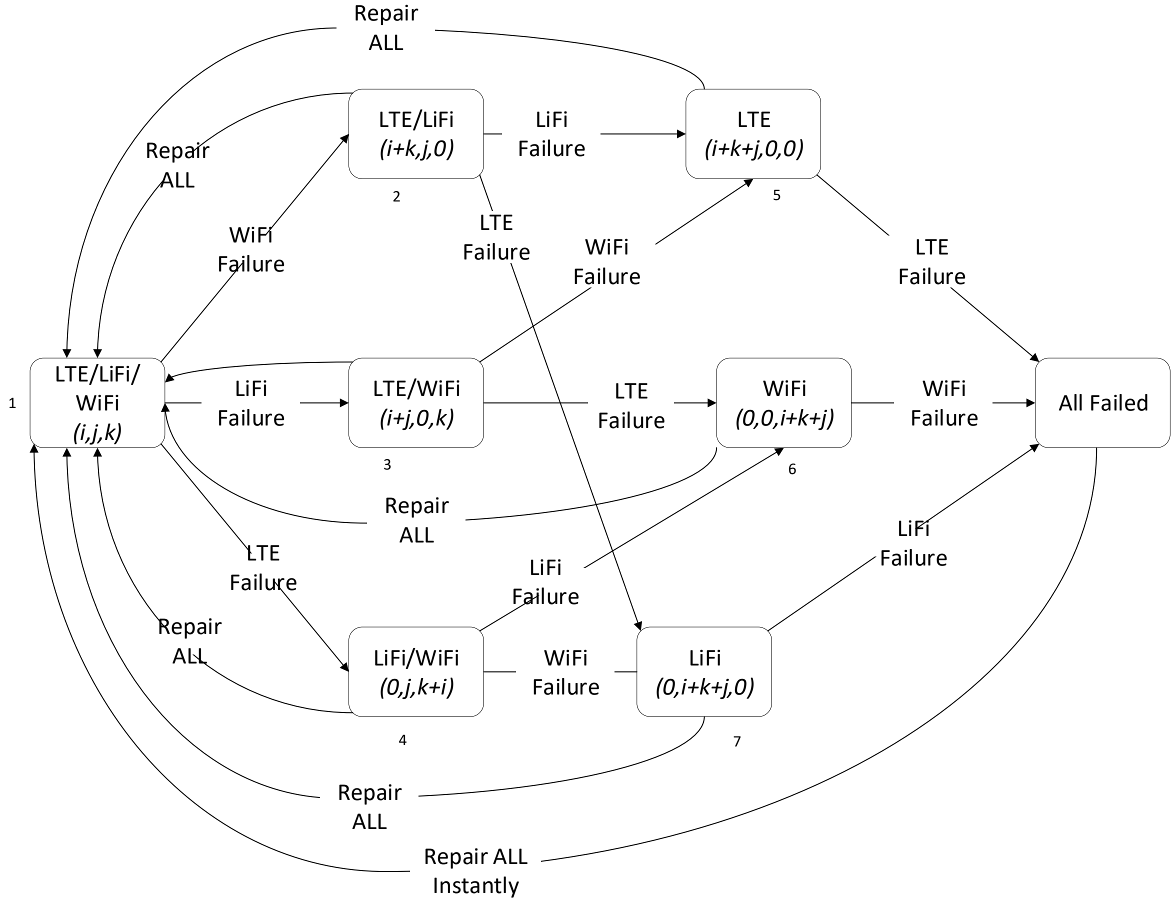

Figure 22 Repair/failure transition states of the on-board multi-technology access network comprising LTE/LiFi/Wi-Fi

The transmission matrix of the state diagram shown inFigure 22 is given by

$$p = \begin{bmatrix} 0 & F & F & F & 0 & 0 & 0 & 0 \\ R & 0 & 0 & 0 & F & 0 & F & 0 \\ R & 0 & 0 & 0 & F & F & 0 & 0 \\ R & 0 & 0 & 0 & 0 & F & F & 0 \\ R & 0 & 0 & 0 & 0 & 0 & 0 & F \\ R & 0 & 0 & 0 & 0 & 0 & 0 & F \\ R & 0 & 0 & 0 & 0 & 0 & 0 & F \\ R & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

where R denotes the repair rate and F the failure rate. For simplicity we assume that the failure rate of all technologies is equal. However, the analysis can be easily extended to cover different failure rates. A numerical example showing the probability for all APs to fail for the case where the average failure rate per AP is 1/1000h and the average repair time varies between 10 and 2000h is shown in Figure 23. As expected, the probability of APs to fail increase with the time interval between repairs.

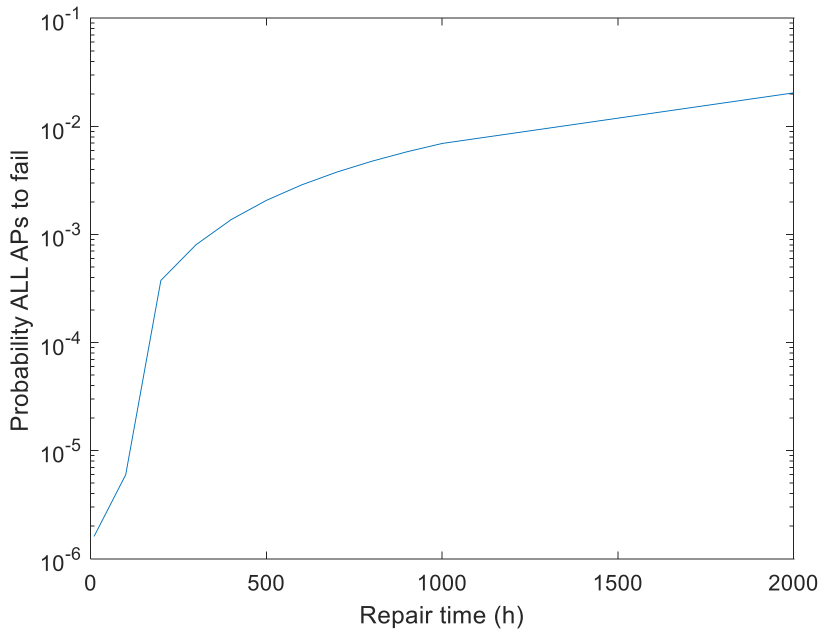

Figure 23 Failure probability of all APs as a function of the repair frequency

5.2 HetNet performance evaluation

Figure 24 shows the dropping probability (service disruption) as a function of the arrival rate per AP for different average repair time. As expected, for higher values of repair times service disruption probability increases as the probability for the APs to fail also increase. Service disruption also increases with the offered load as in case of failure for high values of service requests the remaining capacity is not sufficient to cover all demands. In this case, call dropping is performed.

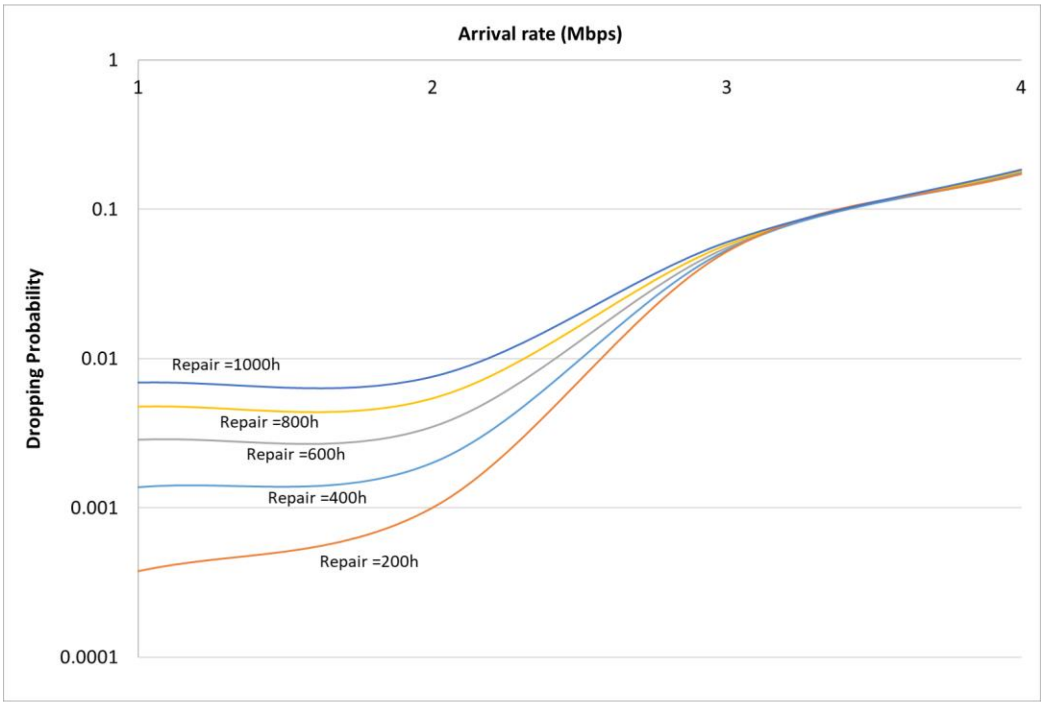

Figure 24 Dropping probability as a function of the arrival rate per AP for various repair time intervals.

The proposed Multi-technology access scheme is compared in terms of resilience with the traditional solution based on Wi-Fi/LTE solution. The state diagram of the LTE/Wi-Fi solution is shown in Figure 25 where its transition matrix is given by:

$$p = \begin{bmatrix} 0 & F & F & \\ R & & & F \\ R & & & F \\ R & 0 & 0 & 0 \end{bmatrix}$$

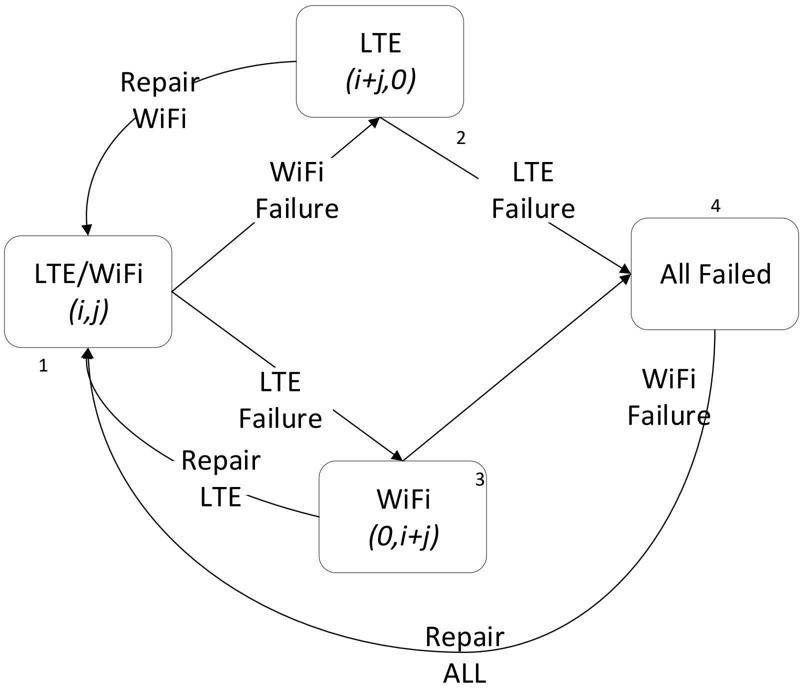

Figure 25 Repair/failure transition states of the on-board multi-technology access network comprising LTE/Wi-Fi

From Figure 26 we observe that by integrating LTE/LiFi and Wi-Fi in the on-board segment the probability of all technologies to fail reduces. Therefore, the same reliability level can be ensured with less frequent repairs leading to lower operational costs.

Finally, the dropping probability (service disruption) as a function of the arrival rate per AP for different average repair time and different combinations of access technologies is shown in Figure 27. As expected, the introduction of LiFi increases overall capacity and reliability of the overall system leading to lower service disruption probabilities.

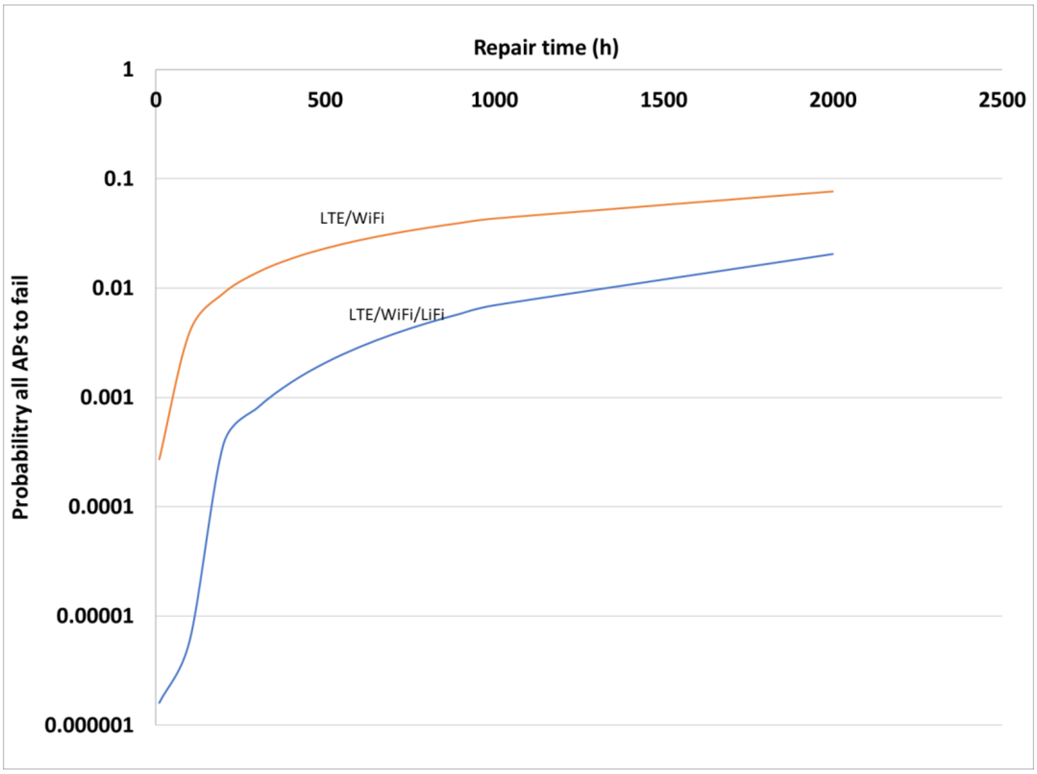

Figure 26 Failure probability of all APs as a function of the repair frequency for the LTE/Wi-Fi vs the converged LTE/LiFi/Wi-Fi solution.

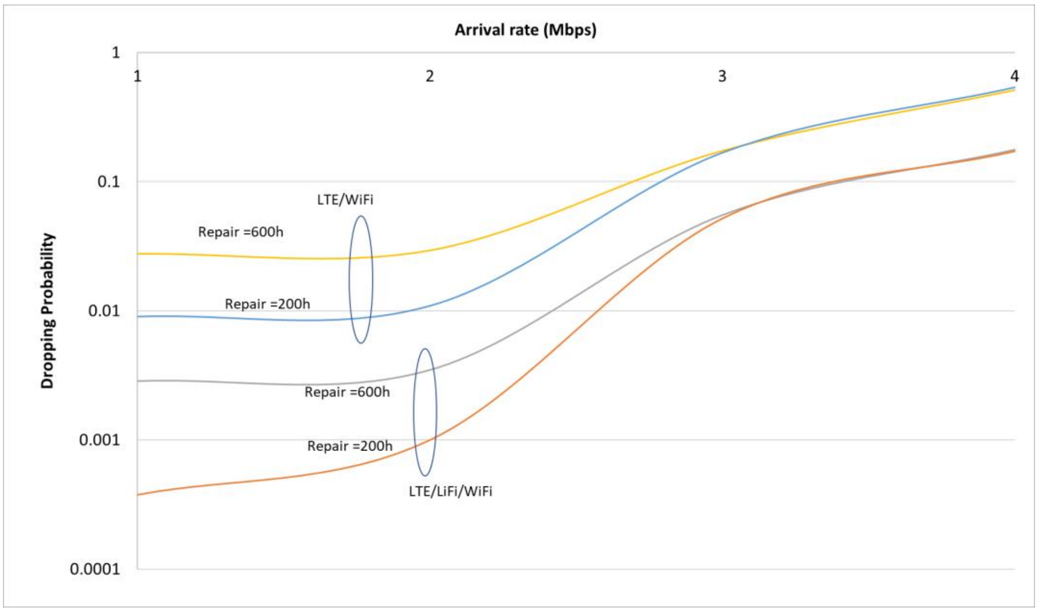

Figure 27 Dropping probability as a function of the arrival rate per AP for various repair time intervals.

6 Summary and Conclusion

An on-board communication platform based on LTE, Wi-Fi and LiFi was introduced, while free-space optical communication can be used for the inter rollingstock and rollingstock to the station communication (backhaul) links. The optimization of a heterogeneous network (HetNet) based on the three access technologies, i.e. LTE, Wi-Fi and LiFi, for on-board communications was presented in this deliverable which is based on the network of queues approach. The performance of the proposed approach, i.e. network softwerization, was evaluated according to the optimization approach and modelling. Results show that the addition of LiFi technology to the HetNet can dramatically improve the connectivity performance in terms of network/access-point failure and call dropping.

Task 2.2 will be continued to the end of IN2DREAMS life time. The task will continue working on the on-board and train to ground communication technology design and optimization, by specifying the rollingstock scenario in terms of heterogeneous network planning and including on-board devices, e.g. sensors, smart phones, etc.

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