Deliverable D2.2

System Functional Requirements and Architecture

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Deliverable nature:	Report (R)
Dissemination level: (Confidentiality)	Public (PU)
Contractual delivery date:	31 January 2018
Actual delivery date:	
Suggested readers:	Architects from companies such as Zaha Hadid, Arup, Yiangou Architects; Civil Engineering Design companies such as Buro Happold, Atkins; Telecom network operator companies such as BT, O2; Consumer Product OEMs such as Samsung, Huawei
Version:	1.0
Total number of pages:	159
Keywords:	system architecture, hardware architecture, software architecture, networking, position sensing, remote radio head

Abstract

This report describes the system hardware architecture of the remote radio light head and UE to support IoRL software structure for Access Layer, Network Layer, Orchestration Layer and Service Layer. The software architecture of Infrastructure Layer, Network Layer, Orchestration Layer and Service Layer is also described in this report. This report provides also the details of IoRL position sensing architecture. Finally, the light system electro-mechanical architecture and consumer products electro-mechanical architecture is presented in this report.

Disclaimer

The research leading to these results has received funding from the European Union Horizon 2020 Programme under grant agreement number 761992 — IoRL — H2020-ICT-2016-2017/H2020-ICT-2016-2.

Impressum

Internet of Radio Light

IoRL

WP2 Usage Scenarios, Requirement Specifics and System Design

Task 2.3 System Functional Requirements Document

Task 2.4 System Architectures

Definition and Description of the IoRL System Functional Requirements Architecture

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[19 man-months]

Executive summary

The 5G PPP Internet of Radio Light (IoRL) project is about integrating the 5G network with wireless LAN, VLC and mmW with a 5G gNB interface. This document describes the IoRL system functional requirements and high level system architecture. It presents the system requirements for the hardware architecture of remote radio light head (RRLH) based on the system functional requirements. It then identifies mmW transceiver and VLC transmitter structure at RRLH. The document also describes the IoRL technology of RRLH controller fully compatible with 5G 3GPP standard. Similarly, the system hardware architecture of UE of IoRL network is described in the document with the details of IoRL UE principle structure and VLC receiver structure. It then explores the IoRL access layer software architecture based on the access layer hardware architecture in section 3 and section 4. The access layer software includes 5G radio frame, link level simulation framework, 5G L1 protocol stacks and 5G TDD timing synchronization. The IoRL network and orchestration layer software architecture integrates the NFV/SDN, 5G L2 protocol stacks, protocols for internet interface and 4G/5G interface, protocols for handover of 4G/5G in home, protocols for 4G/5G QoS flow, multi-source stream and security framework. Moreover, IoRL service layer software architecture discovers the various application software architecture based on the scenarios and user requirements in D2.1. This document also provides the description for indoor position architecture for mmW and VLC sub-systems. Also, this document provides the lighting system electro-mechanical architecture design, which includes existing lighting system structure, electronic platform dimension and position and initial synthesis of system design for museum, tunnels and home use cases. Furthermore, it identifies the consumer product electro-mechanical architecture with existing consumer product structure, user terminal mechanical design and initial synthesis of system design. Finally, this document describes the key performance indicators for IoRL use cases in the appendix.

This deliverable serves as guideline for the identification of the functional requirements and the further elaboration and development of the system architecture that is presented in more details in Deliverables D2.3, D3.1, D4.1 and D5.1 of the IoRL project.

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Abbreviations

3D	Three Dimensional
5G	Fifth Generation (mobile/cellular networks)
5G PPP	5G Infrastructure Public Private Partnership
APP	Application
BRE	Building Research Establishment
CAD	Computer Aided Design
CHDCS	Cloud Home Data Center Server
CO	Carbon Monoxide
CO2	Carbon Dioxide
DoS	Denial of Service
FD	Forwarding Device
HDTV	High Definition Television
HiFi	High Fidelity
IHIPGW	Intelligent Home IP Gateway
IoRL	Internet of Radio Light (project)
IP	Internet Protocol
IPTV	Internet Protocol Television
KPI	Key Performance Indicator
LAN	Local Area Network
LED	Light Emitting Diode
MNO	Mobile Network Operator
NFV	Network Function Virtualization
NFVI-PoP	NFV Infrastructure point-of-presence
PaP	Picture and Picture
PC	Personal Computer
PD	Photo Diode
PiP	Picture in Picture
PNF	Physical Network Function
PoE	Power Over Ethernet
PV	Photo Voltaic
R&D	Research and Development
RRLH	Remote Radio Light Head
SCS	Subcarrier Spacing
SDN	Software Defined Networks
SSC	Smart Shopping Cart
TRxP	Transmission and Reception Point
TV	Television
UC	Use Case
UE	User Equipment
uRLLC	Ultra-Reliable Low-Latency Communications
VLC	Visible Light Communications
VNF	Virtual Network Function
VR	Virtual Reality
xMBB	Extreme Mobile BroadBand

1 Introduction

This is the second technical document produced by the 5G PPP IoRL project.

1.1 Objective of this document

The main objectives of this document are to:

- Describe the system hardware architecture for 5G Internet of Radio Light broadband access networks in buildings, which have been established in the IoRL project, taking into account the work in other 5G projects and forums.
- Describe the system software architecture for Infrastructure Layer, Network Layer, Orchestration Layer and Service Layer for the IoRL solution.
- Describe the details of the IoRL position sensing architecture and its operation and procedures.
- Describe the light system electro-mechanical architecture and consumer products electro-mechanical architecture.

1.2 Structure of this document

The rest of the document is organized as follows:

- Section 2provides an overview of the system architecture
- Section 3 system hardware architecture of Remote Radio Light Head,
- Section 4 system hardware architecture of UE,
- Section 5 IoRL access layer software architecture,
- Section 6 IoRL networking layer and orchestration software architecture,
- Section 7 IoRL service layer software architecture,
- Section 8 IoRL position sensing architecture,
- Section 9 IoRL light system electro-mechanical architecture,
- Section 10 IoRL consumer products electro-mechanical architecture,

2 System Architecture Overview

The goal of the IoRL project is the syntheses of license free **R**adio **F**requency (RF) 60 GHz and the **V**isible **L**ight **C**ommunication (VLC) in one system. The symbiosis of the two technologies enables new application fields and the reuse of already existing infrastructure. However, to provide a system that will be accepted by the user the new system needs to offer new capabilities and applications, and a compatibility with existing system/standards like the IEEE 802.11 and 802.15 or 3GPP. This is essential for successful market launch of the IoRL system. The current versions of **W**ireless **L**ocal **A**rea **N**etworks (WLAN) mostly use frequencies around 2 GHz and 5 GHz and are limited in frequency bandwidths and therefore also in their maximum data rates. The second problem with the currently used frequency bands is the overload of the microwave ISM bands with WLAN devices and other applications like Bluetooth etc. Here the combined use of **m**illi**m**etre **Waves** (mmW) and VLC can help to relax the situation. However, to develop a **R**emote-**R**adio-**L**ight-**H**ead (RRLH) with 60 GHz and VLC it is necessary to establish the right configuration for the **A**ccess **P**oint (AP) and **U**ser **E**quipment (UE).

Different realization options exist for the concept of a compact and cost-efficient RRLH. In this document we present alternative realisation concepts for the 60 GHz RF interfaces and a vision of the overall concept for IoRL AP and UE.

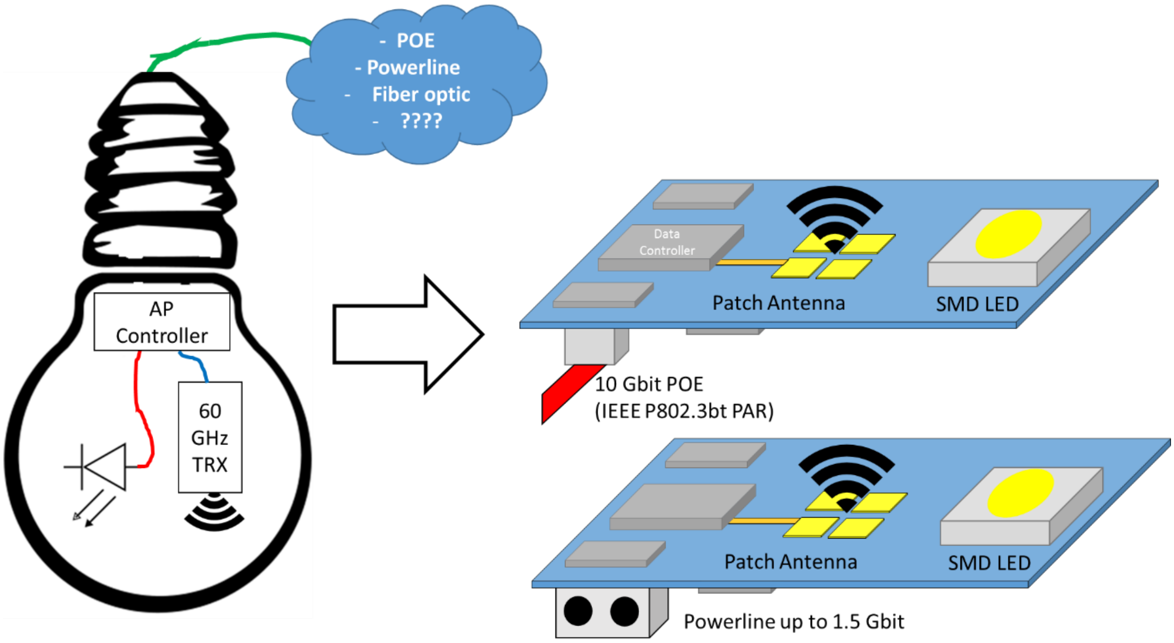


Figure 2-1: RRLH Access Point with POE or PLC for the data and power supply of the interface

The **Figure 2-1** shows different options for the data and power supply for the IoRL AP. One is the reuse of the already existing power supply of the light infrastructure with the Powerline standard. This is one possible solution for the backhauling of the different RRLH's. However, the data rates of Powerline are limited by the cable structure of the current lights installation. Here we need to think about a solution for new buildings to persuade future users to install such systems within their infrastructures. A simple network cable installation using **P**ower **O**ver **E**thernet (POE) offers the possibility of high data rates and provides the necessary power for the lighting task of the RRLH AP.

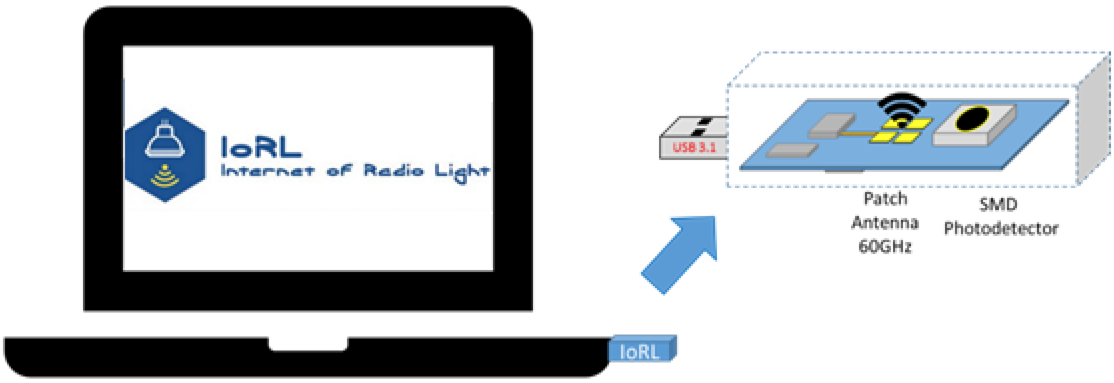


Figure 2-2: Vision of the IoRL user equipment with a USB 3.1 connection for different device types

For the UE is currently the USB 3.1 (see **Figure 2-2**) maybe the best option for the power supply and feeding of data rates up to 10 Gbit/s to the user equipment. This tool is a vision of the final product for the UE.

The IoRL architecture is a layered architecture consisting of four layers namely: Service, Network Function Virtualisation (NFV), Software Defined Network (SDN) and Access, as shown in **Figure 2-3**.

The Service layer is required to run server-side applications to stream audio-video, receive, store results on databases and monitor security etc. from a multi-core Cloud Home Data Centre Server (CHDCS) and is required to run mobile apps from User Equipment (UE) i.e. Smart Phones, Tablet PCs, Virtual Reality Headsets and HDTVs.

At the SDN Layer resides the SDN Forwarding Device (FD) to route IP packets to/from their 5G Layer 2/3 Protocol Processors and the SDN Controller. The Network Function Virtualization Orchestrator (NFVO) invokes various virtual functions required for an Intelligent Home IP Gateway such as Access & Mobility Management, Deep Packet Inspection and Network Security Functions, among others.

The Access Layer consists of six RRLH Controllers. Each RRLH Controller drives up to eight VLC and mmW RRLH pairs with the same Transmission Block Sub-Frame, thereby providing a Multiple Input Single Output (MISO) transmission on downlink paths and Single Input Multiple Output (MISO) on uplink paths for its coverage area, which is typically a room or floor areas of a building.

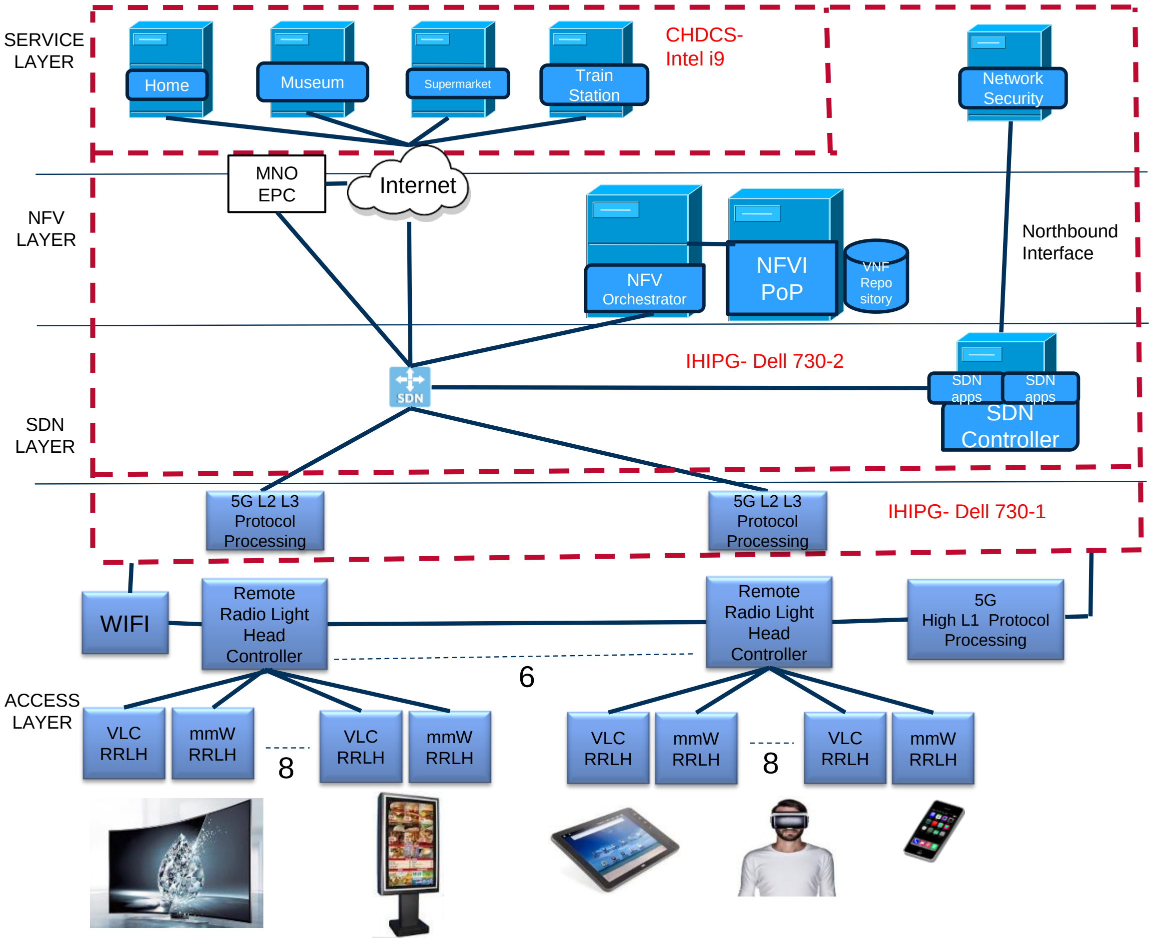


Figure 2-3: IoRL Layered Architecture

Each room or floor area in a building can be provisioned by a single RRLH Controller with its group of eight RRLHs and intra-building handover performed between these areas with the aid of VLC and mmW location sensing application that continuously records the positions of UE in the building.

A UE can either obtain direct access to the Internet, by only using 5G protocols on the Access Layer interface to the UE, to deliver IP packets to the Network Layer and thence to the Server Applications in the Service Layer or obtain access to the Mobile Network Operator's (MNO) Evolved Packet Core (EPC), by using 5G protocols on the Access Layer interfaces to both the UE and EPC, to deliver IP packets to the Network Layer and thence to the applications supported by the MNO. This latter approach allows applications, such as Facebook, on a Smart phone to be accessed on both the outside Mobile Network as well as the Intelligent Home Network with handover between them. The Virtual Network Functions on the NFV Layer identify the destination of IP packets and the SDN Controller directs these IP packets to their appropriate destination.

Therefore our proposed solution will enable the building owner to have connectivity to different operators to facilitate the use of different devices registered with different operators, as well as exploiting the license-free spectrum for accessing the home network.

From the operator's point of view, it represents an excellent solution for an existing issue as it will allow more efficient use of the scarce spectrum by utilizing license free VLC communication and mmW instead of their spectrum as an access mechanism to the network; however it will support larger number of users only by allowing the IHIPGW to be connected to their systems and being registered with MNOs.

In the Network Layer a logically centralized controller is required that is capable of forwarding UE traffic to different destinations, such as Internet, Mobile Network, WiFi and different RRLH Controllers of the IoRL RAN Network, based on the type of traffic categorized by different network entities and applications such as DPI, as shown in **Figure 2-4**. Here the SDN Layer part of the IHIPG is realized on the building premises, thereby requiring a greater capex investment. In the Virtual Network Layer version this logical centralized controller is realized in the Cloud Home Datacenter Server (CHDCS) , as shown in **Figure 2-5** and is connected by a tunnel for example using, GRE, IPsec, L2F, L2TP. Here the SDN part of the IHIPG is realized virtually in the cloud thus reducing the capex investment of realizing the system on the building premises.

Network Operator-related traffic will be sent to the MNO by the use of 4G/5G data and control protocols. When a Smart Phone enters a building, Internet packet flow from 4G/5G eNB/gNB in the outside Mobile Network will be handed over to the building network and accessed via the 4G/5G HeNB-GW/HgNB-GW. This will offload traffic from the MNO thereby improving performance by relieving congestion and reducing delay.

From the UE point of view, it will improve the user's experience who is registered with one MNO by experiencing better coverage via VLC and mmW access network, faster Internet by reducing the delay from MNO and offloading him to the local Internet connection, and also enjoying a set of local services provided by the local server.

The Access Layer architecture uses a 10G Common Public Radio Interface (eCPRI) ring Ethernet, to interconnect a High Layer 1 FPGA processor with up to six Remote Radio Light Head (RRLH) Controller FPGSs each hosting two Lower Layer 1 processors, the first that generates an IF signal to drive up to 8 VLC MISO modules using a 1 to 8 RF splitter and a second that generates an IF signal to drive or be driven by up to 8 mmW RF Duplex modules using a 1 to 8 RF splitter, as shown in **Figure 2-6**. The functional split between the RRLH Remote Unit and the Central Unit in the Physical Layer is planned to be in line with option 7, as shown in **Figure 2-7** below. The Upper PHY layer unit will include the interface with the MAC and upper RAN layers and will mainly include the FEC encoders (LDPC and Polar) and decoders and will drive over the 10 Gbps Ethernet ring the data units along with their related control descriptors destined to the RRLH Controller units. The 10 Gbps Ethernet ring can be looped from room to room in a building from one RRLH to another similar to the way electric light circuits are connected in a home. A 10 MHz GPS reference is sent to IHIPG, High L1 Protocol Processor and RRLH Controller for use in 5G synchronization algorithms at these layers.

Hypothetical MAC, beam and LED addresses have been assigned to each device on this Ethernet network and will be used to illustrate the frame and packet flow through this network later on throughout this document. Address assignments are summarized in Table 2—1.

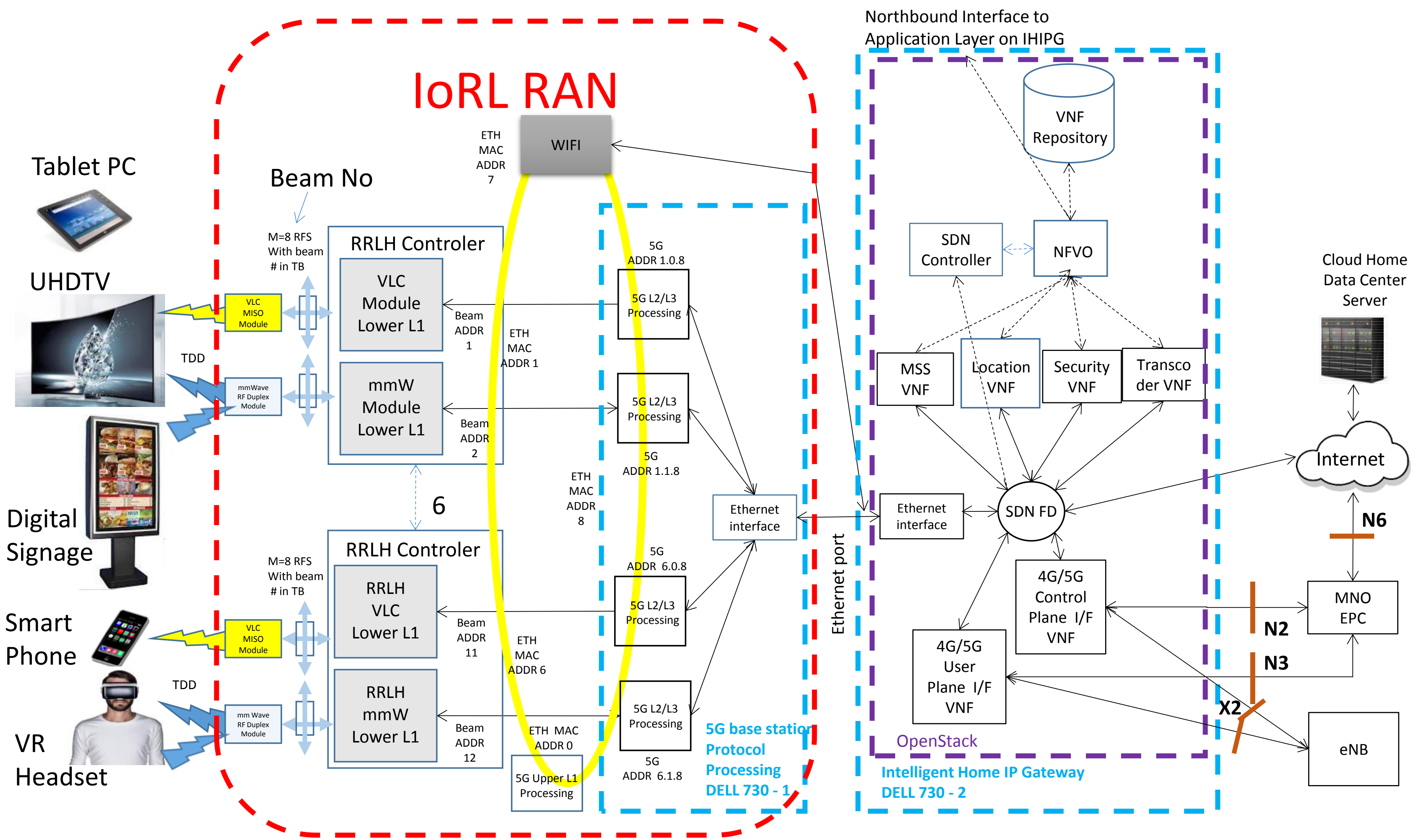


Figure 2-4: Network Layer Architecture (Note: VNFs can have connections to SDN Controller and NFVO that are not shown in figure for the sake of clarity)

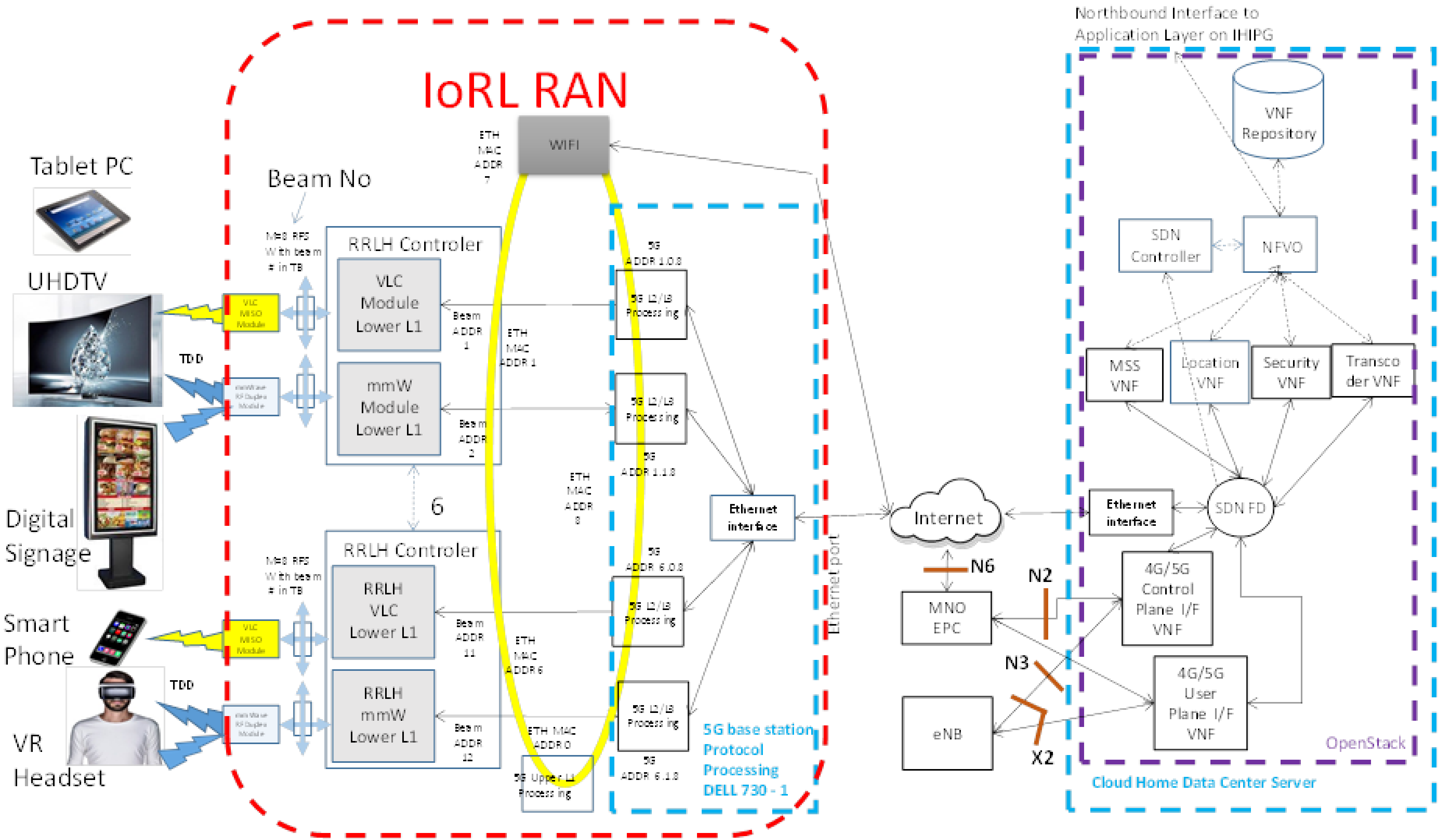


Figure 2-5: Virtual Network Layer Architecture (Note: VNFs can have connections to SDN Controller and NFVO that are not shown in figure for the sake of clarity)

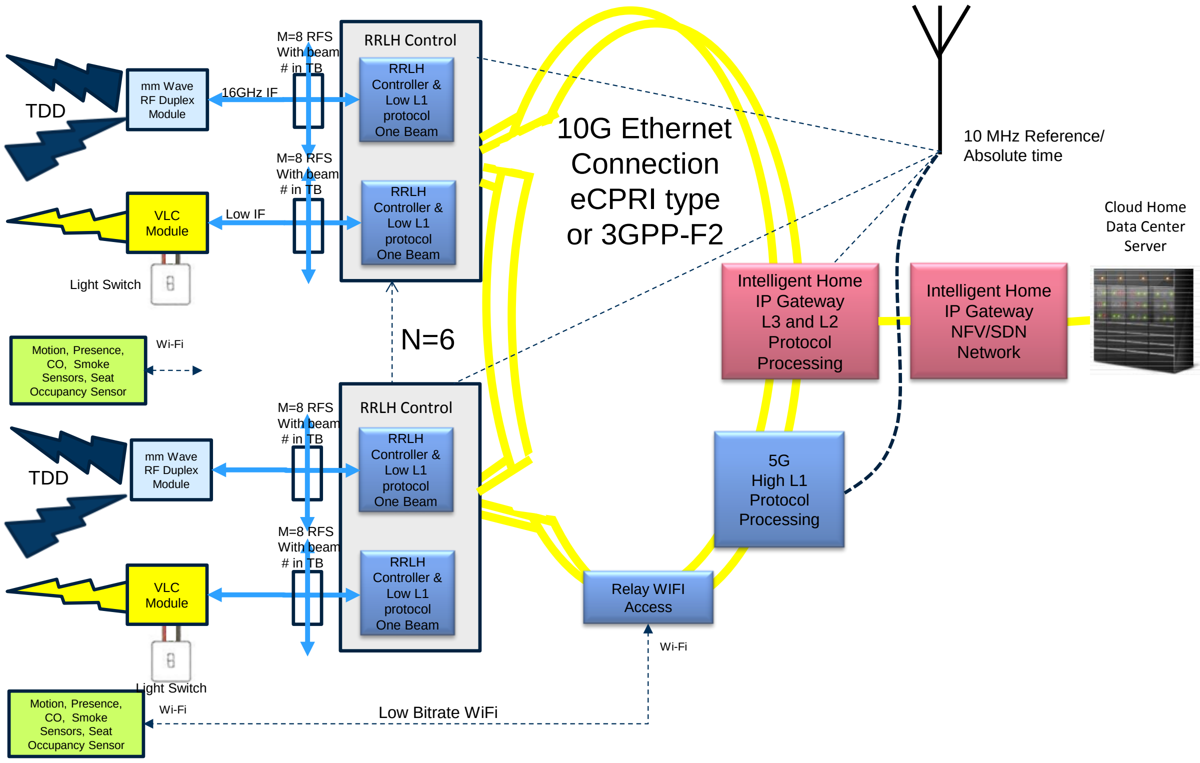


Figure 2-6: Access Layer Architecture with External WLAN

The functional split between the RRLH Remote Unit and the Central Unit in the Physical Layer 1 can be at splits A, B and C on the protocol stack, as shown in **Figure 2-7**. The eCPRI Ethernet ring can be looped from room to room in a building from one RRLH to another in a similar way to the electric light circuit in a home. A 10 MHz GPS reference is sent to IHIPG, Upper Layer 1 Protocol Processor and RRLH Controller for use in 5G synchronization algorithms at these layers.

Table 2—1: Hypothetical MAC Addresses of Ethernet Network Devices

Device	**Eth Mac Address (hypothetical)**	**5G Device**	**5G Beam Number**
5G Upper L1 Processing	aa.bb.cc.dd.ee.00	N/A	N/A
RRLH Controller 1	aa.bb.cc.dd.ee.01	VLC Module (with POF extension)	1 (LED1,…,LED8)
		mmW Module	2 (Ant1,…, Ant8)
RRLH Controller 2	aa.bb.cc.dd.ee.02	VLC Module	3 (LED1,…,LED8)
		mmW Module	4 (Ant1,…, Ant8)
RRLH Controller 3	aa.bb.cc.dd.ee.03	VLC Module	5 (LED1,…,LED8)
		mmW Module	6 (Ant1,…, Ant8)

RRLH Controller 4	aa.bb.cc.dd.ee.04	VLC Module	7 (LED1,…,LED8)
		mmW Module	8 (Ant1,…, Ant8)
RRLH Controller 5	aa.bb.cc.dd.ee.05	VLC Module	9 (LED1,…,LED8)
		mmW Module	10 (Ant1,…, Ant8)
RRLH Controller 6	aa.bb.cc.dd.ee.06	VLC Module	11 (LED1,…,LED8)
		mmW Module	12 (Ant1,…, Ant8)
WIFI	aa.bb.cc.dd.ee.07	N/A	N/A
IHIPG-1	aa.bb.cc.dd.ee.08	N/A	N/A
IHIPG-2	aa.bb.cc.dd.ee.09	N/A	N/A

As there is a limited amount of space available in Light Rose housing within which the VLC and mmW RRLH is housed, the concept of Network Function Virtualization (NFV) is adopted to off-load the complexity of the upper layer protocol processing of the communication systems required in the RRLH onto the Intelligent HIPG or CHDCS. This complexity consists of Network Layer 3 and MAC Layer 2 processing and network functions such as Admission Control, Routing, Deep Packet Inspection, Caching, Firewall, Watermarking and Transcoding. The Upper level 1 Protocol processing is likely to be at Split B and further splits within the RRLH may be set at split C.

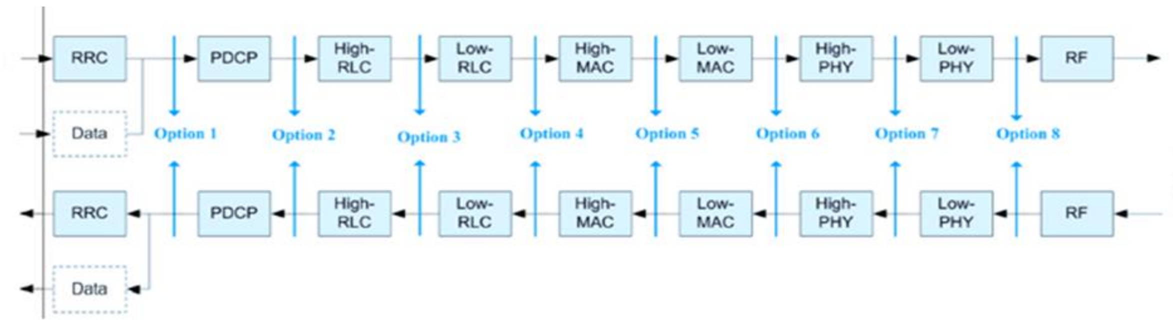


Figure 2-7: eCPRI Functional split options

DC-OFDM modulation is used for VLC transmission, which is compatible with the New Radio 5G frame formats. The bandwidth of the VLC LEDs is up to 10 MHz but this can potentially be extended to 100 MHz depending on the quality of the LEDs lights used, which means that subcarrier spacing (SCS) of 15, 30 and 60 kHz from the 5G NR Frequency Range 1 (FR1) frame formats can be used, as shown in **Figure 2-8**, potentially providing maximum downlink bitrate of 691.2M bits/sec when using 256-QAM and 100MHz bandwidth, as shown in **Figure 2-10**. Since the IoRL project intends to use VLC LEDs of 10MHz bandwidth and SCS of 60 kHz, then this will provide a maximum downlink bitrate of 56.32 Mbit/sec.

SCS [kHz]	5MHz	10MHz	15MHz	30 MHz	20 MHz	25 MHz	40 MHz	50MHz	60 MHz	70 MHz	80 MHz	90 MHz	100 MHz
	NRB	NRB	NRB	NRB	NRB	NRB	NRB	NRB	NRB	NRB	NRB	NRB	NRB
15	25	52	79	[160]	106	133	216	270	N.A	N.A	N.A	N.A	N.A
30	11	24	38	[78]	51	65	106	133	162	[189]	217	[245]	273
60	N.A	11	18	[38]	24	31	51	65	79	[93]	107	[121]	135

Figure 2-8: 5G NR Frame Formats and Channel Bandwidths for Frequency Range Designation 1 (450MHz - 6000MHz)

The NR FR2 frame format, as shown in **Figure 2-9**, can use much higher bandwidths of up to 400 MHz, using SCS of 60 or 120 kHz and operating in mmW spectrum thereby providing uplink and downlink bit rates ranging up to 2.7 G bits/sec depending on the TDD frame type used, as shown in **Figure 2-11**. Since the IoRL project intends to use mmW bandwidth of 100MHz and SCS of 60 kHz, then this will provide a maximum downlink or uplink bitrate of 675.84 Mbit/sec.

SCS [kHz]	50MHz	100MHz	200MHz	400 MHz
	NRB	NRB	NRB	NRB
60	66	132	264	N.A
120	32	66	132	264

Figure 2-9: 5G NR Frame Formats and Channel Bandwidths for Frequency Range Designation 2 (24250MHz - 52600MHz)

MISO diversity is used in the downlink where the same data is transmitted from different mmW antennas / VLC LEDs by the RRLHs at the same time, thereby increasing reliability. In effect this creates a manmade multipath environment where if one or more of the light or mmW paths is occluded then there is always the availability of the other paths to ensure continued communications, as shown in Figure 2-12.

Sub Carrier Spacing (KHz)	OFDM Symbol Duration (µs)	QAM Order	Channel Bandwidth (MHz)												
			5	10	15	20	25	30	40	50	60	70	80	90	100
15	66.7	4	8	16.64	25.28	33.92	42.56	51.2	69.12	86.4					
		16	16	33.28	50.56	67.84	85.12	102.4	138.24	172.8					
		64	24	49.92	75.84	101.76	127.68	153.6	207.36	259.2					
		256	32	66.56	101.12	135.68	170.24	204.8	276.48	345.6					
30	33.3	4	7.04	15.36	24.32	32.64	41.6	49.92	67.84	85.12	103.68	120.96	138.88	156.8	174.72
		16	14.08	30.72	48.64	65.28	83.2	99.84	135.68	170.24	207.36	241.92	277.76	313.6	349.44
		64	21.12	46.08	72.96	97.92	124.8	149.76	203.52	255.36	311.04	362.88	416.64	470.4	524.16
		256	28.16	61.44	97.28	130.56	166.4	199.68	271.36	340.48	414.72	483.84	555.52	627.2	698.88
60	16.7	4		14.08	23.04	30.72	39.68	48.64	65.28	83.2	101.12	119.04	136.96	154.88	172.8
		16		28.16	46.08	61.44	79.36	97.28	130.56	166.4	202.24	238.08	273.92	309.76	345.6
		64		42.24	69.12	92.16	119.04	145.92	195.84	249.6	303.36	357.12	410.88	464.64	518.4
		256		56.32	92.16	122.88	158.72	194.56	261.12	332.8	404.48	476.16	547.84	619.52	691.2

Figure 2-10: Bitrates at different QAM orders for different symbol durations and Channel Bandwidths

Sub Carrier Spacing (KHz)	OFDM Symbol Duration (ms)	QAM Order	Channel Bandwidth (MHz)			
			50	100	200	400
60	16.7	4	84.48	168.96	337.92	
		16	168.96	337.92	675.84	
		64	253.44	506.88	1013.76	
		256	337.92	675.84	1351.68	
120	8.33	4	81.92	168.96	337.92	675.84
		16	163.84	337.92	675.84	1351.68
		64	245.76	506.88	1013.76	2027.52
		256	327.68	675.84	1351.68	2703.36

Figure 2-11: Bitrates at 256-QAM for different symbol durations and No of Resource blocks

SIMO diversity will be used in the uplink where the same data is received by different mmW antennas at the RRLHs and maximum ratio combined higher up in the layered protocol thereby increasing reliability, as shown in Figure 2-12.

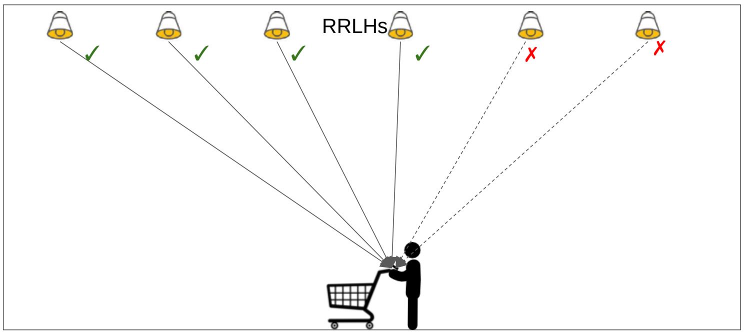


Figure 2-12: Downlink MISO and Uplink SIMO Diversity

In the case when all the paths are occluded, for example when someone conceals the Photo Diode (PD) receiver and mmW antenna at the User Equipment (UE), then Multi Source (MS) streaming is used to ensure that there is always the availability of another low capacity WLAN path for continued communications and synchronization with the streaming audio/video, as shown in Figure 2-13. The Deep Packet Inspection NFV function is used at IHIPG to identify video streams and video transcoding is used to generate a lower quality MS Stream for the WLAN path to the UE, whereas the original higher quality SHDTV stream is transmitted by the broadband radio-light network.

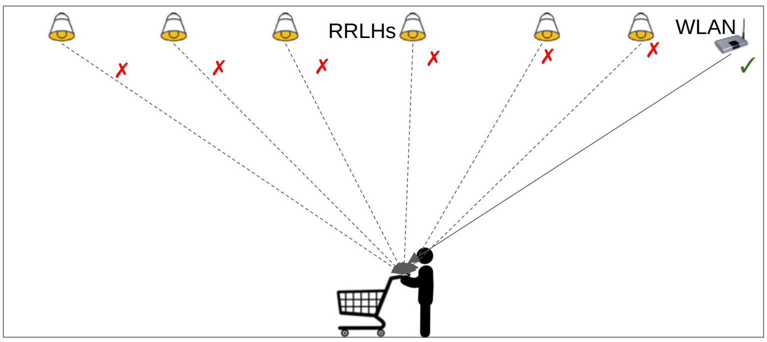


Figure 2-13: Multi Source Streaming to ensure connectivity

A SDN forwarding device in the IHIPG is used to route these higher and lower quality video streams to RRLHs and WLAN. At the UE each of these streams is aggregated with each other to produce a video signal of increasingly better quality as more and more streams are combined.

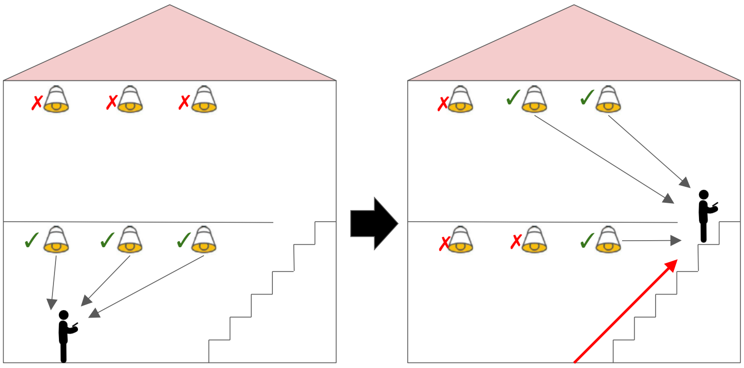


Figure 2-14: Intra Building Handover

Intra building handover between rooms or floors of a home network could either be performed by the MS Streaming application at the Service Level since its content consumption scheduler handles stream synchronization from multiple paths and multiple sources transmitted from different parts of the property or it could be performed at SDN Level by performing a handover between RRLHs depending on the measured location of the UE, as shown in Figure 2-14.

The Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ) of the outside radio network together with knowledge of the UE's location in the home radio-light network could be measured by the UE and reported to the LTE's Mobility Management Entity (MME) to initiate a conventional inter (outside and building) network handover procedure.

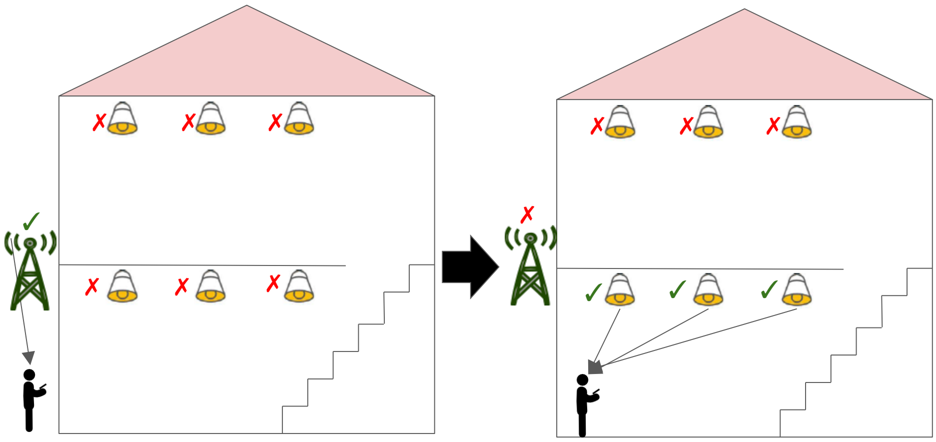
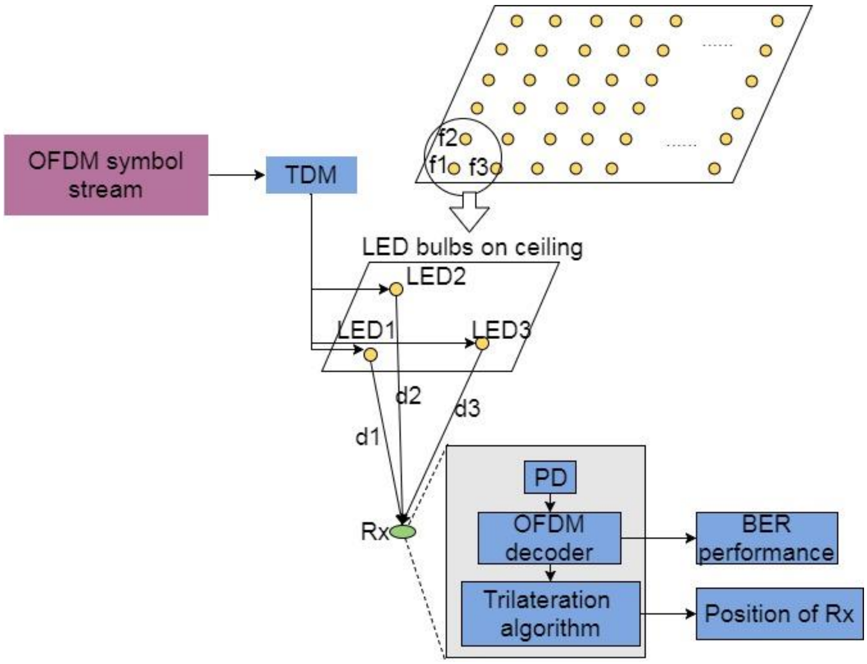


Figure 2-15: Outside to Inside Building Handover

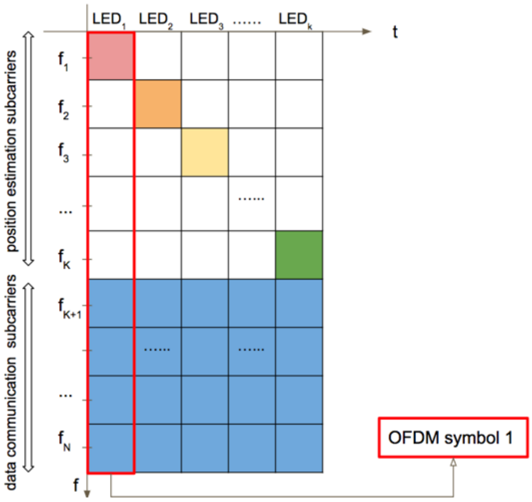
In IoRL project, the positioning system consists of two parts: VLC-based positioning system and mmWs-based positioning system. A high positioning accuracy, which is less than 10cm, could be provided by combining both techniques.

The positioning system based on VLC uses visible light signals for determining the positioning of target where the signals are transmitted by RRLH lamps (e.g. LEDs) and received by light sensors (e.g. photodiode (PD) or camera), on the target UE as shown in Figure 2-15.

Eight reference amplitude sub-carriers from the Transport Block (TB) are dedicated to be sent by each of the eight lights in a MISO group. The received signal strength (RSS) at the UE PDs is proportional to the distance travelled from each of the light and can be used to estimate position from at least three distance measurements. Once the target is located, the positioning information will be sent back to RRLH.



(a) : General scenario for VLC IPS



(b) Reference TDM based amplitude sub-carriers

Figure 2-16 (a & b): VLC Positioning System

VLC-IPS can be installed inexpensively since they utilize existing illumination systems with few modifications. It can be used in RF-inappropriate environments, like hospitals, underground mines and gas stations. Another advantage of VLC-IPS is that there is less effect of multipath on visible light than on RF signal, so the position estimation could be more accurate.

The positioning system based on mmW uses electromagnetic waves to determine the location of UEs. In contrast to the VLC based localization, the mmW target is intended to be a transmitter in our IoRL architecture. Multiple lamps (RRLH) located at a priori known positions receive its transmitted signal. The RRLH controller estimates location relevant signal parameters such as the round trip time of arrival, or the received signal strength. These estimates are communicated to the central unit, which calculates locations of UEs. The mmW based localization can benefit from the large absolute bandwidth of license free frequency bands. The majority of mmW frequency bands that are deregulated by FCC for 5G communication systems such as 37-38.6 GHz, 38.6-40 or 64-71 GHz have an absolute bandwidth covering couple of GHz. The FCC/ECC license free 60GHz WLAN ISM band (57-66GHz) and the related standard 802.11ay exploit an absolute bandwidth even much larger. It can simultaneously span 8 GHz. Such frequency bands can provide excellent time resolution which may result in sub-decimeter localization accuracy. This accuracy corresponds to the vision suggested for 5G networks and clearly outperforms accuracy of the commercial global navigation satellite system with its outdoor accuracy of about 5 meters, or the accuracy of indoor wireless local area network fingerprinting techniques which is about 3-4 meters.

The above mentioned positioning system can be also utilized to increase overall network security for the previously mentioned Denial of Service (DoS) attacks on the museum networking IoRL infrastructure. Using this functionality, it is possible to not only to detect but also precisely locate hostile devices launching such attacks. Therefore such a security approach can help museum security staff to quite precisely identify potential attackers as well as to efficiently remove rouge devices.

Apart from that it must be emphasized that currently every newly designed system should follow “security by design” principle. This means that the dedicated security mechanisms and solutions should be designed and developed during the architecture creation phase. Moreover, the continuous cyber security threats assessment should be performed during the consecutive steps of IoRL systems implementation and deployment. Taking advantage also from the experiences of the previous 5G PPP Phase 1 projects and the security framework they proposed (e.g. within the 5G PPP Phase 1 Security Landscape document) IoRL will be equipped (among others) with security monitoring & management functions, which will be able to efficiently detect cyber security-related incidents and react accordingly to them in a near real-time manner. The developed system will rely on the SDN (Software Defined Networking) and NFV (Network Function Virtualisation).

In summary, all the threats which will be identified based on the thorough analysis of the proposed IoRL architecture will be first addressed during the design phase and then continuously assessed during the implementation and deployment ones. Therefore cyber security will be an important part of the overall IoRL system architecture.

3 System Hardware Architecture of Remote Radio Light Head

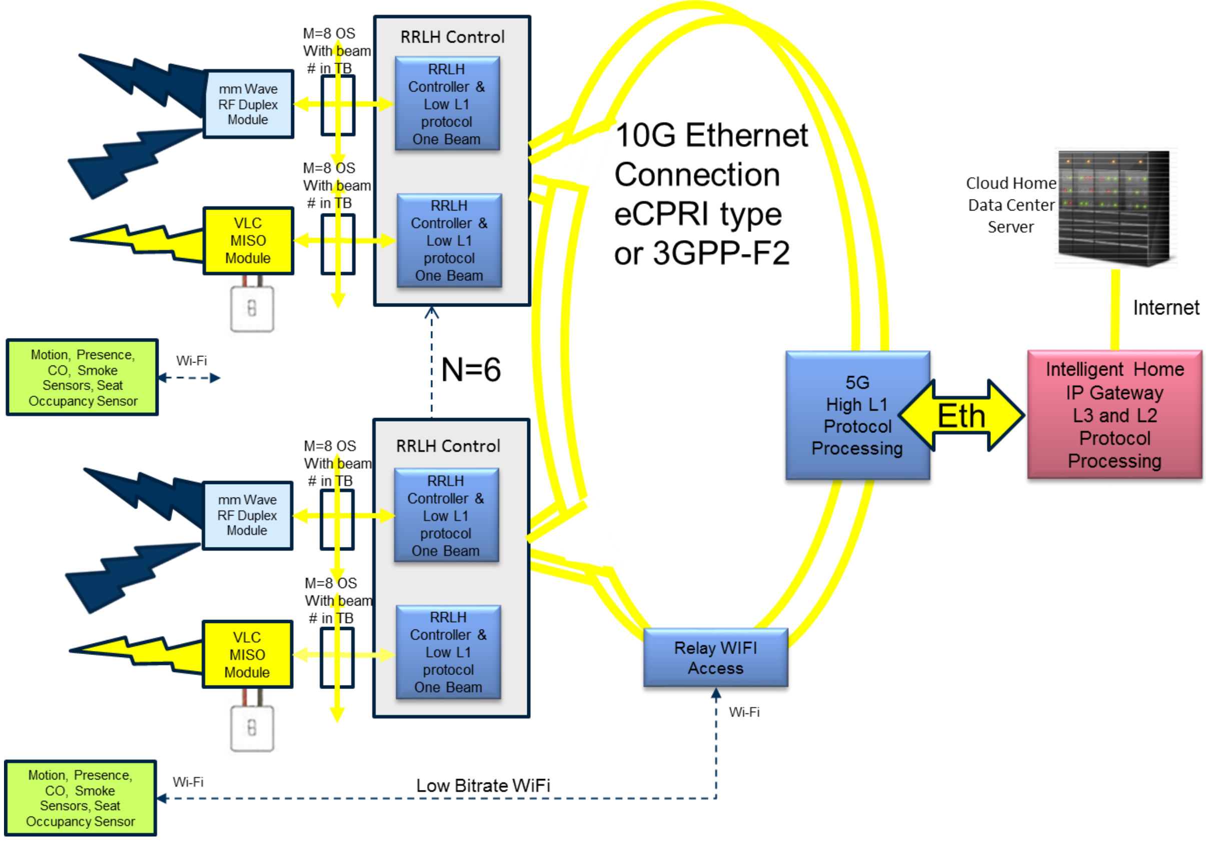


Figure 3-1: Hardware structure for RRLH

RRLH architecture will be designed to transmit IP packets from CHDC server through Intelligent HIPG and RRLH to UEs reliably and with sufficient throughput using mmW and VLC multifunctional MIMO networks integrated within remote light roses. MIMO diversity requires the same data to be transmitted from different mmW antennas / VLC LEDs at the same time thereby increasing reliability whereas MIMO multiplexing requires different data to be transmitted from different mmW antennas / VLC LEDs thereby increasing throughput. The IoRL project will develop an API in its open source development environment to allow third party software developers to design a multifunctional MIMO system that can assign mm Wave antennas / VLC LEDs to operate using different configurations of MIMO diversity and/or MIMO multiplexing.

3.1 System functional requirements for remote radio light head

Remote radio light head (RRLH) should serve as the access part of IoRL system for the key flavours of 5G services including: enhanced mobile broadband (eMBB), ultra-reliable low latency communications (uRLLC) and massive machine type communications (mMTC). Key protocols, components, functions to be addressed are described in **Table 3**—1 below:

Table 3—1: Key functional requirements for RRLH

Sub-System	Protocols (L1/L2/L3/Application)	Component	Function	Function Description
RRLH	application level	Audio/Motion/position sensor & light switch	motion detection, VLC and mmW position and light switch	This component is to provide the motion detection, position estimation by VLC and mmW
	application level	RRLH controller	SDN switch configuration	The component is to provide the software interface from RRLH to SDN switch
	L1	VLC MIMO module	VLC spatial MIMO array, VLC modulation and optical driver	This component is to provide the VLC MIMO transmitter
	L1	RRLH switch	VLC and mmW link software switch	The component is to select the mmW and VLC link based on the SDN configuration
	L1/L2	Sparq-2020 5G transmitter	sparq-2020 RDB	The component is to provide the system on chip solution for 5G uRLLC service
	L1	mmW RF and MIMO module	mmW RF up-conversion, filtering, amplifier and MIMO antenna	This component is to provide the mmW MIMO transmission and the interface to 6GHz
	LI	Plastic Optical Fiber (POF) connection	power, data and radio connectivity	This component to enable delay sensitive applications and range extension of IoRL signals through VLC-over-POF

3.2 System requirements

3.2.1 Peak data rate

Peak data rate is the highest theoretical data rate which is the received data bits assuming error-free conditions assignable to a single mobile station, when all assignable radio resources for the corresponding link direction are utilized (i.e., excluding radio resources that are used for physical layer synchronisation, reference signals or pilots, guard bands and guard times). The target for peak data rate should be 10Gbps for downlink and 10Gbps for uplink. Analytical evaluation is used as the evaluation methodology.

The TDD configuration option for 5G will be realized in a flexible way. At the base station side, the radio resource control (RRC) module plays the main role to configure DL/UL radio resources. For difference service types, RRC set up different types for radio Bearers, which defines how packet data transmitted between UE and Internet. In legacy LTE systems, services, such as VoIP call, video call, interactive gaming etc., with different latency and throughput requirements will be supported with corresponding radio Bearers. These Bearers takes different priorities on radio resource allocation. The lower layers, such as MAC and PHY layer, would generate corresponding downlink signal and process uplink channels based on Bearer configuration

3.2.2 Peak Spectral efficiency

Peak spectral efficiency is the highest theoretical data rate (normalised by bandwidth), which is the received data bits assuming error-free conditions assignable to a single mobile station, when all assignable radio resources for the corresponding link direction are utilised (i.e., excluding radio resources that are used for physical layer synchronization, reference signals or pilots, guard bands and guard times).

The target for peak spectral efficiency should be 30bps/Hz for downlink and 15bps/Hz for uplink.

Higher frequency bands could have higher bandwidth, but lower spectral efficiency and lower frequency bands could have lower bandwidth but higher spectral efficiency. Thus, peak data rate cannot be directly derived from peak spectral efficiency and bandwidth multiplication.

Analytical evaluation is used as the evaluation methodology.

3.2.3 Bandwidth

Bandwidth means the maximal aggregated total system bandwidth. It may be supported by single or multiple RF carriers. IoRL target to use maximum 100 MHz bandwidth at mmW band and VLC bandwidth 20MHz bandwidth at VLC

3.2.4 Control plane latency

Control plane latency refers to the time to move from a battery efficient state (e.g., IDLE) to start of continuous data transfer (e.g., ACTIVE).

The target for control plane latency should be 10ms.

Analytical evaluation is used as the evaluation methodology.

NOTE1: For satellite communications link, the control plane should be able to support RTT of up to 600ms in the case of GEO and HEO, up to 180ms in the case of MEO, and up to 50ms in the case of LEO satellite systems.

3.2.5 User plane latency

The time it takes to successfully deliver an application layer packet/message from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point via the radio interface in both uplink and downlink directions, where neither device nor Base Station reception is restricted by DRX. In IoRL, the target for user plane latency should be 4ms for UL, and 4ms for DL.

3.2.6 Latency for infrequent small packets

For infrequent application layer small packet/message transfer, the time it takes to successfully deliver an application layer packet/message from the radio protocol layer 2/3 SDU ingress point at the mobile device to the radio protocol layer 2/3 SDU egress point in the RAN, when the mobile device starts from its most "battery efficient" state.

For the definition above, the latency shall be no worse than 10 seconds on the uplink for a 20-byte application packet (with uncompressed IP header corresponding to 105 bytes physical layer) measured at the maximum coupling loss (MaxCL) of 164dB.

Analytical evaluation is the baseline evaluation methodology and system level evaluation can be considered if needed.

3.2.7 Mobility interruption time

Mobility interruption time means the shortest time duration supported by the system during which a user terminal cannot exchange user plane packets with any base station during transitions.

The target for mobility interruption time should be 0ms.

This KPI is for both intra-frequency and inter-frequency mobility for intra-NR mobility.

Mobility support can be relaxed for extreme rural scenarios for the Provision of minimal services for very low-ARPU areas: Inter RAT mobility functions can be removed. Intra-RAT mobility functions can be simplified if it helps decreasing the cost of infrastructure and devices. Basic idle mode mobility shall be supported as a minimum.

Analytical evaluation is used as the evaluation methodology.

3.2.8 Reliability

Reliability can be evaluated by the success probability of transmitting X bytes within a certain delay, which is the time it takes to deliver a small data packet from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point of the radio interface, at a certain channel quality (e.g., coverage-edge).

A general URLLC reliability requirement for one transmission of a packet is $1\text{-}10^{-5}$ for 32 bytes with a user plane latency of 1ms.

Note that target communication range and reliability requirement is dependent of deployment and operation scenario (e.g., the average inter-vehicle speed).

Link level evaluation with deployment scenario specific operating point and system level simulation are to be performed for the evaluations of Indoor Hotspot, Urban Macro, Highway, and Urban grid for connected car.

NOTE1: Other reliability requirements may be added, if needed, e.g. for critical communications relating to high-speed train, and more detailed requirements for eV2X should refer to the SA1 requirements in 3GPP TS 22.886 [18].

3.2.9 Coverage

MaxCL in uplink and downlink between device and Base Station site (antenna connector(s)) for a data rate of 160bps, where the data rate is observed at the egress/ingress point of the radio protocol stack in uplink and downlink.

The target for coverage should be 80dB pathloss for mmW.

Link budget and/or link level analysis are used as the evaluation methodology.

3.2.10 Area traffic capacity

Area traffic capacity means total traffic throughput served per geographic area (in Mbit/s/m^2). This metric can be evaluated by two different traffic models: Full buffer model and Non full buffer model

- By full buffer model: Total traffic throughput served per geographic area (in Mbit/s/m^2). The computation of this metric is based on full buffer traffic.
- By non full buffer model: Total traffic throughput served per geographic area (in Mbit/s/m^2). Both the user experienced data rate and the area traffic capacity need to be evaluated at the same time using the same traffic model.

The area traffic capacity is a measure of how much traffic a network can carry per unit area. It depends on site density, bandwidth and spectrum efficiency. In the case of full buffer traffic and a single layer single band system, it may be expressed as:

area capacity (bps/m^2) = site density (site/m^2) X bandwidth (Hz) X spectrum efficiency (bps/Hz/site)

In order to improve area traffic capacity, 3GPP can develop standards with means for high spectrum efficiency. To this end, spectrum efficiency gains in the order of three times IMT-Advanced are targeted. Furthermore, 3GPP can develop standards with means for large bandwidth support. To this end, it is proposed that at least 1GHz aggregated bandwidth shall be supported.

The available bandwidth and site density NOTE2, which both have a direct impact on the available area capacity, are however not under control of 3GPP.

NOTE2: Site here refers to single transmission and reception point (TRxP).

It is proposed to perform full buffer evaluation, using the spectrum efficiency results together with assumptions on available bandwidth and site density in order to derive a quantitative area traffic capacity KPI for information.

3.2.11 User experienced data rate

User experienced data rate NOTE1 can be evaluated for non-full buffer traffic and for full buffer traffic.

NOTE1: Non-full buffer simulations are preferred for the evaluation of this KPI.

For non-full buffer traffic, user experienced data rate is the 5%-percentile (5%) of the user throughput. User throughput (during active time) is defined as the size of a burst divided by the time between the arrival of the first packet of a burst and the reception of the last packet of the burst.

For full buffer traffic, user experienced data rate is calculated as:

user experienced data rate = 5% user spectrum efficiency X bandwidth

Here it should be noted that the 5% user spectrum efficiency depends on the number of active users sharing the channel (assumed to be 10 in the ITU evaluations ITU-R report M.2135 [5]), and that the 5% user spectrum efficiency for a fixed transmit power may vary with bandwidth. To keep a high 5% user spectrum efficiency and a few users sharing the channel, a dense network is beneficial, i.e. 5% user spectrum efficiency may vary also with site density (Site here refers to single TRxP).

To improve user experienced data rates, 3GPP can develop standards with means for high 5% user spectrum efficiency. To this end, 5% user spectrum efficiency gains in the order of three times IMT-Advanced are proposed. Furthermore, 3GPP can develop standards with means for large bandwidth support. To this end, it is proposed that at least 1GHz aggregated bandwidth shall be supported.

The available bandwidth and site density, which both have a strong impact on the available user experienced data rates, are however not under control of 3GPP.

Based on this, the full buffer experienced user data rate is evaluated for information without numerical requirements.

For non-full buffer evaluation, a joint system level evaluation is to be performed for Indoor Hotspot, Dense Urban, Rural, and Urban Macro. The non-full buffer user experienced data rate target is applicable at a certain area traffic level.

3.2.12 Connection density

Connection density refers to total number of devices fulfilling a target QoS per unit area (per km2), where the target QoS is to ensure a system packet drop rate less than 1% under given packet arrival rate l and packet size S. Packet drop rate = (Number of packet in outage) / (number of generated packets), where a packet is in outage if this packet failed to be successfully received by destination receiver beyond packet dropping timer. The target for connection density should be 1 000 000 device/km^2 in urban environment. 3GPP should develop standards with means of high connection efficiency (measured as supported number of devices per TRxP per unit frequency resource) to achieve the desired connection density. Analytical, link level evaluation and system level evaluation are to be performed for Urban coverage for massive connection (Urban environment).

3.2.13 Mobility

Mobility means the maximum user speed at which a defined QoS can be achieved (in km/h).

The target for mobility target should be 1m/s.

Evaluation methodology should be link level evaluation with deployment scenario specific operating point. Tunnel Use Case Scenario

The “Tunnel” use case is concerned with performing intervention in the Nuevos Miniserios railway station tunnel and platform for the purposes of improving communications and safety of maintenance railway workers. Additional value can also be provided by installing IoRL devices in the Nuevos Miniserios platform offering service to public users.

3.3 mmW transceiver structure at RRLH

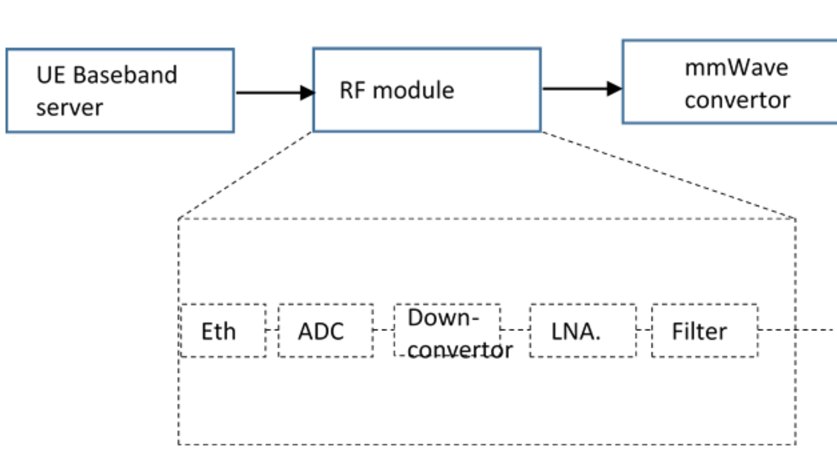


Figure 3-2: mmW Transceiver structure at RRLH

At the UE side, the mmW receiver will consist of baseband and RF part. And RF part will be divided into sub-6GHz signal receiver and mmW frequency convertor. The received mmW signal will firstly be down converted to sub-6 GHz by mmW convertor and then be down converted to baseband by RF receiver. The baseband processor will be responsible for L1/L2/L3 data processing. The receiver structure is shown in **Figure 3-2**.

3.3.1 mmW converter design

As previously described is the vision of the IoRL project the combination of VLS and mmW communication in license free bands. The best case is the integration of the radio interface and the optical interface in one module. Nevertheless, for the demonstrator are also other configuration useful to show the advantage of the IoRL concept. Thus, for the first demonstrator setup the RF and VLC interfaces will be separate in different modules. For the design of the mmW band converter are some open questions. One is the implementation of a bi-directional communications. In principle, we have three options.

1. Development of separate Transmitter and Receiver modules
2. Transmitter and Receiver on one module but with separate antennas for Tx and Rx
3. Transmitter and receiver on one module with one antenna under the use of a directional coupler for the separation of the transmit and receive signal

For option, one and two is the development effort similar but for the option three required a 60 GHz direction coupler which need to be develop in a compact form in our LTCC technology. This require a lot of effort and is not possible in the timeframe of the IoRL project. Under the assumption, of a **T**ime **D**ivision **M**ultiplexing (TDM) transmission, we prefer option two as solution. This ensures a compact design and makes the development within the project feasible.

3.3.2 Polarisation challenge for mmW

The second open question is the compensation of the polarisation orientation between the AP und the UE polarization. Due to the alignment of AP to UE, it can lead to a polarisations mismatch, which in the worst case leads to break down of the communication link. To force this is a dual polarized antenna in minimum on one side of the link required. A second option is the use of a circular antenna on one side. Here we need to discuss the best solution for the IoRl cluster and compare the develop effort with the previews planned setup, because this question was not remarked in the proposal but can be lead in a faulty demonstration.

3.3.3 Converter options for the mmW link

To convert the baseband (BB) or the intermediate frequency (IF) to the mmW band different conversion principles possible. Mostly, the use of the IF signal is easier for the up and down conversion and promises a higher probability for the planned timeline. To understand the different of the complexity for the both option in the IoRL project we are illustrate the signal location and the functional diagram in the following figures (**Figure 3-3** and **Figure 3-4**).

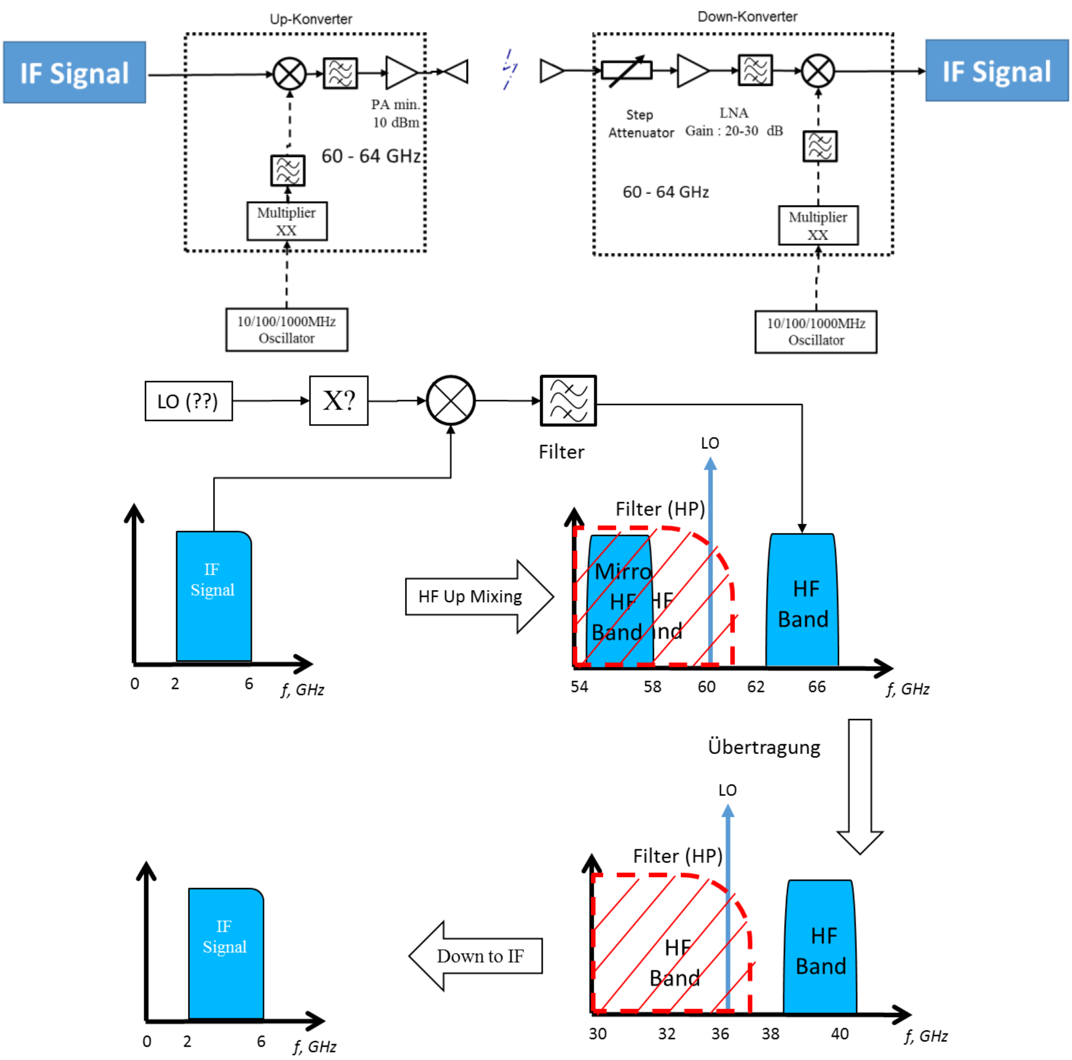


Figure 3-3: Functional diagram and signal location for the IF signal converters (60GHz as an example of mmW band)

The last RF conversion stage is for both realisation almost equal but for the I/Q baseband version is an I/Q modulator and demodulator necessary. The advantage of a simple IF-signal mixing stage is the easy extension of the COB demonstrate to mmW band. For the implementation of the mmW band I/Q interface the realisation is more complex and thus houses more risks. The best solution for the realisation of the signal conversion to mmW band is the availability of both version. However, because of the limited man power and budged only one realisation can be process in the frame of IoRL. The FhG prefers an IF-signal version due to the manageable expenses and the limited budged for in the IoRL project for this task.

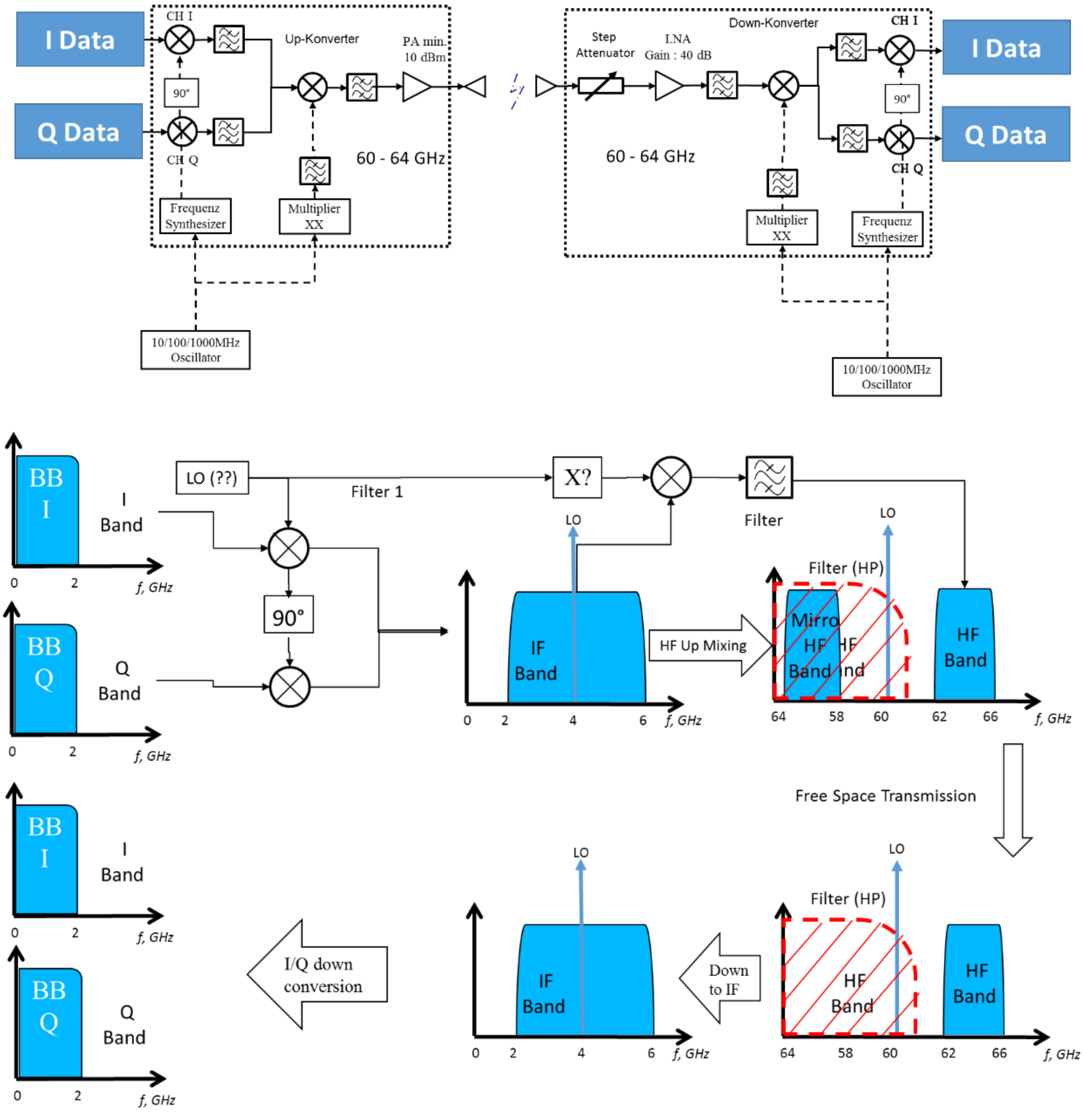


Figure 3-4: Functional diagram and signal location for the I/O Baseband signal converters (60GHz as an example of mmW band)

3.3.4 Selection for antenna type at AP and UE

For the IoRL demonstration, the FhG partner would like to provide a compact self-developed mmW band up and down converter based on the previous work. From the previous work the FhG use the single polarized patch antennas with around 6 dBi gain, 60° Half Power Beam Width (HPBW) and an 3dB bandwidth of 4 GHz. In addition, a single polarized waveguide connector is available. The materials (all chips, connectors and power supply) and manufacturing cost are located currently per up or down convert for the IF-signal version by around 2500 € per module. Our plan is to provide in minimum four transmitters and four receiver units, which can be also integrate on one substrate for the IoRL demonstrator. If the possibility available to build up more RF modules we also to like to provide this to the IoRL cluster.

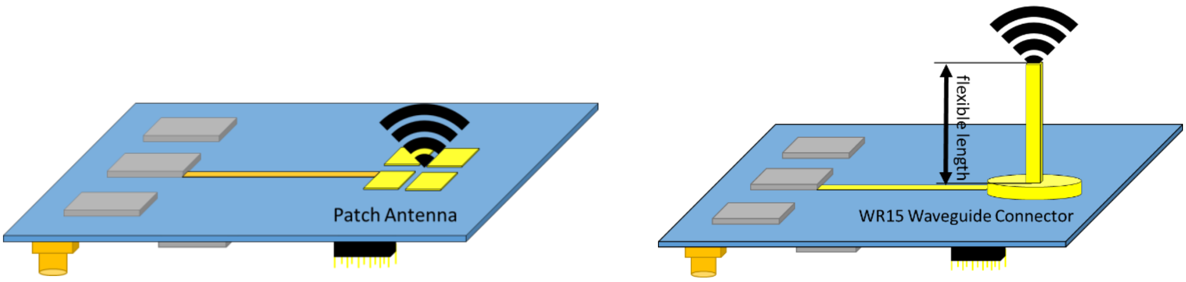


Figure 3-5: Realisation of the up or down converters with patch antenna or waveguide

3.4 VLC transmitter structure

In the transmitter of DC-biased OFDM (DCO-OFDM) systems, OFDM signals are usually generated by inverse fast Fourier transform (IFFT) in FPGA/DSP devices, after going through digital-to-analog converters (DACs) and power amplifiers, they are loaded on the LEDs. In order to get the analysis results about the characteristic of the visible light communication (VLC) channel, we use a specially designed OFDM signal structure to produce the field tests. The block diagram of the indoor VLC system is shown in **Figure 3-7**. As is shown, the computer output IP data turn into two one-way transport stream data after interface converting and are transmitted by two sets of one-way VLC systems. This system uses OFDM at the physical layer to realize the comprehensive processing of signals in both time domain and frequency domain. Specially, PN-MC sequences are inserted into the guard interval. PN-MC sequences are the Inverse Discrete Fourier Transform (IDFT) of frequency domain binary sequence (we use PN-MC256 in our system), which can be used for synchronization and channel estimation. Thus it does not need additional pilot overhead and possesses high spectrum efficiency.

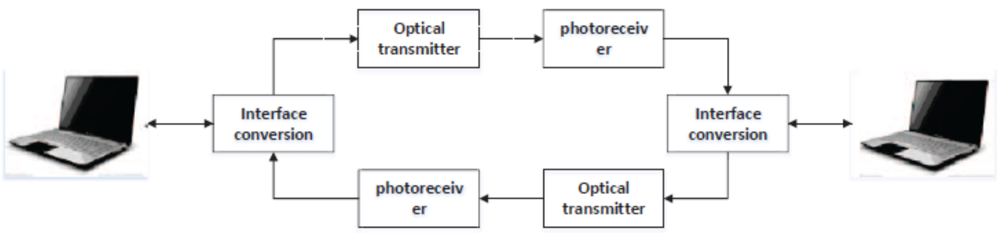


Figure 3-6: The block diagram of the indoor VLC system

The digital part of interface converting, optical transmitter and optical receiver are integrated into one piece of FPGA in order to simplify the design and improve the reliability. The block diagram of the optical transmitter-receiver is shown in **Figure 3-7**.

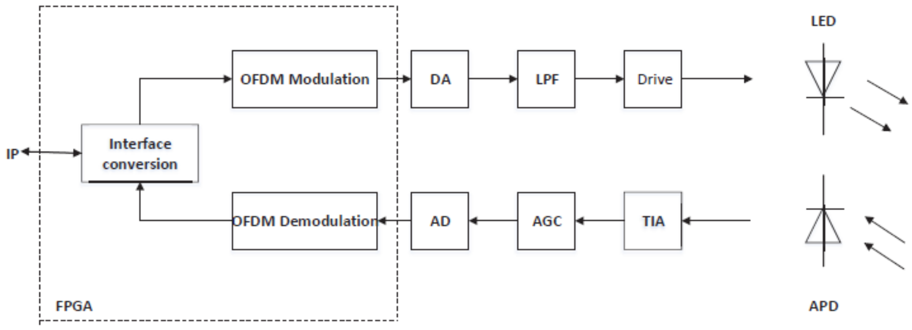


Figure 3-7: The block diagram of the optical transmitter-receiver

After the digital base band processing, we use square root raised cosine (SRRC) filter with roll-off factor α = 0.05 for baseband pulse shaping to obtain the base band transmission signals. This signals form radio-frequency (RF) signals after quadrature up-conversion. The RF signals after digital-to-analog conversion (DA), low pass filter (LPF) are modulated to the light intensity to drive LED.

At the receiver which is not necessary in the project, APD photodetector generates light current after receiving the signals from LED lights. The output spectrum of optical detector is shown **Figure 3-8**. The light current is sent to OFDM demodulation module after transimpedance amplification, automatic gain control (AGC) and analog-to-digital conversion (AD). After demodulation, the TS stream reverts to IP data at the interface transfer module.

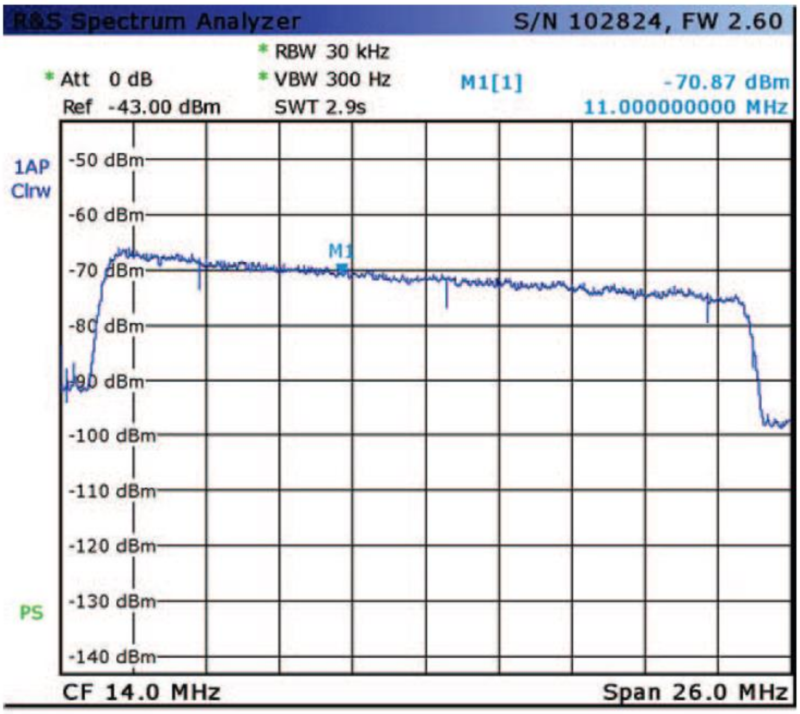


Figure 3-8: The output spectrum of optical detector

3.5 RRLH Control

This RRLH is a flexible 5G PHY Radio Head implementing 5G NR (3GPP Rel-15 standard).

The RRLH Enables Ultra Reliable Low Latency Communication (URLLC), enhanced Mobile Broadband (eMBB) and Massive Machine Type Communication (mMTC) use cases.

Will meet 5G NR novel enhancements, including:

- Multi numerology OFDM radio modem
- Air interface resources allocation by a flexible slot configuration including mini-slot support
- State of the art data coding using LDPC for data plane and polar codes for control plane
- Support of Multi User MIMO (MU-MIMO), by using several and more antennae network capacity and coverage can be improved. Enabling several and more spatial data streams significantly increases the spectral efficiency and enables to enhance transmitted bits per Hertz. Smart beamforming techniques can extend the range of the RRH by focusing the RF energy in specific directions.
- Spectrum bands support including mmW bands. In the mmW the available spectrum is much broader and high rate eMBB services can be supported.

Using CoMP (Coordinated Multi Point) techniques can further enhance the reliability and robustness of the wireless links connections.

The QoS and QoE of bearer services is managed and controlled by the system and ascertains meeting the user's expectations.

In the following depicted is the integrated RRLH block diagram.

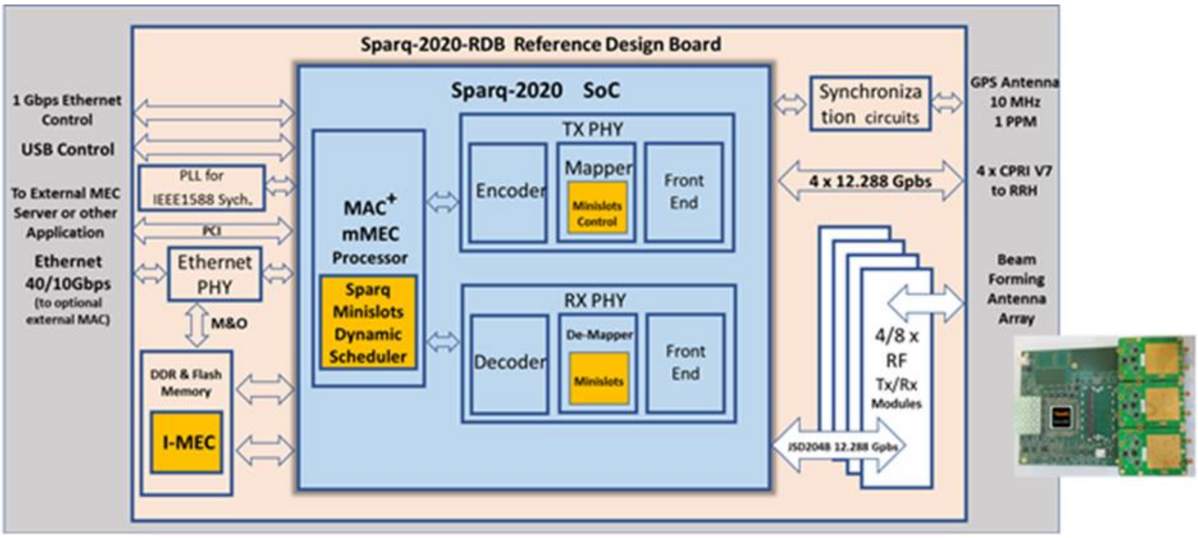


Figure 3-9: RRLH Integrated block diagram

For the IoRL project the RRLH is split to Upper L1 unit and up to 6 RRLH controllers as depicted in

.

Each RRLH Controller will include two radio heads to handle VLC an mmW respectively.

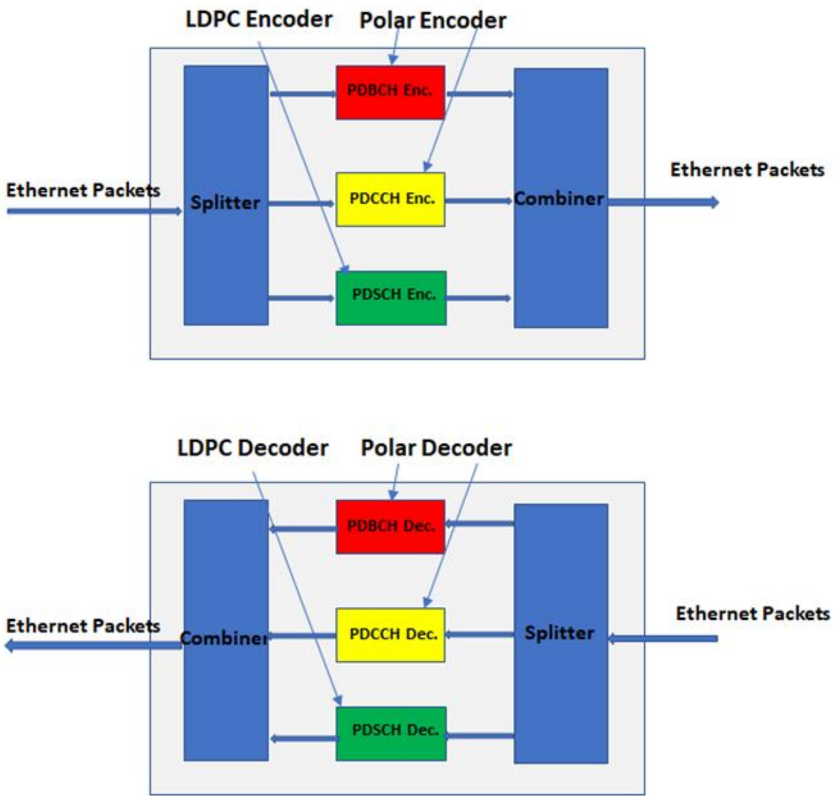


Figure 3-10: Upper L1 Unit Block diagram

The Upper L1 the (also called the Distributed RAN (DRAN) unit) is the Physical layer central unit. On one hand it connects with the MAC layer via its 10 Giga bit interface and on the other hand it connects with the 10Gbps Ethernet ring over which it is linked with the RRLH controllers.

This unit major tasks include the FEC encoding and decoding. The data plane data units are LDPC encoded/decoded while Polar code (as defined by 3GPP Rel-15) is used for the broadcast and control data. This unit handles the 10Gbps interface with the MAC layer which runs the air interface scheduler and more.

The unit distributes the encoded data units to its related RRLH controllers including descriptors which defines for the RRLH Controller units how to handle (modulation scheme-MCS, layers number-rank, resource block assignment, beam management and more) the data unit.

This unit major tasks include the FEC encoding and decoding, scrambling and more. The data plane data units are LDPC encoded/decoded while Polar code (as defined by 3GPP Rel-15) is used for the broadcast and control data. This unit handles the 10Gbps interface with the MAC layer which runs the air interface scheduler and more.

The 10 Gbps Ethernet ring topology is depicted in the following figure.

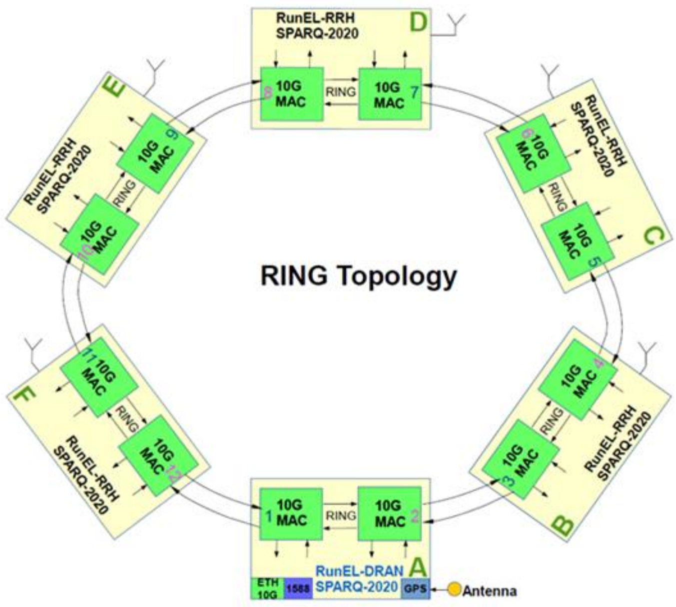


Figure 3-11: 10Gbps Ring Topology

The lower L1 unit - the RRLH controller block diagram is depicted below.

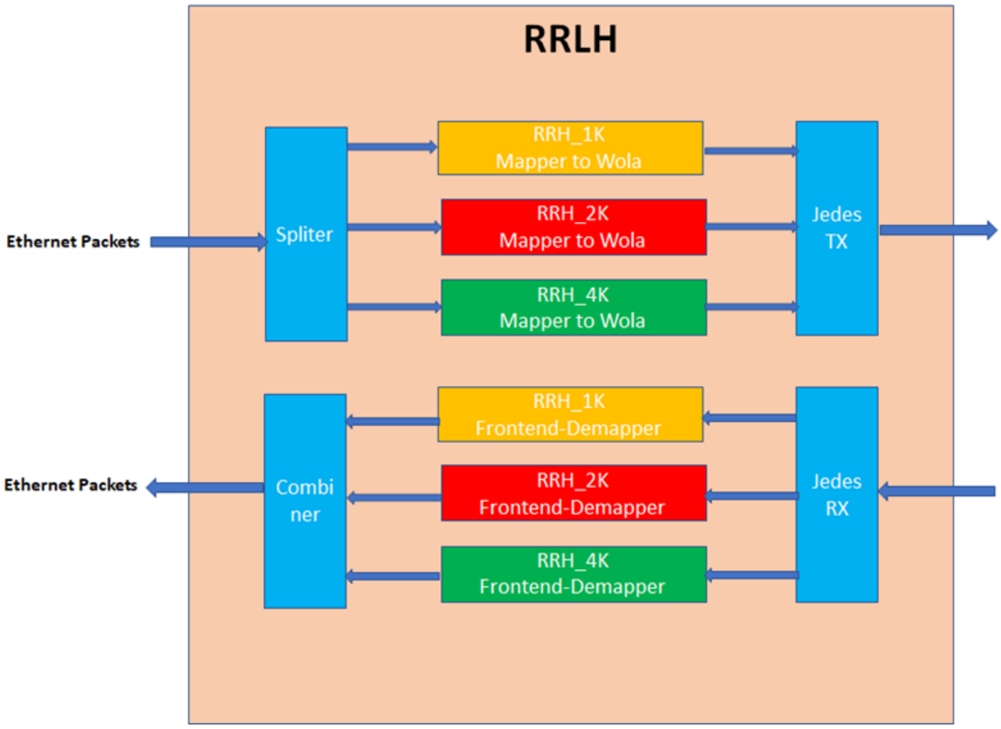


Figure 3-12: RRLH Unit Block Diagram

This unit carries out for the shared, control and broadcast channels the WOLA mapper, pre-coding, IFFT, CP insertion, windowing, and symbol overlapping processes in the down link.

For the uplink the processing Include FFT, channel estimation, data detection, LLR, and measurements handling.

As stated above the RRLH controllers connect with the Upper L1 unit via a 10Gbps Ethernet ring. Each controller interface has a unique MAC address. Data units destined to a controller are detected and downloaded from the ring interface for further processing in the RRLH. All other frames are transparently replicated on the ring outlet and delivered to other RRLH controllers connected on the ring.

In the RRLH controller the downloaded information is split between the VLC and mmW RRLH units according with the data unit descriptor.

RRLH Main Features and Advantages

- FPGA based (16 nm technology)
- 5G 3GPP standard compliant (Rel-15)
- Integration with mmW and VLC
- Optimized for URLLC (including mini-slot)
- Customization support
- VLC interface via zero IF DC offset IQ interface
- mmW interface via 3.5 GHz RF signal
- Can support up to 3 x 200 MHz channel BW
- Over 10 Gbps Capacity (with carrier aggregation)
- Short Latency < 0.5 msec
- CoMP support
- Indoor and Outdoor operation
- Based on RunEL Sparq-2020 FPGA including 4 ARM cores
- 64 bits DDR4 to FPGA Logic
- X-Haul Interface is via 4 x 10G SFP+ (Aggregated 40 Gigabit) Ethernet connection to XHaul)
- Power feed by -48VDC (-35 to-75VDC), board is powered by 12DCV.

The concept of Beam management processes is covered partially in paragraph 9.2.4 of TS-38300 3GPP document and in paragraph 8.2.6 of TR 38.912 3GPP document (not finalized yet).

IoRL is targeting Indoor coverage using millimeter wave frequencies mixed with VLC. IoRL has selected a simple and efficient profile. Takin into account that the selected operational spectrum has difficulty to propagate to other rooms, we may assume that each room will be covered by one TRxP and this TRxP can be considered as an isolated beam, so each room transceiver will get different Beam Index.

The RRC and the MAC scheduler will manage for each user the Beam Index (which represents a room) where it is located and receive the best signal, and use it for transmitting and receiving. the VLC and the mmW Beam Index will have separate Beam Index numbers (up to 12).

The general process may be as follows (accurate 3gpp compline will finalized by June 2018 the Stand-Alone mode):

- The TRxP is transmitting periodically (~5ms) SSS, PSS and BRCH signals to all the rooms (it may scan at different times different rooms or the same time in all the rooms), for simplicity we will use the same transmit time to all the rooms with the same BS ID to all the rooms (one gNB).
- The users will synchronize to the RRLH in their room and if there is more than one user in the room they will share the spectrum in OFDMA approach.

- The user will start the 4 steps PRACH process (including time advanced and user ID.) the gNB at the end of this process will recognize the user and affiliate him to the Room/Beam #,
- The User will get a subgroup of beams (neighbour rooms) and will measure the Quality of them using CSI RS, DMRS and also using the P1, P2 and P3 measured periodically and send them to the BS. The BS will use them for tracking the user beam (room) and switch between rooms.
- The D-RAN will get a Beam/room # per packet from the MAC Layer, and route the messages to them accordingly using the Ethernet MAC address to the specific RRLH Beam. So, the routing will reach the right RRLH and then to the VLC or the mmW.

3.6 RRLH with range extension based on Plastic Optical Fiber

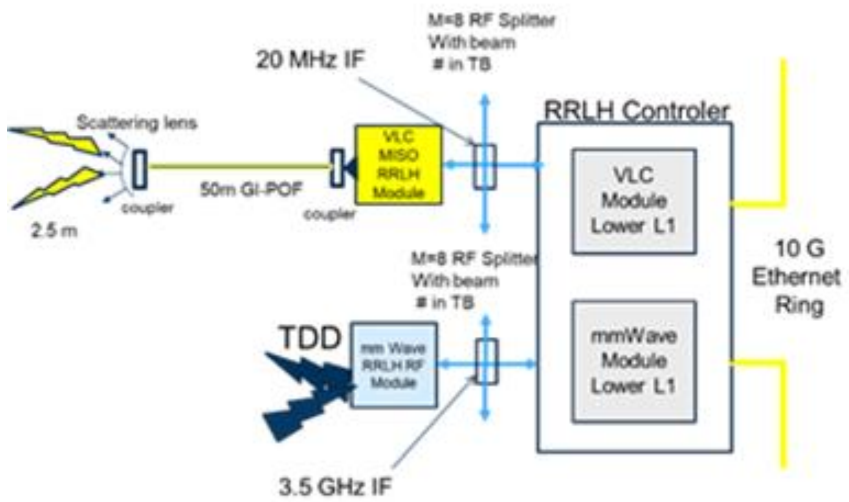


Figure 3-13: Access Layer Architecture with range extension over Plastic Optical Fiber (POF)

High transmission losses are the key problems that limit the performances of visible light communication system that work on wavelength division multiplexing (WDM) technology. In order to overcome this problem, we propose a novel design for a 1×3 optical demultiplexer based on photonic crystal fiber (PCF) structure that operates at 450 nm, 550 nm, 650 nm. The new design is based on replacing some air-holes zones with silicon nitride material along the PCF axis with optimization of the PCF size. Numerical investigations were carried out on the geometrical parameters by using a beam propagation method. Simulation results show that the proposed device can transmit 3-channel that works in the visible range with low crosstalk ((-16.88)-(-15.93) dB) and bandwidth (4.02-4.69nm).

Another structure to be investigated is for a 1×4 optical demultiplexer based on the multimode interference (MMI) in slot-waveguide structures that operates at 547 nm, 559 nm, 566 nm and 584 nm. Gallium-nitride (GaN) and silicon-oxide (SiO_2) were found to be excellent materials for the slot waveguide structures. Simulation results show that the proposed device can transmit 4-channels that work in the visible light range with a low transmission loss of 0.983-1.423 dB, crosstalk of 13.8-18.3 dB and bandwidth of 1.8-3.2 nm.

In [18] a demonstration of more than 100Gb/s over Graded Index POF (GI-POF) is shown, based external cavity laser. In IoRL we are focused on VLC technologies which are inherently short-range communications limited to few meters [18].

Hence, it is highly desired in certain use cases to enable simple VLC-over-POF to extend the range. This concept is denoted VLC-Distributed Antenna System (VLC-DAS).

Updated information on available GI-POF on the market are given in Appendix to Section 3.6.

Several architectures are possible for range extension.

(A) Cossu [19] has discussed and demonstrated a VLC over hybrid 2.5 m wireless link and 50 m POF using two hot spots. This approach consists of two stages:

1. E/L implemented through POF-Tx followed by 50m GI-POF range extension followed by POF-Rx (LED) followed by down-conversion to IF followed by LPF.
2. Variable electrical attenuator (VEA) to adjust white led intensity over wireless distance d.

This architecture is depicted in Figure 3-6.

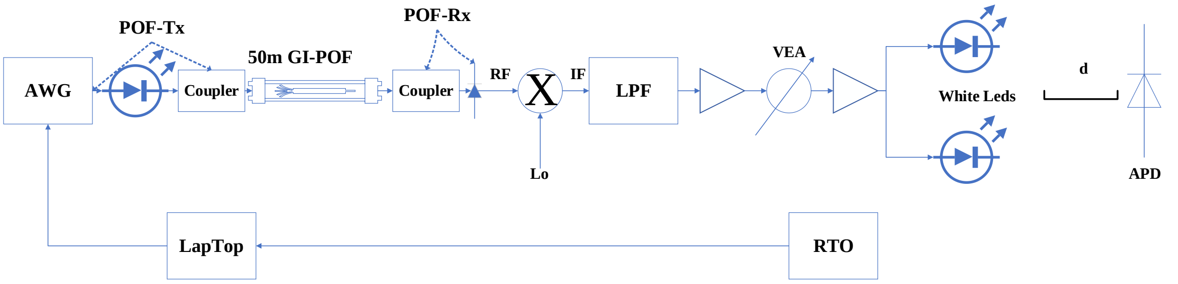


Figure 3-14: Experimental setup for VLC over hybrid POF-wireless channel. VEA: variable electrical attenuator; AWG: arbitrary waveform generator; RTO :real time oscillator

(B) A new simplified architecture consists of E/L + range extension over POF followed by modulated VLC through convex lens over the air.

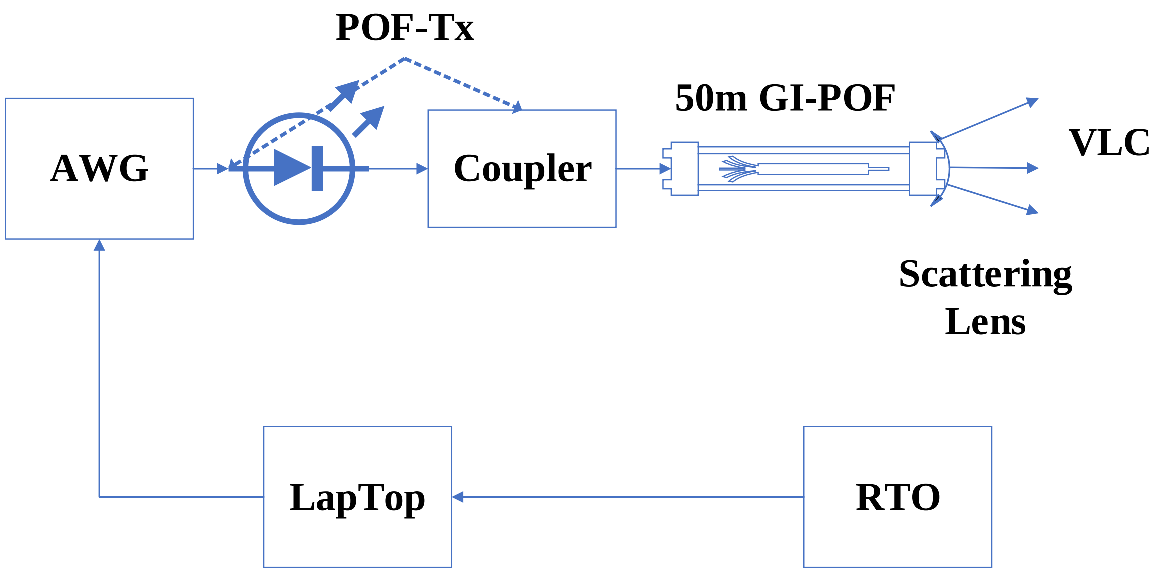


Figure 3-15: New experimental setup for VLC over hybrid POF-wireless channel

4 System Hardware Architecture of UE

Table 4—1: Key functional requirements for UE

Sub-System	Protocols (L1/L2/L3/ Application)	Component	Function	Function Description
UE	Application	mmW positioning	mmW position module	This component is to provide the position estimation by mmW (AOA, RSS or TDoA)
	Application	VLC positioning	VLC position module (VLP)	This component is to provide the position estimation by VLC
	Application		Record the RRLH, VLC and mmW LTE configuration parameters	Allows entry of configuration parameters via smart phone
	L1/L2/L3	5G UE L1, L2, L3 protocols	USRP module	This component is to provide the light version of 5G L1,L2 and L3 protocol stacks
	L1	VLC diode	VLC light diode	This component is to provide the LED light detection diode for VLC receiver
	L1	mmW RF module	mmW receiver module	This component is to provide mmW RF down conversion, filtering, amplifier

4.1 IoRL UE principle structure

In Figure 4-1 we can see a possible block diagram of a 5G UE include the application part for the possible slicing applications.

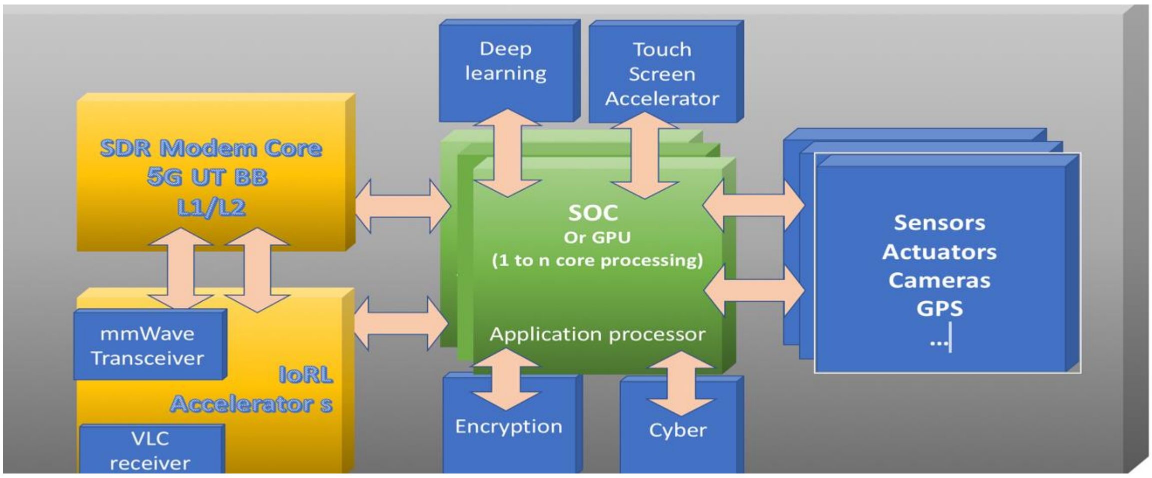


Figure 4-1: System block diagram of 5G UE

The reference user equipment design is similar to the RAN design mentioned above but clearly with much less computer processing power as shown in **Figure 4-2**. Using one RF chain of the RAN, a single VLC and mmW antenna pair UE can be built with similar structure of the RAN. The mmW card is used to convert between mmW and radio frequency. The National Instrument Universal S/W Radio Peripheral (NI-USRP) RF card can switch the RF signal to baseband I/Q signal and transmit it into the 5G L1/L2/L3 protocol stack processing server for signal processing. Several UEs can be located at different positions in a room for multiuser access. The connection between the TV and Cobham dongle will be USB 3.0 or Gbps Ethernet port.

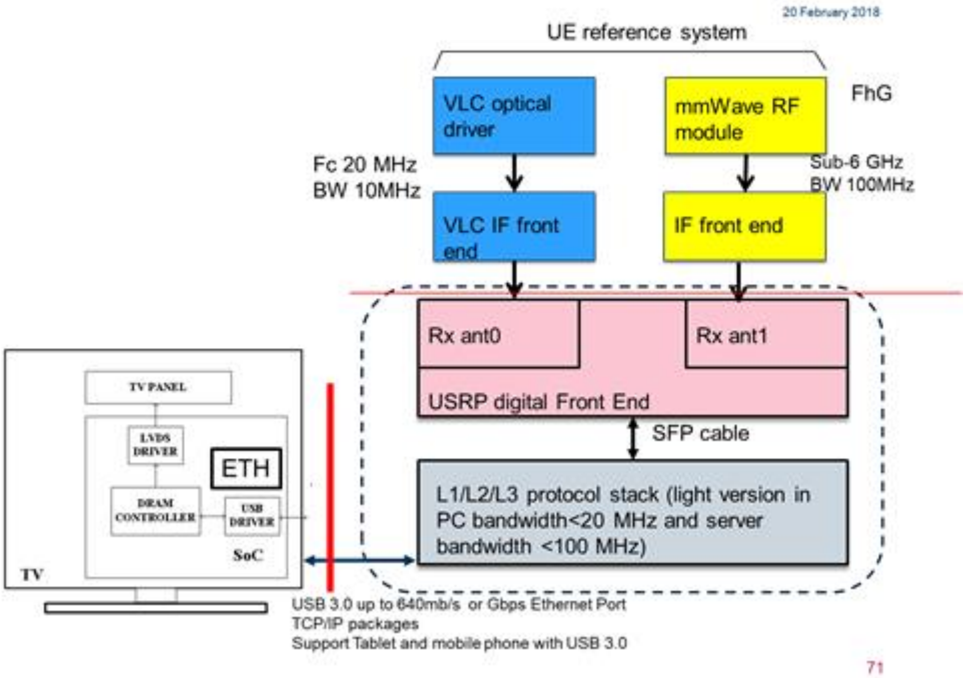


Figure 4-2: IoRL UE Hardware Architecture

4.2 mmW transceiver structure UE

The mmW transceiver structure at UE side is the same as at the RRLH side.

4.3 VLC receiver structure

Based on VLC transmission requirements, the receiver will have a centre frequency of 10 MHz with a total bandwidth equal to 10MHz. The IF signal Power Level is between 5 dBm and -35 dBm. The electronic scheme is shown in **Figure 4-3**. From left to right we find in a wide field-of-view lens the first element. The lens will be capable to obtain the incoming signal from more than one VLC transmitter lighting; the optical filter that follows will remove other kind of visible radiation. In the scheme some pass-band filters are visible before and after the variable gain amplifier. Note that USB is included to couple with PHY stage that will be provided by Cobham.

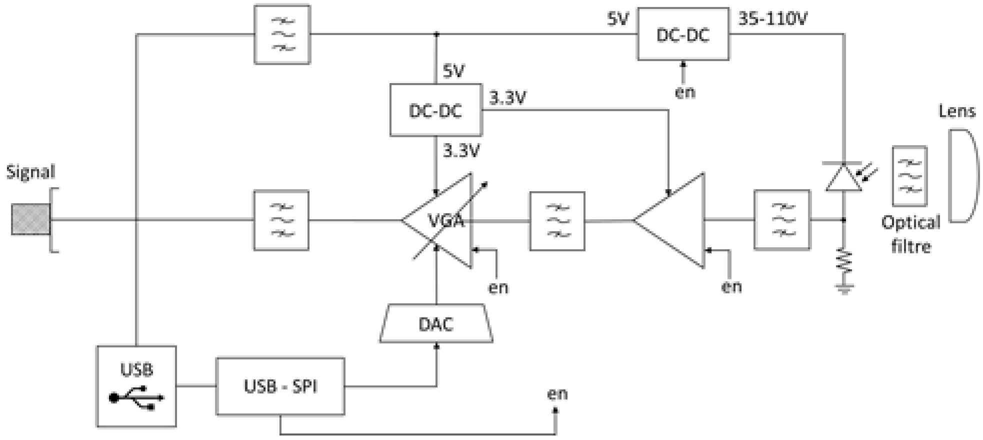


Figure 4-3: IoRL VLC receiver

5 IoRL Access layer Software Architecture

5.1 System functional requirements for Access layer Software Architecture

Access layer in IoRL should consist of the following subsystems as shown in **Figure 2-5**:

1. RRLH 5G high L1 protocol processing,
2. Relay of low bitrate WiFi
3. 10G Ethernet eCPRI type or 3GPP-F2 protocols connecting RRLHs controllers
4. RRLH controllers that enable to transmit each pair of VLC Lower L1 and mmW Lower L1, i.e. 12 Transport Blocks (TBs) in total.
5. One TB should capable to be sent to 8 (or 4) VLC MISO modules and 8 (or 4) mmW RF duplex using RF splitter

5.2 5G over VLC transmission scheme

The 5G baseband signal will be modulated to low intermediate frequency (IF) band, which could be directly modulated by light modulator. The IF signals then modulated to into visual light band, as shown in the **Figure 5-1** below:

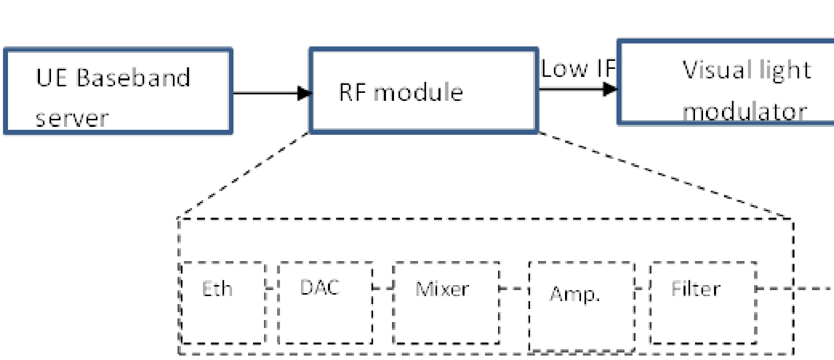


Figure 5-1: VLC transmitter structure at RRLH

While VLC is drawing more and more attention, 5G OFDM frame has been applied in VLC systems widely. It is well known that OFDM is characterized by a large peak-to-average power ratio (PAPR). When the OFDM signal goes through nonlinear devices, system performance can deteriorate significantly. In VLC the main source of nonlinearity is the light emitting diode (LED). The impact of the LED focuses mainly on two aspects: amplitude distortion and clipping of the peak. A predistorter can be used to compensate LED's non-linear transmission characteristic and condition the signal prior to the LED modulation. Clipping on OFDM has been widely studied before. Generally, according to the Bussgang theorem and the central limit theorem (CLT), clipping noise can be modeled as attenuation of the data-carrying subcarriers at the receiver and addition of zero-mean complex valued Gaussian noise. This puts a limitation on system performance. Solutions such as power back-off and PAPR reduction techniques (clipping, filtering, constrained coding, and selective mapping) have been proposed. However, power back-off may result in a power efficiency penalty and can reduce signal coverage. When using PAPR (Peak-to-Average Power Ratio) reduction techniques, the system becomes more complex and/or its bandwidth efficiency becomes lower. These methods are all realized in electrical domain.

In the transmitter of DC-biased OFDM (DCO-OFDM) systems, OFDM signals are usually generated by inverse fast Fourier transform (IFFT) in FPGA/DSP devices, after going through digital-to-analog converters (DACs) and power amplifiers, they are loaded on the LEDs. In the new scheme, we use multiple LEDs and transmit a sinusoidal subcarrier by one LED which can also be implemented in FPGA/DSP devices. In view of the incoherence of the light emitted by LED, superposition of optical power of the LEDs generates the OFDM signal in optical domain and the superimposed optical power is received by photo diode (PD) at the receiver. The subcarrier signal can be restricted in the linear range of LED. Thus the influence of OFDM signals' PAPR on transmitter can be eliminated. Receivers of the two systems are the same. Besides, by using look-up table computational complexity of the digital part of the transmitter can be decreased while bandwidth efficiency remains unchanged.

In optical OFDM serial data bits in the time domain are divided into parallel ones in the frequency domain, and after being mapped into quadrature amplitude modulation (QAM) symbols, they are modulated on a number of orthogonal subcarriers. Usually IFFT is used to generate the time domain sampled waveform of an OFDM symbol in transmitter. In VLC Hermitian symmetry is applied to the input of the IFFT operation so that a real OFDM signal is generated in consideration of intensity modulation. Generally, the baseband sampled signal at the output of IFFT can be described as

$$x(n) = \frac{1}{\sqrt{2N}} \sum_{k=0}^{2N-1} \left[X(k) \exp\left(\mathrm{j}2\pi k \frac{n}{2N} \right) \right]$$
$$n = 0, 1, \cdots, 2N-1.$$

2N is the size of IFFT. X(k) is a QAM symbol and is commonly complex. It is constrained by Hermitian symmetry,

$$X(k) = X^*(2N-k), \quad k = 1, 2, \cdots, N-1$$

where X(0)=0, X(N)=0. And the equation can be simplified as

$$x(n) = \frac{2}{\sqrt{2N}} \sum_{k=1}^{N-1} |X(k)| \cos\left\{ 2\pi k \frac{n}{2N} + \arg\left[X(k) \right] \right\}$$
$$n = 0, 1, \cdots, 2N-1.$$

It is shown that x(n) is real but bipolar. The sampled OFDM signal goes through a DAC and then the analog OFDM signal is used to change the injection current of the LED to modulate LED's optical intensity. The LED is biased using dc-current to ensure the modulating signal is non-negative.

Usually, to avoid clipping, the bias point and power back-off should be adjusted deliberately. Different QAM modulation orders should also be considered. The system model of the proposed scheme is shown in **Figure 5-2.**

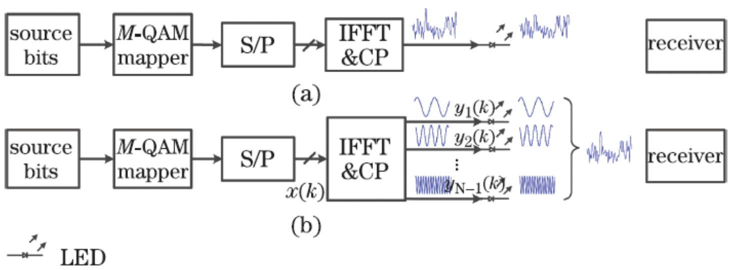


Figure 5-2: System model of DCO-OFDM. (b) System model of the new scheme.

Implementation of other parts of the system is much the same as the DCO-OFDM system except for generation of OFDM signals. DACs and bias-T modules are not presented in the figure for simplicity. Define y(n, k) as

$$y(n,k) = \frac{2}{\sqrt{2N}} |X(k)| \cos\left\{2\pi k \frac{n}{2N} + \arg[X(k)]\right\}$$
$$n = 0, 1, \cdots, 2N-1; \quad k = 1, 2, \cdots, N-1.$$

Then relation between x(n) and y(n,k) can be described as

$$x(n) = \sum_{k=1}^{N-1} y(n,k), \quad n = 0, 1, \cdots, 2N-1.$$

In view of y(n, k) is real signal, different LEDs can be used to transmit the parallel signals. After the DAC, digital signal y(n, k) is converted into analog signal yk(t). Then LED 1 transmits y1(t), LED 2 transmits y2(t), LED 3 transmits y3(t), and so on. Suppose all LEDs are identical and transmit signals synchronously. The signals are detected by the same PD at the receiver.

According to previous study, if the LEDs are placed close to each other and set to emit light in the same direction, i.e., the same azimuth and elevation, attenuation of the channel paths are very similar. Thus time domain channel impulse response hk between LED k and the PD is similar with each other. So the signal g(t) at input of the PD can be described as

$$\begin{aligned} g(t) &= h_1(t) \otimes y_1(t) + h_2(t) \otimes y_2(t) + \cdots + h_{N-1}(t) \\ &\quad \otimes y_{N-1}(t) + w(t) \\ &= h(t) \otimes [y_1(t) + y_2(t) + \cdots y_{N-1}(t)] + w(t), \end{aligned}$$

Where, yk(t) is the signal transmitted by LED k and assume yk(t) lies in the linear range of LED. w(t) is an additive white Gaussian noise (AWGN) which stands for the sum of thermal noise and shot noise in receiver. Suppose x(t) is the analog signal corresponding to x(n). We can get

$$x(t) = \sum_{k=1}^{N-1} y_k(t).$$

If N-1 LEDs are used to send signals, i.e., LED k transmits signal yk(t). A simplified equation can be derived,

$$g(t) = h(t) \otimes x(t) + w(t)$$

The OFDM signal x(t) is generated in optical domain instead of electrical domain as shown in **Figure 5-2**(b). The signal at the input of PD remains the same compared with DCO-OFDM systems so the receiver doesn't have to make a change. LEDs transmit sinusoidal carrier signals with different initial amplitude and phase separately. Signals can be constrained in the linear range of LED effectively. Impact of the high PAPR on the LED or even the power amplifier (PA) disappears. So the new scheme can eliminate the system degradation caused by large PAPR of OFDM signals at the transmitter.

Except for elimination of the impact of PAPR, the scheme can also reduce the computational complexity of the digital part of the transmitter by using look-up table. After being mapped into QAM symbol X(k), the sampled sinusoidal signal y(n, k) in each sub-channel will be read from a look-up table. IFFT operation is no longer needed in the new scheme. Implementation principle is as follows. In one OFDM symbol, 2N data points should be computed for each sub-channel. If realized in real-time IFFT operation costs both time and hard-ware resources. Considering a M-QAM symbol X(k), it belongs to a finite set with M elements. The initial amplitude and phase of y(n, k) also belong to a finite set with M elements. Therefore y(n, k) can be calculated in advance and stored in an array, i.e., a lookup table. Matched with the input M-QAM symbol X(k), the corresponding sampled sinusoidal signal y(n,k) in each sub-channel can be retrieved efficiently.

5.3 Link level simulation for the transmission algorithms

5G new radio link level simulation chain consists of the following parts: transmitter side simulation chain and receiver side simulation chain. The functionality of transmitter side simulation chain is to generate 5G baseband signal, which provides test vectors for receiving side performance simulation. Whereas the receiver side simulation chain is mainly used to study receiving algorithms, including frequency/timing correction algorithm, power control, positioning. Simulation chain for receiving algorithm will be presented later.

For uplink and downlink transmission side, the simulation chain is responsible for UL baseband generation, as shown in the following figure:

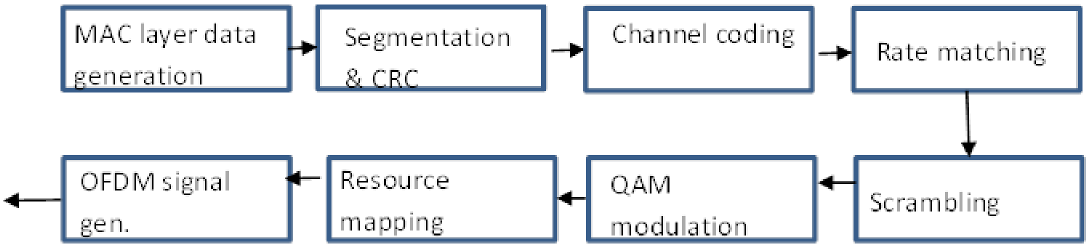


Figure 5-3: Tx Uplink baseband at UE

The payload data from MAC layer is feed into simulation chain and will pass through the following modules:

Block segmentation, CRC adding, channel coding, rate matching, scrambling, QAM modulation, resource mapping and OFDM signal generation.

At the receiving side, the whole link level simulation for received signal will be shown as below. Firstly, cell search will be conducted. This step will give basic timing and frequency synchronization for preceding signal processing. Then, after FFT, data will be processed in frequency domain. Channel estimation/equalization/phase error compensation will correct impairments brought by channel and hardware. Then, bit level simulation will be conducted. In the simulation chain, the impact of visible light channel and mmW channel and corresponding hardware impairments will be investigated.

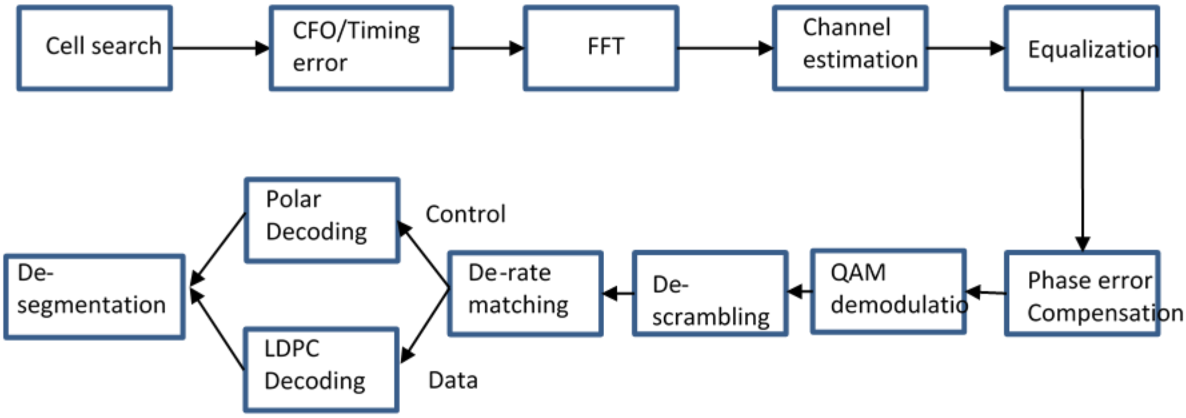


Figure 5-4: Rx Downlink at UE

5.4 5G High Layer 1 Protocol Processing

The reference design base station as shown in **Figure 3-1**, working in TDD/FDD mode, is built with Cohbam 5G testbed and RunEl Sparq chips via the eCPRI interface which can support about 10 Gbps throughput. The bandwidth of each RF chain is 100 MHz with a throughput of 1.2 Gbps. This design is targeted to 5G over mmW band, and 5G protocol stack is utilized. The X86 server provides L2 protocol stack and RunEL sparq chip provides L1 protocol stack and RF front-end. The mmW card is used for the conversion between mmW and radio frequency. Due to the difficulty of phase alignment of mmW, it is not practical to use beamforming. Hence precoding is used at the base station to serve multiple users simultaneously.

The interface between Cobham L2/L3 and Sparq2020 RunEL L1 is called L1 API, which will be development based on Functional Application Platform Interface (FAPI). As current FAPI protocol resides within the LTE base station, the detailed interface used in IoRL project will be modified based current FAPI specification version to meet 5G-NR requirements. The figure below provides an example of how the difference L2/L3 protocol layers will interact with L1 API. It highlights the separation of control- and data-plane information, which is maintained throughout the RAN network. In this example, a PHY control entity is responsible for configuration procedures (P5). The MAC layer is responsible for the exchange of data-plane messages with the PHY (P7). The PHY configuration sent over the P5 interface may be determined using SON techniques, information model parameters sent from the upper later, or a combination of both methods. If carrier aggregation is supported, then one instance of the L1 API exists for each carrier.

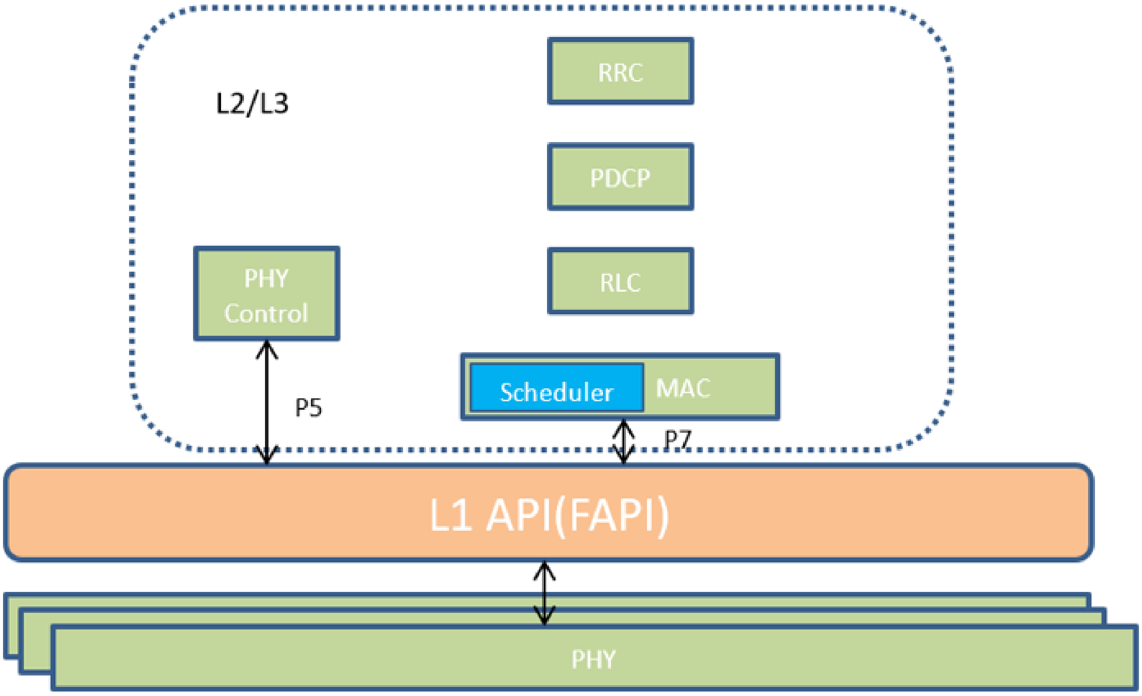


Figure 5-5: L1 Interface

The high Layer 1 unit includes a FAPI like interface protocol (option 6) to the L2 layers as described in **Figure 5-4a** below (taken from 3GPP TS-38.816). IoRL will use in the DL option 7.3 making the FEC functions for all the beams for the RRLHs including the Polar error correction codes for Control Plane, PBCH and the LDPC for Data Plane. In the uplink IoRL will use option 7.2 for the case of CP OFDM (that is almost like option 7.3) IoRL will send the LLRs to the centralized point in order to achieve in the future a diversity receiver from different RRLHs. The solution enables IoRL to get all the future centralized solutions like SON, COMP.

The other interface to the RRLH is via Ethernet.

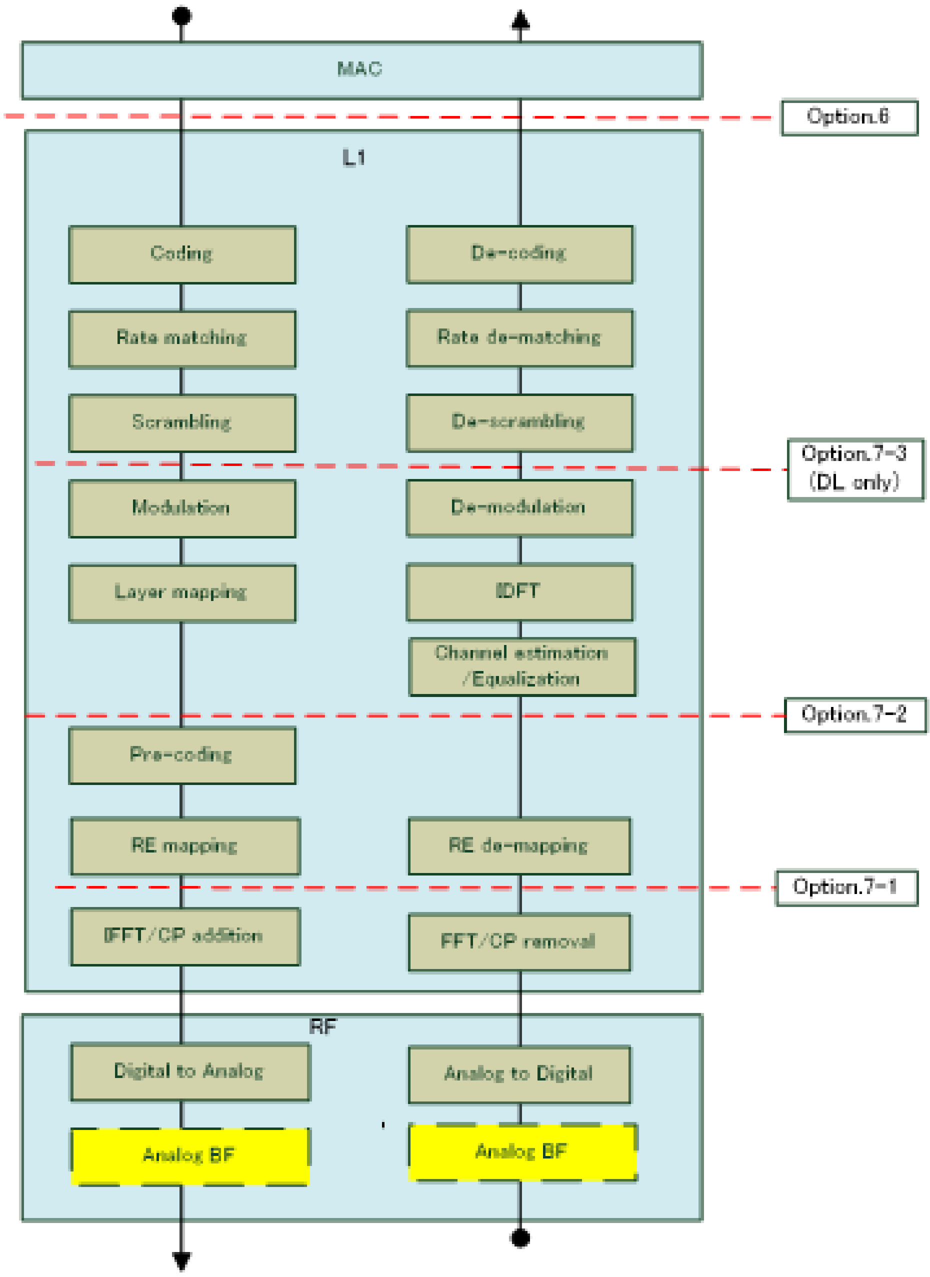


Figure 5-6: Non-exhaustive, functional split options for DL (left) and UL (right)

5.5 5G TDD Timing Synchronization

The proposed solution of TDD timing synchronization for IoRL is based on GPS, instead of precision time protocol (PTP). The whole synchronization scheme is shown in the figure below. The outdoor GPS will be received, amplified broadcasted to indoor environment. Then each network elements in IoRL, include home gateway, L1/L2 server will be equipped with GPS receiver, which provide absolute time stamp, pps signal and 10 MHz reference signal. Compared with PTP protocol, this method does not need PTP server, PTP switch, complicate timing receiving protocol and PTP frequency generator. In this way, the complexity of system will be reduced.

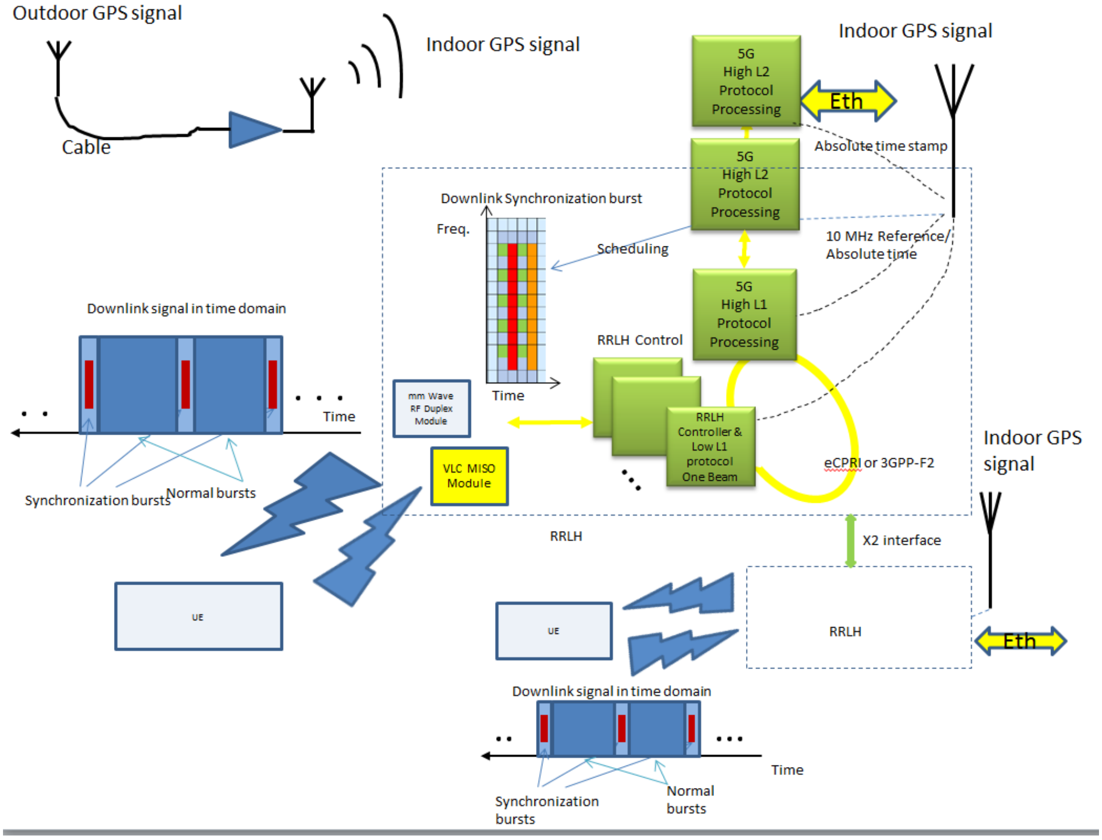


Figure 5-7: TDD Time Synchronization for mmW

6 IoRL Networking Layer and Orchestration Layer Software Architecture

The IoRL RAN has been abstracted as a "black Box" with an Ethernet interface to it to facilitate focus on the design of the NFV/SDN network, as shown in Figure 6-1.

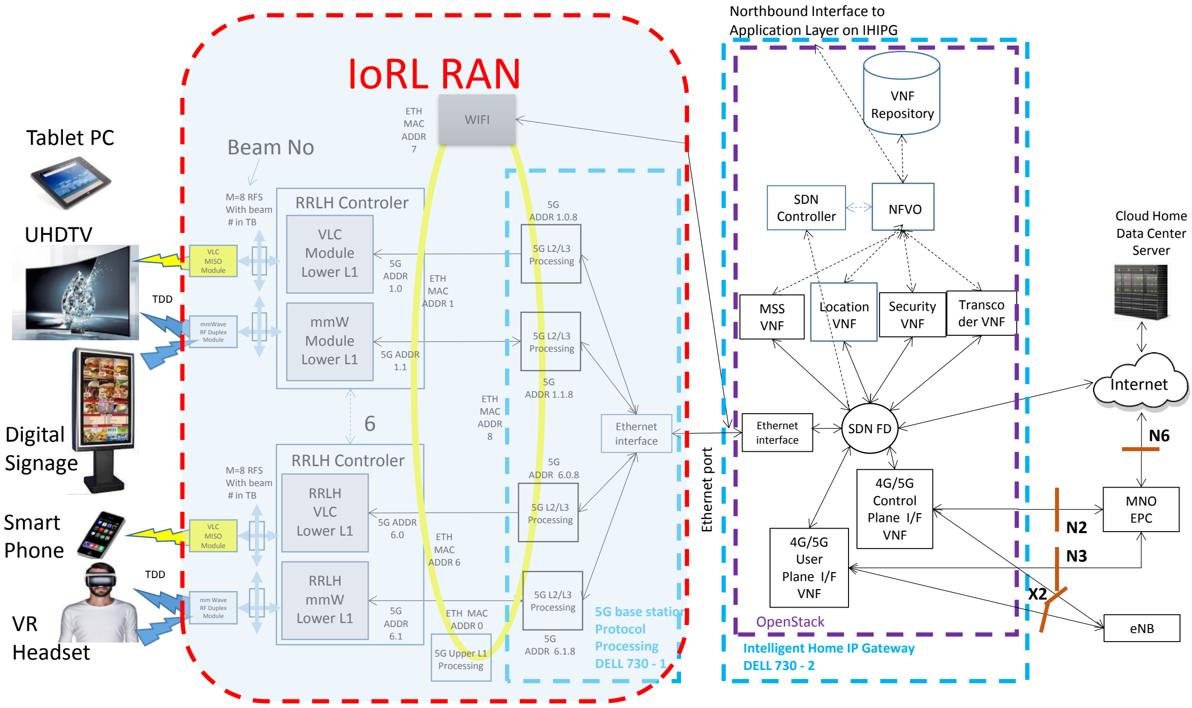


Figure 6-1: IoRL Network Layer and Orchestration Software Architecture

6.1 System functional requirements for networking layer software architecture

The NFV segment is required to run the NFV-Orchestrator, which coordinates the resources and networks needed to set up cloud-based services, applications and the NFV infrastructure points-of-presence (NFVI-PoPs), which are where the VNFs, including resources for computation, storage, and networking, are deployed by a network operator. NFVI networks should interconnect the computing and storage resources contained in an NFVI-PoP.

The definition of the functional and non-functional requirements, follows the wording of IETF RFC 2119:

1. MUST This word, or the terms "REQUIRED" or "SHALL", mean that the definition is an absolute requirement of the specification.

2. MUST NOT This phrase, or the phrase "SHALL NOT", mean that the definition is an absolute prohibition of the specification.

3. SHOULD This word, or the adjective "RECOMMENDED", mean that there may exist valid reasons in particular circumstances to ignore a particular item, but the full implications must be understood and carefully weighed before choosing a different course.

4. SHOULD NOT This phrase, or the phrase "NOT RECOMMENDED" mean that there may exist valid reasons in particular circumstances when the particular behavior is acceptable or

even useful, but the full implications should be understood, and the case carefully weighed before implementing any behavior described with this label.

5. MAY This word, or the adjective "OPTIONAL", mean that an item is truly optional. One vendor may choose to include the item because a particular marketplace requires it or because the vendor feels that it enhances the product while another vendor may omit the same item. **Table 6**—1 below presents the NFVO functional requirements of the HIPG.

Table 6—1: NFVO functional requirements

Req. number		
VNF		
VNF_01	**VNF On-boarding**	MUST be able to upload a VNF image and the assorted description in the local VNF repository and catalog
VNF_02	**VNF Image Uploading**	MUST be able to upload the appropriate VNF images at the deployment points (aka NFVI PoPs)
VNF_03	**VNF Instantiation**	MUST be able to direct instantiation command to the VIM (s) in order to bootstrap the VNF images per tenant or per service. It MAY request the creation of appropriate flavours for each VNFC accommodation (information is provided in the VNFD)
VNF_04	**VNF Configuration**	The orchestrator MUST provide means for post-configuring the VNF according to the tenant policies
VNF_05	**VNF monitoring**	The VNFM MUST be able to retrieve VNF instance run-time information for monitoring purposes.
VNF_06	**VNF termination**	The VNFM MUST be able to terminate a VNF, upon request.
VNF_07	**VNF Image Store**	Repository of VNF images and VNF descriptors
VNF_08	**VNF Forwarding Graph**	Internal VNF Forwarding Graph MUST be described in the VNFD.
Network Service		
NS_01	**NS request**	The Orchestrator SHALL be able to accept and handle NS requests.
NS_02	**NS deployment**	The Orchestrator SHALL be able to deploy the requested NSs by provisioning the necessary computing, network and storage resources needed for the deployment of the NS service.

NS_03	**NS configuration**	The Orchestrator SHALL be able to configure or update the configuration of an instantiated NS, upon request or automatically.
NS_04	**NS termination**	The Orchestrator SHALL be able to terminate a NS upon request.
NS_05	**NS elasticity**	The Orchestrator SHALL be able to dynamically scale-up/down the allocated resources to existing VNF services to deal with traffic variation and SLA contracts.
NS_06	**NS monitoring**	The Orchestrator SHALL be able to retrieve NS information on a real-time basis for monitoring purposes, aggregate and consolidate all monitoring VNF metrics.
NS_07	**NS Catalog**	Repository of NS Descriptors
NS_08	**NS Composition**	The orchestrator SHALL be able to compose network services
NS_09	**Service Function Chaining**	The orchestrator SHOULD construct via the NS Composition process a service function chain to be realized over the virtualized infrastructure.

6.2 NFV/SDN functions and structure

In the IoRL architecture, we consider an NFV Orchestrator as the top-level management entity of the HIPG domain. The NFVO is the orchestration entity, which is responsible for the management of the NS lifecycle, which includes the NS instantiation, the dimensioning and the termination. The NFV Orchestrator receives appropriate commands from the upper layer (i.e. application layer) by use-case specific applications, which include the Logic of each use-case and provide to the NFVO appropriate Network Service (NS) descriptors, which will initiate the VNF instantiation with the appropriate network configuration internally in the HIPG, which acts as a NFVI PoP.

Coming to the architectural details of the NFVO, as **Figure 6-2** depicts, we consider appropriate to inherit the functional structure of the Orchestrator, which is compliant with the ETSI proposal for network service orchestration and therefore most of the functional blocks described below are inherited from the ETSI specification document and are in line with the most popular NFVOs, such as OpenBaton, OSM etc.

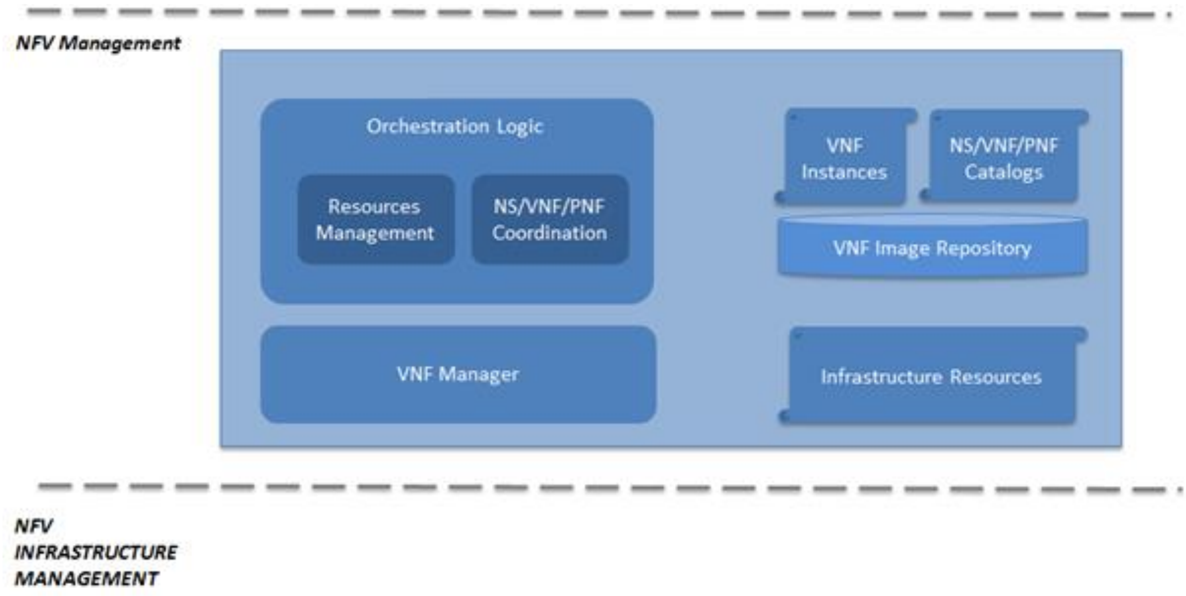


Figure 6-2: NFVO basic functional components.

As seen, the Orchestrator platform comprises both catalogs/repositories as well as execution components:

- The **VNF/PNF Catalogue** represents the repository of all of available on-boarded VNF and PNF Packages, supporting the creation and management of the VNF Package (VNF Descriptor (VNFD) and PNF Descriptor (PNFD). The information contained in the VNFD/PNFD is defined by ETSI. Again, it is clarified that the VNF/PNF Catalogue contains a list of the available VNFs/PNFs which can be included in an NS, not the deployed VNFs themselves. In a similar way, a similar catalogue can be used -if necessary- in order to contain specific Network Services (i.e. combination of VNFs/PNFs) that are described by the respective NS Descriptors.
- The **VNF Instances Repository** contains information of all service instances, which have been actually deployed. The repository is frequently updated, to reflect the status and the lifecycle of the deployed virtualized services.
- The **Infrastructure Resources Repository** holds information about available / reserved / allocated NFVI resources as abstracted by the VIM across operator's Infrastructure Domains, thus supporting information useful for resources reservation, allocation and monitoring purposes.
- The **VNF Manager (VNFM)** is responsible for the lifecycle management of VNF instances. Each VNF instance is assumed to have an associated VNF Manager. A VNF manager may be assigned the management of a single VNF instance, or the management of multiple VNF instances of the same type or of different types. Operations carried out by the VNF Manager are VNF instantiation and feasibility checking; integrity management; VNF instance modification / scaling / healing / termination.
- The **Infrastructure Resources** is the component which mainly interacts with the VIM for resource discovery, allocation and management, allowing the NFV Orchestrator to manage and control distributed resources across multiple NFVI-PoPs.
- Finally, the **NFV Orchestration Logic** is the core decision-making component, actually the “kernel” of the NFV Orchestrator. The NFV Orchestration Logic instantiates VNFs,

which are part of network services orchestrated by FNRM, (using the VNF templates in the corresponding catalogues) and manages the whole VNF lifecycle. For this purpose, it communicates with the VNFM and the Infrastructure Resources for the control of VNF instances and the (re-)allocation of virtualized resources. This task includes the control of the network assets, for virtual network establishment and QoS provision.

6.2.1 Network Function Lifecycle

Considering the virtualization of the satellite hub elements and the ground segment functions, it is necessary to define hereby the Network Function lifecycle, which comprises eight stages, as depicted in **Figure 6-3**.

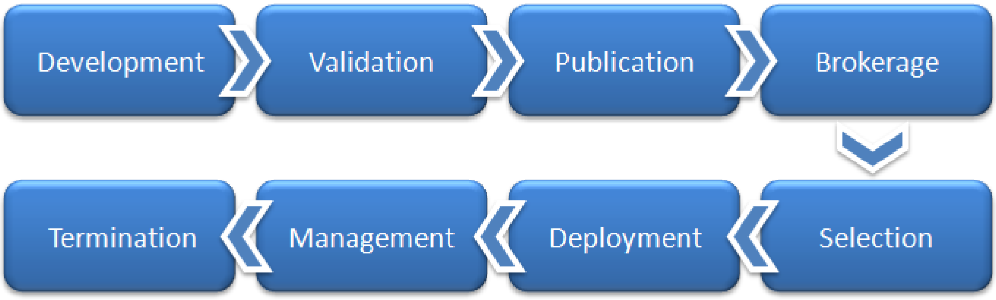


Figure 6-3: Virtual Network Function Lifecycle

The development of the VNFs is performed by Function Developers, the role of which can be played by either the Service Providers themselves, or third-party entities, but also software houses, which will be capable of entering to the current HW-specific market, since many HW-based elements will be gradually softwarised.

Validation and debugging is also an important procedure, to ensure that the developed function works and performs as expected. Buggy function code can have severe impact on the stability of the service, affecting both the performance and the reliability of the service provider. Function code and VMs will be digitally signed to ensure authenticity and, in any case, each service provider reserves the right to disallow the deployment of certain third-party functions into the network infrastructure. Although network traffic analyzed by the NFs will correspond to a portion of the total network traffic, as the Federator/Orchestrator and SDN functions will only forward specifically selected flows towards each VNF.

Publication of functions should be performed at various Function Stores, whose repository will host both the function image (as stand-alone application or integrated VM) and the associated description/metadata. Through the functions stores, the service providers will have the option to download the respective function in a similar way as mobile apps are disseminated. Alternatively, the SDN/NFV-enabled service provider may limit the installation of function to only internal ones, without extending its installation to external sources.

In case that the external installation of a function is allowed by the business model, then Function Brokerage is undertaken by the brokerage platform, which will be able to match user “high-level” service requirements with the specific technical specifications of the NFs, ensuring that the resources required for VNF deployment are available.

Upon VNF S*election* by the user, the Deployment phase includes the transfer of the VM image containing the function from the Store to in-network cloud infrastructure and the VM instantiation. The Orchestrator utilizes the SDN control plane for network reconfiguration.

After instantiation, to facilitate Management*,* the function will expose, as aforementioned, an open VNF Control API for uniform VNF configuration and parameterization by operator, the customers and also by their applications.

Function Termination involves the removal of the VNF instance from the virtualized infrastructure, also involving the necessary network re-configuration.

6.2.2 NFV Deployment Template

The VNF details, e.g., deployment rules, scaling policies, and performance metrics, are described in the VNF Descriptor. A VNF Descriptor (VNFD) is a deployment template which describes a VNF in terms of deployment and operational behaviour requirements. The VNFD also contains connectivity, interface and KPIs requirements that can be used by NFV Orchestrator functional blocks to establish appropriate Virtual Links within the NFVI between VNFC instances, or between a VNF instance and the endpoint interface to other Network Functions.

TOSCA specification provides a language to describe service components and their relationships using a service topology, and it provides for describing the management procedures that create or modify services using orchestration processes. The combination of topology and orchestration in a Service Template describes what is needed to be preserved across deployments in different environments to enable interoperable deployment of cloud services and their management throughout the complete lifecycle, e.g., scaling, patching, monitoring, etc., when the applications are ported over alternative cloud environments.

A network service is a composition of Network Functions that defines an end-to-end functional and behavioral specification. Consequently, a network service can be viewed architecturally as a forwarding graph of Network Functions (NFs) interconnected by supporting network infrastructure. The deployment template in NFV fully describes the attributes and requirements necessary to realize such a Network Service. Network Service Orchestration coordinates the lifecycle of VNFs that jointly realize a Network Service. This includes (not limited to) managing the associations between different VNFs, the topology of the Network Service, and the VNFFGs associated with the Network Service.

The deployment template for a network service in NFV is called a network service descriptor (NSD), it describes a relationship between VNFs and possibly PNFs that it contains the links needed to connect VNFs.

There are four descriptors defined apart from the top-level Network Service (NS) information element:

- Virtualized Network Function (VNF) descriptor,
- Physical Network Function (PNF) descriptor,
- Virtual Link (VL) descriptor,
- VNF Forwarding Graph (VNFFG) descriptor.

A VNF Descriptor (VNFD) is a deployment template which describes a VNF in terms of its deployment and operational behavior requirements.

A VNF Forwarding Graph Descriptor (VNFFGD) is a deployment template which describes a topology of the Network Service or a portion of the Network Service, by referencing VNFs and PNFs and Virtual Links that connect them.

A Virtual Link Descriptor (VLD) is a deployment template which describes the resource requirements that are needed for a link between VNFs, PNFs and endpoints of the Network Service, which could be met by various link options that are available in the NFVI.

A Physical Network Function Descriptor (PNFD) describes the connectivity, Interface and KPIs requirements of Virtual Links to an attached Physical Network Function.

The NFV Orchestrator receives all descriptors and on-boards to the catalogues, NSD, VNFFGD, and VLD are “on-boarded” into a NS Catalogue; VNFD is on-boarded in a VNF Catalogue, as part of a VNF Package. At the instantiation procedure, the sender (operator) sends an instantiation request which contains instantiation input parameters that are used to customize a specific instantiation of a network service or VNF. Instantiation input parameters contain information that identifies a deployment flavor to be used and those parameters used for the specific instance.

A major change brought by NFV is that virtualization enables dynamic methods rather than just static ones to control how network functions are interconnected and how traffic is routed across those connections between the various network functions.

To enable dynamic composition of network services, NFV introduces Network Service Descriptor (NSD) that specify the network service to be created. Aside from general information about the service, these Network Service Descriptors typically include two types of graphs:

- A Network Connectivity Topology (NCT) Graph that specifies the Virtual Network Functions that make up the service and the logical connections between virtual network functions. NFV models these logical connections as Virtual Links that need to be created dynamically on top of the physical infrastructure.
- One or more Forwarding Graphs that specify how packets are forwarded between VNFs across the Network Connectivity Topology graph in order to accomplish the desired network service behavior.

A network connectivity topology is only concerned with how the different VNFs are connected, and how data flows across those connections, regardless of the location and placement of the underlying physical network elements. In contrast, the network forwarding graph defines the sequence of VNFs to be traversed by a set of packets matching certain criteria. The network forwarding graph must include the criteria that specify which packets to route through the graph.

A VNF Network Connectivity Topology (NCT) graph describes how one or more VNFs in a network service are connected to one another, regardless of the location and placement of the underlying physical network elements. A VNF NCT thus defines a logical network-level topology of the VNFs in a graph. Note that the (logical) topology represented by a VNF-NCT may change as a function of changing user requirements, business policies, and/or network context.

In NFV, the properties, relationships, and other metadata of the connections are specified in Virtual Link abstractions. To model how virtual links connect to virtual network functions, NFV introduces uses Connection Points (CPs) that represent the virtual and/or physical interfaces of the VNFs and their associated properties and other metadata.

The following **Figure 6-4** shows a network service example given by the NFV MANO specification[1]. In this example, the network service includes three VNFs. Each VNF exposes different number of connection points.

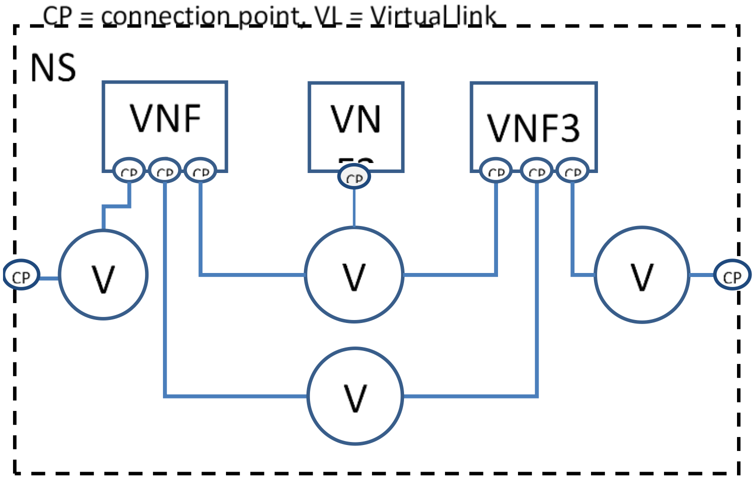


Figure 6-4: Example network connectivity topology graph.

Each Virtual link (VL) describes the basic topology of the connectivity as well as other required parameters (e.g. bandwidth and QoS class). Examples of virtual link types in VNF-NCTs include:

- Different types of Virtual LANs or Private Virtual LANs (e.g. IETF RFC 3069).
- Different types of Layer 2 Virtual Private Networks (e.g. IETF RFC 4464).
- Different types of Layer 3 Virtual Private Networks (e.g. IETF RFC 3809).
- Different types of Multi-Protocol Label Switching Networks (e.g. IETF RFC 3031).

6.2.3 VNF related procedures

This section illustrates the set of most common procedures associated with the deployment and management of VNFs (e.g. on-boarding, instantiation, monitoring, scaling, etc.). To describe the VNF procedures, the following assumptions are made:

- The VNF is composed by one or more VNFC[2]s;
- Each VNFC has a dedicated VM;
- VNFCs are interconnected through Virtual Network Links;
- The VNF, as well as the constituent VNFCs, is instantiated within a single data center, which implies that no scenarios involving the inter-NFVI PoP network is applicable.

6.2.4 On-boarding

VNF on-boarding refers to the process of making the NFV Orchestrator aware that a new VNF is available at the VNF Image Repository.

[1] ETSI GS NFV-MAN 001 v1.1.1
[2] A single VNF which is hosted by a single VM is called a Virtual Network Function Component (VNFC)

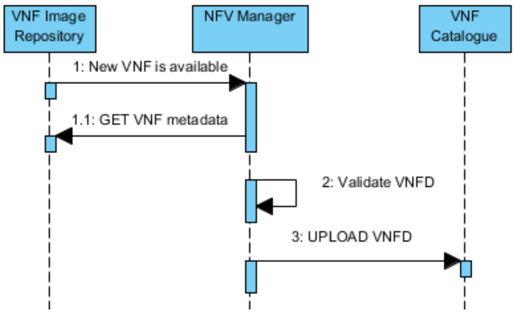


Figure 6-5: VNF On-boarding Procedure.

The on-boarding process, as it is depicted in the following sequence diagram does not refer to the "on-boarding" of the VNF image itself, but practically of its descriptor to the VNF catalogue.

The VNF onboarding process sequence is as following:

1. A new VNF is uploaded to the VNF Image Repository. As a result, the NFV Orchestrator is notified that a new VNF is available.
2. The NFV Orchestrator requests the metadata (VNF Descriptor) of the new VNF.
3. The NFV Orchestrator validates the VNFD to check if the structure is compliant.
4. The NFV Orchestrator uploads the VNFD to the VNF Catalogue.

6.2.5 Instantiation

VNF instantiation refers to the process of creating and provisioning a VNF instance. **Figure 6-6** shows the instantiation process.

Steps VNF Instantiation - NFV Orchestrator View:

1. NFV Orchestrator calls the VNFM to instantiate the VNF, with the instantiation data.
2. The VNFM validates the request and processes it. This might include modifying/complementing the input instantiation data with VNFD data and VNF lifecycle specific constraints.
3. The VNFM then calls the NFV Orchestrator for resource allocation.
4. The NFV Orchestrator retrieves VNF image(s) from the VNF Image Repository.
5. VNF Image Repository delivers the VNF image(s) to the NFV Orchestrator.
6. The NFV Orchestrator executes any required pre-allocation processing work.
7. The NFV Orchestrator requests the allocation of resources from the VIM (compute, storage and network) needed for the VNF instance (and delivers the VNF image(s)).
8. The VIM instantiates the required compute and storage resources from the infrastructure, for further details see VNF Instantiation Procedure.
9. The VIM instantiates the internal connectivity network - a VNF may require dedicated virtual networks to interconnect it's VNFCs (networks that are only used internally to the VNF instance), for further details see VNF Instantiation Procedure.
10. The VIM interconnects the instantiated internal connectivity network with the VNFCs, for further details see VNF Instantiation Procedure.
11. Acknowledgement of completion of resource allocation back to NFV Orchestrator.
12. The NFV Orchestrator acknowledges the completion of the resource allocation back to VNFM, returning appropriate configuration information.

13. After the VNF is instantiated, the VNFM configures the VNF with any VNF specific lifecycle parameters (deployment parameters).
14. The VNF sends an acknowledgement to the VNFM that the configuration process is completed.
15. The VNFM acknowledges the completion of the VNF instantiation back to the NFVO.

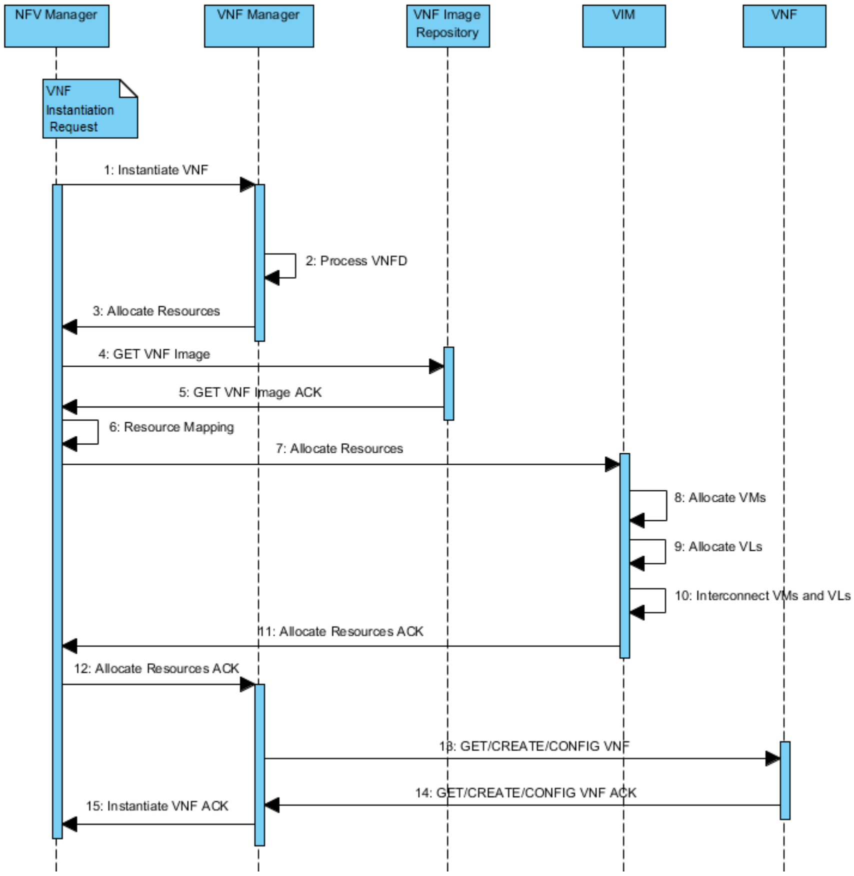


Figure 6-6: VNF Instantiation Procedure.

6.2.6 SDN network architecture

IoRL IHIPGW is more akin to a Radio-Light Home eNode suitable for a single building rather than an EPC suitable for a whole country, the development of which we will be performed in three steps, namely, first to provide direct Internet access to the home radio network, second to interface it to existing 4G Networks through a EPC emulator and then to test this interface with a real 4G Network if possible, and last third step continuously reviews the evolving 5G core Network architecture in 3GPP to quickly adapt our architecture to it.

In the first step all external application servers are accessed via Internet directly (i.e. not through any EPC), as shown in **Figure 6-7**. A local SDN network with a 5G IoRL Random Access Network (RAN) with local IoRL Radio Resource Control (RRC) will be developed for the IHIPGW and enhanced with Connection Acceptance Control, Radio Adaptation Control, Radio Security Control (and more) functions, as shown in **Figure 6-8**. This RRC function will be provided by the existing Cobham wireless software to route packets to the appropriate RRLHs using a combination of SDN network application and UE location estimation algorithms, which will make the network look like a uniform home network to the outside world and signaling will not be required to be forwarded to the Internet.

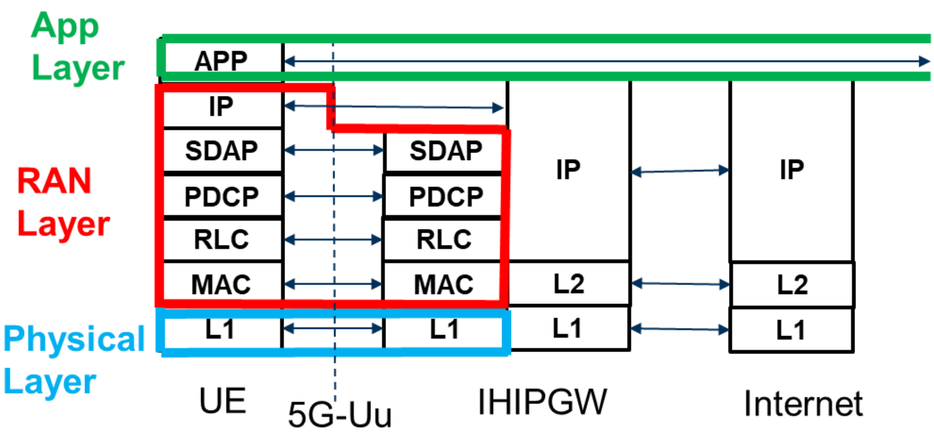


Figure 6-7: User Plane Protocol flow for Internet Interface to IoRL system

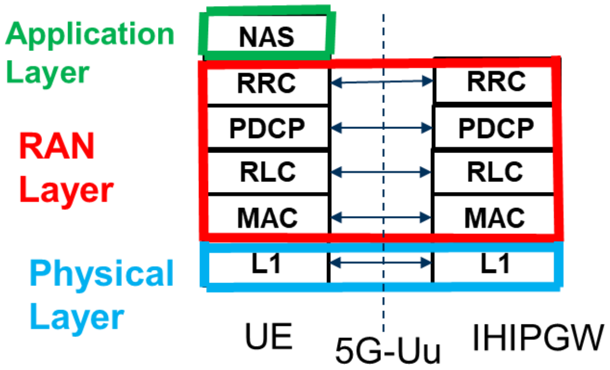


Figure 6-8: Control Plane Protocol flow for Internet Interface to IoRL system

A local server will represent the infrastructure Provider (InP) for our SDN network deployment, it will provide the required resources for constructing the underlying forwarding plane, which will be managed by a logically centralized SDN controller via a southbound interfacing, network policy will be determined according to network applications that being deployed at the application layer to satisfy scenario-specific services.

SDN controller being instantiated at the control plane will enforce these policies to the forwarding devices to ensure packet flows in the suitable pathways.

The UE will be assigned an IP address by the PGW of the MNO he is registered with, and the packets will be forwarded to MNO by the aid of GTP protocol, while using an IP address assigned locally by IHIPGW along with network address translation NAT service in order to connect directly to the local internet provider.

The deployed system will enable the forwarding of different types of traffic (as explained earlier) from one point to another in the system by the aid of network applications developed, and layer two addressing of the RRLH controllers to provide an end to end solution to fulfill the requirement of different services.

The SDN network will be constructed bottom-up in the following manner;

- The data plane layer, it comprises of the forwarding devices, these devices include hardware switches and software switches (OpenVswitch) [20], links, ports, and the south bound interface which will be the (OPENFLOW) protocol
- Control plane layer, it comprises of network Hypervisor, SDN controller (OpenDaylight), and the northbound interface (REST and RESTCONF) protocols.
- Management plane, it contains the network applications that reflects the network policies and operator's requirements.

As shown in **Figure 6-1** the northbound interface will provide the abstraction of the network to management plane applications to enable the development of the required applications based on the simplified abstraction provided, the SDN controller will inforce the policies coming from the applications on the forwarding devices by configuring the network to an application complaint topology and implement the rules that will manage the packets flow from one forwarding devices (FD) to another, as well as configuring the required middle boxes to perform the required task.

The FDs will be connected to RRLH controllers and will traverse the packets to the appropriate mmW module or the VLC module based on the application requirements and user location information.

- Implementation and configuration:

Constructing the IHIPG by using OpenStack platform as a hypervisor to provide the infrastructure-as-a-service for our system, where the network applications will be implemented using object-oriented programming languages, such as Java, Python, etc.

Network Function Virtualization technology NFV to implement the OpenVswitches as well as network functions such as Deep Packet Inspection DPI, Fire walls FW, and the rest of the middle boxes on VMs. Using the Network Function Virtualization technology NFV to implement the OpenVswitches as well as network functions such as Deep Packet Inspection DPI, Fire walls FW, and the rest of the middle boxes on VMs. OpenDaylight controller will be implemented on VM to act as the SDN controller and will translate the network policies to forwarding rules, communicating to the forwarding devices using OpenFlow as the southbound API, while using RESTCONF, or JAVA will be used as the northbound protocol enabling third party application developers to manipulate flow tables and flow entries on networking devices. Controller rules will be transformed into commands to be installed into the forwarding devices' tables to dictate the behavior of the forwarding device.

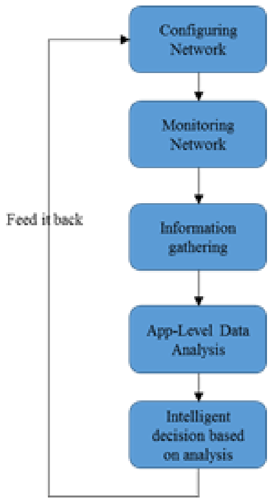


Figure 6-9: Powerful SDN programming technique

- Network configuration using OpenFlow protocol

OpenDaylight controller will be connected to the underlying network using OpenFlow protocol, it will make the rules and use the OpenFlow to update the flow tables of the networking devices e.g. switches, fire walls, load balancers, and so on, traffic will flow according to the current flow tables updated by OpenFlow protocol. FDs will use transport level security TLS protocol to provide secured connection over the OpenFlow channel, flow entry consists of three parts specifically, match field, instruction field, flow statistics field.

OpenFlow protocol header contains many match fields such as ingress port, destination MAC, source MAC, source IP, destination IP, etc.

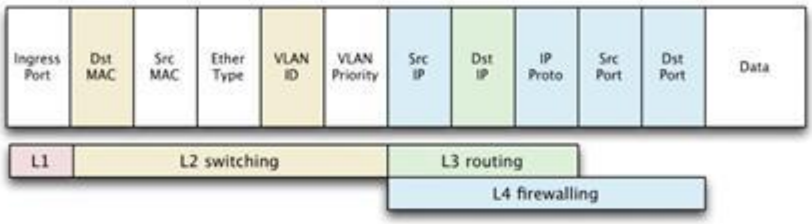


Figure 6-10: OpenFlow protocol header

When packet comes in one of the FDs, the packet header will be matched to the table fields if a match found, an action will be taken, see Figure 6-11, and a counter will be updated. Counters will be per table, per flow, per port, etc., these counters will be useful in the SDN monitoring and data gathering stages which are crucial for inelegant decision making based on data analysis mentioned earlier

A group table consists of group entries, each group entry consists of, a 32-bit group identifier, group type field, counter field, and action buckets. It enables OpenFlow to represent additional methods of forwarding, for instance one of the instructions associated with group table is the Multipath, where the same flow sent to different ports, this action will be useful when implementing the multiple streaming as the same copy of data sent along different pathways.

- location algorithm requirements:

  For the scenarios that require location based forwarding information (Museum scenario), the SDN controller will require a separate and uniquely identified addressing scheme for each module in the RRLH controller, in order for the controller to enforce the rules on the forwarding devices to update their flow tables accordingly.

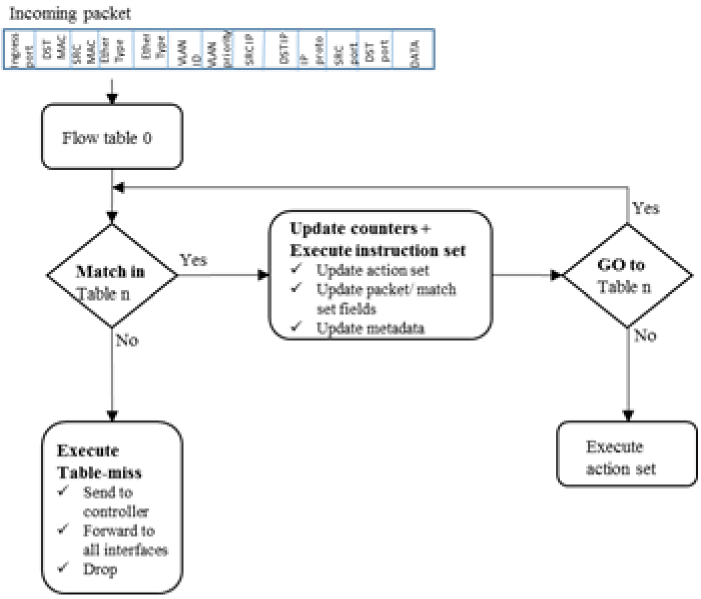


Figure 6-11: OpenFlow protocol packet flow

- Scenario based application identification requirement:

  One of the purposes that DPI application will be used for, its ability to distinguish the packet flows that meant to go to the local data base of certain scenario from the rest of the flow which goes to the service provider, or breakout to the local internet provider. So, when a UE handed over from outside to inside, it is important for him to keep his ongoing sessions e.g. Facebook and start over new session to the local server regarding local services.

Network function algorithms

- Routing

  Routing application will create the network routing policy based on the network abstraction provided by the SDN controller, the abstraction will be based on information gathered from the network in the data plane layer, the delivery of packets will be based on best possible path between two points in the network.

  Forwarding rules will be proactively installed in our forwarding devices when the flow destined to the local server for faster forwarding procedure, and reactive behavior for packets routing whenever controller involvement required, and packets will be sent to UE either via VLC or millimeter wave module depending on the type of data stream.

- Handover
  - ✓ Outdoor-indoor handover:

  UE approaches to an indoor environment (Home, Museum, etc.), UE measurement reports will show receives better signal from the IHIPGW, therefore serving eNodeB will trigger handover procedure as it would normally do to the IHIPGW, the UE will be handed over and will be able to continue his connection to his MNO as well as enjoying the extra features provided by the IHIPGW.

  - ✓ Indoor-Indoor handover

When UE moves from one room to another inside an indoor scenario, location information will be sent to the SDN controller, which will forward these information to location estimation service application, which runs location estimation algorithms to work out the location of the UE with respect to the closest RRLH and send this information back to the controller to make rules for updating the forwarding tables of the FDs and forward the packets accordingly.

✓ Security

Security architecture replacing backhaul and access network switches with OpenVswitches and virtualized middle boxes, many security applications can be adopted since they can run as software applications such as SDM (Software Defined Monitoring) app, GTP TM (Tunnel Management) app, SRO (Security Resource Optimization) app , NTF (Network Telemetry and Forensic) app, and SPC (Security Policy Control) app. With possibility to implement as many apps as required. The use of OpenFlow protocol provides OpenDaylight the ability to monitor, detect, and protect the network from DDoS attacks by filtering the network data. However, the biggest challenge is the potential threat for the controller itself, from DDoS attack.

6.3 5G L2 Protocol Processing

The layer 2 of NR is split into the following sublayers: Medium Access Control (MAC), Radio Link Control (RLC), Packet Data Convergence Protocol (PDCP) and Service Data Adaptation Protocol (SDAP). The two figures **Figure 6-12** and **Figure 6-13** below depict the Layer 2 architecture for downlink and uplink, where:

- The physical layer offers to the MAC sublayer transport channels;
- The MAC sublayer offers to the RLC sublayer logical channels;
- The RLC sublayer offers to the PDCP sublayer RLC channels;
- The PDCP sublayer offers to the SDAP sublayer radio bearers;
- The SDAP sublayer offers to 5GC QoS flows;
- Comp. refers to header compression and segm. to segmentation in Figure 6-12 and Figure 6-13;
- Control channels (BCCH, PCCH are not depicted for clarity).

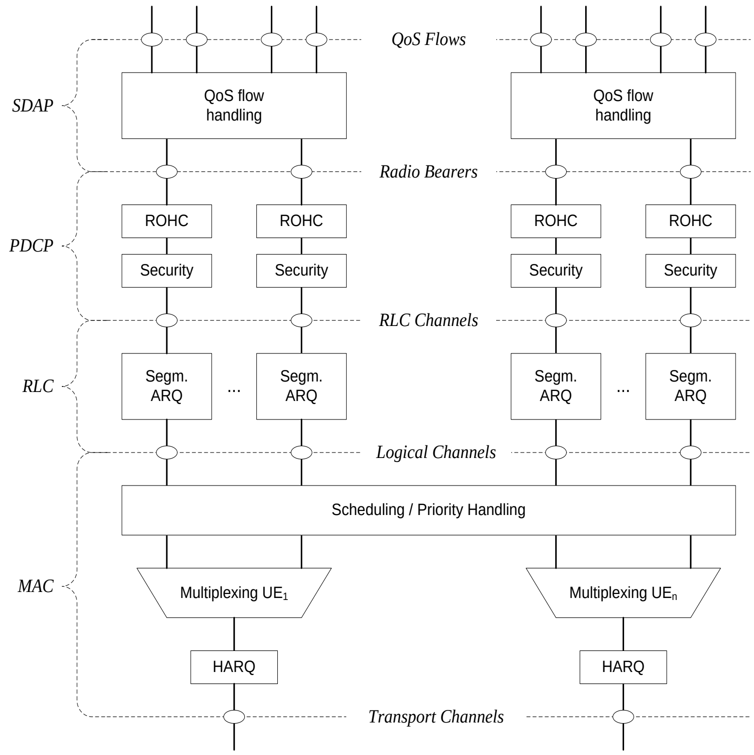


Figure 6-12: Downlink Layer 2 Structure

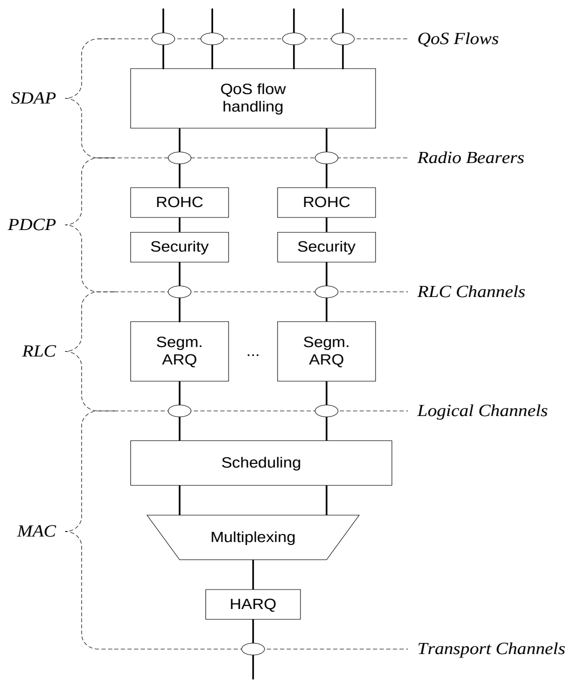


Figure 6-13: Uplink Layer 2 Structure

Radio bearers are categorized into two groups: data radio bearers (DRB) for user plane data and signaling radio bearers (SRB) for control plane data.

6.3.1 MAC Sublayer

6.3.1.1 Services and Functions

The main services and functions of the MAC sublayer include:

- Mapping between logical channels and transport channels;
- Multiplexing/demultiplexing of MAC SDUs belonging to one or different logical channels into/from transport blocks (TB) delivered to/from the physical layer on transport channels;
- Scheduling information reporting;
- Error correction through HARQ (one HARQ entity per carrier in case of CA);
- Priority handling between UEs by means of dynamic scheduling;
- Priority handling between logical channels of one UE by means of logical channel prioritization;
- Padding.

A single MAC entity can support one or multiple numerologies and/or transmission timings and mapping restrictions in logical channel prioritization controls which numerology and/or transmission timing a logical channel can use.

6.3.1.2 Logical Channels

Different kinds of data transfer services as offered by MAC. Each logical channel type is defined by what type of information is transferred. Logical channels are classified into two groups: Control Channels and Traffic Channels. Control channels are used for the transfer of control plane information only:

- Broadcast Control Channel (BCCH): a downlink channel for broadcasting system control information.
- Paging Control Channel (PCCH): a downlink channel that transfers paging information and system information change notifications.
- Common Control Channel (CCCH): channel for transmitting control information between UEs and network. This channel is used for UEs having no RRC connection with the network.
- Dedicated Control Channel (DCCH): a point-to-point bi-directional channel that transmits dedicated control information between a UE and the network. Used by UEs having an RRC connection.

Traffic channels are used for the transfer of user plane information only:

- Dedicated Traffic Channel (DTCH): point-to-point channel, dedicated to one UE, for the transfer of user information. A DTCH can exist in both uplink and downlink.

6.3.1.3 Mapping to Transport Channels

In Downlink, the following connections between logical channels and transport channels exist:

- BCCH can be mapped to BCH;
- BCCH can be mapped to DL-SCH;
- PCCH can be mapped to PCH;

- CCCH can be mapped to DL-SCH;
- DCCH can be mapped to DL-SCH;
- DTCH can be mapped to DL-SCH.

In Uplink, the following connections between logical channels and transport channels exist:

- CCCH can be mapped to UL-SCH;
- DCCH can be mapped to UL- SCH;
- DTCH can be mapped to UL-SCH.

6.3.1.4 HARQ

The Hybrid Automated Repeat Request (HARQ) functionality ensures delivery between peer entities at Layer 1. A single HARQ process supports one Transport Block (TB) when the physical layer is not configured for downlink/uplink spatial multiplexing, and when the physical layer is configured for downlink/uplink spatial multiplexing, a single HARQ process supports one or multiple TBs.

6.3.2 RLC Sublayer

6.3.2.1 Transmission Modes

The RLC sublayer supports three transmission modes:

- Transparent Mode (TM);
- Unacknowledged Mode (UM);
- Acknowledged Mode (AM).

The RLC configuration is per logical channel with no dependency on numerologies and/or TTI durations, and Automatic Repeat Request (ARQ) can operate on any of the numerologies and/or TTI durations the logical channel is configured with.

For SRB0, paging and broadcast system information, TM mode is used. For other SRBs AM mode used. For DRBs, either UM or AM mode are used.

6.3.2.2 Services and Functions

The main services and functions of the RLC sublayer depend on the transmission mode and include:

- Transfer of upper layer PDUs;
- Sequence numbering independent of the one in PDCP (UM and AM);
- Error Correction through ARQ (AM only);
- Segmentation (AM and UM) and re-segmentation (AM only) of RLC SDUs;
- Reassembly of SDU (AM and UM);
- Duplicate Detection (AM only);
- RLC SDU discard (AM and UM);
- RLC re-establishment;
- Protocol error detection (AM only).

6.3.2.3 ARQ

The ARQ within the RLC sublayer has the following characteristics:

- ARQ retransmits RLC PDUs or RLC PDU segments based on RLC status reports;
- Polling for RLC status report is used when needed by RLC;
- RLC receiver can also trigger RLC status report after detecting a missing RLC PDU or RLC PDU segment.

6.3.3 PDCP Sublayer

6.3.3.1 Services and Functions

The main services and functions of the PDCP sublayer for the user plane include:

- Sequence Numbering;
- Header compression and decompression: ROHC only;
- Transfer of user data;
- Reordering and duplicate detection;
- PDCP PDU routing (in case of split bearers);
- Retransmission of PDCP SDUs;
- Ciphering, deciphering and integrity protection;
- PDCP SDU discard;
- PDCP re-establishment and data recovery for RLC AM;
- Duplication of PDCP PDUs.

The main services and functions of the PDCP sublayer for the control plane include:

- Sequence Numbering;
- Ciphering, deciphering and integrity protection;
- Transfer of control plane data;
- Reordering and duplicate detection;
- Duplication of PDCP PDUs

6.3.4 SDAP Sublayer

The main services and functions of SDAP include:

- Mapping between a QoS flow and a data radio bearer;
- Marking QoS flow ID (QFI) in both DL and UL packets.

A single protocol entity of SDAP is configured for each individual PDU session.

6.3.5 L2 Data Flow

An example of the Layer 2 Data Flow is depicted on **Figure 6-14**, where a transport block is generated by MAC by concatenating two RLC PDUs from RB_x and one RLC PDU from RB_y. The two RLC PDUs from RB_x each corresponds to one IP packet (*n* and *n+1*) while the RLC PDU from RB_y is a segment of an IP packet (*m*).

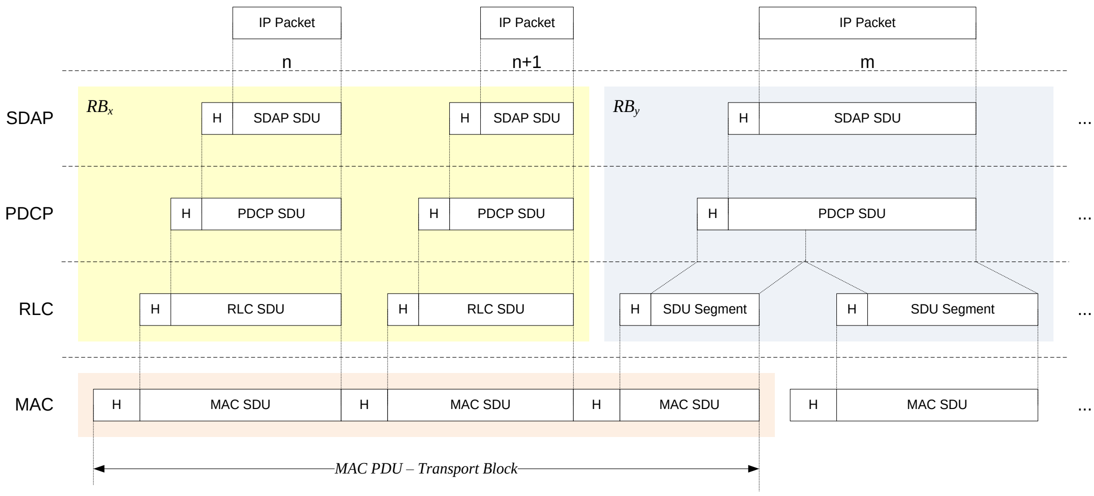


Figure 6-14: Data Flow Example (NOTE: H depicts the headers and subheaders.)

6.4 Example of Protocol Sequencing for Internet Interface

The IoRL system should be compliant with the ISO OSI layered model. In this model IP addresses are used by the L3 (Network layer) for end-to-end addressing. In the IoRL system for example, for IP addresses of the UE device and used by the user web server in the Internet, for example www.google.com. Except the usage of NAT these addresses are not changed during packet forwarding. Hop-by-hop addressing between directly connected devices is performed by the L2 (Data-link layer), for example MAC addresses in the Ethernet frames.

Due to performance reasons 5G L3 and L2 processing will be performed on the dedicated machine (DELL R730 - 1) and 5G L1 processing on dedicated FPGAs and circuits, which will be connected to the rest of the IHIPG (DELL R730 - 2) using direct 1G/10G Ethernet link.

Data exchange between IoRL RAN and the IHIPG SDN network depends on the used data plane - control or user.

The control plane for Internet interface is local to the UE and RAN and has is fixed with a single radio bearer within a single PDU session per UE.

The interface used between "5G L3-RRC and L2 processing" unit and the SDN FD at the user plane uses a direct Ethernet link and Ethernet frames, which contain exact IP data generated at the UE. In the SDN network side all packets destined to or sourced from the SDN network use single MAC address (aa.bb.cc.dd.ee.09) that is characteristic for the SDN network. The addresses to or from the RAN part is associated with the exact RRLH or used module (VLC or mmW) which forwards this packet further.

Figure 6-15 presents an Ethernet frame which is sent from "5G L2 processing" unit to the SDN FD when the user UE located below the RRLH1 sends data to the Google search engine. **Figure 6-16** presents the response packet from the Google web server which will be sent to the appropriate VLC or mmW module MAC address. When, in the presented example, the user changes his location to e.g. the location just below the RRLH 6 the source MAC address of the Ethernet frame at changes. Now it is associated with the RRLH6 VLC or mmW module, which later allows for appropriate routing of the frames. This situation is presented in the **Figure 6-17**.

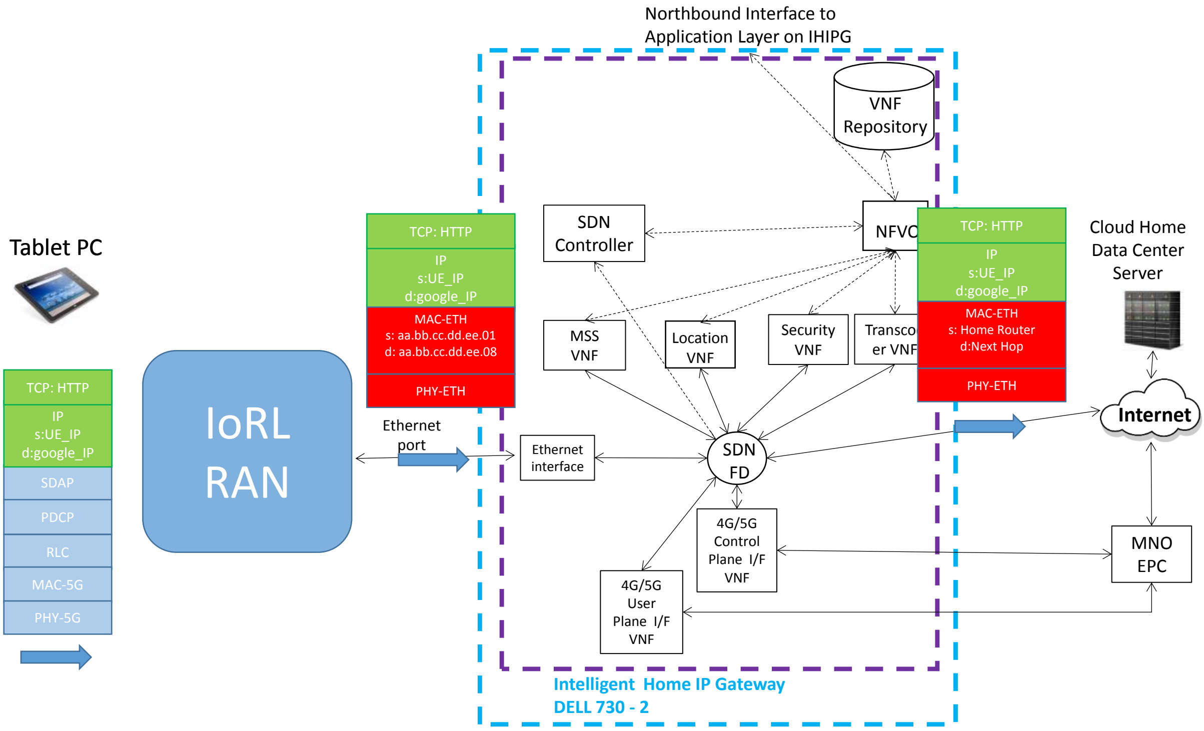


Figure 6-15: Ethernet frame to the SDN FD when the UE located below the RRLH1

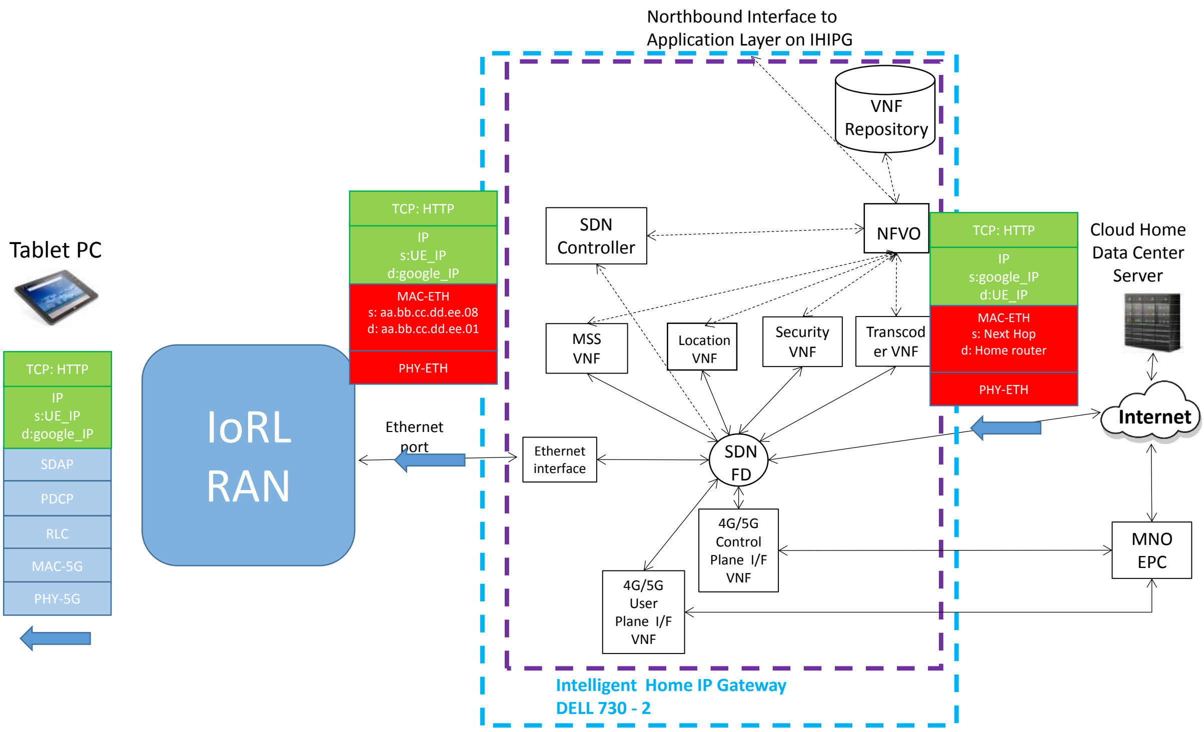


Figure 6-16: Response Ethernet frame from the SDN FD to UE located below the RRLH1

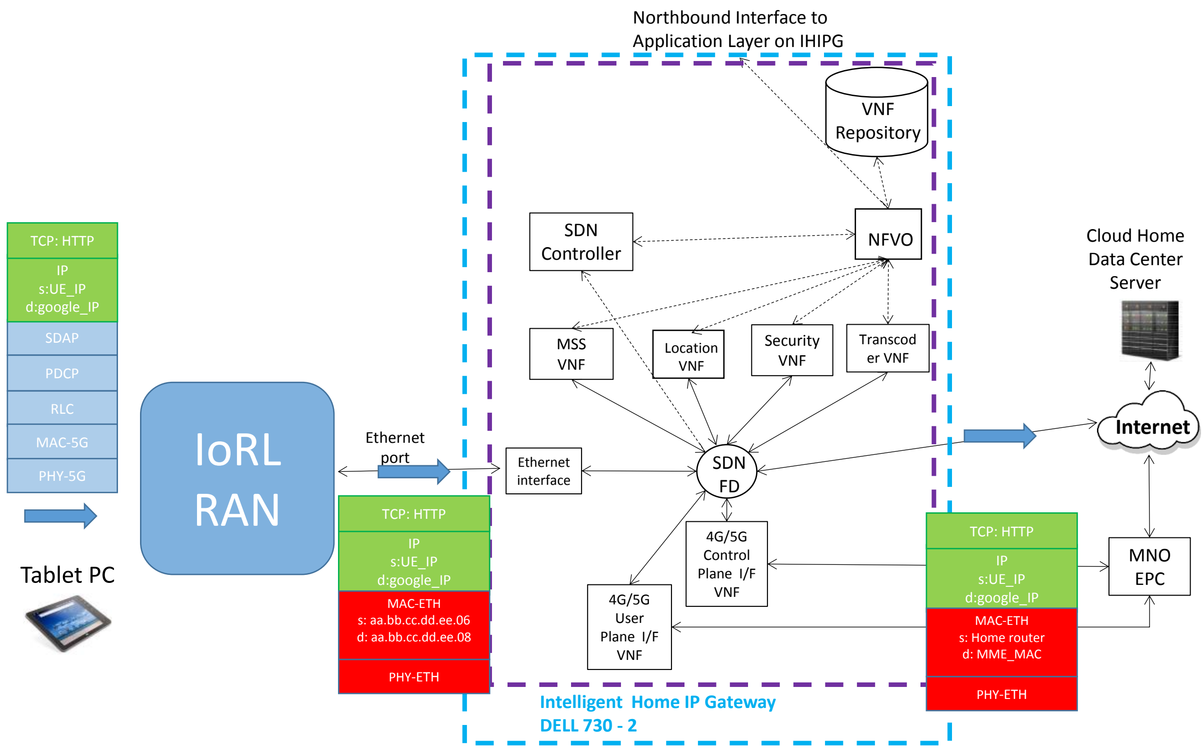


Figure 6-17: Ethernet frame to the SDN FD when the UE located below the RRLH6

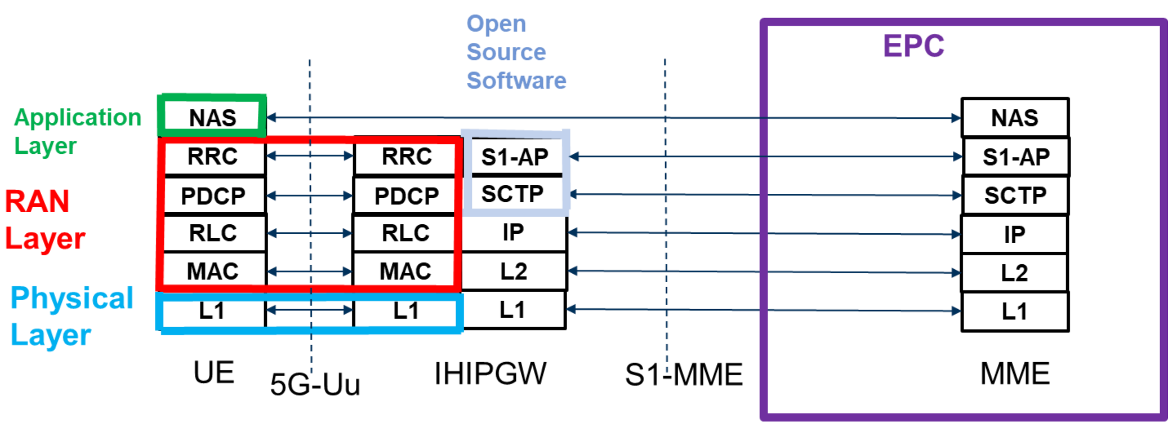


Figure 6-18: Control Plane Protocol flow for EPC Interface to IoRL system

Integration with a real EPG of a MNO requires the cooperation of a real MNO in order to register both IoRL IHIPGW and UEs on its MME and HSS databases. The IoRL project has relations with BT with EE and Telefonica with O2, who we may approach at the right later stage of the project.

Finally, third and final the evolving 5G Core Network architecture in 3GPP will continuously be reviewed to adapt the IoRL Network architecture to it.

6.5 Outdoor Handover protocol flow for 4G/5G in home

In order for our solution to be operational and compatible with the current 4G networks, it would require the MNO to add the IHIPGW as another eNodeB in their systems. This is possible if the Non-Stand Alone Mode 5G profile of 5G is selected for IoRL gNB, see **Figure 6-19**.

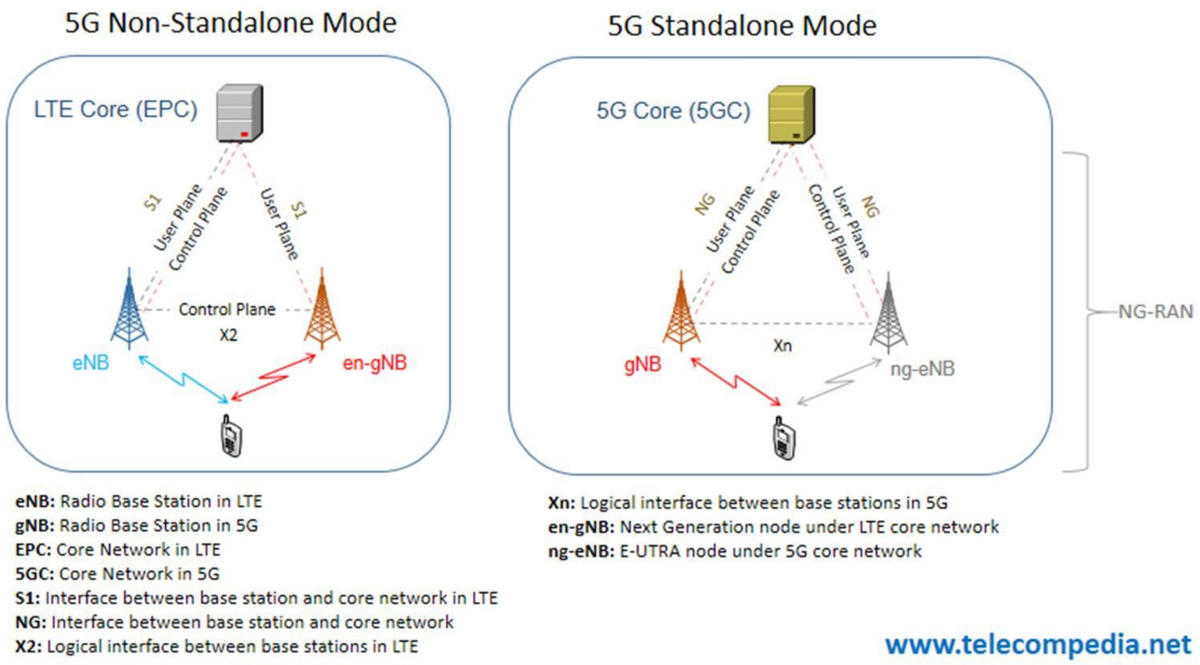


Figure 6-19: 5G Stand Alone and No-Stand Alone Modes

This will facilitate the packet flow to/from the MNO by letting the system perform normal handover, this enables the UE to maintain the use of IP address assigned by MNO the end user is registered with, which allows the end user to continue using the services provided by the MNO even when being handed over to or from any building that is using this solution in addition to the ability to communicate to the services provided by the local server inside the buildings.

The first step towards achieving integration with a real EPG of a MNO is integration with an emulated "external" EPC, such as OpenAirInterface please see: http://www.openairinterface.org/. In order to support GTP-U between the IHIPGW and EPC, GTP tunneling capability that must be added to OpenVswitch as well as SDN application (for configuring the GTP tunnel parameters in the switch), see **Figure 6-20**.

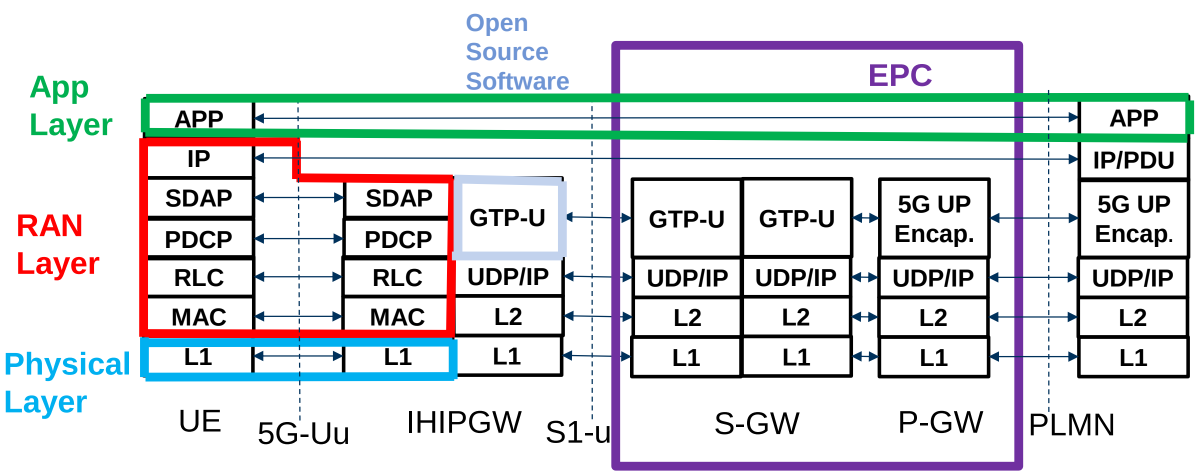


Figure 6-20: User Plane Protocol flow for EPC Interface to IoRL system

The UE will be assigned an IP address by the PGW of the MNO he is registered with, and the packets will be forwarded to MNO by the aid of GTP protocol, Network Address Translation NAT will be used to change the source IP address of UE in order to forward its traffic to the Internet connection instead of SGW.

PDU layer corresponds to the PDU carried between the UE and the DN over the PDU Session. When the PDU Session Type is IPV6, it corresponds to IPv6 packets; When the PDU Session Type is Ethernet, it corresponds to Ethernet frames; etc. 5G Encapsulation supports multiplexing traffic of different PDU Sessions (possibly corresponding to different PDU Session Types) over N9 (i.e. between different UPF of the 5GC). It provides encapsulation on a per PDU Session level. This layer carries also the marking associated with a QoS.

The GTP-U protocol entity provides packet transmission and reception services to user plane entities in the RNC, SGSN, GGSN, eNodeB, SGW, ePDG, PGW, TWAN, MME, gNB, N3IWF, and UPF. The GTP-U protocol entity receives traffic from a number of GTP-U tunnel endpoints and transmits traffic to a number of GTP-U tunnel endpoints. There is a GTP-U protocol entity per IP address. GTP-U tunnel could actually be the bearer that could carry QoS Flow.

The TEID in the GTP-U header is used to de-multiplex traffic incoming from remote tunnel endpoints so that it is delivered to the User plane entities in a way that allows multiplexing of different users, different packet protocols and different QoS levels. Therefore no two remote GTP-U endpoints shall send traffic to a GTP-U protocol entity using the same TEID value except for data forwarding as part of mobility procedures.

NAS is a control protocol between the UE and the MME, and the IoRL IHIPGW, which acts as a relay to forward the NAS messages to the MME. For example, when a service request message is received by the IHIPGW, NAS payload is attached to S1-AP as a UeInitialMessage and sent to the MME, which means the handling of NAS message is performed by either the UE or the MME without the intervention of the IHIPGW.

OpenSource software of GTP-U, SCTP, S1-AP and NAS control protocols will be used from GitHub or SourceForge repositories or from OMNET simulation model and adapted for use in the project, as shown in **Figure 6-21**.

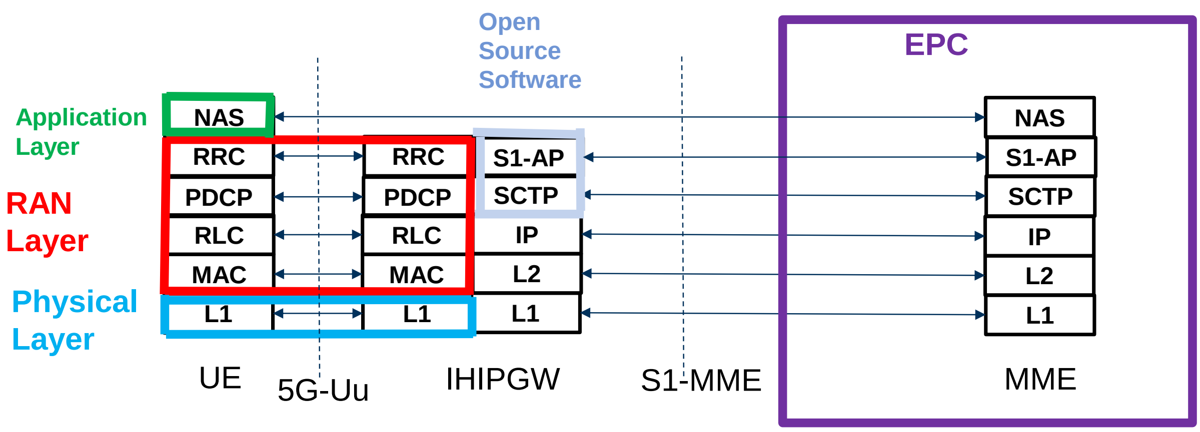


Figure 6-21: Control Plane Protocol flow for EPC Interface to IoRL system

The final step is integration with a real EPC of a MNO, which requires the cooperation of a real MNO in order to register both IoRL IHIPGW and UEs on its MME and HSS databases. The IoRL project has relations with BT with EE and Telefonica with O2, who we may approach at the right later stage of the project.

6.6 IoRL 4G/5G QoS flow

The evolving 5G Core Network architecture in 3GPP will continuously be reviewed to adapt the IoRL Network architecture to it.

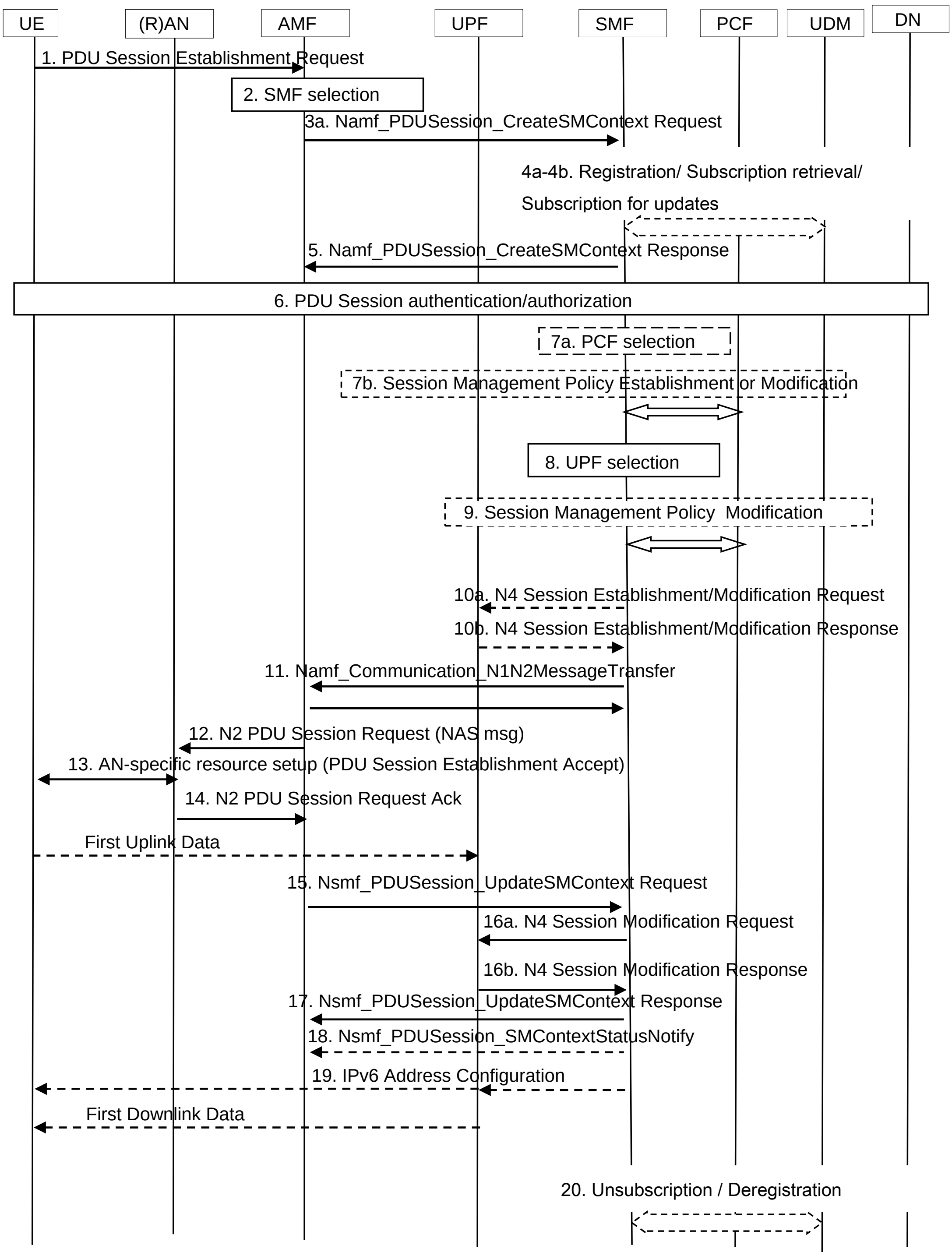


Figure 6-22: UE Requested PDU Session Establishment

The procedure is used to establish a new PDU Session; handover a PDN Connection in EPS to PDU Session in 5GS without N26 interface; switch an existing PDU Session between non-3GPP access and 3GPP access and request a PDU Session for Emergency services. The next generation of core network includes AMF(Access and Mobility Management Function), SMF(Session Management Function), UPF(User Plane Function), PCF(Policy Control Function), UDM(Unified Data Management)

The SMF performs the binding of SDFs to QoS Flows based on the QoS and service requirements (e.g. the received PCC rules). The SMF assigns the QFI for a new QoS Flow and derives its QoS profile from the information provided by the PCF. When applicable, the SMF provides the QFI together with the QoS profile to the (R)AN, and optionally a transport level packet marking value (e.g. the DSCP value of the outer IP header over N3 tunnel) to the (R)AN for the UL traffic. The SMF provides the SDF template i.e. Packet Filter Set associated with the SDF received from the PCF) together with the SDF template precedence value included in the PCC rule as defined in TS 23.503, the QoS related information, and the corresponding packet marking information, i.e. the QFI, the transport level packet marking value (e.g. the DSCP value of the outer IP header over N3 tunnel) for downlink traffic and optionally the Reflective QoS Indication to the UPF enabling classification, bandwidth enforcement and marking of User Plane traffic. For each SDF, when applicable, the SMF generates a QoS rule Each of these QoS rules contain the QoS rule identifier, the QFI of the QoS Flow the Packet Filter Set of the UL part of the SDF template, optionally the Packet Filter Set for the DL part of the SDF template, and the QoS rule precedence value set to the precedence value of the PCC rule from which the QoS rule is generated. The QoS rules are then provided to the UE.

The principle for classification and marking of User Plane traffic and mapping of QoS Flows to Access Network (AN) resources is illustrated in **Figure 6-23**.

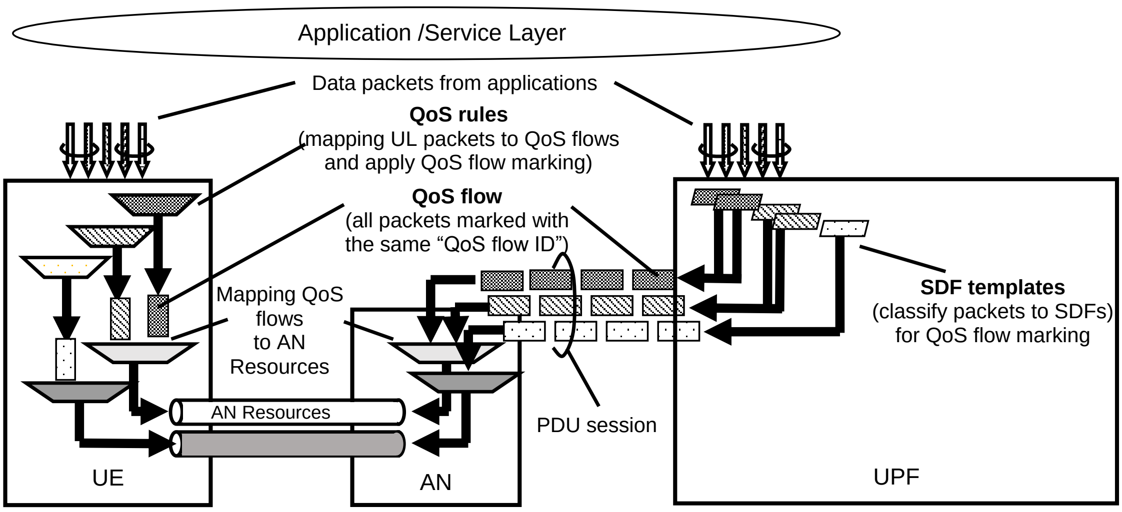


Figure 6-23: The principle for classification and User Plane marking for QoS Flows and mapping to AN Resources

In DL, incoming data packets are classified by the UPF based on SDF templates according to the precedence of the PCC rule authorizing the service data flow, (without initiating additional N4 signalling). The UPF conveys the classification of the User Plane traffic belonging to a QoS Flow through an N3 (and N9) User Plane marking using a QFI. The AN binds QoS Flows to AN resources (i.e. Data Radio Bearers of in case of 3GPP RAN). There is no strict 1:1 relation between QoS Flows and AN resources. It is up to the AN to establish the necessary AN resources that QoS Flows can be mapped to, and to release them. The AN shall indicate to the SMF when the AN resources onto which a QoS flow is mapped are released. If no match is found and all QoS Flows are related with a DL Packet Filter Set, the UPF shall discard the DL data packet.

In UL, the UE evaluates UL packets against the Packet Filter Set in the QoS rules based on the precedence value of QoS rules in increasing order until a matching QoS rule (i.e. whose packet filter matches the UL packet) is found. The UE uses the QFI in the corresponding matching QoS rule to bind the UL packet to a QoS Flow. The UE then binds QoS Flows to AN resources. If no match is found and the default QoS rule contains an UL Packet Filter Set, the UE shall discard the UL data packet.

The MBR (and if applicable GBR) per SDF, if received from PCF over N7, is signaled on N4. For further information regarding MBR and GBR over N7.

The QoS Flow parameters include 5QI, ARP, RQA, Notification control, Flow Bit Rates, Aggregate Bit Rates, Default values, Maximum Packet Loss Rate. The 5G QoS characteristics should be understood as guidelines for setting node specific parameters for each QoS Flow e.g. for 3GPP radio access link layer protocol configurations. Signaled QoS characteristics are included as part of the QoS profile including Resource Type, Priority Level, Packet Delay Budget, Packet Error Rate, Averaging Window, Maximum Data Burst Volume.

6.7 Example of Protocol Sequencing for 4G/5G Interface

The IoRL 5G system control plane protocol flow is shown in Figure 6-24, Figure 6-25 and Figure 6-26. The interface used between "5G L3-RRC and L2 processing" unit and the SDN FD at the control plane uses a direct Ethernet link and Ethernet frames, which contain exact NAS data generated at the UE. In the EPC side all packets destined to or sourced from EPC use single MAC address (AMF_MAC) that is characteristic for the EPC AMF via N2 interface. The addresses to or from the RAN part is associated with the exact RRLH or used module (VLC or mmW) which forwards this packet further.

Figure 6-24 presents an Ethernet frame which is sent from "5G L2 processing" unit to the SDN FD when the user UE located below the RRLH1 sends data to EPC. **Figure 6-25** presents the response packet from EPC server which will be sent to the appropriate VLC or mmW module MAC address. When, in the presented example, the user changes his location to e.g. the location just below the RRLH 6 the source MAC address of the Ethernet frame at changes. Now it is associated with the RRLH6 VLC or mmW module, which later allows for appropriate routing of the frames. The inner processing of EPC for the control plane shown in **Figure 6-26**.

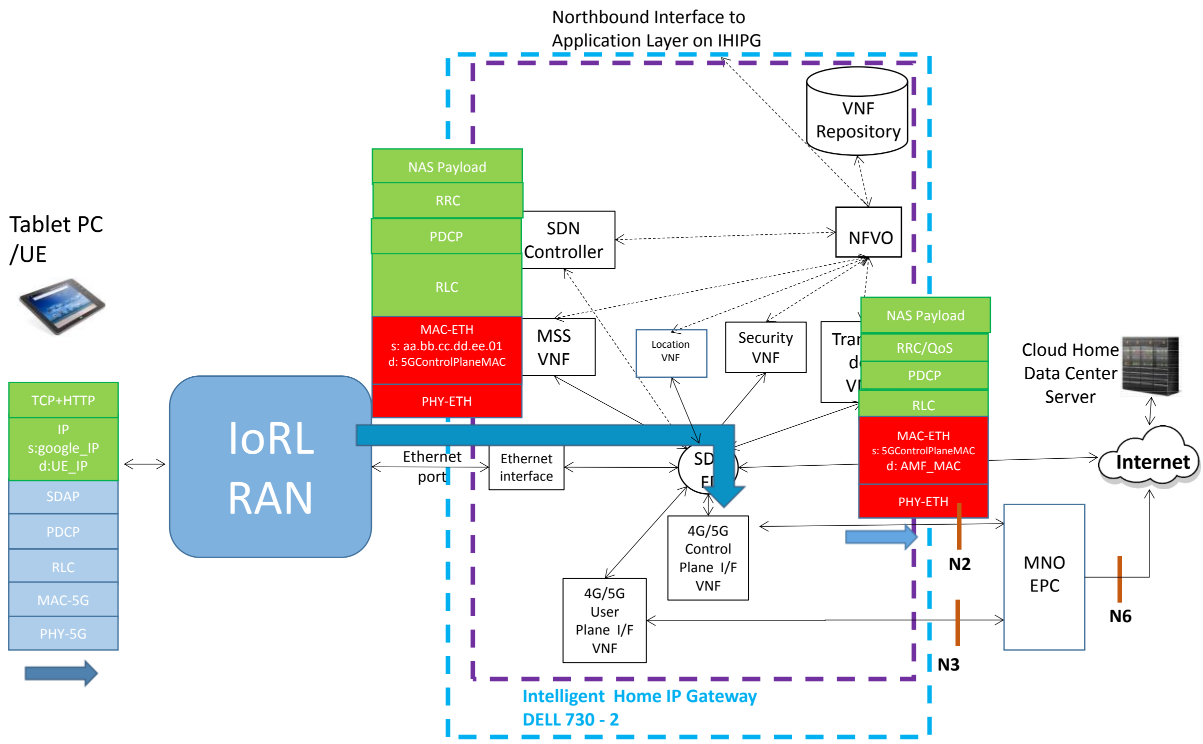


Figure 6-24: 5G system control plane protocol flow (Uplink)

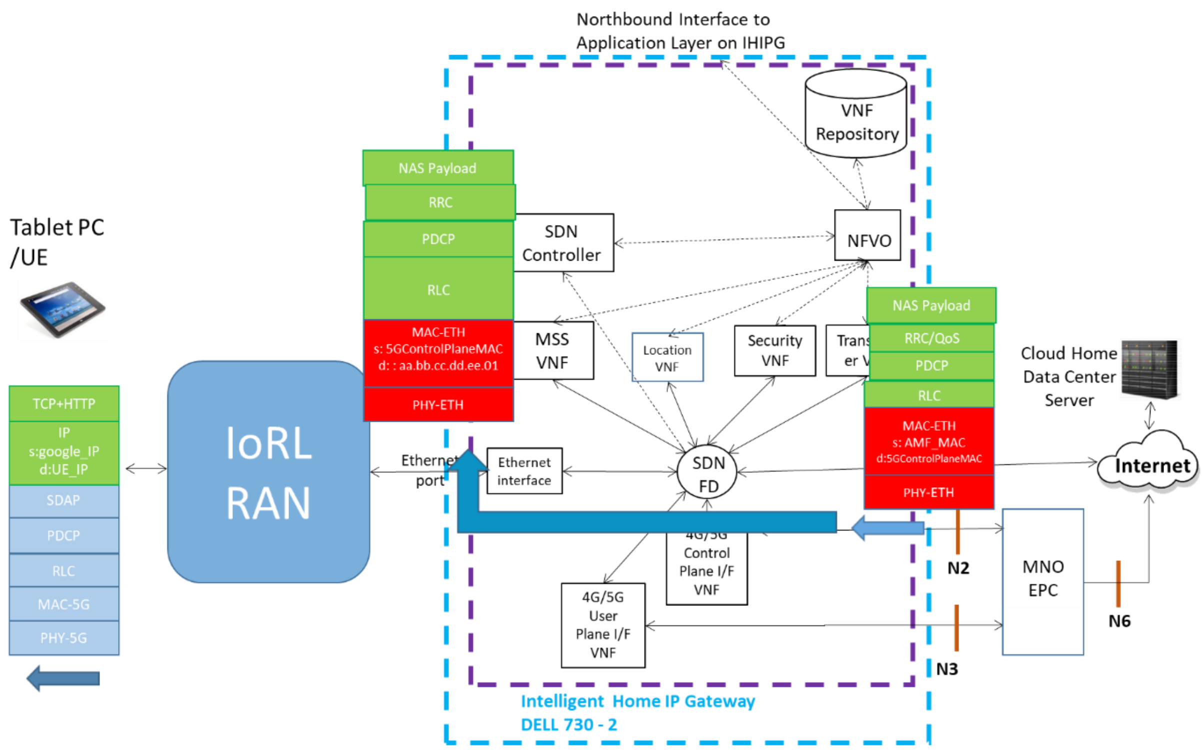


Figure 6-25: 5G system control plane protocol flow (Downlink)

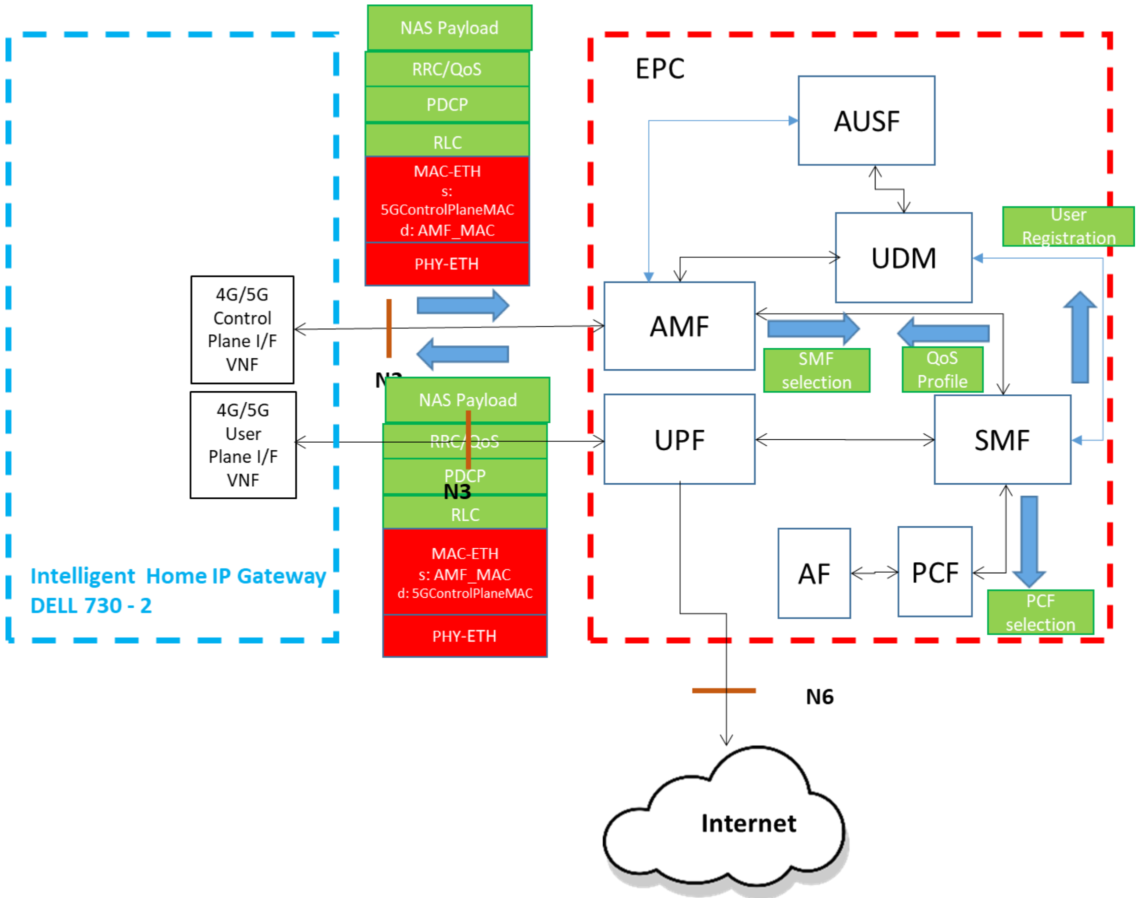


Figure 6-26: 5G system control plane protocol flow (Inside EPC)

The IoRL 5G system user plane protocol flow is shown in **Figure 6-27** and **Figure 6-28**. The interface used between "5G L3-RRC and L2 processing" unit and the SDN FD at the user plane uses a direct Ethernet link and Ethernet frames, which contain exact IP data generated at the UE. In the EPC side all packets destined to or sourced from EPC use single MAC address (UPF_MAC) that is characteristic for the EPC UPF via N3 interface. The addresses to or from the RAN part is associated with the exact RRLH or used module (VLC or mmW) which forwards this packet further.

Figure 6-27 presents an Ethernet frame which is sent from "5G L2 processing" unit to the SDN FD when the user UE located below the RRLH1 sends data to EPC. Figure 6-28 presents the response packet from EPC server which will be sent to the appropriate VLC or mmW module MAC address. When, in the presented example, the user changes his location to e.g. the location just below the RRLH 6 the source MAC address of the Ethernet frame at changes. Now it is associated with the RRLH6 VLC or mmW module, which later allows for appropriate routing of the frames.

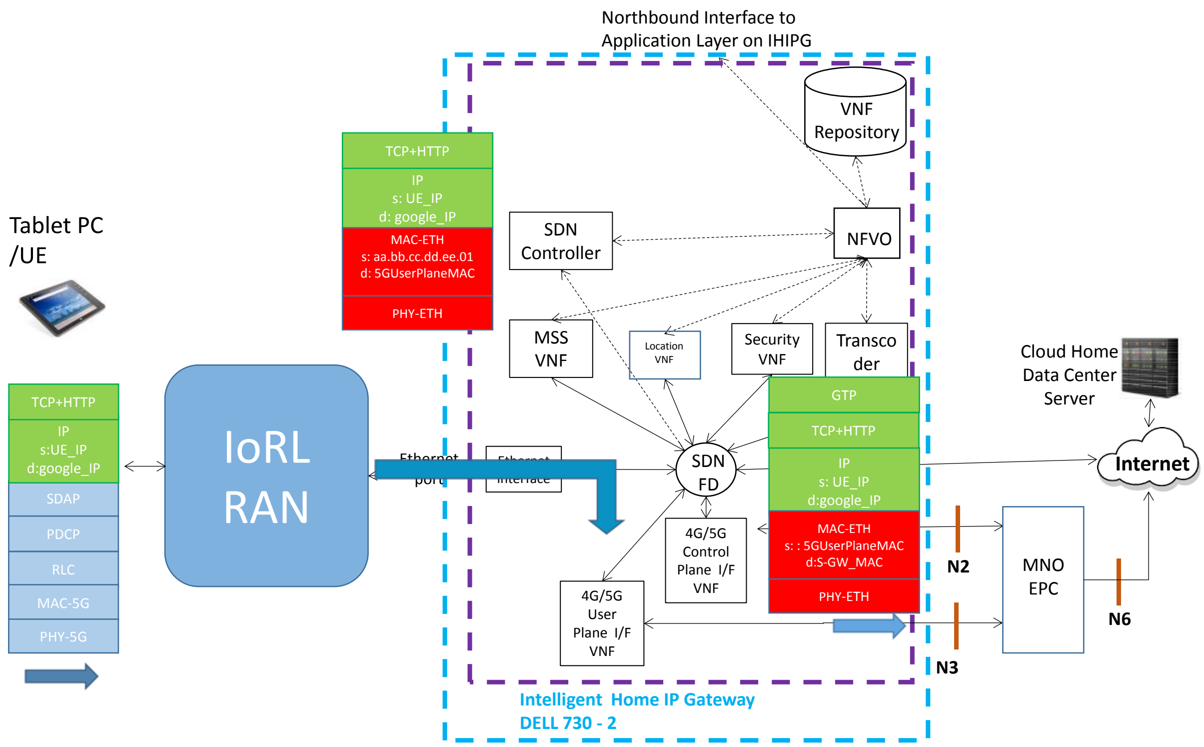


Figure 6-27: 5G system user plane protocol flow (Uplink)

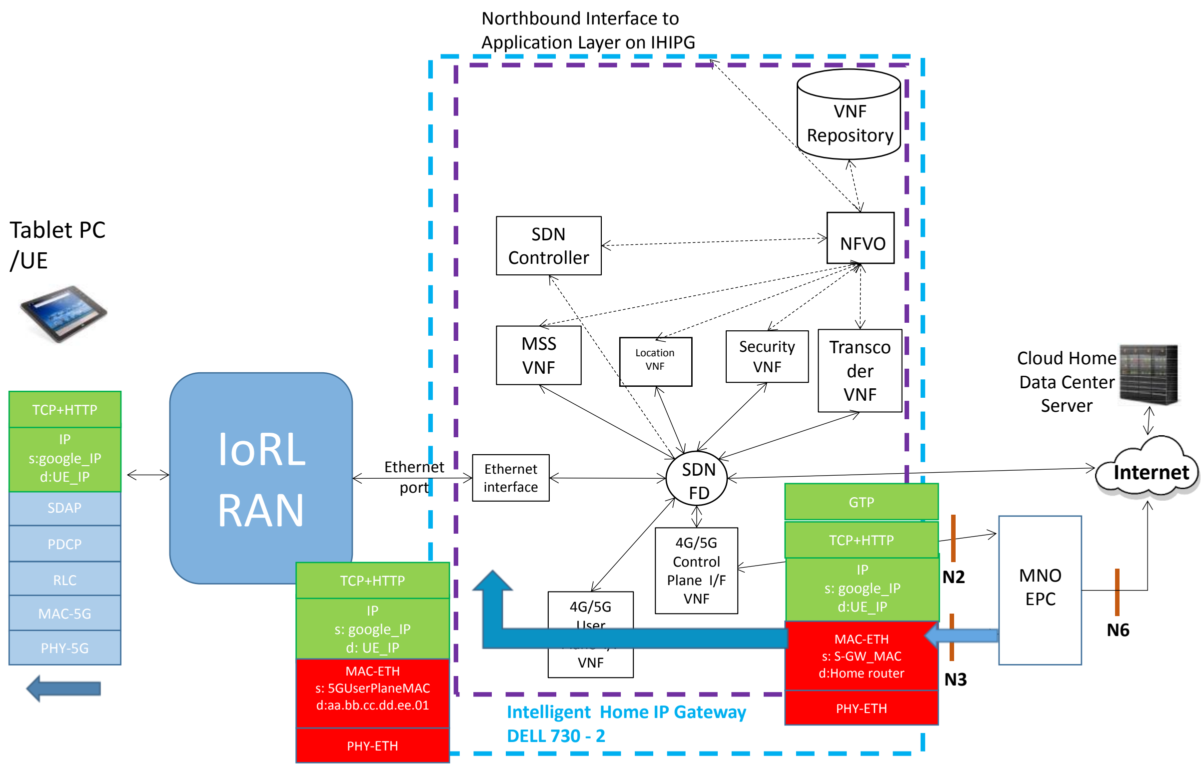


Figure 6-28: 5G system user plane protocol flow (Downlink)

6.8 Example of Protocol Sequencing for 4G/5G Handover

In the case of inside IoRL (source) to outside e/gNB (target) handover, the Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ) of the outside radio network together with knowledge of the UE's location in the home radio-light network is measured by the UE and used to commence a inter network handover procedure through signaling initiated from IoRL RAN to the e/gNB on the X2 interface, as shown in Figure 6-29.

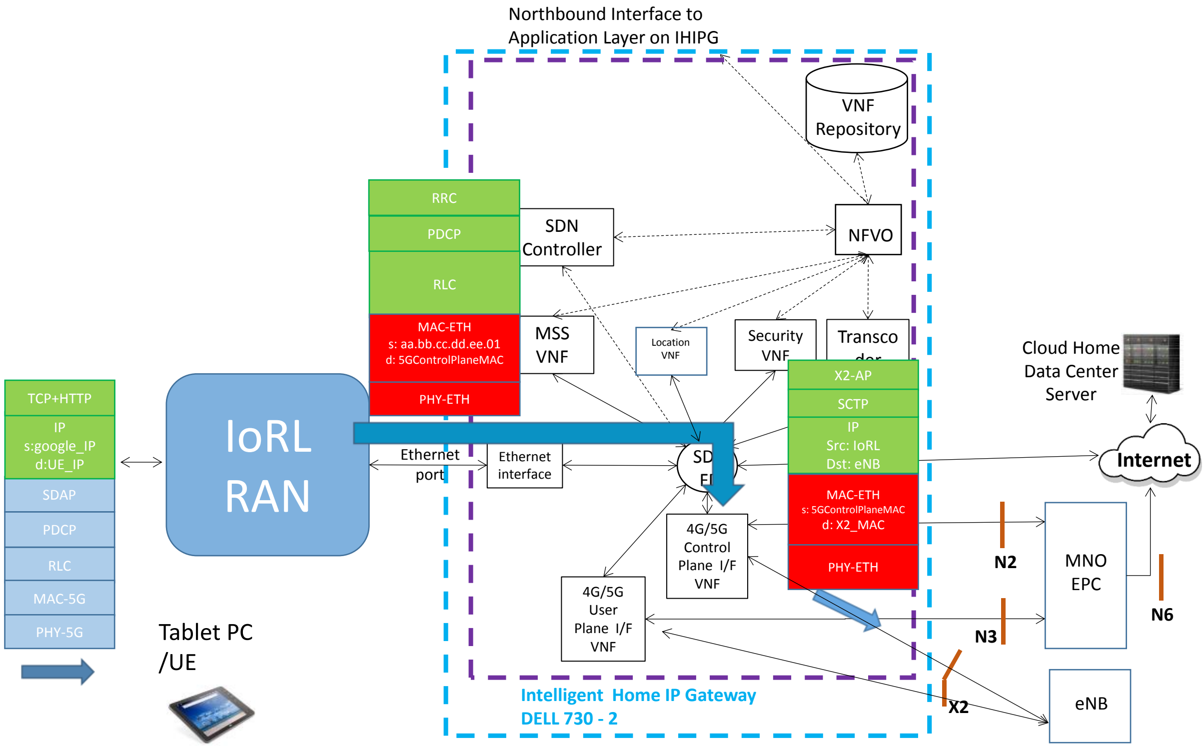


Figure 6-29: Control Plane Protocol Flow IoRL to gNB Handover

Any subsequent user plane packets misdirected to the IoRL network then get redirected to the target e/gNB over the X2 interface, as shown in **Figure 6-30**.

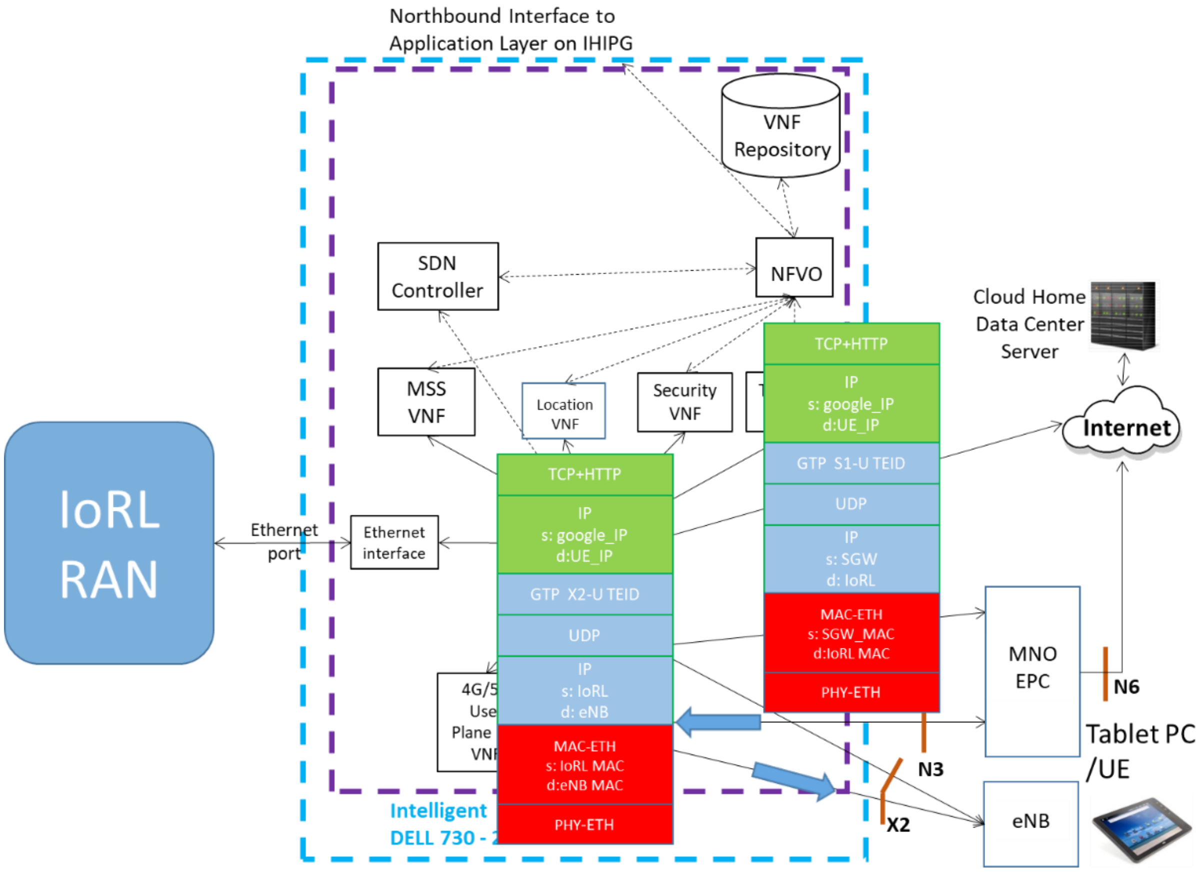


Figure 6-30: User Plane Protocol Flow IoRL to gNB Handover

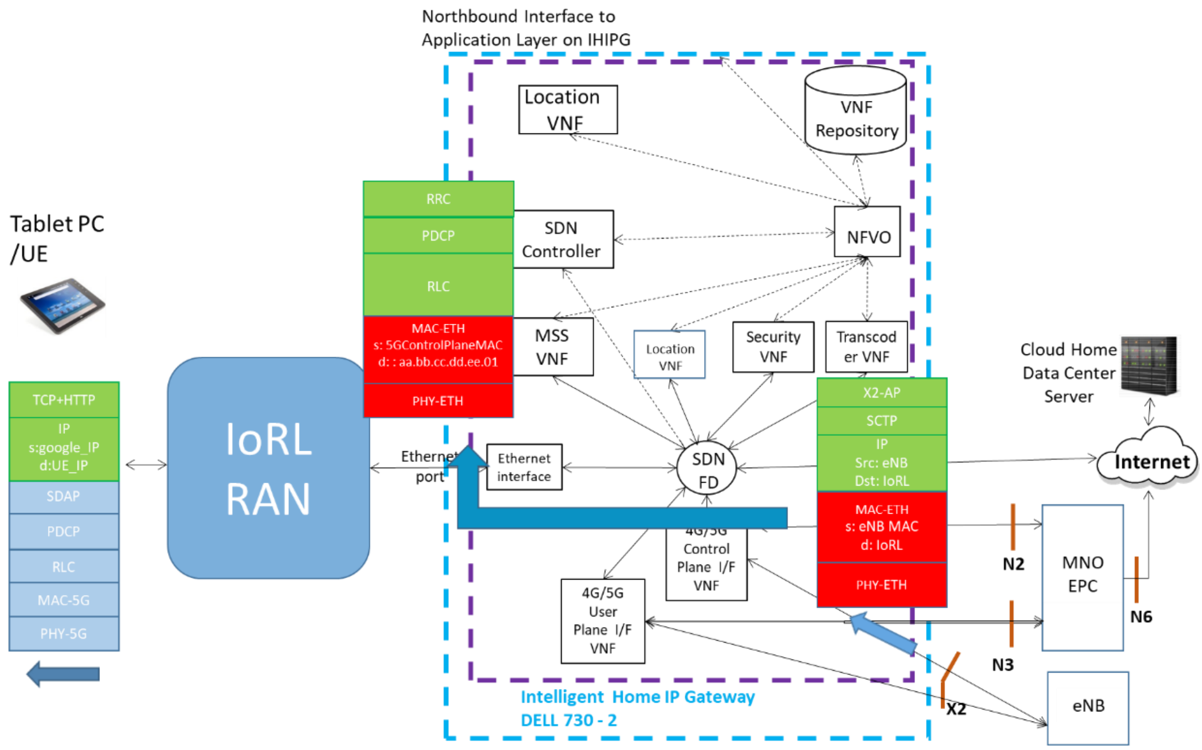


Figure 6-31: Control Plane Protocol Flow gNB to IoRL Handover

In the case of outside e/gNB (source) to inside IoRL (target) handover, the Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ) of the outside radio network together with knowledge of the UE's location in the home radio-light network is measured by the UE and used to commence a inter network handover procedure through signaling initiated from e/gNB to the IoRL RAN on the X2 interface, as shown in **Figure 6-31**.

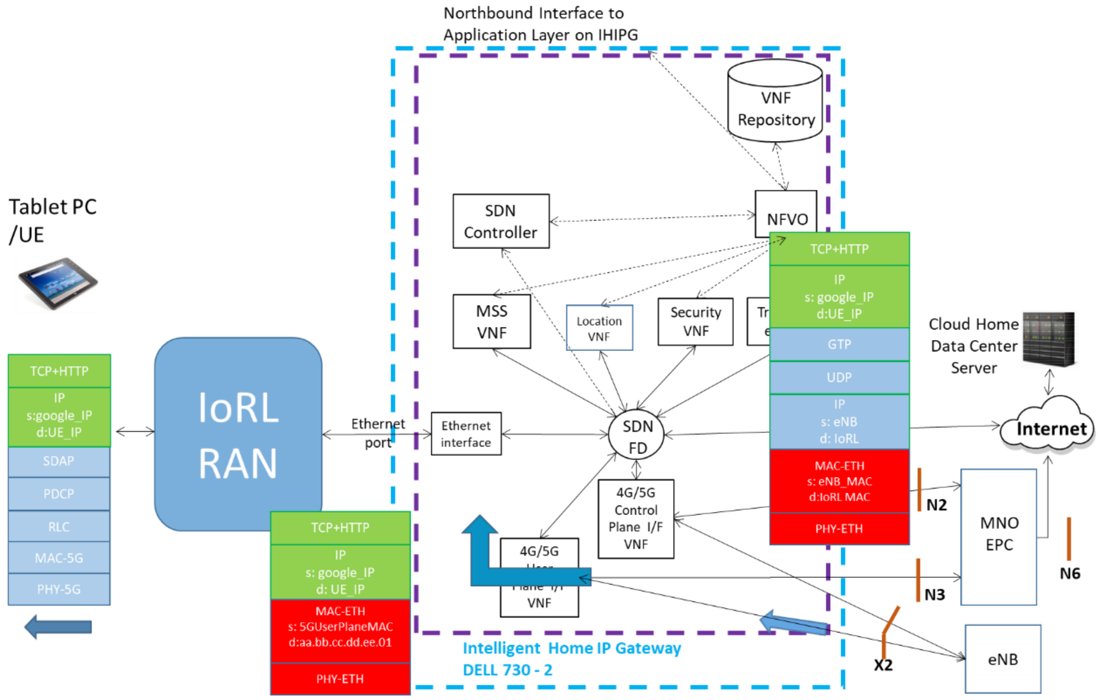


Figure 6-32: User Plane Protocol Flow gNB to IoRL Handover

Any subsequent user plane packets misdirected to the gNB then get redirected to the target IoRL network over the X2 interface, as shown in **Figure 6-32**.

6.9 Multi-Source Streaming over remote radio light head

Multiple-Source Streaming over remote radio light head is composed of three main modules: the **MS-Stream Server**, the **MS-Stream Player** and the **Transcoder**. Both the MS-Stream Server and the Transcoder compose the server side and can be deployed in the Intelligent Home IP Gateway. The MS-Stream Player is to be deployed at the client side, inside of an application running in the UE. On the client side, the MS-Stream Player is a video player that can be integrated in a web page and accessed through a web browser. This client may also be running in a native application for specific UE. As the algorithm of MS-Stream is defined as client-centric, the MS-Stream Client is responsible for the creation of the requests sent to the MS-Stream Server through the RRLH Network and the Relay WIFI Access for a Multiple-Source Streaming session.

On the server side, the MS-Stream Server is an application that can answer client requests for specific video contents. This module is responsible for the creation of video segments adapted to Multiple-Source Streaming. The video segments are created from video data transcoded in numerous different qualities. For that purpose, the Transcoder comes along with the server. The Transcoder is a module that can transcode input video data into Multiple-Source-ready video data in one or several qualities. Those data then can be pushed to the MS-Stream Server and be available for the MS-Stream Player in the UE. In IoRL Software Architecture, the role of the MS-Stream modules is to stream the videos from the Intelligent Home IP Gateway to the UE through multiple paths: the RRLH network and the

WIFI network. The video data streamed through the SDN FD, from live TV or over-the-top video platforms, can be redirected to the Transcoder. At this point, the stream is transcoded into lower qualities and sent to the MS-Stream Server. Then, the client would be able to get the Multiple-Source-adapted video data through both the RRLH network and/or the WIFI network.

6.10 Security scheme for IoRL

The main issue addressed within IoRL from the network security perspective is the threat analysis and development of the integrated security framework for the use cases defined within the project.

IoRL project integrates various concepts and networking technologies (WLAN, eNB/HeNB, mmW, VLC and SDNs) and each of them have a specific set of characteristic features and potential security threats and vulnerabilities that still are often not completely resolved and still need addressing. For such a heterogeneous system a careful threat analysis is needed in order to identify the most important security hazards. In more detail, the potential IoRL system threats can be assigned to one of the following groups:

- *IoRL end user devices-related threats (user-specific)*: These threats include e.g. Man-in-the-Middle (MitM) attacks performed by the malicious users in order to influence legitimate IoRL users or their devices in order to capture their sensitive data (like credentials), to tamper with the legitimate users' communication (in order to impersonate them) or to disrupt it via Distributed Denial of Service (DDoS) attacks. Finally some privacy-related attacks can be envisioned where the attacker tries to gain e.g. targeted users location information, their movements and/or habits patterns, etc.
- *IoRL infrastructure-related threats (component-specific)*: These include e.g. attacks on crucial points of the IoRL architecture in order to overload or impersonate them e.g. by performing DDoS attacks on the SDN or RRLH controllers or eavesdropping and then spoofing their communication. It is also worth noting that these type of attacks can be launched by malicious IoRL users (inside threat) or by remote attackers (remote threat) residing somewhere in the Internet or in the vicinity of the IoRL system components, for example, mmW or VLC receivers and/or transmitters.
- *IoRL-related threats (architecture-specific)*: Such attacks can be possible or could be amplified because of the heterogeneous nature of the proposed system involving coexistence and integration of various networking technologies. Due to this fact some unexpected interactions or vulnerabilities can be discovered. For example, due to integration of diverse types of technologies some simplifications may be needed to ensure their cooperation which may lead to the situation that no security is provided or there are security mechanisms however they are not compatible.

The initial analysis of the current state of the IoRL architecture and the developed uses cases revealed the following possible threats:

- Eavesdropping of the sensitive, unencrypted data leaked via non-curtained window or via a key hole in the smart home scenario,
- Introduction of the network rogue VLC transmitter in the museum use case that forwards visitors to the hostile web server instead of museum web server,

- Exploiting handovers - the perfect timing to setup a rogue node that will relay the intercepted communication is especially dangerous in public places like museums, supermarkets, or train station,
- Jamming/Interfering with the signal by overloading the (Hybrid mmW-VLC) RAN, which can lead to DoS attack and disrupt the process of travel tickets selling and validation in the Train Station Scenario.

Based on the detailed analysis of the above mentioned IoRL-related potential threats groups the dedicated security framework will be designed and developed that will provide secure communication and preserve users' privacy. The proposed security framework will be an integral part of the developed IoRL architecture following security-by-design rule.

The design and implementation of the security monitoring and management system will be tailored to the requirements of the IoRL use cases. The focal point of the IoRL security system will be SDN and NFV security-related functions implemented there. Utilization of the SDN technology will allow to design and create a centralized system for security monitoring and manageability providing near real-time awareness of network incidents status and effective enforcement of security policy. This functionality will be implemented utilizing SDN feature called SDN application. The SDN application is a dedicated software which interacts with the SDN controller: It receives data from the controller for further analysis and later sends flows descriptions and actions that are implemented within the switches. In result, various security actions can be implemented, for example, blocking of unwanted traffic. During the IoRL project we will develop SDN security application which monitors network traffic and detects various kinds of attacks, for example, Denial of Service and scanning activity. Moreover, detected attacks will be mitigated by appropriate reconfiguration of the SDN switches flow tables. Therefore hostile traffic associated with DoS and scanning attacks will be simply removed as soon as possible from the network and never reaches the victims. The security monitoring system, in cooperation with the position sensing architecture, could not only detect potential attacks but it also indicates possible position of the offending device. This could be especially important in the bigger and publicity accessible localizations, for example, museums, supermarkets, or train stations where there are numerous places in which rogue devices which perform attack or other unwanted activities can be left unnoticed for a long time. In result security personnel will receive more complete information containing possible location of potential security-related threats which reduces time needed for attack mitigation.

The details of the proposed security architecture for IoRL should be tightly coupled with the overall architecture of the IoRL system. As the proposed IoRL architecture will be finally established once this deliverable is published thus all the specifics of the proposed SDN-based IoRL security solution will be included in the Deliverable 2.4 (Threats Analysis and Integrated Security Framework for IoRL Use Cases).

7 IoRL Service Layer Software Architecture

7.1 Introduction

Table 7—1: IoRL User Scenarios

Themes Addressed	Home	Museum	Tunnel	Supermarket	Conference
AV Streaming (from Stream Server)	1.3 Multiple Contents Display and Recording 1.6 Online Gaming		3.8 Commercial Signage	4.5 Viewing Cartoons for Children on Shopping Cart Chair	
AV Streaming Communications	1.4 Broadband Office in the Home		3.2 Tunnel video conference communication	4.6 Virtual Shopping for the Disabled via the Carer	5.4 Conference Organizers Communications
AV Streaming (from live camera)	1.5 Virtual Reality Tourism from your Living Room 1.9 Secure Home using Outside Monitoring	2.4 Exploring Current and Past Museum's Expositions in the restaurant or externally		4.4 Monitoring Baby in the Nursery	5.2 Recording, Real Time Viewing and Downloading Sessions
Indoor Location based data access		2.2 Updating Information System for Exhibits in the Exhibition Hall	3.4 Instant information and ultra-high bandwidth downloading	4.3 Highlighting Product Features on Shelves	5.1 Accessing the Conference Proceedings and Social Apps
Indoor Location monitoring and guiding		2.3 Navigation Guide and Information System on Visitors' Activities in Museum	3.1 Accurate location and information provision under tunnel premises	4.2 Store Guide and Route from Shopping List	

Interaction		2.1 Treasure Hunt in the Museum		4.1 Preparing a Shopping List	5.3 Delegate Chat, Speaker Rating and Conference Rating

7.2 Streaming

Internet service providers (ISP) provide internet access. ISP's will provide a user with a Modem, this Modulates and demodulates data between digital data and electronic signals used by user equipment (UE). A router connected to the modem allows multiple devices to share the Local Area Network (LAN) signal. In most cases, the router and modem are a single unit. A user device may connect to the router in two ways, via either wired or wireless. Ethernet connection is a wired connection between the router and device. Common routers come equipped with Radio frequency transmitters and receivers to deliver a Wi-Fi signal. Wi-Fi capable user devices have internal or external Wi-Fi chips, boards or dongles allowing for wireless connection to the router. As illustrated in **Figure 7-1**.

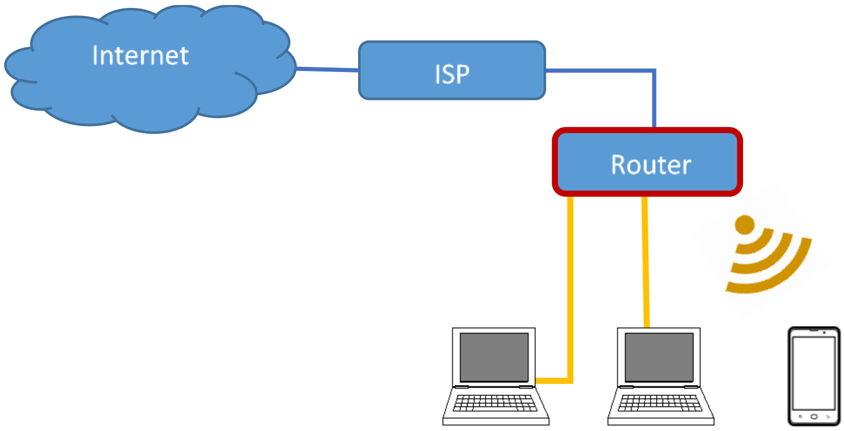


Figure 7-1: WiFi network structure

Figure 7-2, below, illustrates the architecture of the IoRL project. The IoRL project offers an alternative intermediate transmission method between the user's device and the modem. This is managed by replacing slower Wi-Fi radio transmission with faster 5G capable mmW and VLC transmission.

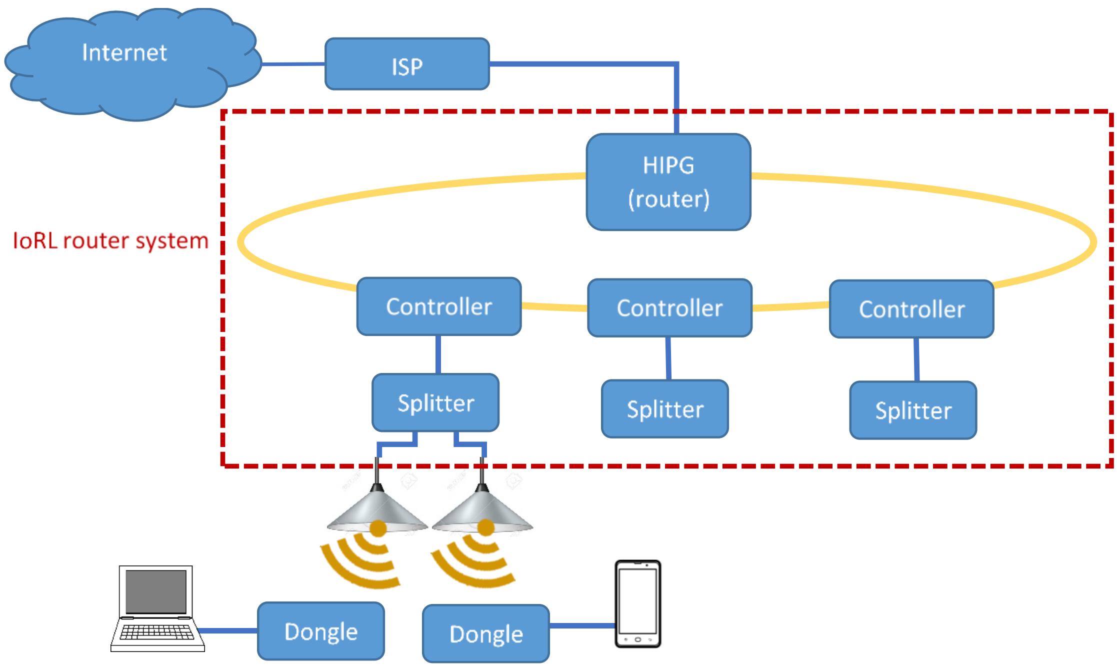


Figure 7-2: IoRL network structure

7.2.1 System connection and bandwidth allocation

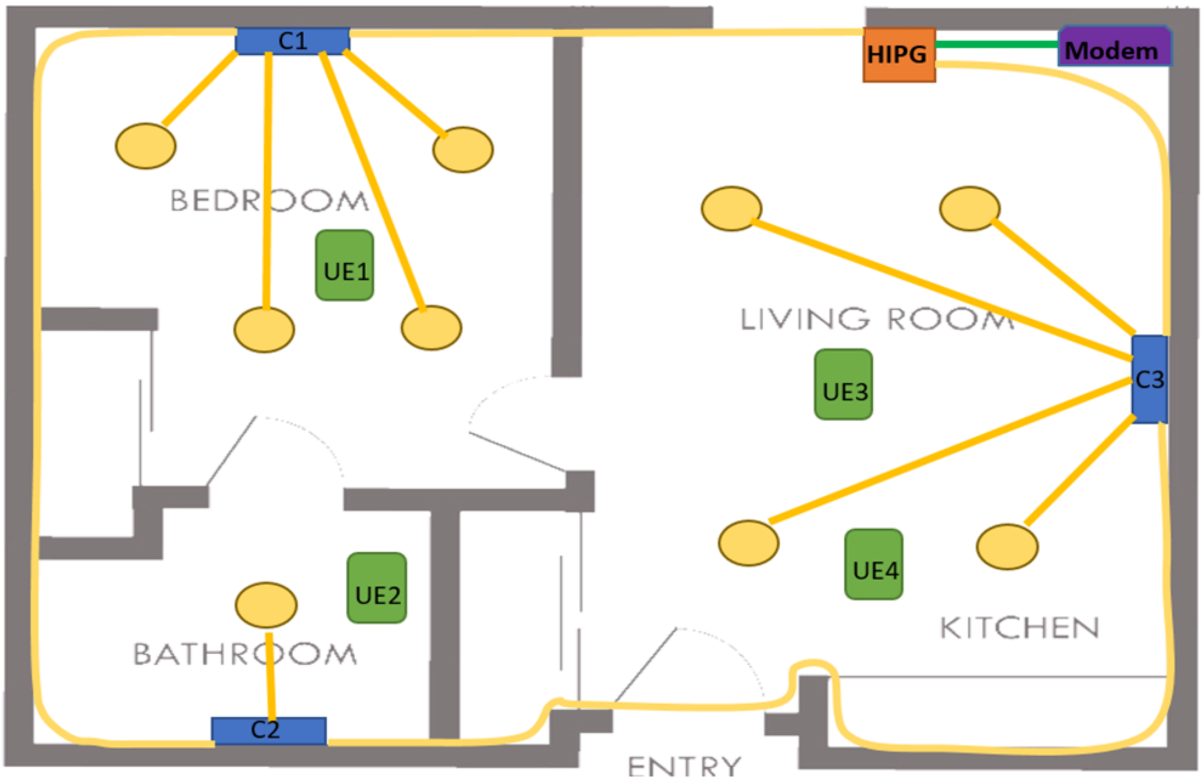


Figure 7-3: indoor floor plan

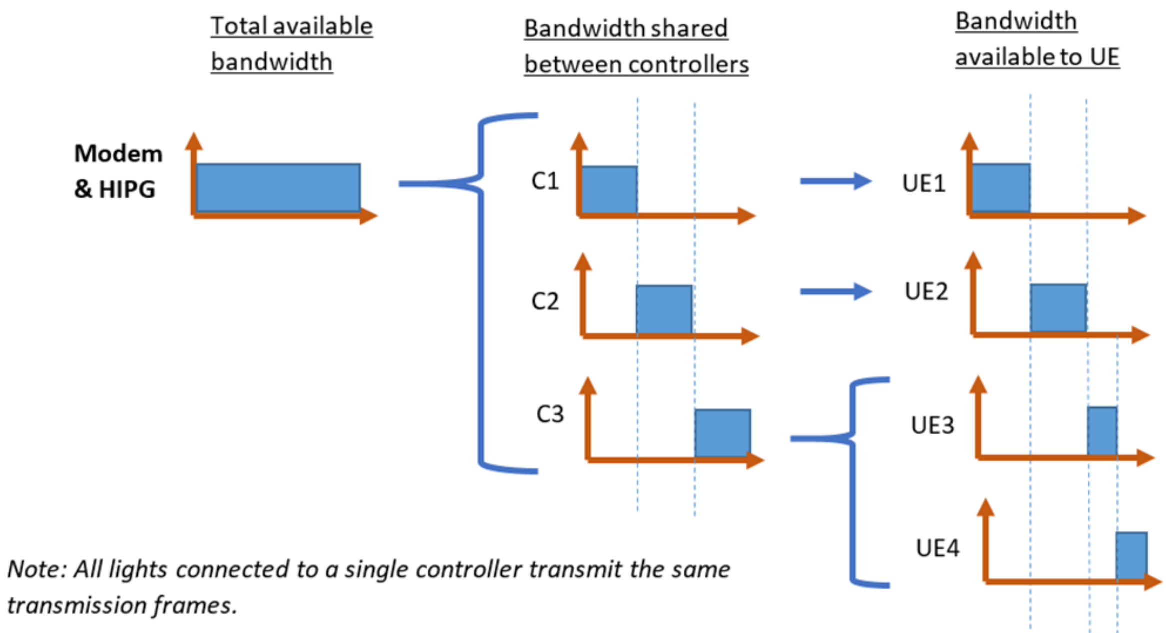


Figure 7-4: bandwidth allocation

Figure 7-3 illustrates the concept layout and general connections of the RRLHs, controllers and HIPG within a floor of a building. **Figure 7-4** depicts how the bandwidth is allocated and distributed between the individual controllers and then between the separate UE in each room.

7.2.2 Overall system architecture for general streaming use cases

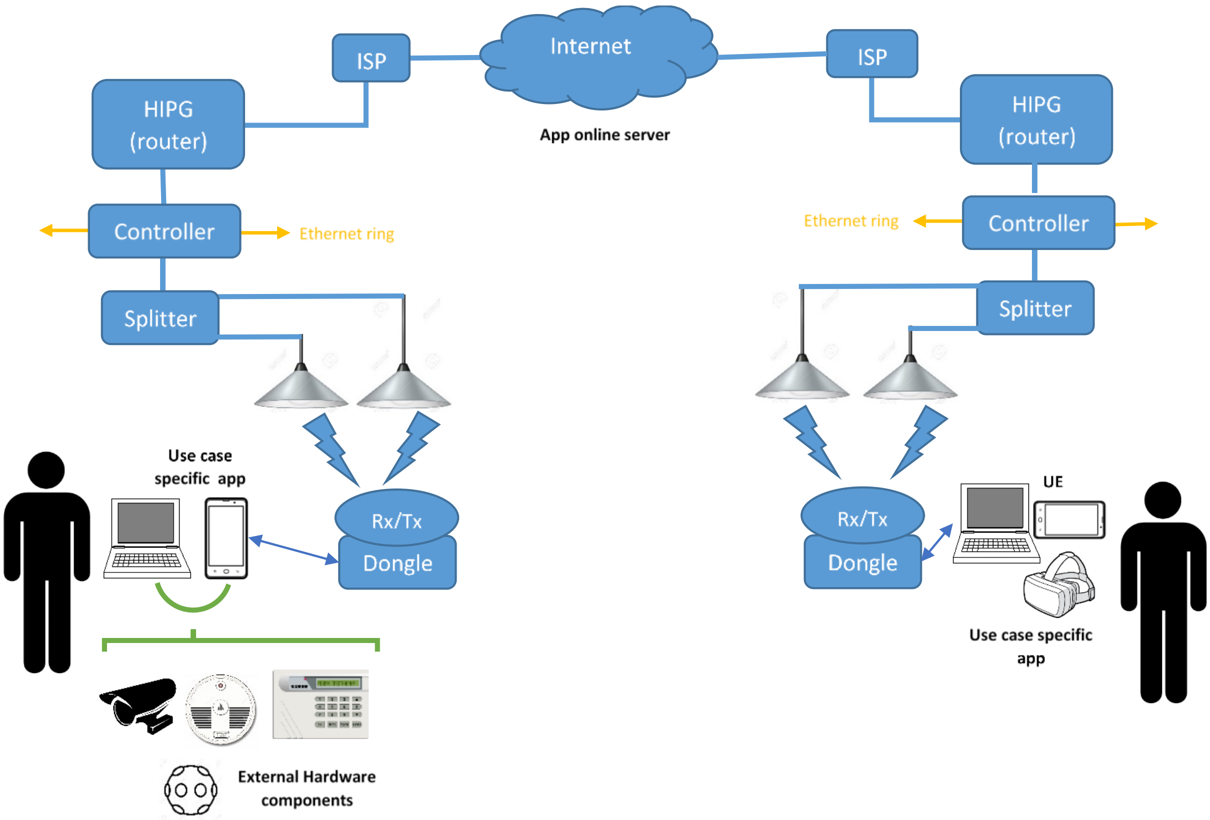


Figure 1

Figure 7-5: General stream structure

Everything in blue represents the IoRL architecture used for streaming data, this remains the same for every use case.

7.2.3 Use case Breakdown

Each use case can be broken down into the six stages.

All systems in terms of hardware beyond the User devices are exactly the same. The RRLH, splitters, controllers, modem, ISP and internet are the main system that bring 5G internet capabilities to the end user devices.

Table 7—2: Use Case Breakdown

Use Case	External devices	User equipment	Application	Streaming online	Application	User equipment
1.3				Routing data to devices		
1.4				Routing data to devices		
1.5	360 Camera (live)	Phone, PC, tablet	360 Live stream app	Streaming application data	360 Live stream app	PC / mobile VR headset
1.6				Streaming application data	Game server	PC / mobile VR headset
1.9	Security camera, Fire alarm, security system	Phone, PC, tablet	Security app	Streaming application data	Security app	Phone, PC, tablet
2.4	360 Camera	Phone, PC, tablet	360 viewing app	Streaming application data	360 viewing app	PC / mobile VR headset
3.2		Phone, PC, tablet (with camera and microphone)	Video call app	Streaming application data	Video call app	Phone, PC, tablet
3.8		Phone, PC, tablet	Display app	Streaming application data	Display app	Phone, PC, tablet, signage
4.4	Nursery camera	PC, tablet	Nursery app	Streaming application data	Nursery app	Phone, PC, tablet
4.5				Streaming application data	Cartoon app	Phone, PC, tablet
4.6		Phone, PC, tablet (with camera and microphone)	Video call app	Streaming application data	Video call app	Phone, PC, tablet
5.2	Camera and microphone	Phone, PC, tablet	Conference presentation app	Streaming application data	Conference presentation app	Phone, PC, tablet
5.4		Phone, PC, tablet	Display app	Streaming application data	Display app	Phone, PC, tablet, signage

7.2.4 Combining use cases and tasks

From **Table 7**—2 it is possible to combine several use cases that appear to highly similar.

Routing data (multi-streaming)- UC1.3 and UC1.4 - Both focus on routing the data through the IoRL network from internet to user devices.

Redirecting data UC1.6 and UC4.5 both use existing online services that must be accessed via the IoRL network. These are very basic level use cases.

Video communication - UC 3.2 and UC4.6 - These involve allowing users to communicate via online conferencing services. This principle can then be applied in a tunnel or in a supermarket.

Displaying content remotely - UC3.8 and UC5.4. Displaying content from an application on another device.

Other use cases can be grouped together as they contain only slight differences.

VR experiences - UC1.5 and UC2.4 - Both cases involve using a 360 camera and VR headset displays.

UC1.5 - 360 data uploaded and displayed in live app

UC2.4 - 360 data uploaded and stored in Virtual tour app

Therefore the differences lie in the application used.

Monitoring services - UC1.9 and UC4.4 - These use cases both involve using external equipment to monitor either a home or a nursery.

UC1.9 - Monitor alarm systems and relay live video to a display

UC4.4 - Relay live video to a display

UC4.4 can be seen as a home monitoring system (UC1.9) without the security and fire alarms

Again the differences lie in the application used. This leaves us with the following table of use cases:

Table 7—3: Use Cases

Use Case	External devices	User equipment	Application	Streaming online	Application	
1.3/ 1.4				Routing data to devices		
1.5 / 2.4	360 Camera (live/not live)	Phone, PC, tablet	360 Live stream app / 360 Tour app	Streaming application data	360 Live stream app/ 360 Tour app	PC / mobile VR headset
1.9 / 4.4	Security/ nursery camera, Fire alarm, security system	Phone, PC, tablet	Security app/ Nursery app (monitoring app)	Streaming application data	Security app / Nursery app (monitoring app)	Phone, PC, tablet
3.2 / 4.6		Phone, PC, tablet (with camera and microphone)	Video call app	Streaming application data	Video call app	Phone, PC, tablet
3.8 / 5.4		Phone, PC, tablet	Display app	Streaming application data	Display app	Phone, PC, tablet, signage
4.5/1.6				Streaming application data	Cartoon app/ gaming server	Phone, PC, tablet
5.2	Camera and microphone	Phone, PC, tablet	Conference presentation app	Streaming application data	Conference presentation app	Phone, PC, tablet

7.2.5 Overview

As the project simply offers an intermediate faster data transmission method there should be no significant changes to how the end users use their devices and beyond the modem. This means each use case should be possible with existing applications that may be modified or taken for reference to meet each scenario specific use case demands.

The prime objectives are to develop compatibility with the IoRL system and any external user equipment as well as develop or find apps that meet the requirements of each use case.

7.3 Indoor Location Based Data Access

The following has four combined scenarios (2.3, 3.4, 4.3, 5.1) that are based the ILBDA. They are related to each other and can be done by one application.

A location-based system would allow for the Museum to deliver data related to an artefact. For a supermarket it would allow data to be delivered related to what is immediately in front of a shopper on the shelves. For a train it would allow data to be delivered to a traveller on entry to a station or a platform. For a conference it would allow the user to obtain the agenda and proceedings on entry to the conference lobby. For homes it will allow selective control of lights and sensors depending on who is in the room.

Indoor location-based data access (ILBDA), combines four different scenarios, where all can be implemented in a one unique application with different functionalities, as shown in **Figure 7-6**.

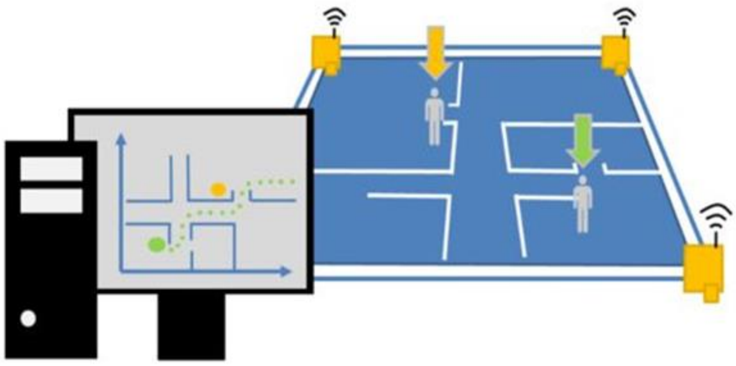


Figure 7-6: ILBDA

The museum would be able to detect when people are in a vicinity of a VLC RRLH and that would allow them to track their location. The tunnel station would be able to keep a record of all the IP addresses of passengers that have bought tickets on line and when they are detected in the railway tunnel environment downloads all information that they might require such as a map with directions to their platform, places where they could relax whilst waiting for their train to arrive etc. Additionally, the supermarket would have an internet page that is associated to VLC light access point that will be downloaded to shoppers' Tablet PCs when they are in the vicinity of the VLC RRLH. Finally, the conference room would have an announcement app that allows conference organisers to make announcements to speakers and delegates.

User Interface (services and products)

The user interface should be easily accessible, simple and user friendly.

Products: Tablet PCs, Smart Phones

- **Super Market (Shopper)** needs a Barcode Decoder.
- **Conference Organizers** need digital signs.

Services: Application, Database, Multi stream server, Seat occupancy sensing, Location based information, Proceedings access, Conference server.

The services information above includes are the services offered by all the scenarios combined but it doesn't mean that all of them will offer the same services as for example seat occupancy sensing is only needed for the tunnel scenario and will never be used in any other scenario.

Use Case Diagram

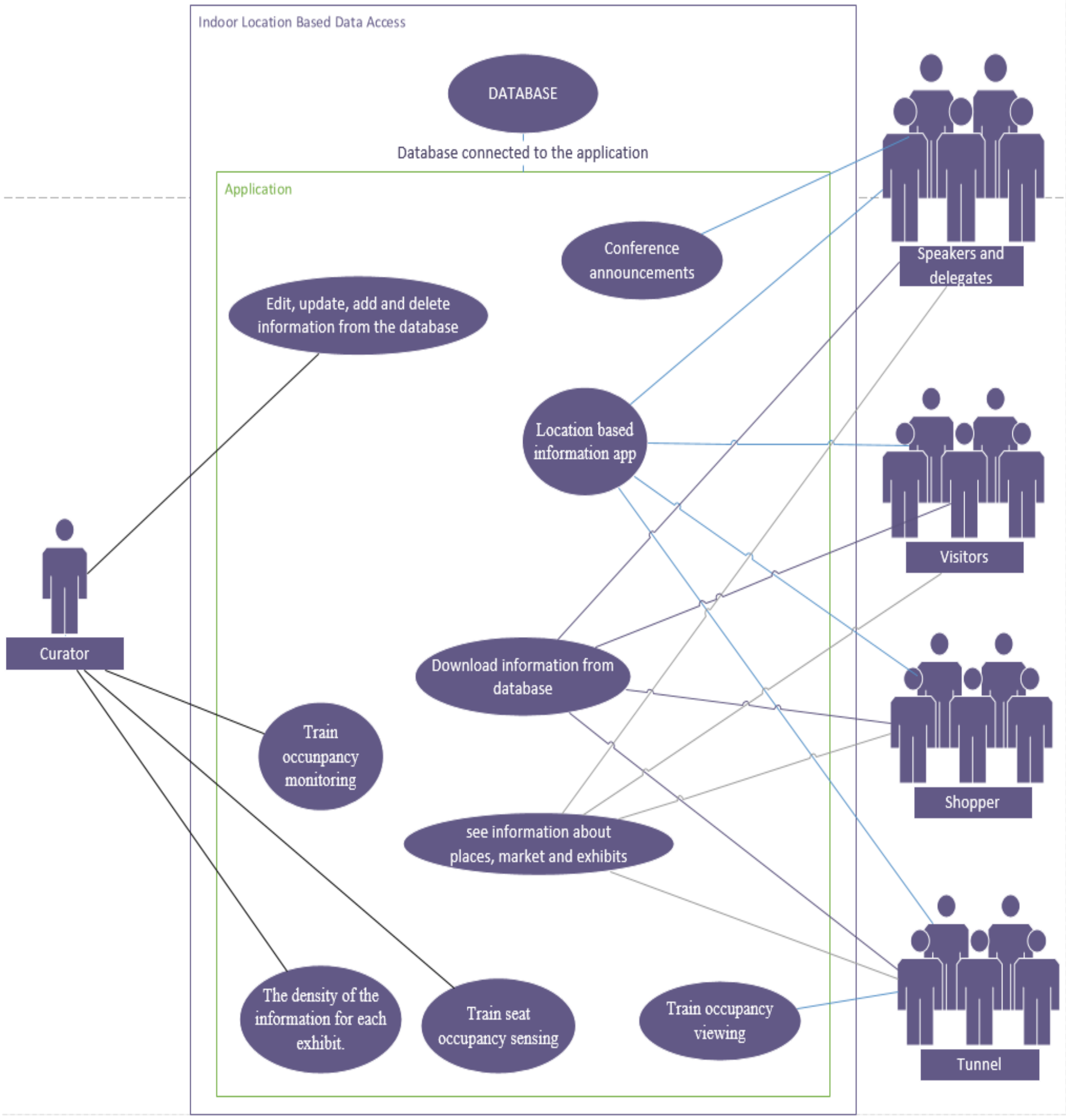


Figure 7-7: Use case diagram for indoor location-based data access

7.4 Indoor Location Monitoring and Guiding

The following document has three combined scenarios (2.3, 3.1, 4.2) that are based the ILMAG. They are related to each other and can be done by one application.

Monitoring Applications

Indoor location monitoring would allow the museum to record the behaviour of the visitors. This in turn will benefit with the below scenarios.

- *The visitor's path through the museum.*
- *The amount of time each visitor spent at each exhibit.*
- *The most visited exhibit by visitors.*
- *The density of visitors in the museum at any one time.*

In addition, it would allow the services manager in the control office to monitor and locate the maintenance workers that are performing activities in the tunnel.

Guiding Applications

Indoor location guiding would allow the visitors with a floor plan to navigate their way around easily. For the tunnel, it will allow to guide the maintenance staff to the specific location of the maintenance activity that's taking place. It would allow the shopper at the supermarket to find the relevant route to the products according to their own shopping list.

Indoor location monitoring and guiding (ILMAG), combines the three different scenarios, where all can be implemented by providing a guide and a floor plan assist the users, as shown in **Figure 7-8** and **Figure 7-9.**

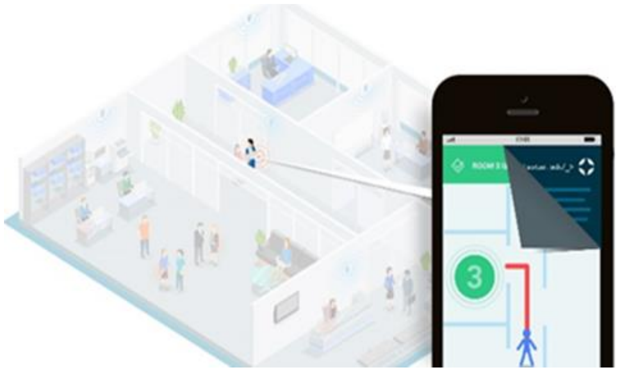


Figure 7-8: Indoor Location Monitoring

The museum would use the application with the floor plan on the visitor's electronic device (tablet, phone) that records their behavior and feedbacks the data to the database. The tunnel station would have control application of map of building coverage area with locations and identities of specified set of users within the building; using the SDN tracking to obtain the location. Additionally, to be able to have a conference call Co-working (e.g. Webex) of various types of data to maintenance workers.

Figure 7-9: Indoor Location Guiding

The museum would be able to use the application to guide visitors to needed destination. The tunnel station would be allowed to guide the maintenance workers to a specific location, where maintenance need to take place. The supermarket would have a Smart Shopping Cart server that imports a shopping list from a customer's smart phone to guide shopper through store. A Learning curve per customer which allows route calculation and suggests relevant product content (promotions, reviews and feedbacks).SSC can compare using SSC-mobile connection prices with other supermarkets in the area.

User Interface (services and products)

The user interface should be easily accessible, simple and user friendly.

Products: Tablet PCs, Smart Phones

Services:

- **Museum**
  - *UI for Management*
    - Update the exhibition's location.
    - *See live information about the visitors.*
      - The visitor's path through the museum.
      - The amount of time each visitor spent at each exhibit.
      - The most visited exhibit by visitors.
      - The density of visitors in the museum at any one time.
  - *UI for Visitors*
    - Full Floor plan.
    - Directions around the museum.
    - Find the most visited exhibits.
- **Tunnel**
  - *Services for Management*
    - *The provided services for the Management*
      - Location based staff analysis
      - Conference co-working communications
  - *Services for Maintenance working staff*
    - Smartphone
      - Streaming video app (You Tube).
      - Multiple source streaming viewer app

- **Super Market**
  - *Services for Shop Management*
    - *The provided services for the Management*
      - Smart shopping cart server.
      - In store guidance routing service; promotions reviews, recipes and other suggestions service; stock status and alternative foods service.
  - *Services for Shopper*
    - Smartphone
      - Smart shopping cart app.
      - In store guidance routing service; promotions reviews, recipes and other suggestions service; stock status and alternative foods service.

7.4.1 Use Case Diagram

This is the use case diagram for all the above scenarios.

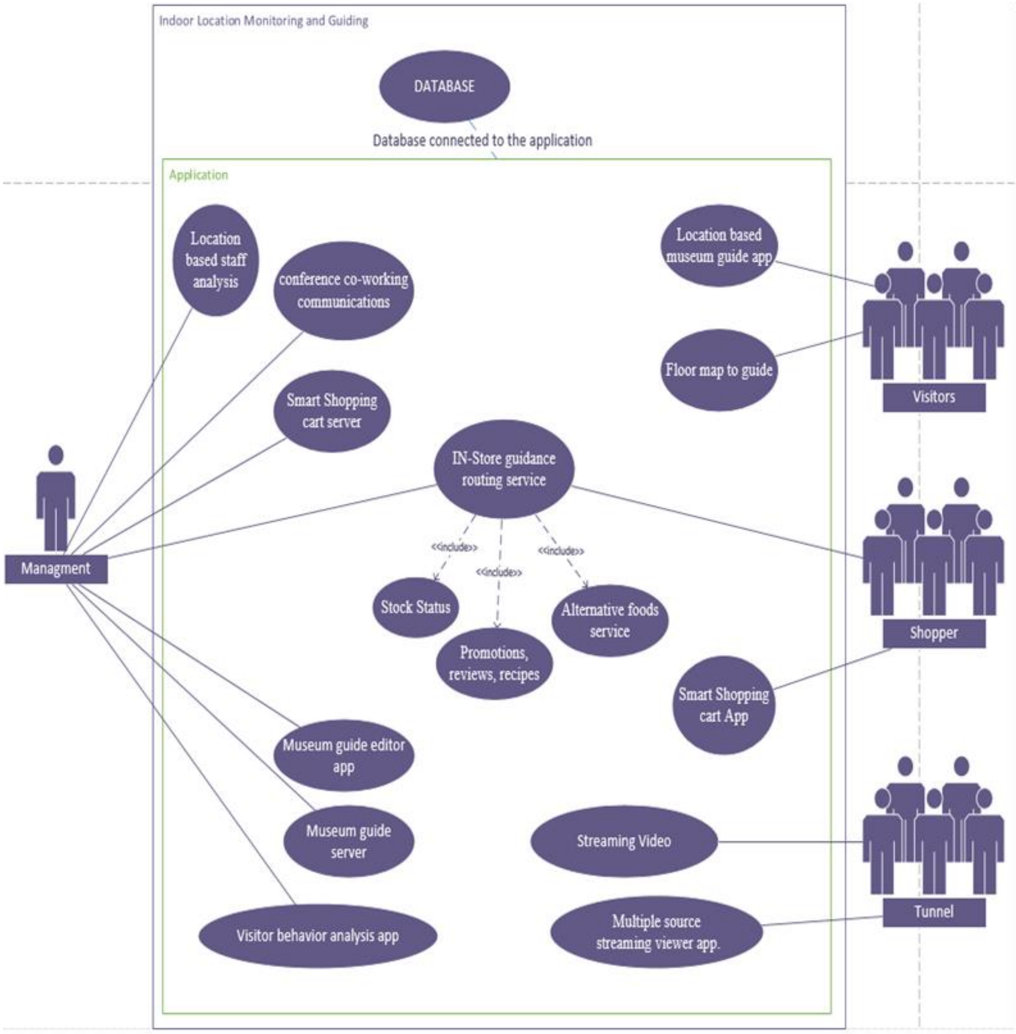


Figure 7-10: Use case diagram for indoor location monitoring and guiding

7.5 Interaction

The following document has three combined scenarios (2.1, 4.1, 5.3)

Interaction would allow the children to play a game “Treasure Hunt” inside the museum, where it provides the children with clues to locate a picture within the museum. The supermarket would provide the customers with an application through a secure IoRL link “Smart Shopping Cart” (SSC), that allows them to prepare the shopping list and find relevant products. In the conference room, the application would allow the delegates to discuss questions and answers, as well as, rating the speakers and the conference.

Interaction includes three different scenarios, where all can be implemented based on the interactions of each of the user, as shown in **Figure 7-11**.

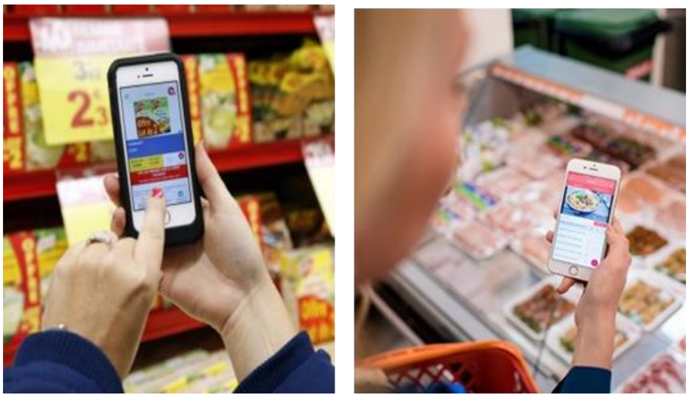


Figure 7-11: Interaction

The children in the museum would be able to upload photos to the database for the treasure hunt game. The supermarket would provide a shopping list app that allows customer to compile a shopping list on his/her smart phone. The conference room would have an application that allows the delegates to communicate with each other, allow delegates to rate speakers and allow delegates and speakers to rate the conference.

User Interface (services and products)

The user interface should be easily accessible, simple and user friendly.

Products: Tablet PCs, Smart Phones

Services: Shopping list creation application, Treasure Hunt Game Master Application, database for game, supermarket online shopping product server, conference server, conference application.

As shown above in the services part all three scenarios need an application and a (database/server).

7.5.1 Use Case Diagram

This is the use case diagram for all the above scenarios.

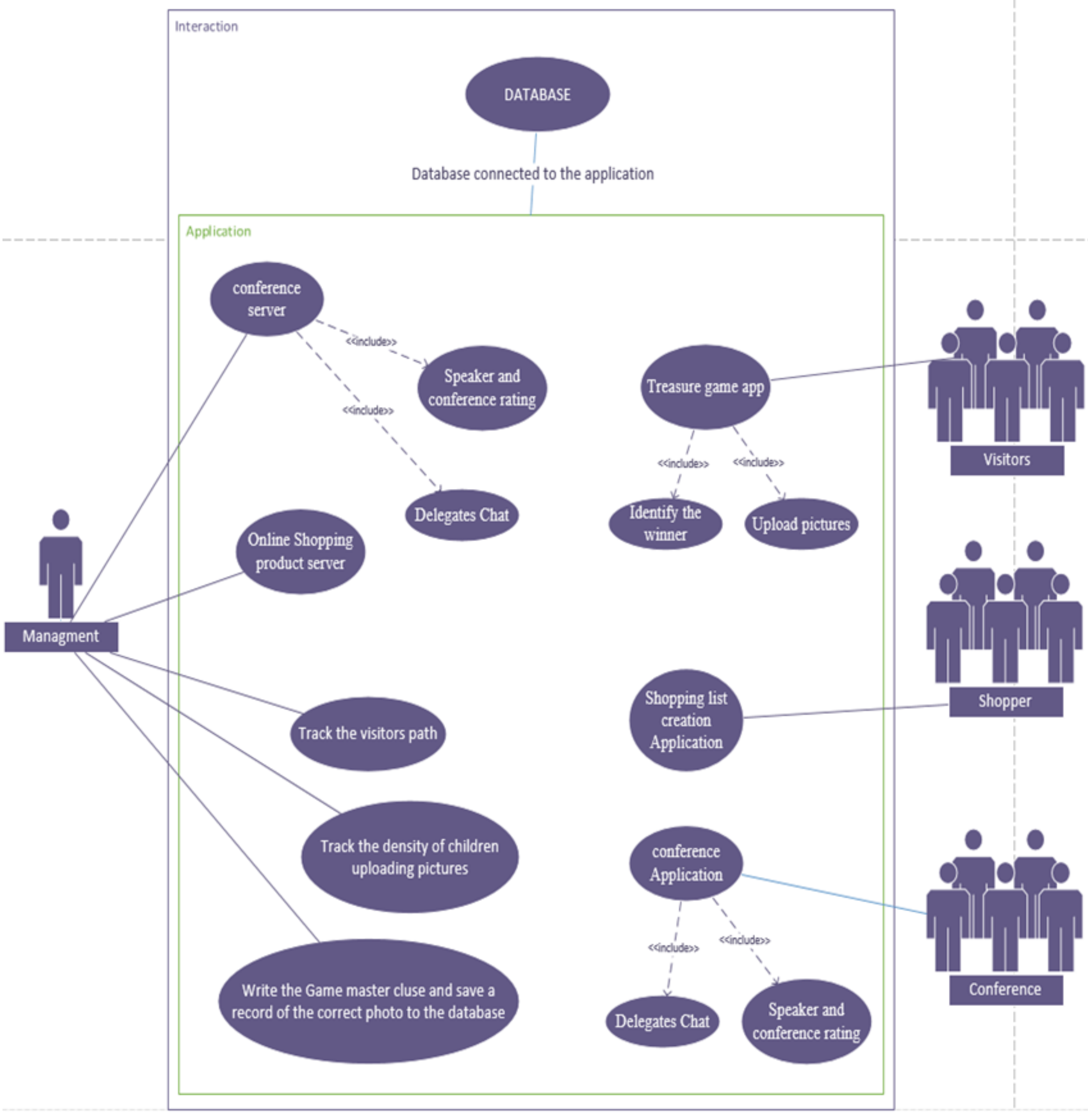


Figure 7-12: Use case diagram for interaction

Development Steps for (ILBDA, ILMAG, INTERACTION)

The application is being created and developed to not only meet the scenarios requirements but also to be user friendly. This will be a multi-function application, that it simplifies all the different scenarios into a single application. The report will be discussing the ILBDA, ILMAG and interaction in details and their development steps. The application development process will need Backend (SQL), Frontend (Android App) and to connect the API to the SQL. However, for the API to be established there should be an inter-connection connecting the backend with the frontend together.

8 Position sensing architecture

As the specification for 5GNR for positioning is not completed, we might use LTE positioning signal for position sensing. The following paragraph only serves reference for IoRL's potential positioning sensing solution when 5GNR positioning specification is not ready.

The supported positioning methods in LTE rely on the high-level network architecture shown in **Figure 8-1**. As one of the design goals for LTE was to decentralize everything, the network architecture has been defined in that way, that it is generally independent from the underlying network. There are three main elements involved in the process, the Location Service Client (LCS), the LCS Server (LS) and the LCS Target. A client, means the requesting service, is in the majority of the cases installed or available on the LCS target. This service obtains the location information by sending a request to the server. The location server is a physical or logical entity that collects measurements and other location information from the device and base station and assists the device with measurements and estimating its position. The server basically processes the request from the client and provides the client with the requested information and optionally with velocity information.

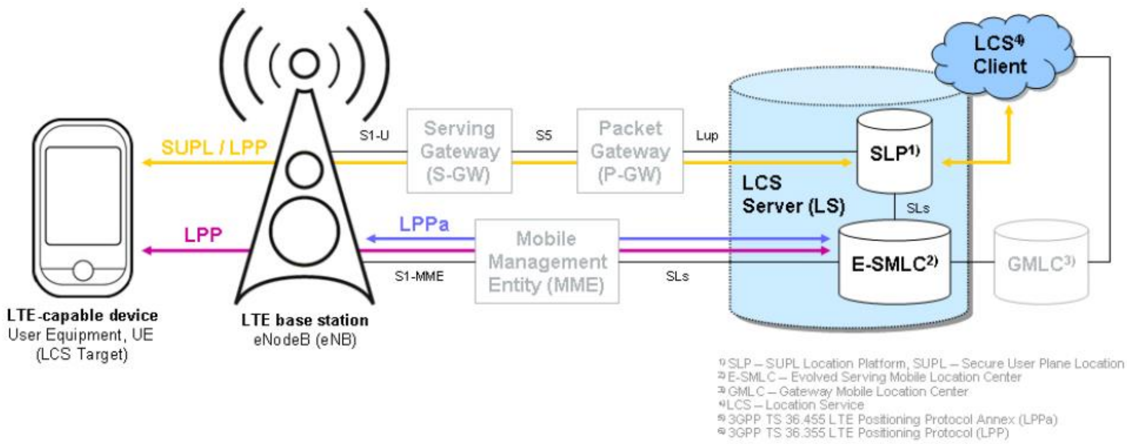


Figure 8-1: Positioning protocol[3]

In LTE Positioning Reference Signals (PRS) have been introduced for antenna port 6 for positioning. It is a pseudo-random QPSK sequence that is being mapped in diagonal patterns with shifts in frequency and time to avoid collision with cell-specific reference signals and an overlap with the control channels (PDCCH). PRS are defined by bandwidth (N_{RB}^{PRS}), offset (Δ_{PRS}), duration (N_{PRS}= number of consecutive subframes) and periodicity (T_{PRS}). It's worth noting, that PRS bandwidth is always smaller than the actual system bandwidth (N_{RB}^{DL}). PRS are always mapped around the carrier frequency, the unused DC subcarrier in the downlink. In a subframe where PRS are configured, typically no PDSCH is transmitted

[3] LTE Location Based Services Technology Introduction White Paper, Mike Thorpe, and al., ROHDE&SHWARZ April 2013

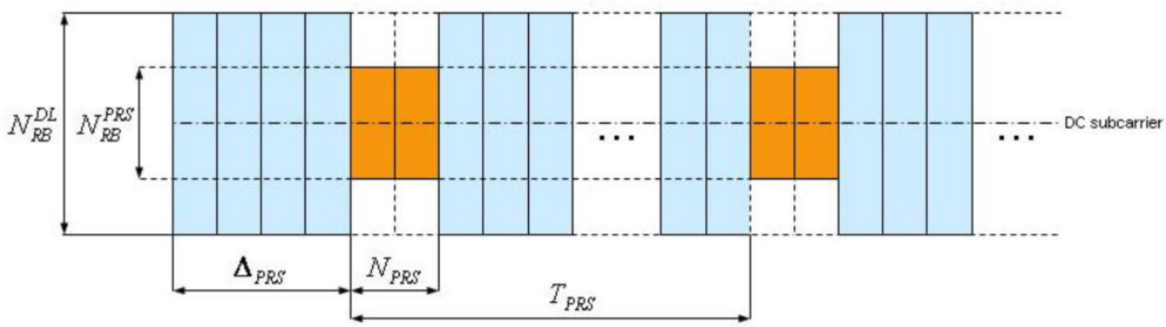


Figure 8-2: PRS in Positioning protocol[4]

PRS can be muted on certain occasions to further reduce inter-cell interference. All this information, means PRS configuration and PRS muting is provided via the LPP protocol from the Location Server.

From the LTE UE side, the following measurements can be used for position: Timing Advance (TDAV), Round Trip Time (RTT), Angle-of-Arrival (AoA) and Observed Time Difference of Arrival (OTDOA).

With 3GPP Release 9 the timing advance measurement has been enhanced, so that there are now a Type 1 and a Type 2 measurement. The Type 2 measurement relies on the timing advance estimated from receiving a PRACH preamble during the random-access procedure. Type 1 is defined as the sum of the receive-transmit timing difference at the eNB (positive or negative value) and the receive-transmit timing difference at the terminal (always a positive value). The base station measures first its own timing difference and reports to the device to correct its uplink timing per Timing Advance (TA) command, a MAC feature. The UE measures and reports its receive-transmit timing difference as well. Both timing differences allow the calculation of the Timing Advance Type 1, corresponding to the Round Trip Time (RTT).

The eNB can usually estimate this angle on any part of the uplink transmission, however typically Sounding Reference Signals are used for this purpose. But the Demodulation Reference Signals (DM-RS) also provide sufficient coverage. In addition, the antenna array configuration has a key impact to the AoA measurements. Basically, the larger the array, the higher the accuracy. With a linear array of equally spaced antenna elements, the received signal at any adjacent elements is phase-rotated by a fixed amount THETA. And the value for THETA is a function of the AoA, as well as the antenna element spacing and carrier frequency.

OTDOA is the positioning solution of choice when GNSS signals cannot be used due to a lack of a clear line of sight. OTDOA uses neighbor cells (eNB's) to derive an observed time difference of arrival relative to the serving cell. Current solutions are based on both Inter-Band and Intra-Band eNB measurements. With future network deployments of LTE Advanced Carrier Aggregation (LTE-A CA), OTDOA can be further extended to measurements of LTE-A Component Carriers (CC's).

[4] LTE Location Based Services Technology Introduction White Paper, Mike Thorpe, and al., ROHDE&SHWARZ April 2013

The measurement of (OTDOA) taken between a pair of eNB's is defined as Reference Signal Time Difference (RSTD) [5]. The measurement is defined as the relative timing difference between a subframe received from the neighboring cell j and corresponding subframe from the serving cell i. These measurements are taken on the Positioning Reference Signals, the results are reported back to the location server, where the calculation of the position happens. In the case of Hybrid Mode these RSTD measurements can be combined with GNSS measurement to calculate the position of the device.

8.1 System functional requirements for position sensing architecture

Positioning information exchange between RRLH controllers and the CHDCS must be enabled by an appropriate positioning protocol. We will refer to it as the IoRL positioning protocol (IPP). The main functions of the IPP have to be:

- Notification of CHDCS about the positioning capabilities of RRLH controllers (VLC, mmWs, GNNS, which kind of measurements, etc.),
- Transport of assistance data from between CHDCS and RRLH controllers like co-ordinate positions of RRLHs,
- Transport of measured data.
- Report possible errors during the positioning and
- Support hybrid positioning with VLC and mmW based location sensing or even fusion with GNSS base localization if GNSS are available at RRLH controllers.

8.2 Position sensing architecture and algorithm for mmW

The positioning system based on mmWs uses electromagnetic waves to determine the location of UEs. The location relevant parameters can be basically estimated either at UE (in the downlink) or at the RRLH controller (in the uplink).

In the uplink case, the UE is a transmitter. Multiple lamps (RRLHs) located at a priori known positions receive a signal transmitted from the UE. The RRLH controller performs measurements and estimates location relevant signal parameters such as the received signal strength (RSS), round-trip times (RTTs), or the time-difference of arrival (TDOA) between different RRLHs. The time offsets caused by different cable length between mmW antennas of each RRLH and the RRL controller must be a priori known to allow proper estimation of TDOAs and RTTs. In order to estimate RTT, the RRLH controller must transmit a signal over a particular RRLH and the UE must respond to it by transmission of localization signal. The response time of the UE must be a priori known at the RRLH controller for the proper estimation of the RTT in the uplink. The RTT estimation has to be performed successively for each RRLH.

In the downlink case, the UE is a receiver. Multiple lamps (RRLHs) located at a priori known positions transmit signals towards the UE. The UE performs measurements and estimates location relevant signal parameters for each of transmitted signals from RRLHs. The controller must generate orthogonal (time, frequency and/or code) signals that will be simultaneously received by the UE. The UE needs to estimate TOAs for each RRLH signal and compute TDOAs. As well as in the uplink, the time offsets caused by different cable length between mmW antennas of each RRLH and the RRL controller must be a priori known to allow proper estimation of TDOAs and RTTs. In order to estimate RTT in the downlink, the UE must transmit a signal which is received by multiple RRLHs connected to the RRLH controller.

The RRLH controller responds to UE using orthogonal signals over multiple RRLHs. The response time of the RRLH must be a priori known at the RRLH controller for each RRLH which is connected to it. The UE is estimating TOAs for each RRLH signal and computes corresponding RTTs.

In both, the uplink and the downlink case, the estimated parameters are communicated to the CHDCS (Cloud home data control server) which location related service calculates locations of UEs. The position sensing architecture is illustrated in **Figure 8-3**. In this example 3 UEs are communicating with 2 RRLH controllers using mmW signals over 6 RRLHs. The RRLH controllers or UEs estimate corresponding RTTs, TDOAS or RSS and transfer the estimates to the CHDCS. The localization service at CHDCS computes positions of UEs from the a priori know positions of RRLHs and estimated signal parameters.

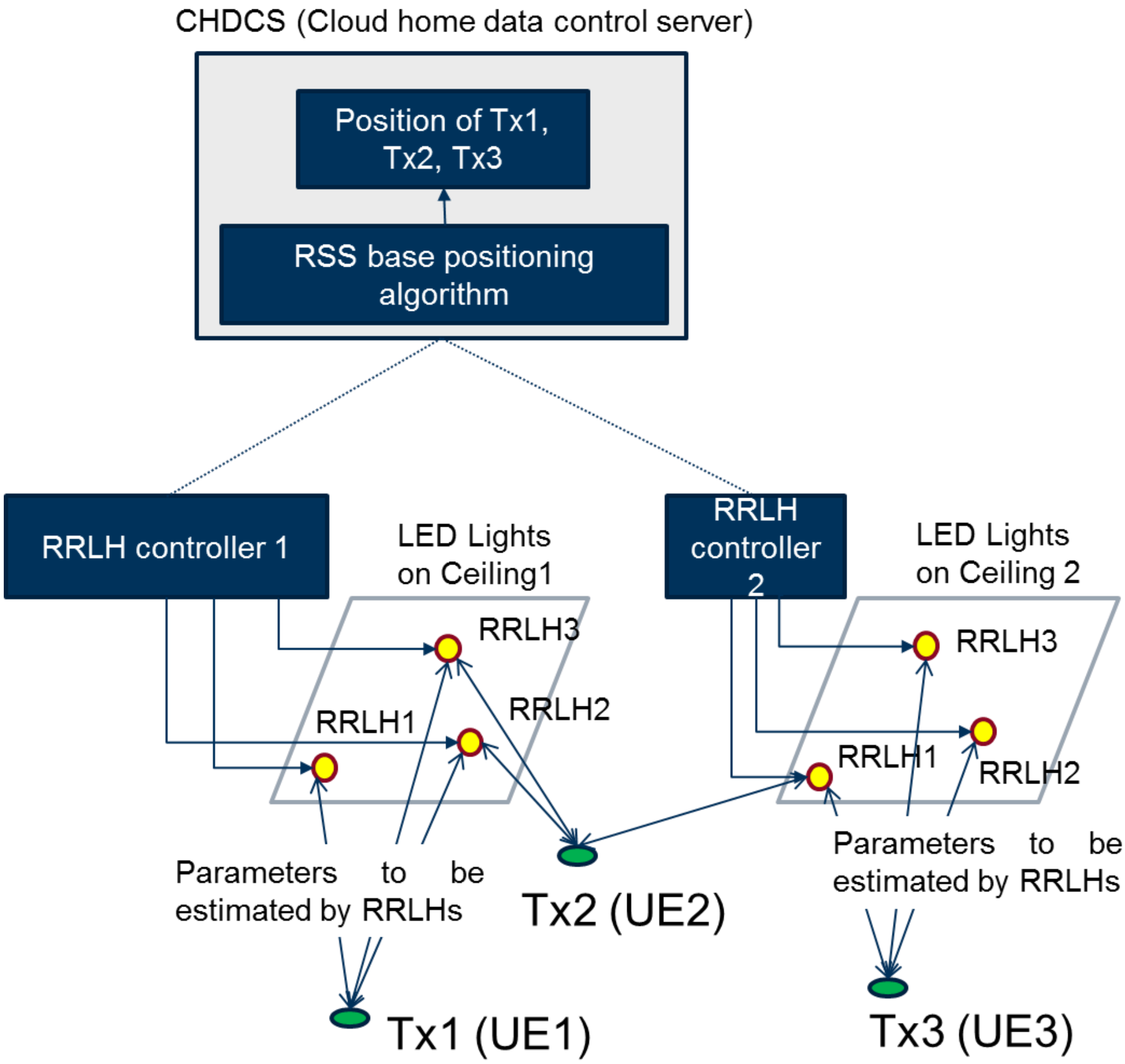


Figure 8-3: Example of the position sensing architecture for mmWs

The precision of location estimation is basically given by the:

- bandwidth of signals that are used for positioning,
- the radio environment (multipath, fading),

- geometry of the scenario (GDOP - Geometrical Dilution of Precision)
- RRLH synchronization
- 3D-coordinates of RRLHs and
- Network planning influencing interference among multiple UEs and RRLHs.

It is expected that the due to the large frequency bandwidth of bands that were deregulated for 5G communication systems the RTT and the TDOA based localization will outperform the RSS based localization which does not exploit benefits of mmW signals with their available bandwidth. Majority of mmW frequency bands that are deregulated by FCC for 5G communication systems such as 37-38.6 GHz, 38.6-40 or 64-71 GHz have an absolute bandwidth covering couple of GHz. The FCC/ECC license free 60GHz WLAN ISM band (57-66GHz) and the related standard 802.11ay exploit an absolute bandwidth even much larger. It can simultaneously span 8 GHz. Such frequency bands can provide excellent time resolution which may result in sub-decimeter localization accuracy. This accuracy corresponds to the vision suggested for 5G networks [15], [16] and clearly outperforms accuracy of the commercial global navigation satellite system with its outdoor accuracy of about 5 meters, or the accuracy of indoor wireless local area network fingerprinting techniques which is about 3-4 meters [15].

Even the above described deregulated frequency bands offer very large absolute bandwidth the communication devices (UE and RRLHs HW) must also support such a large bandwidth for RTT, or TDOA measurements. If RTT and TDOA are estimated by a conventional estimator and not by a model based high resolution estimators, then the achievable precision is basically given by the available bandwidth. Achievable precisions according to the available bandwidth are e.g. ~1.9cm @ 8GHz bandwidth (already supported by 802.11ay technical standard for wireless networks using bonding of 4 channels), ~7.5cm @ 2GHz (already supported by 802.11ad technical standard for wireless networks), ~75cm @ 200MHz, ~1.5m @ 100MHz and ~7.5m @ 20MHz (available for LTE localization). Thus, in order to reach sub-decimeter precision, the UE and the RTLH must exploit localization signals which have at least about 2 GHz of bandwidth.

The large bandwidth is not the only feature which influences the precision of the location estimation. The IoRL system must also use appropriate geometrical distribution of RRLHs that results in a good GDOP, the RRLHs must be properly synchronized, their 3D coordinates must be known a priori with accuracy that is high enough and the network planning must reduce possible interference among multiple UEs and RRLHs. Examples on how these parameters influence the precision of location sensing in LTE communication networks are given e.g. in [17].

The TDOA technique in the downlink is basically similar to the LTE positioning technology standardized in the 3GPP Release 9, or to the GNSS positioning calculation methodology. The uplink localization is just a reversed scenario, but the computation of UE positions is basically the same and it is based on TOA measurements either at RRLH controller (the uplink localization) or at UE (the downlink localization). These measurements are related to geometrical positions of UEs and RRLHs. In comparison to the LTE positioning, the location estimation in IoRL scenarios must be performed in 3-D Cartesian coordinate system and not in 2-D. This is mainly due to the indoor scenario and expected precision of the positioning. Indoor scenarios feature much smaller distances among RRLHs and UE in comparison to LTE outdoor scenarios. Due this and the expected precision of about 10cm, the height cannot be neglected. The TDOA measurement between the *i*-th and *j*-th RRLHs can be described as

$$TDOA_{i,j} = \frac{\sqrt{(x_{UE}-x_i)^2+(y_{UE}-y_i)^2+(z_{UE}-z_i)^2}}{c} - \frac{\sqrt{(x_{UE}-x_j)^2+(y_{UE}-y_j)^2+(z_{UE}-z_j)^2}}{c} + (n_i - n_j)$$

where $[x_{UE}, y_{UE}, z_{UE}]$ are the unknown 3-D Cartesian coordinates of the UE that shall be localized, $[x_i, y_j, z_j]$ are the a priori known coordinates of the *j*-th RRLH, c is the speed of light and n_j are the measurement errors due to the imperfect system calibration (cable length between RRLH and RRLH controller), synchronization errors, etc. Similarly, to the GNSS base 3-D positioning, at least 4 RRLHs are required to estimate 3-D coordinates of UE. Such a system of equations can be solved e.g. by linearization based on Taylor series.

8.3 Position sensing architecture and algorithm for VLC

8.3.1 Position sensing architecture for VLC

In 5G, a highly accurate localization from 10 m to less than 1m on 80% occasions, and better than 1m for indoor is reported [1] through millimeter wave (mmW) at the expense of a high cost deployment. 5G - IoRL will provide a high accuracy location service by using low cost VLC - based indoor localization technologies. VLC location system holds potential to overcome the position's instability inherent to wireless channel thanks to the most multipath - free propagation brought by VLC. It can achieve decimeter to centimeter precision, using specialized “beaconing LEDs” as landmarks [2]. However, this digital ID beaconing cannot be modified after its placement. 5G - IoRL project proposes to use the orthogonal frequency division multiplexing access (OFDMA) scheme, in which part of the subcarriers will be used for indoor positioning and where pilot tones will be at different frequencies for different LEDs. Contrary to classical “beaconing LEDs”, the proposed system will be able to get receiver's accurate position as well as providing data for communication. The position sensing architecture is shown below:

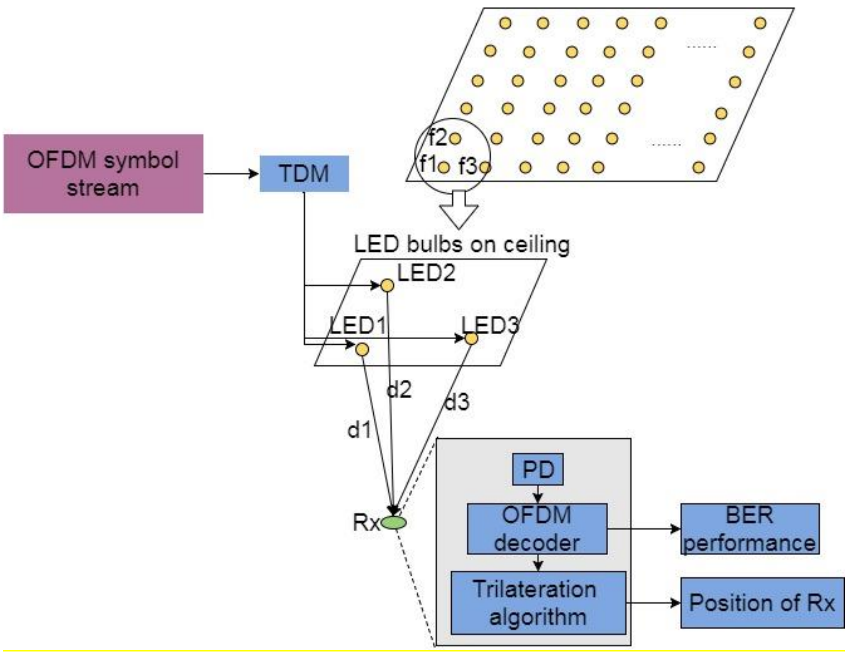


Figure 8-4: VLC Positioning Structure

The data signal transmitted by LEDs is encoded with allocated subcarrier, respectively and the User Equipment (UE) can received all transmitted data signals. Minimum three LEDs with respect to three subcarriers are selected for VLC indoor position estimation. We assume that K LEDs are distributed on the ceiling. To achieve the correct information acquisition objectives, transmitted signals from LEDs are encoded with dedicated subcarrier frequencies fi, where i = 1, 2, 3, …, K. K subcarriers are used for indoor position estimation and N-K subcarriers are used for data transmission, as shown in the figure below:

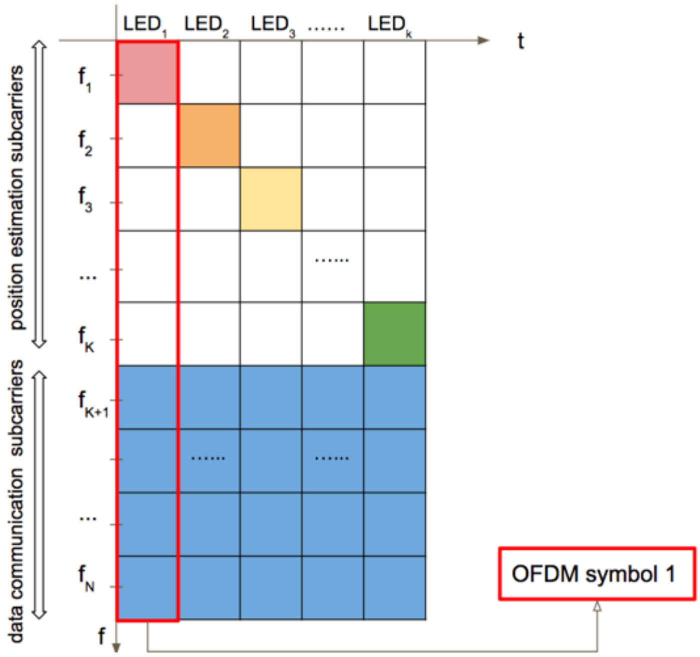


Figure 8-5: VLC Positioning OFDM Frame

In time domain, the each OFDM symbol only carries one position information of the corresponding LED and the common transmitted data. One received signal in time domain for 3 LEDs is shown in the Figure 8-6.

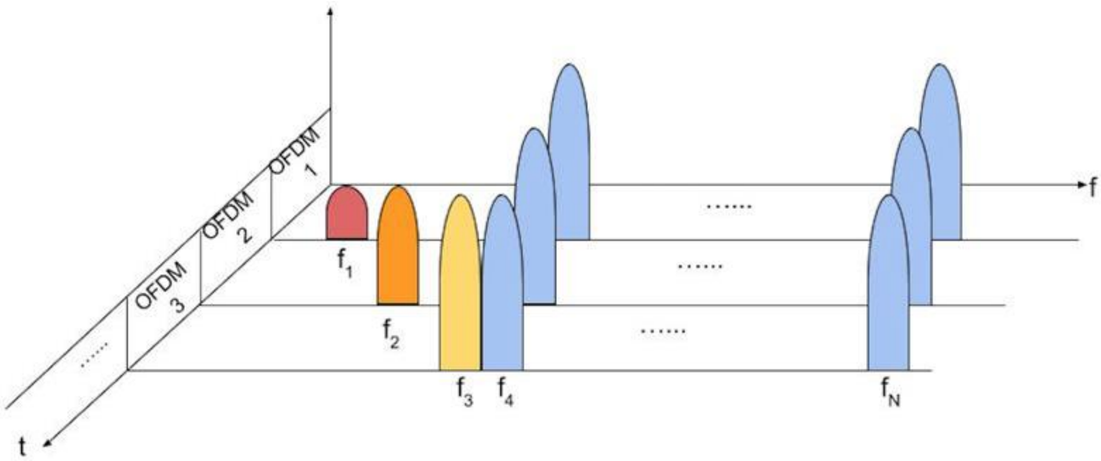


Figure 8-6: The received signal intensity

In practice, the continuous pilot for VLC positioning is not necessary. The pilot insertion for VLC position could be done every 23.4ms about one in every 100 RBs. This can be made programable. In order to save bandwidth and because users are not moving quickly, the scattered pilots every 23.4ms are enough for the positioning to get a high accurate localization information before the movement of the user. The location accuracy depends on the lighting intensity.

For receiver terminal, the UE according to their own location selects the three subcarriers with the maximum received signal intensity as reference nodes to calculate the positioning information. The value of intensity is depending on distance between the transmitters and receiver.

For i-th LED, the signal can be expressed as:

$$S_{LED_i} = Acos(2\pi i\Delta ft + \alpha_i)$$

Where, A is the amplitude of the transmitted signal of i-th LED, Δf is the frequency spacing of adjacent subcarriers, and α_i is the phase of modulated signal of the i-th LED. More details about VLC position sensing testbed and algorithm are descripted in the next section.

8.3.2 IoRL Position sensing existing testbed for VLC

At the early step, an indoor position estimation testbed for VLC is built in LabVIEW for two objectives: to evaluation positioning algorithm performance and to build a correlation method for evaluating positioning accuracy with positioning system for mmW.

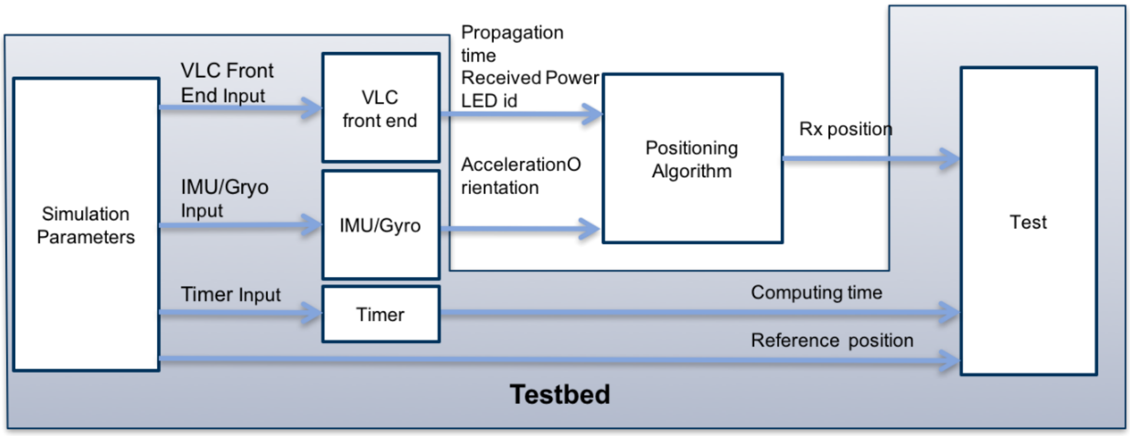


Figure 8-7: VLC Positioning Testbed

This testbed includes five parts: 1. Simulation parameters part stores all the parameters required for simulation, like transmitter/receiver properties, channel model properties, ambient light and Photodiode noise and so on. 2. VLC frontend presents TX and RX of VLC system and also LOS channel. 3. IMU/Database provides additional information for positioning algorithm like mmW positioning results or others environment information. 4. In the positioning algorithm module, the positioning calculation for VLC will be achieved. The algorithms RSS is used in default in this part, but is could be replaced by other algorithms. 5. A performance evaluation module will be placed at the end of this system, which calculates the positioning error (the difference between the estimated position and real-time measured one).

This position estimation system is based on the triangulation method, and it needs to achieve the distance or angle such received signal strength (RSS)[3], time of arrival (TOA), time difference of arrival (TDOA)[4], and angle of arrival (AOA)[5]. The TOA and TDOA require high synchronization between transmitter and receiver and thus is difficult to employ in practical applications [6]. AOA technology ca achieve high accuracy, but it needs a sensor arrays which is very expensive for the system conception. The RSS based method can get the distance between transmitter and receiver by the strength of lighting signal easily. A successful case has been presented in [7] by Aminikashani and al where four modulated LEDs as signal transmitter, and estimated distance between transmitter and receiver by the different receiver lighting power. According to Lambertian radiation model [8], the channel gain between the LED and the detector can be show as:

$$H(0) = \frac{(m+1)Acos^m(\varphi)\cos(\theta)}{2\pi d^2}$$

Where φ is the radiation angle between the LED and the receiver, d is the distance between the LED and the receiver, A is the effective area of the receiver, and θ is the angle of light incident to the receiving surface of the detector. $\varphi_{1/2}$ is the half power angle of LED, and m is the order of Lambertian emission, which is relative to the semi-angle at half power of the LED: $m = \frac{-ln2}{\ln(\cos(\varphi_{1/2}))}$. The received power P of the receiver can be shown as:

$$\mathrm{P} = P_0 \frac{(m+1)Acos^m(\varphi)\cos(\theta)}{2\pi d^2} = P_0 \frac{(m+1)Ah^{m+1}}{2\pi d^{(m+3)}}$$

Where P_0 is the light power of LED. And h is the vertical distance between the receiver and the LED transmitter. The distance from the receiver to one LED transmitter (LED1) can be illustrated as:

$$d_{LED1} \rightarrow Rx = (m+3)\sqrt{(\frac{(m+1)Ah^{(m+1)}}{2\pi})\frac{P_0}{P_1}}$$

Where h is a known constant. Similarly, the distance from the receiver to LED1 or LED2 can also be expressed obtained. Based on this calculation, the projection distance $r_1, r_2, and\ r_3$ between LEDs and receiver can be expressed as:

$$r_1 = \sqrt{d_1^2 - h_1^2}$$

Meanwhile, the distance between each LED transmitter and the receiver can be obtained. The position coordinate (x, y) of receiver can be calculated as follows:

$$\{(x - x_1)^2 + (y - y_1)^2 = r_1^2 (x - x_2)^2 + (y - y_2)^2 = r_2^2 (x - x_3)^2 + (y - y_3)^2 = r_3^2\}$$

Where, $(x_1, y_1), (x_2, y_2), and\ (x_3, y_3)$ are the coordinated of the LEDs transmitter.

Here the RSS based positioning method has been shown via equations (3) to (5), which can solve the location of receiver with the received power of each LED. To set that d_1, d_2, $d_3, \ldots$, d_N is the distance between the receiver and different LED transmitter, which can be obtained from equation $\eqref{3}$. To divide d_1 by d_N, we can get

$$\frac{d_1}{d_N} = (m+3)\sqrt{\frac{P_1}{P_N}}$$

The relative distance of the receiver can be obtained by measuring the intensity of different LED light values received by receiver.

8.3.3 IoRL VLC indoor positioning process Procedure

Figure 8-8 illustrates the IoRL VLC indoor positioning process procedure. UE sends position requirement to RRLH, then the RRLH upload it to the server and the server immediately activates our TDM module to let RRLH transmit different OFDM symbols in different time slots in which the LEDs position information and the transmitted data signals are added to these OFDM symbols.

Once the data is finished transmitting. UE extracts the positioning information and then sends them back to the RRLH then RRLH upload them to server via UDP protocol. After that, server will give an order to RRLH for deactivating. The upload trajectory and location database are presented in the next section.

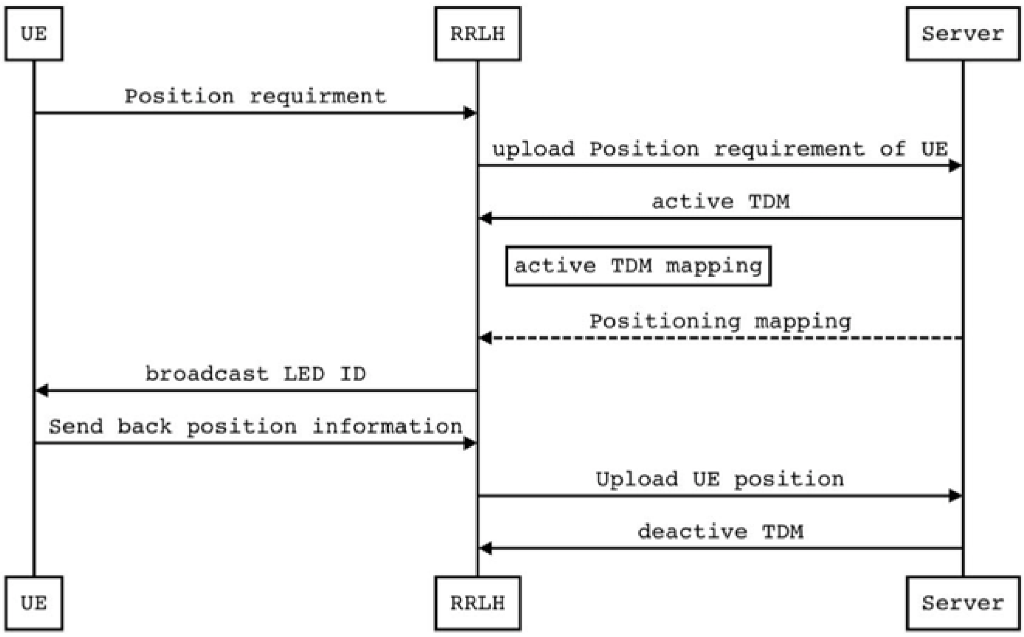


Figure 8-8: IoRL VLC indoor positioning process Procedure

8.4 Location database in SDN

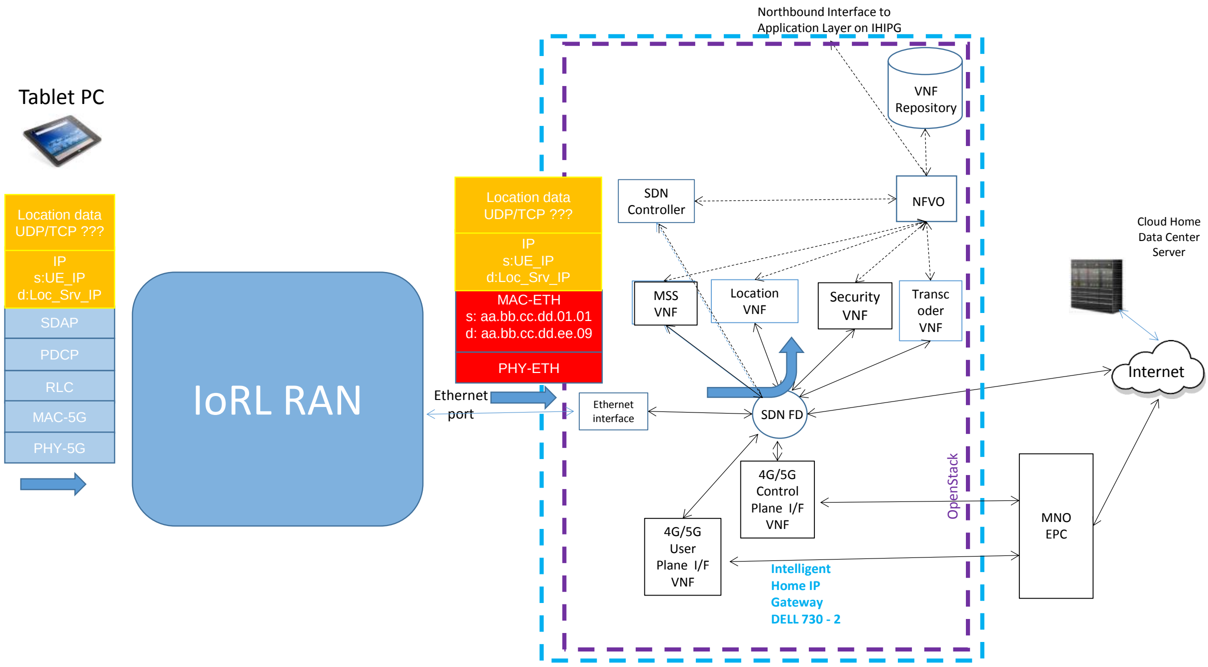


Figure 8-9: Location data format and upload trajectory

There is a location database which includes all of UE estimated positioning information in the SDN as shown in Figure 8-1. Each LED ID on the ceiling will be fixed as reference to defined room coordinate. UE calculated its coordinate via VLC and/or mmW which is detailed in chapter 7. The location data is uploaded to SDN via IoRL RAN Black Box. The structure of this location data is illustrated in **Table 8**—1. (The uploading processing is seen in Chapter 7). As a consequence, the database is updated in real time.

Table 8—1: Location database components in the SDN

	Room ID	UE coordinate			Timestamp
		X	Y	Z	
Number of bits	8	8	8	8	13
Interval	[0,255]	[0,255]	[0,255]	[0,255]	MM/dd/yyyy hh:mm:ss a zzz[5]

It consists 3 components:

1. Room ID: room identification
2. UE coordinate: estimated UE position (X, Y, Z)
3. A timestamp presents the UE position obtaining time

[5] Date time formats with IBM TRIRIGA Application Platform 3.3.2

9 Lighting system electro-mechanical architecture

9.1 System functional requirements for lighting system electro-mechanical architecture

Table 9—1: Key system functional requirements for lighting system electro-mechanical architecture

	Scenario	Dimension & Position & Mechanical constraints	Electro-Mechanical Constraints (Min. Power, Heating)	Coverage	Easy Installation	Flexible design to allow adaptation to more use cases	Accessibility of Environment
1	Museum	3 options: A. 1.5x1.5m stationary Kiosk with 4 PC and 4X 55" screens B. wheeled working station when opened 1.5m x 3m, 1.5m x 0.4m when closed C. Portable Kiosk moving between various IoRL lights	4 batteries and screens to support case C.	~ 20 rooms within a floor each ~100m^2	Smartphone application; smart building	VLC connected to museum DB; guided tours	Single flat floor
2	Tunnel	Steel and glass roof spreads between two brick flanking	mmW antenna should be outside housing of VLC modules	Length 100m Full height 27m	Need mechanical installation of the AP in the tunnel. Range extension of VLC over POF	Connection to alarm systems. Low latency response <1 ms	Flat platform but sleet and rail surfaced tunnel. - Location information under tunnel - Smoke and CO detection - Tunnel video conferencing
3	House	A. Pendant strip light B. Wall light C. Ceiling light (indoor, outdoor)	mmWantenna should be outside housing of VLC modules	100m^2 per floor; 3 rooms per floor	Smart house	Range extension to basement	Single or two flat floors with basement
4	Super-market	Integration with SSC (Smart Shopping Cart)	Reduce heat in areas with perishable products	Typical super area 3000m^2	Smartphone application; smart building	VLP: VLC based positioning < 10cm	Single flat floor
	General remarks	It is preferred to develop light rose that can house the IoRL technology, so LED drivers are placed inside the light rose. However, mmWs antenna should be outside the housing. Thus, special covering is required.					

9.2 Existing lighting system structure

The redesign of the spot light, which is required to include VLC and mmW electronics and transmit antenna with wave guide, can either be integral or separate from the light housing. Integral solution is easier to install whereas the separate solution is more adaptable for application to lights with different form factors.

We tried to minimize the number of different light fixtures to be developed for the IoRL project and still be able to cover all needed area and space in the various scenarios. We set 5 different fixtures as the goal and studied the different scenarios for existing lights.

Following are the different existing lights that we have chosen to replace with IoRL light:

9.2.1 Museum use case scenario

The existing light system in the museum is Spot lights on rail system, our reference is the on-rail spotlight provided by Issy Media (image reference on IoRL Del 2.1, Figure 19).

The models and specification of existing light system are from the Erco catalog and can be found on: IoRL Del 2.1, Appendix 1.

9.2.2 Tunnels use case scenario

Platform

The platforms are currently lit by strip continuous light system. Our reference is the Florescent Tube (AF) light images provided by Ferrovial image on IoRL Del 2.1, figure 23:

The specific fluorescent tube that can be found at Nuevos Miniserios (NM) station platform is: Continuous Luminaire 2x58W AF.

9.2.3 House use case scenario

9.2.3.1 Light rose

We decided to develop a light rose that can house the IoRL technology instead of developing a specific pendant light fixture. By using this approach, we can hope to use various different pendants light fixtures, using identical light roses, thus making any pendant LED lighting into a IoRL light.

The sole requirement is that the LED drivers need to be placed inside the light fixtures itself, or we will need to designate a place inside the light rose for the transformer in case they won't be inside the pendant light itself. SFY also mentioned the option that the VLC module will eliminate the need for a transformer, but, the question is if we can do it since every LED light fixture needs different Voltage and Wattage supply.

Our reference is the Pendant light images provided by BRE and John Cosmas, reference images can be found on IoRL Del 2.1, Section 2.1.13.3 types of existing lights, figure 5 - b and figure 7 - c.

Since the house electricity is constantly changing, we can use a pendant light to our selection. As mentioned we decided to replace the pendant lights with an IoRL redesigned Light rose that will enable us to connect various LED pendants.

9.2.3.2 Recessed and ceiling light

We wanted to develop a Light fixture that can function both as a ceiling light and a recessed light, both indoor and outdoor. This will give us the ability to place it in more locations around the house without having to develop 2 different light fixtures.

Our reference is the Pendant light images provided by BRE and John Cosmas, reference images can be found on IoRL Del 2.1, Section 2.1.13.3 types of existing lights, figure 4 - a,b,c and figure 5 - b and c.

Since the house electricity is constantly changing, we can use a pendant light to our selection (Being part of the BRE project).

	
(a) Integral with LED Housing	(b) Separate from LED Housing

Figure 9-1: Spotlight Designs

9.3 Electronic platform dimension and position

PCB dimensions are approx, 10cmX10cm for each mmW and VLC modules, if possible a double-sided PCB to minimize the sizes of both modules. The Platform to host the electronics will be designed as part of the lighting fixture or the light rose, or, on the other hand could be designed as an independent unit as suggested in example in section 9.4.1.2., regarding the electronics dimensions, PCB dimensions are not final but, if possible we would like a double-sided PCB to minimize the sizes of both modules. At the moment the size required for the VLC receiver is 3.7cm X 4.9cm X 0.45cmH (The final PCB will have some changes according to Oledcomm) , As far as the mmW PCB we still do not know the size and only have an initial estimate of 10X10cm, with a 5mm height.

9.4 Initial synthesis of system design and the manufacture capability

In this section we used all information we have regarding the components and mechanical requirements of the IoRL technology to develop conceptual approaches that might be used to integrate the radio-light electronics with the equivalent SFY light fixtures that will replace the existing lights listed in section 8.2. This stage will help us identify significant factors and issues and the effect they might have over the final, physical implementation of the technology into light fixtures, aiding us to make the best decisions regarding the physical design once we will have all the additional information regarding footprints, electronic requirements and scenarios.

9.4.1 Museums

We have examined the light typology provided by Issy Media to develop preliminary conceptual design principles that will highlight the issues and questions that might come up later in regards to the process. The purpose of this is to help the participants understand the significance and effect that these form factors and physical layouts will have on the light fixtures and their installation in the scenario locations.

9.4.1.1 Alternative light from SFY

Although there are 4 different spot lights in use today in the museum (see sec 9.2) , we have agreed, together with Issy Media, to replace them all with 1 spot light from the SFY collection.

Figure 9-2: Concord, Feilo Sylvania (from catalogue)

We also examined the general dimensions provided by RunEL regarding the RRLH controller and Splitter, as well as other components we already know that will have to be integrated in the system. We realized that there needs to be additional cable inputs other than the traditional building power circuit in order for the IoRL lights to function correctly. We wanted to showcase the problems that this need because when dealing with the mobile lights connected to rails, that are very common in Museums and Galleries, so all participants understand that and contribute to the discussion on how to tackle these issues.

9.4.1.2 Preliminary design concept of VLC/mmW spotlight

In the Museum scenario we divided the Preliminary design concepts into four options. Two for the VLC and mmW module housing and two for the location of the RRLH controller.

<u>VLC and mmW modules</u>

<u>Option A</u>

The VLC/mmW components will be in a separate housing that will be connected to the rail separately from SFY LED spot. The housing will receive Power from the Rail and IF input from the RRLH controller via a separate cable. It will than give an output directly to SFY LED spot.

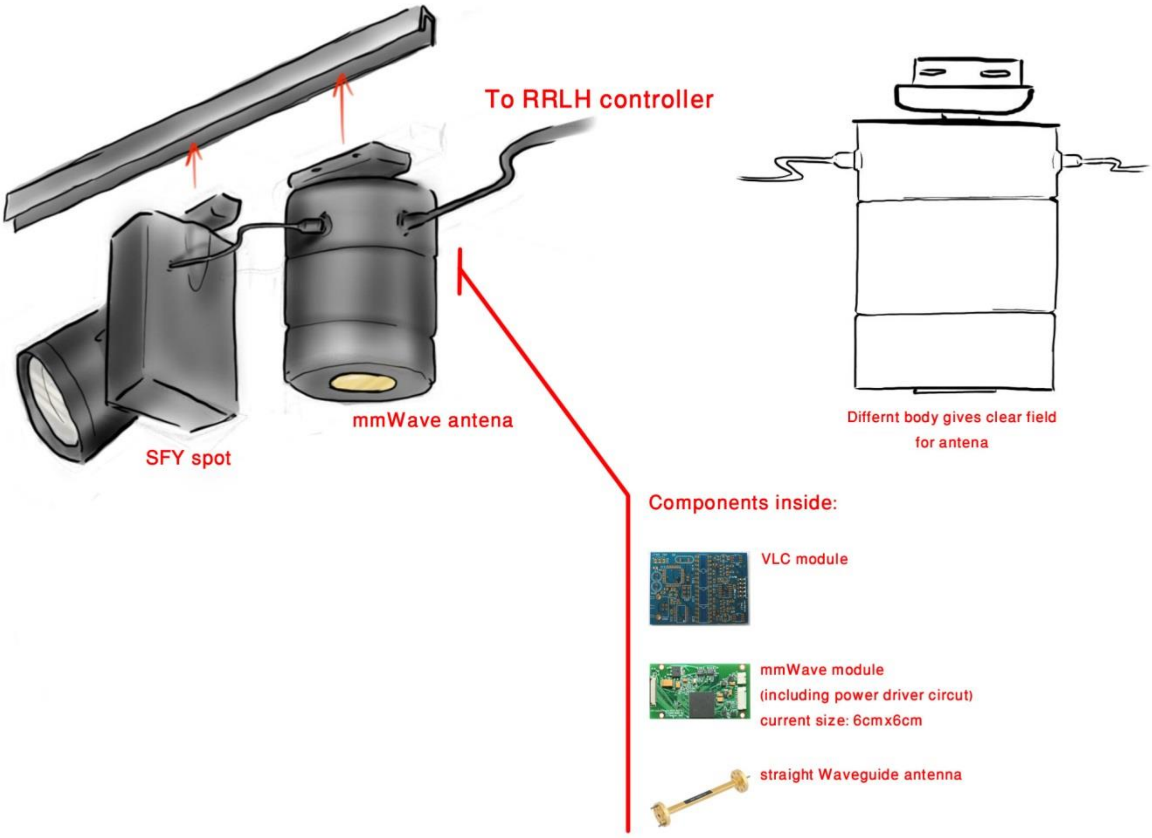


Figure 9-3: Design concept A

Advantages will be a minimum intervention into SFY fixtures, since it will be easier to minimize the mmW antenna obstructions and we will have more design freedom. Disadvantage is that it will be an independent housing design that we will have more bodies on the rail.

<u>Option B</u>

Re-design the SFY spot housing so it can hold the VLC and mmW components inside it. The antenna aperture will be lowered so that the spot light will not obscure it. The re-designed fixture will receive power from the rail and the IF input from the RRLH controller from via a separate cable.

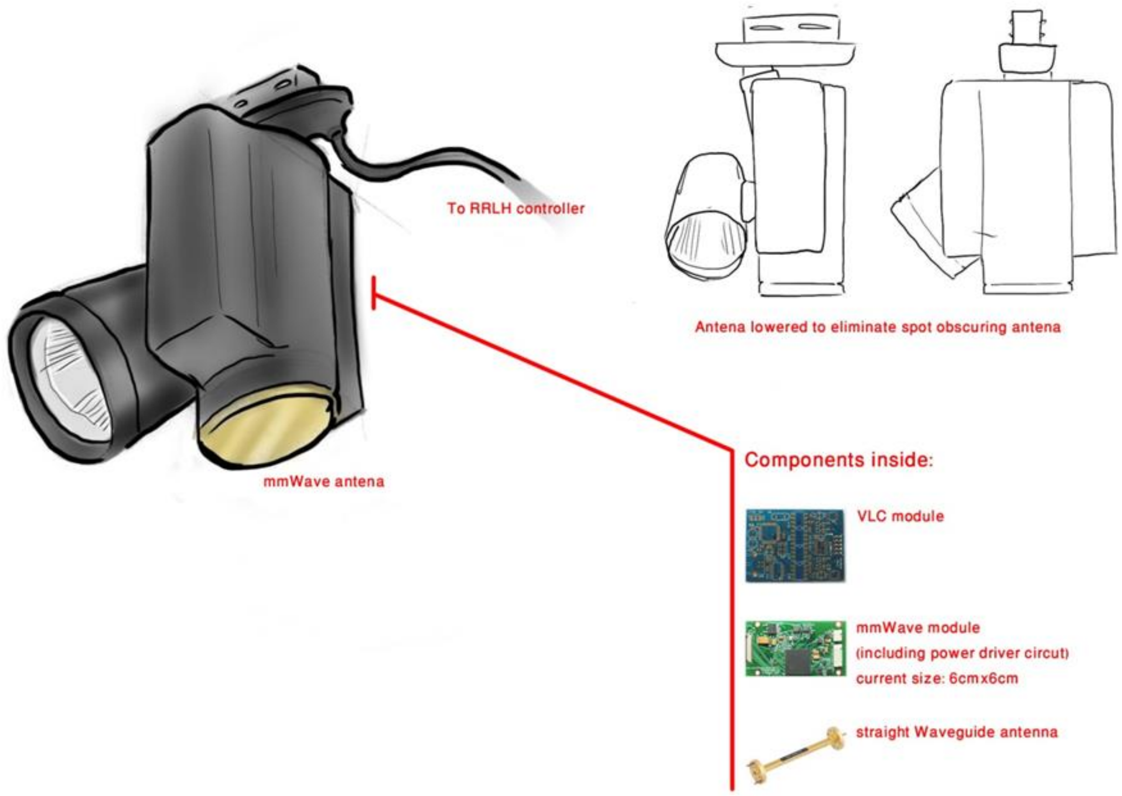


Figure 9-4: Design concept B

Advantages: Single unit with all IoRL capabilities, that is easy to install and housing will part of SFY light;

Disadvantages: Restricted space for components with intervention into SFY lights that might cause problems with obscuring the mmW signal.

RRLH controller location

- The first option is to locate the RRLH controller housing next to the rail and place several connectors on it so the IoRL spot lights along the rail can be connected to it.
- The second option is to locate the RRLH controller housing above the fake ceiling in a center location and connect it to a connectors strip to be located along each rail. The IoRL spot lights will be connected to the connector strip.

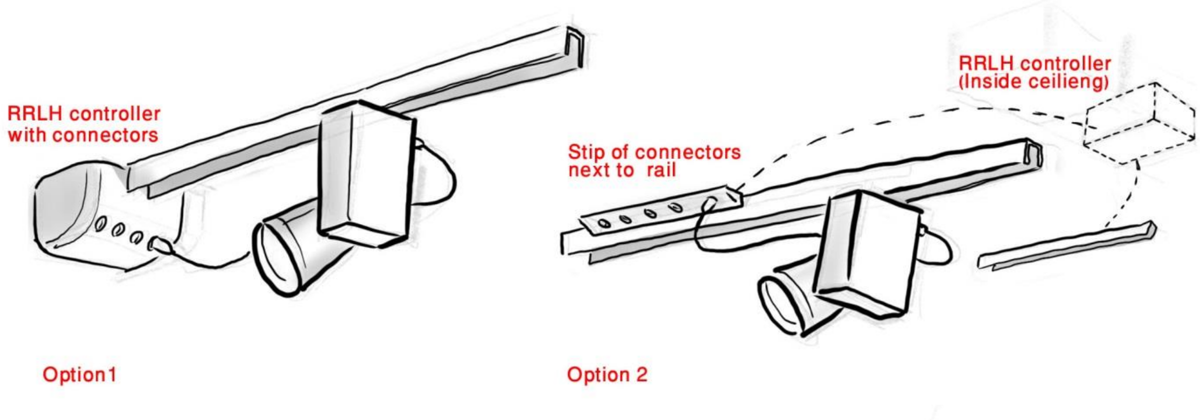


Figure 9-5: RRLH controller design concepts

9.4.1.3 Material challenges

Since the Antenna is outside the housing (for transmitting reasons), we need to see if we can cover its aperture with plastic covering.

9.4.1.4 Required information for design process:

- PCB exact footprints and limitations for locating them.
- SFY manufacturing capabilities.
- Testing antenna signal when covered with various transparent plastics.
- Specifying SFY fixture exact beam of light angle.
- Specifying mmW antenna signal angle.
- Can the RRLH controller be connected to the IoRL lights through the Rail (Linear connection instead of parallel) and identify signal from different fixtures along the rail through some sort of digital ID?
- What components need to be added for each spot to perform as an radio-light that can be switched off independently.
- Number of rails and spots to be deployed at Museum scenario.

9.4.1.5 Flow charts

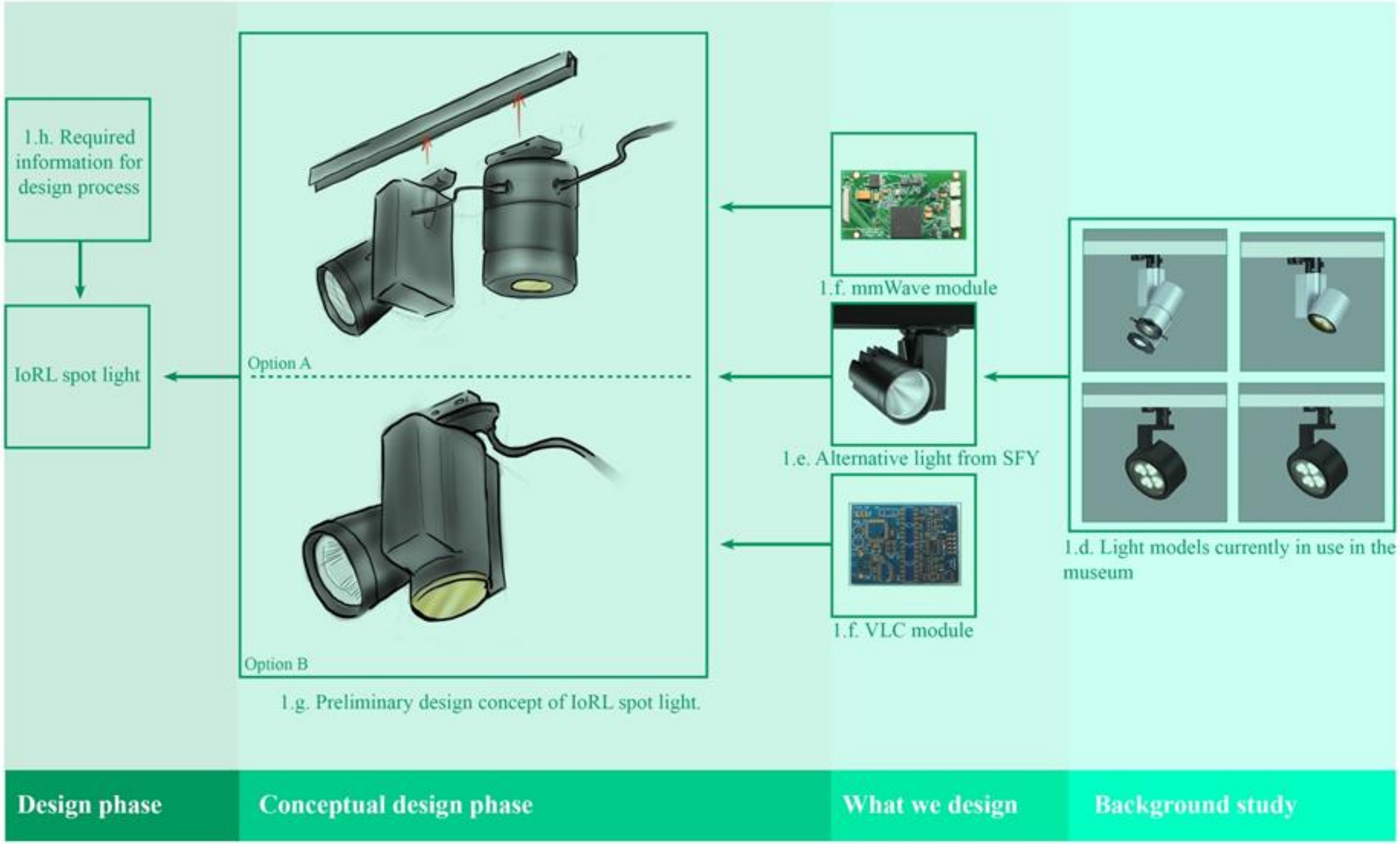


Figure 9-6: Spot light Design process flow chart

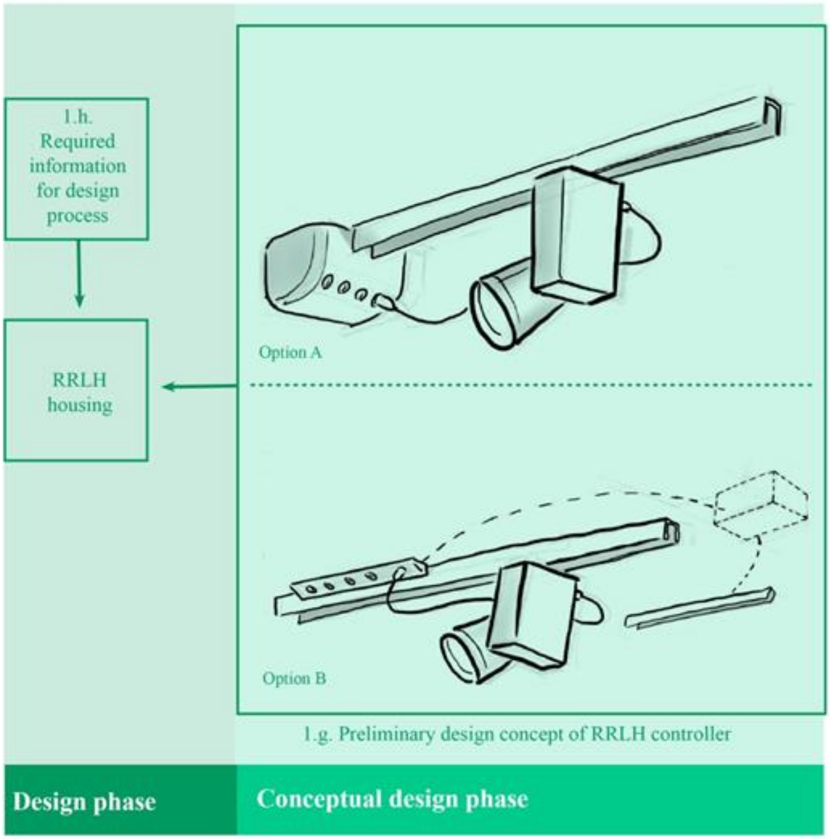


Figure 9-7: RRLH controller, Design process flow chart

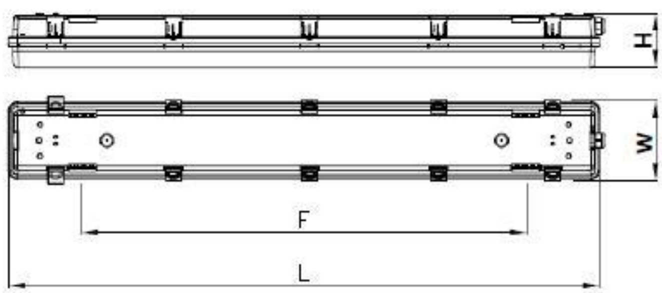
9.4.2 Tunnel

We have examined the light typology provided by Ferrovial to develop preliminary conceptual design principles that will highlight the issues and questions that might come up later in regard to the redesign process. The purpose of this is to help the participants understands the significance and effect that the form factors and physical layout will have over the light fixtures and their installation in the scenario locations.

9.4.2.1 Alternative light from SFY

产品图片 Product image

产品线图 Line drawing



	12W/0.6S	24W/0.6T	24W/1.2S	48W1.2T	40W/1.5S	60W/1.5T	80W/1.5T
L	634	634	1261	1251	1551	1551	1551
W	73	118	73	118	73	118	118
H	77						
F	420	420	900	900	1200	1200	1200

S-Single

T-Twin

Figure 9-8: MSF791 from SFY catalogue (provided by SFY)

The alternative light selected for the platform is the MSF791-80/1.5T LED from the INESA Feilo catalogue.

9.4.2.2 Preliminary design concept of VLC/mmW spotlight

We divided the Preliminary design concepts into 3 options:

Option A

All components will be housed in a separate housing that will be connected as part of the continuous light array. Next to each IoRL light there will be a box that will house VLC module, mmW module and antenna, making sure that the antenna is lowered from the light fixtures and exposed to eliminate signal obstructions.

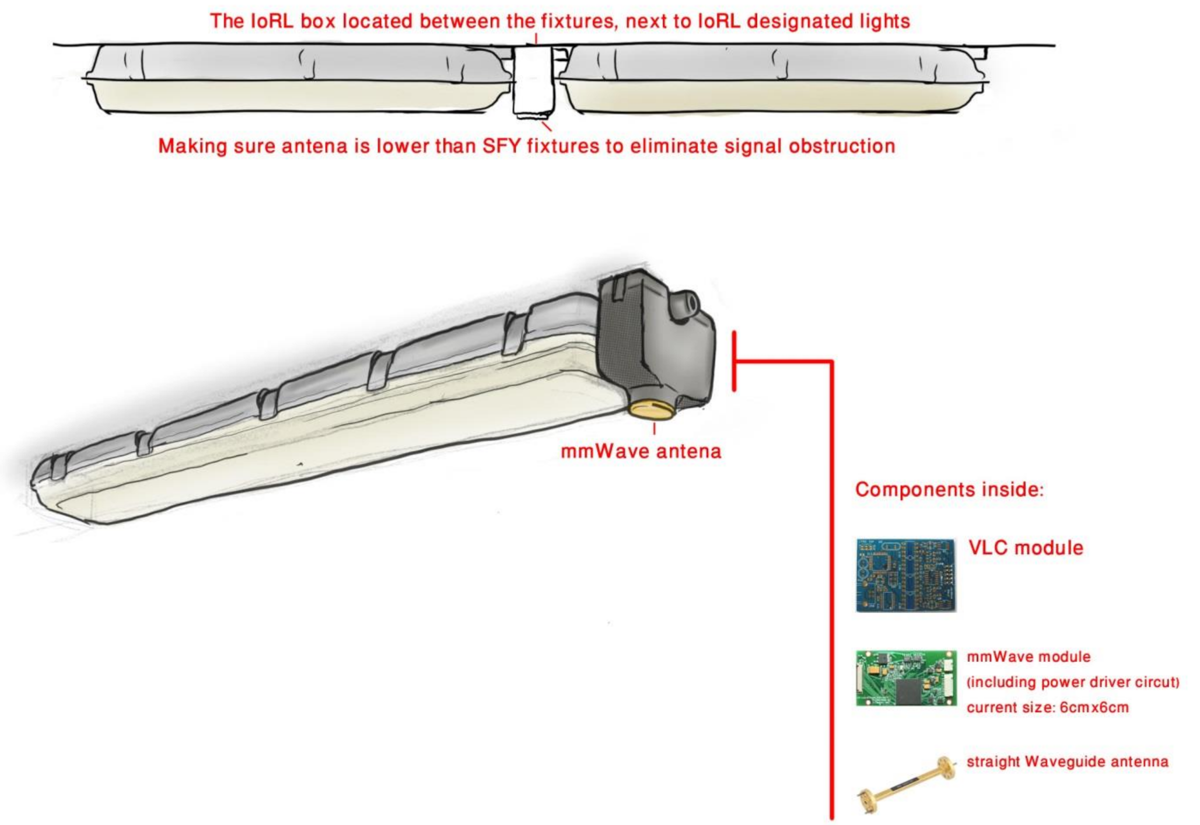


Figure 9-9: Platform design option A

Advantages: We will have a single body that will hold all IoRL capabilities with a minimal intervention in SFY fixtures, no IP65 standard regulations problems since it will be a part of the continues building power network with a clearly exposed mmW antenna.

Disadvantages: It will require us to manufacture a big light body.

- Big separate body to be manufactured
- More design freedom

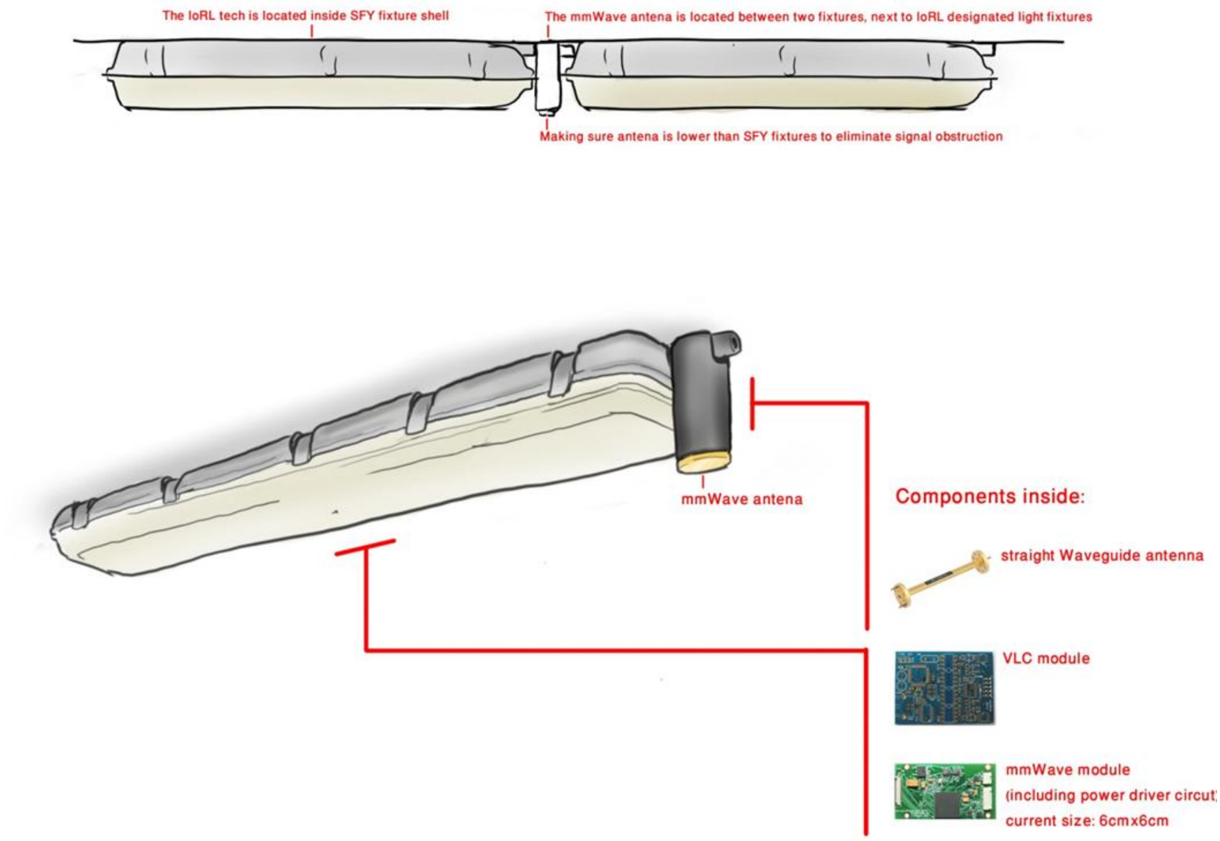


Figure 9-10: Platform design option B

<u>Option B</u>

We will separate the mmW components of the system. The PCBs of the VLC and mmW modules will be housed inside the SFY light fixtures and only the mmW antenna will be housed externally, as part of the continuous building power network, making sure that the antenna is lowered than the SFY light fixtures and exposed to eliminate signal obscuring.

Advantages: No intervention with SFY external shell, IP65 regulation free, and the light will be part of the continuous building power network and will have an exposed mmW antenna.

Disadvantages: it will require a more complex installation.

<u>Option C</u>

All components are housed inside the SFY light system shell, and the mmW shell needs to be altered in order to make sure that the mmW antenna aperture is lower than the main body of the light system so we can eliminate signal obstructions.

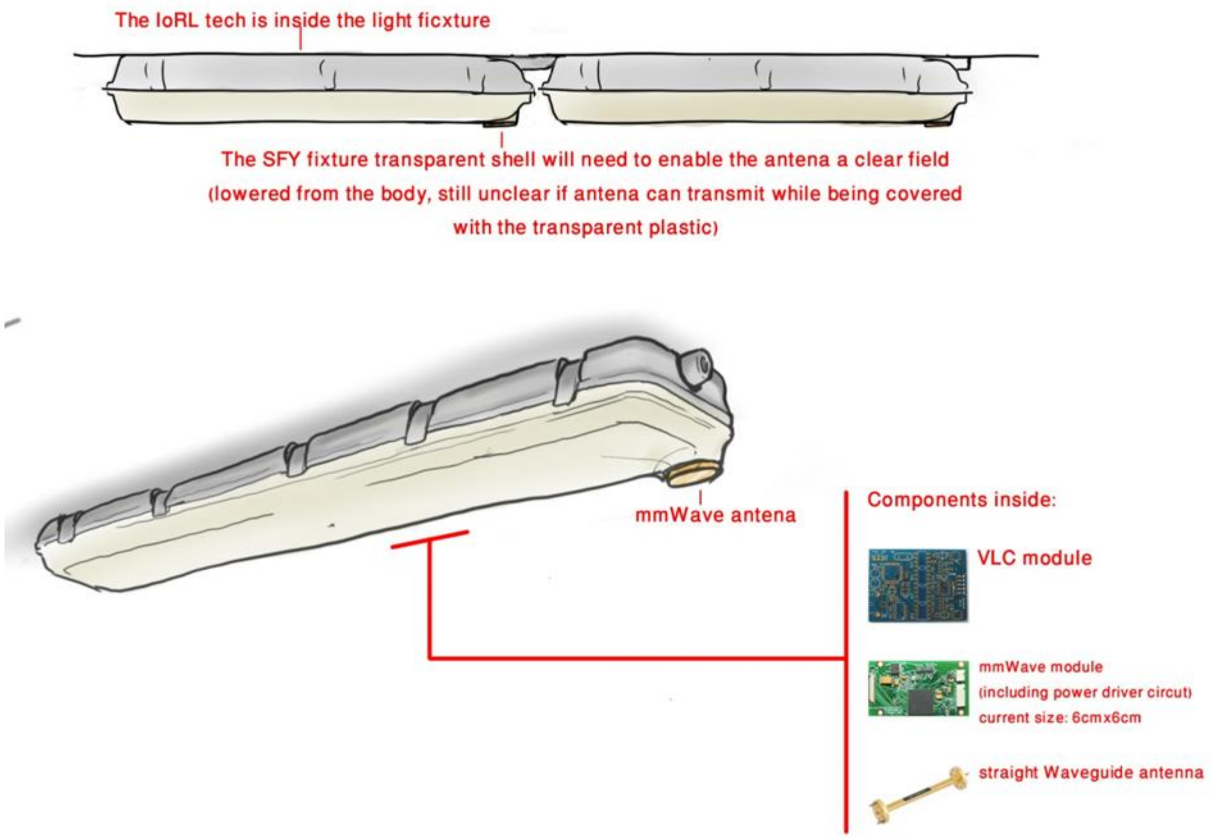


Figure 9-11: Platform design option C

Advantages: the lights will be independent with no additional parts on the building power network, with similar continuous light power network as current.

Disadvantages: it will need alterations in SFY fixture shell which may need to expose an mmW antenna in the design of the whole shell, which might lead to problems with train station standards for light fixtures in station (IP65 for example).

RRLH location

The solution is to house the RRLH controller in a housing that can be connected along the continuous light power network. Every 6 IoRL light fixtures will have to receive one RRLH controller box.

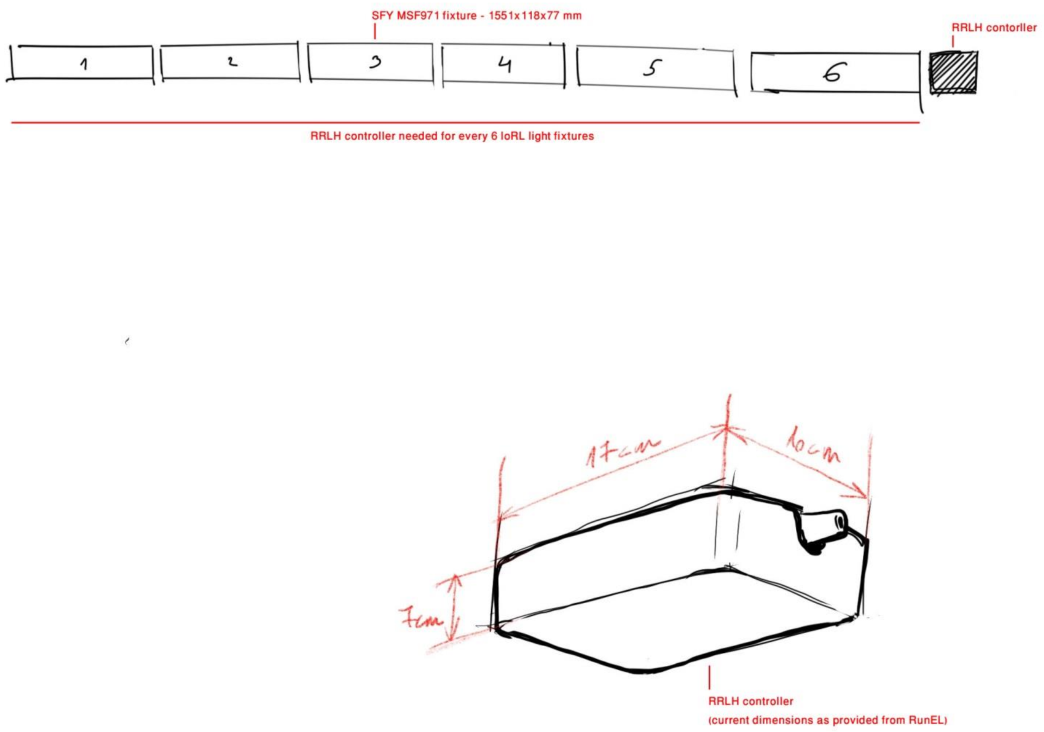


Figure 9-12: Location of RRLH controller in platform

Material challenges

Since the Antenna is outside the housing (for transmitting reasons), we need to see is we can cover It with the help of plastic covering just for the antenna or for the whole casing. It is very relevant for this scenario since the SFY fixture lower side is covered with frosted transparent plastic and we might have a more challenging development if we will need to pierce the shell for the antenna and still be able to adhere to all regulations needed by the train station.

9.4.2.3 Information required for the design process

- PCB exact footprints and limitations for locating them.
- SFY manufacturing capabilities.
- Testing Antenna signal when covered with various transparent plastics.

9.4.2.4 Flow charts

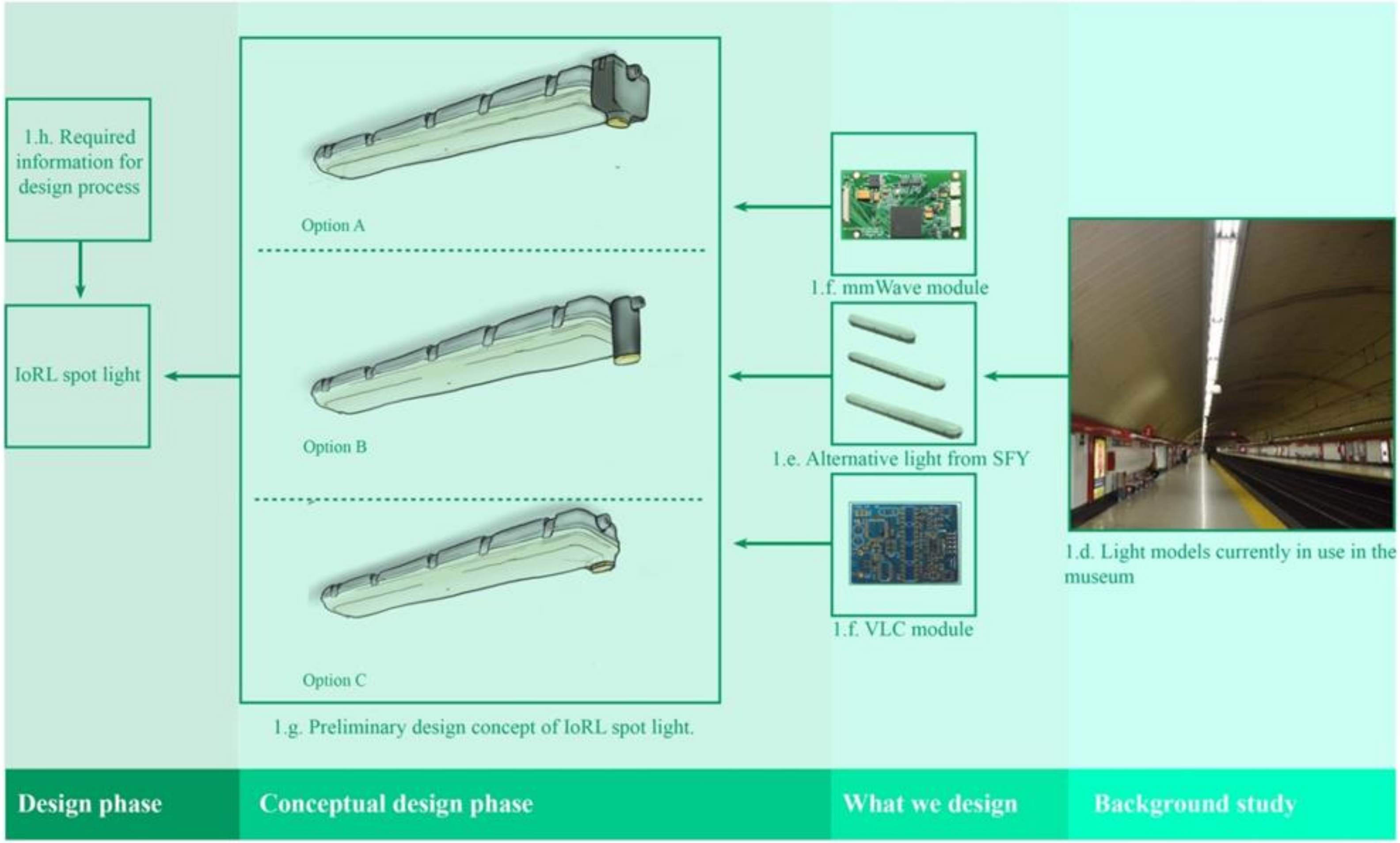


Figure 9-13: Continuous light Design process flow charts

9.4.3 Home - light rose

We have examined the light typology provided by BRE to develop preliminary conceptual design principles that will highlight the issues and questions that might come up later in regard to the process. The purpose of this is to help the participants understand the significance and effect that the form factors and physical layout will have over the light fixtures and their installation in the scenario locations.

In the home scenario, we tried to minimize the different types of light fixtures used so we can support all the spaces required for the use cases using just two different light fixtures. This approach can give us a good Lifi coverage of the house scenario without using excessive funds and effort to develop countless different light fixtures.

9.4.3.1 Alternative light from SFY

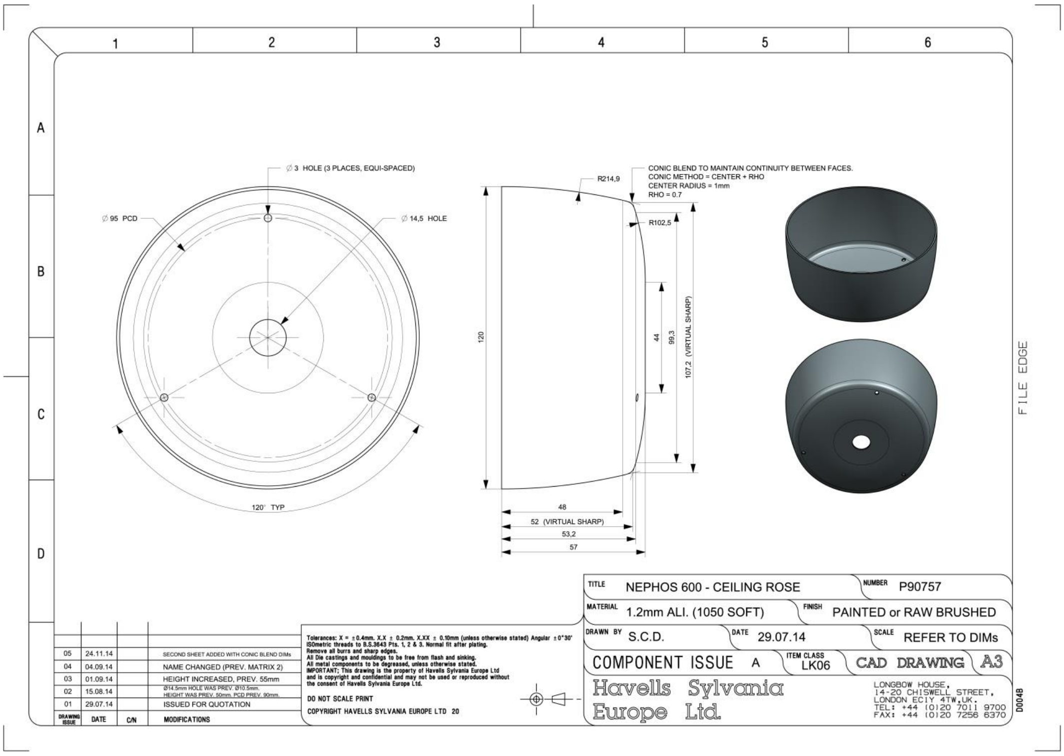


Figure 9-14: Light Rose diagram provided by SFY

9.4.3.2 Preliminary design concept of VLC/mmW light rose.

We divided the solution into two approaches:

Option A

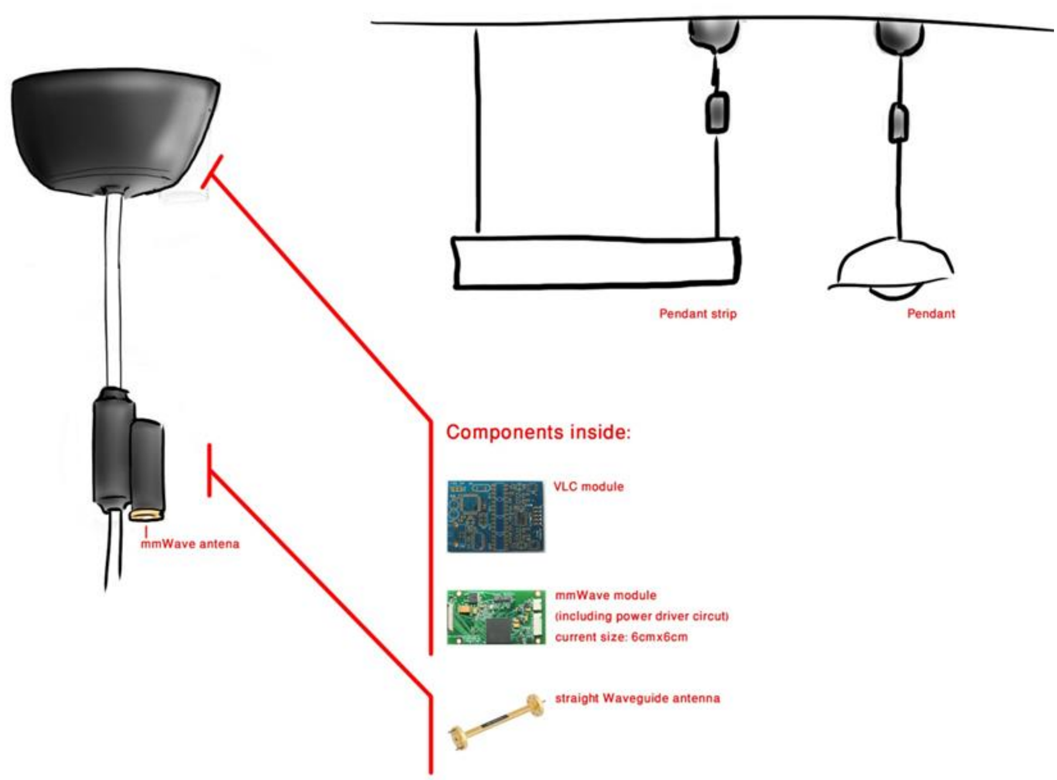


Figure 9-15: Light Rose Preliminary Design Option A

All components are housed inside the 120-mm light rose. The Light rose can be connected to any pendant LED fixture that has its' driver inside the fixture. There will be a nipple like extension for the mmW antenna to minimize signal obstruction; however, in the light rose fixture there will always be some obstruction by the cable going downward to the fixture itself. This could be solved by compensating from nearby fixtures.

Advantages: with a use of separated parts it will be relatively spacious and empty light rose, it will be able to connect to any pendant and will have an easy installation.

Disadvantages: it will always have some obscuring to mm Wave antenna.

Option B

VLC module and mmW module will be placed inside the light rose and the mmW antenna will be housed separately along the cord going downward from the light rose. This minimizes the intervention of the light rose but the cable between the light rose and the antenna house will have to be thicker as it needs to let the cord go back and forth. In this scenario, there will also be an obscuring of the mmW antenna signal.

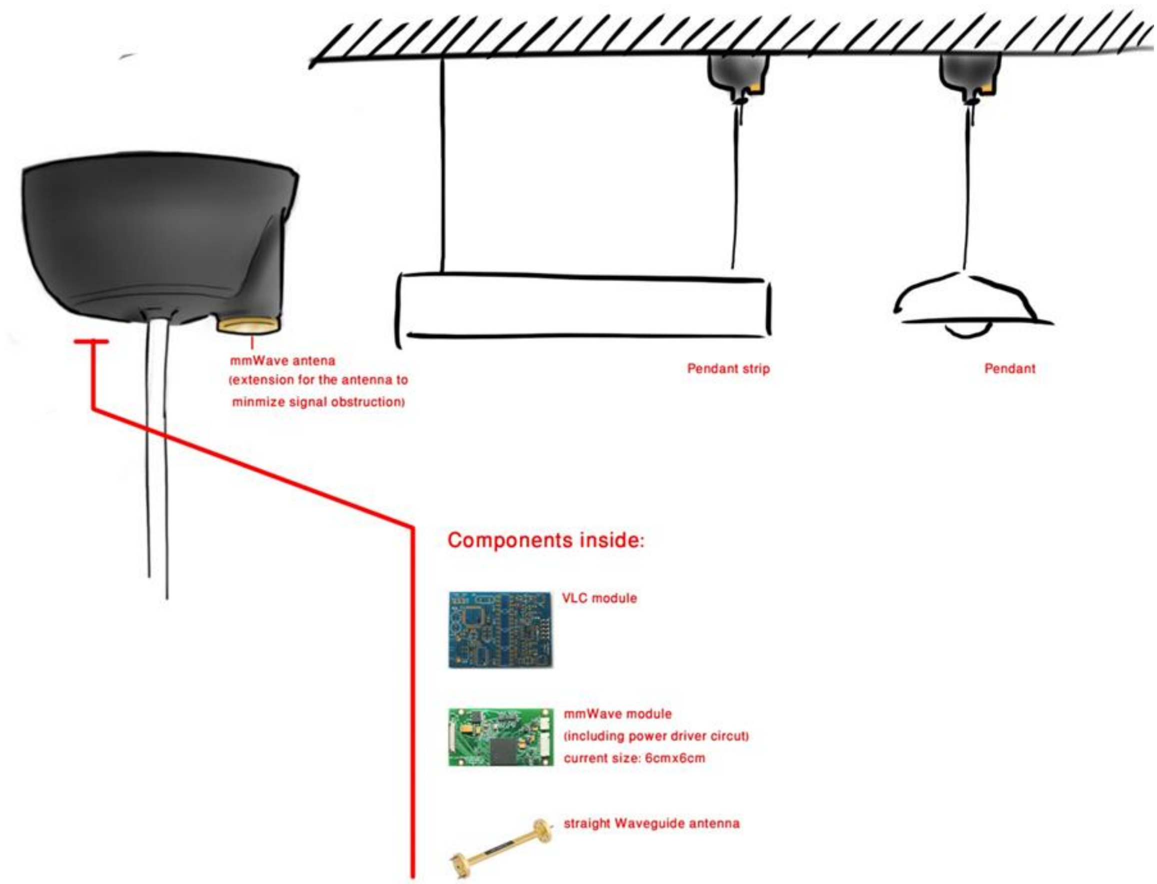


Figure 9-16: Light Rose Preliminary Design Option B

Advantages: it will be easier to house all components without the antenna and to connect to any pendant fixture.

Disadvantages: mmW antenna will be partially obscured by the pendant and will be more complex to install.

9.4.3.3 Material challenges

None at the moment

9.4.3.4 Information required for the design process

- PCB exact footprints and limitations for locating them.
- SFY manufacturing capabilities.
- Specifying mmW antenna signal angle.
- What components need to be added for each spot to perform as an IOT light that can be switched off independently.
- Can nearby mmW compensate for signal problems (Handover?)

9.4.3.5 Flow charts

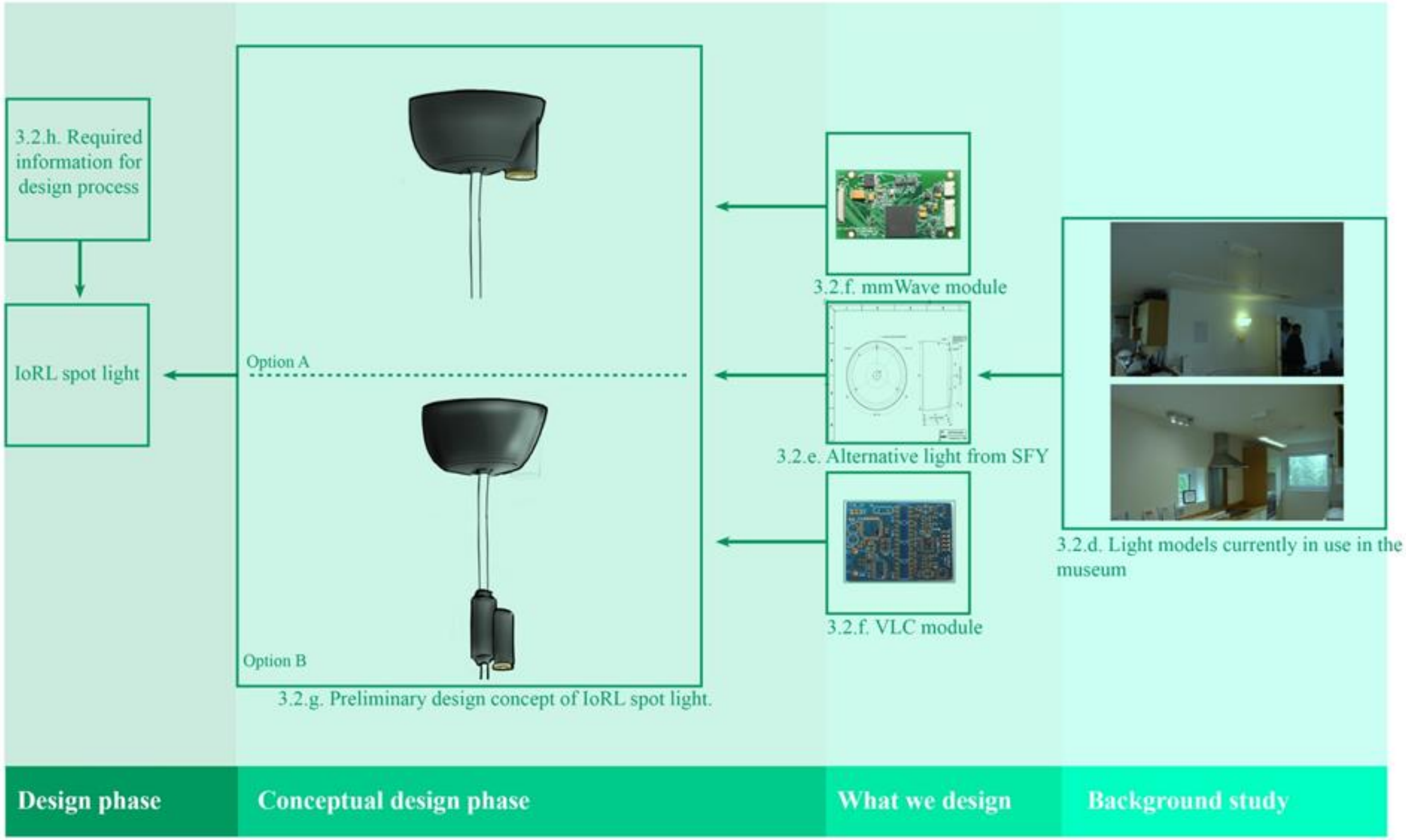


Figure 9-17: Light rose design process flow chart

9.4.4 Home- Recessed and ceiling

9.4.4.1 Alternative light from SFY

The most suitable light is The Giotto LED 335 surface 4000k with the addition of SFY trend ring, the brushed aluminum Giotto 335 can serve as a wall light as well as a recessed and a ceiling light.

Lumiance

Giotto LED 335

Giotto LED 335 Surface 4000K

3032821

Product features

- Ambient and decorative surface round LED bulkhead. Perfect for 1x38W TC-DD replacement. White robust polycarbonate body with opal diffuser. 1510LM. 19W. 80lm/W. 4000K. Drive current: 700mA. CRI 80. Non-dimmable driver. IP44. IK10. 50,000 hrs (L70). (HxWxD) 335x335x110mm. 5 step MacAdam ellipse. Class 1. 220-240V. Energy class: A++, A+, A.

Figure 9-28: Giotto product summery from SFY catalogue

Lumiance

Giotto LED 335

Trend Ring - Brushed Aluminium - Giotto 335

3005820

Product features

- Brushed aluminium trend rIng accessory for Giotto 335 LED recessed type luminaires.

Figure 9-18: Giotto Trend Ring product summery from SFY catalogue

9.4.4.2 Preliminary design concept of VLC/mmW ceiling/recessed light

We divided the solution into two approaches:

Option A

All components are housed inside the main body Giotto LED 335 fixture. The mmW antenna will preferably be based at the base of the transparent plastic canopy (behind it if possible, or sticking out of it) to insure there is minimal, or even no obstruction of the signal.

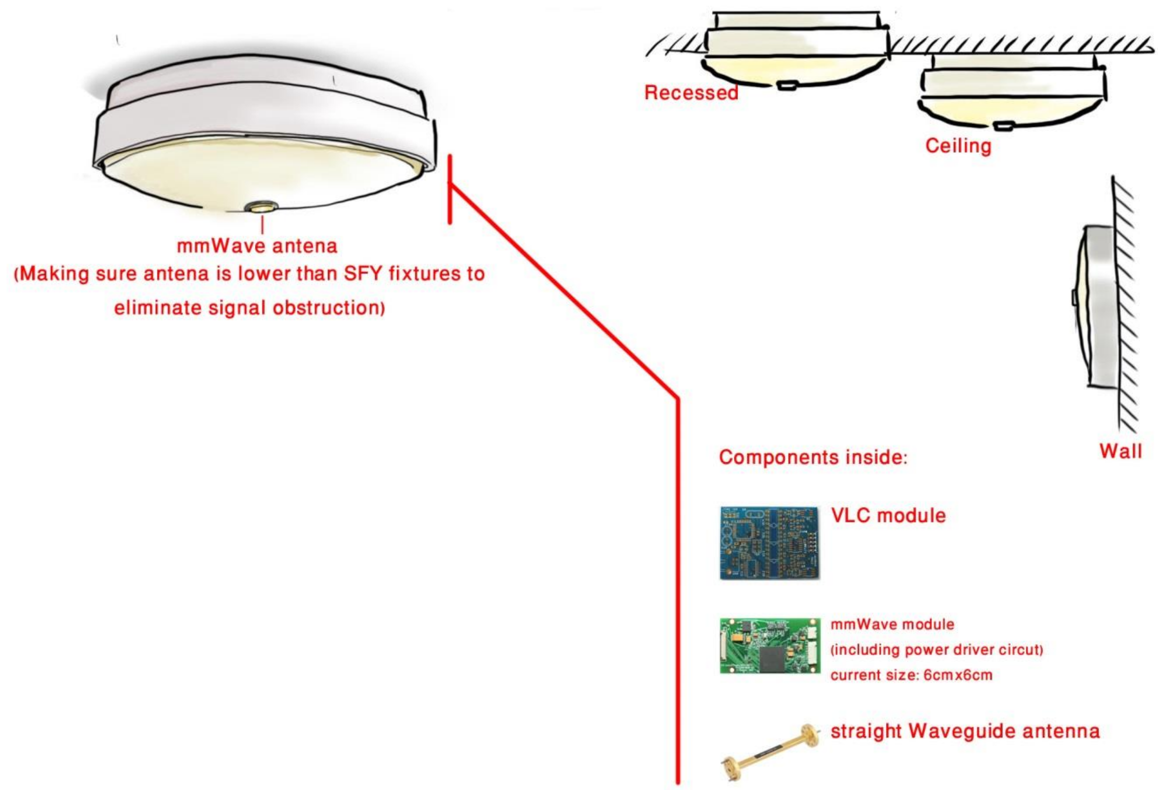


Figure 9-19: Recessed/Ceiling light Option A

Advantages: A clear field for the mmW and can be located and installed as 3 light types: wall light, ceiling and recessed.

Disadvantages: It needs alteration to the transparent plastic canopy, jeopardizing its seal to dust and humidity, also it might make shadows in the light fixture, depending on the inner construction and we will have to make alterations to the light fixture inner components.

Option B

All components are housed inside the space between the main body Giotto LED 335 and the covering of Trend ring. mmW antenna will be placed as low as possible to minimize obscuring of signal.

Advantages: There will be no intervention in main fixture body or holes in plastic canopy and also it is relatively spacious for components to fit in.

Disadvantages: There might involve some signal obscuring for mmW antenna and will be a more complex assembly and will not support a recessed positioning.

9.4.4.3 Material challenges

Since the antenna is outside the housing (for transmitting reasons), we need to see if we can cover It with the help of frosted, milky plastics covering, for just the antenna or for the whole casing.

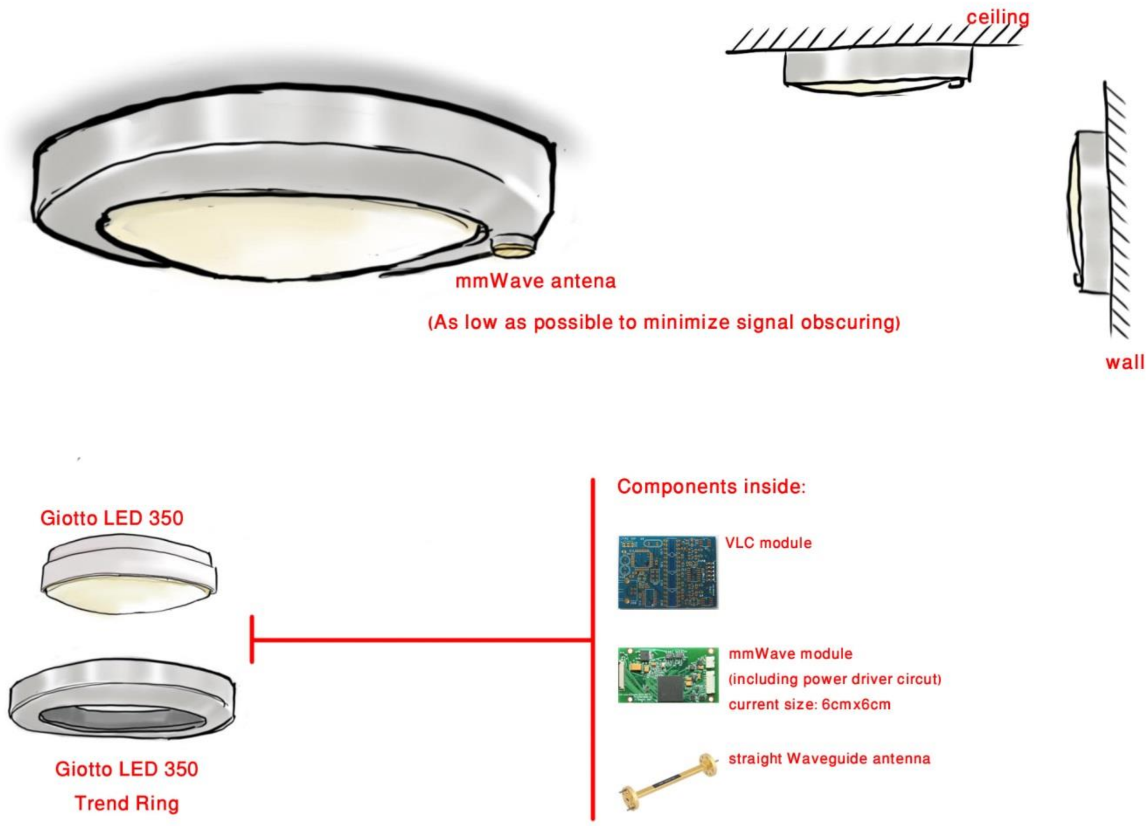


Figure 9-20: Recessed/Ceiling light Option B

9.4.4.4 Information required for the design process

- PCB exact footprints and limitations for locating them.
- SFY manufacturing capabilities.
- Testing Antenna signal when covered with various transparent plastics.
- Specifying mmW antenna signal angle.
- What components need to be added for each spot to perform as a radio-light that can be switched off independently.
- Can the VLC module replace the LED driver usually located inside the light fixture?

9.4.4.5 Flow charts

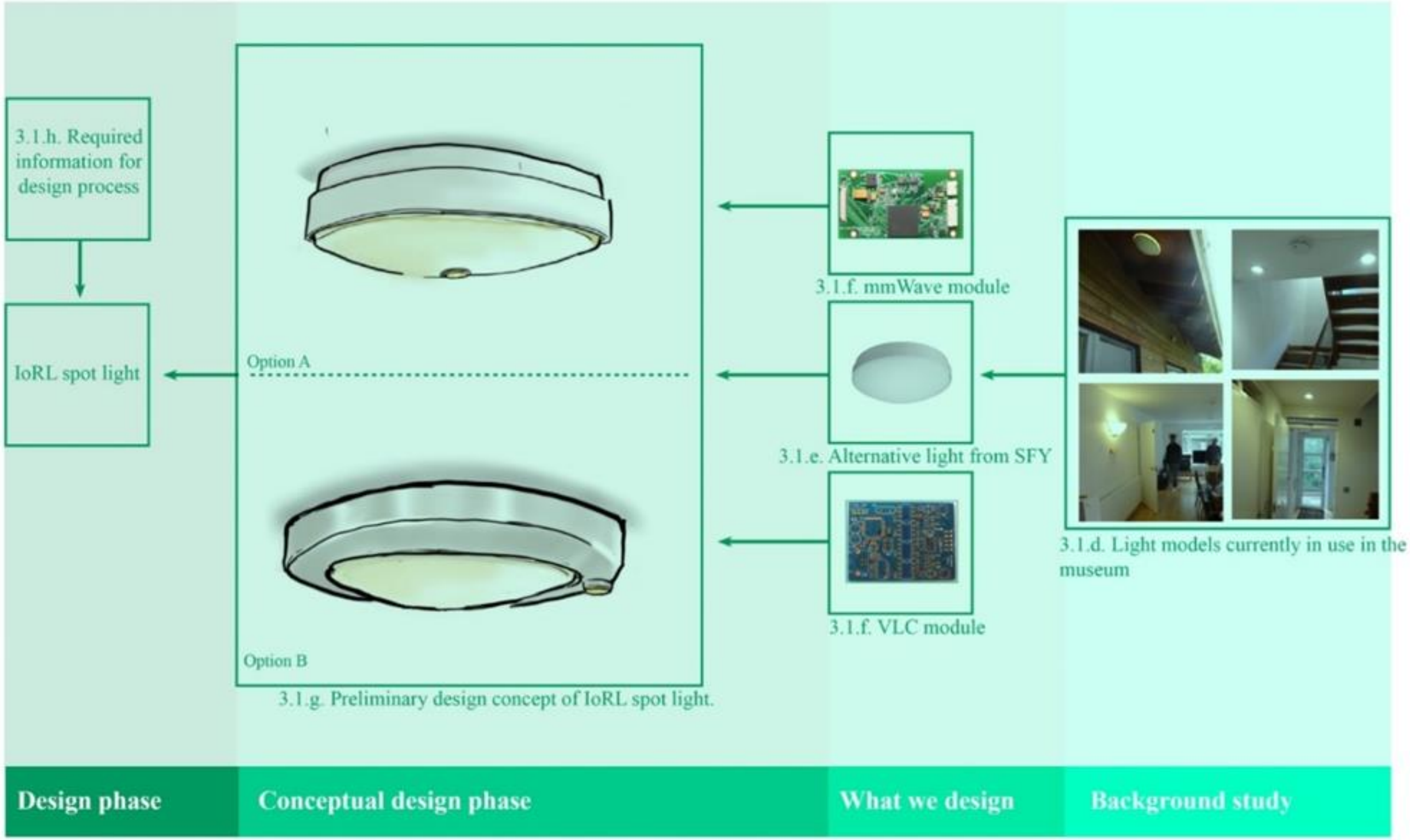


Figure 9-21: Recessed/ceiling light design process flow chart

10 Consumer Products electro-mechanical architecture

10.1 System functional requirements for consumer products electro-mechanical architecture

Figure 10-1 IoRL Consumer Product

Tablet PC + Smart Phone: support of mmW Tx/Rx module+ VLC Rx module

UHDTV: Support of 4K or (Ultra High Definition Digital TV) 4096x2160 on consumer screen per room.

Digital Signage:

- Supermarket commercial manager for updating product information and advertisements for digital signage

Smartphone:

- Mount to Smart Shopping Car (SSC)
- Integrating small factor mmWs transceiver along with VLC PD array

VR Handset relevant system functions:

- Streaming 2xHDTV from Theta S to VR Glasses;
- Multiple Source Stream server;
- SDN-based QoS will be applied in order to prioritize the VR traffic within the HIPG in comparison to other background traffic
- Lens (Field of view (FOV) / Interpupilary distance (IPD) / Eye relief) in the order of 101˚ / 62mm (fixed) / 10mm
- SensorGyro sensor / Proximity sensor/Acceleromer
- Indicator3-color LED * 1ea
- Long battery life

Gear VR (USB Type-C Device Holder, Controller Holder, Micro USB device Holder)

10.2 Existing consumer products structure

Arçelik TV's are consisting of three main parts and other peripherals. Main parts are AC/DC converter, Mainboard and (LCD/OLED/QLED vs.) Panel. Other peripherals vary but mostly Bluetooth and wifi modules are used. Panel is the part where the image is constructed to the viewers. We mostly produce LCD panels.

Oledcomm produces two different VLC LED lamp-based systems. The first one is a low data transfer, low-price and microcontroller-based VLC system. Its transmission rate goes up to 5 Mbps. It was conceived for hospital use and dongles acting as mobile transceivers are available. The second product has just been revealed in the CES in Las Vegas in January 2018.

It consists on a FPGA based technology and data rates are set at 10 Mbps, nevertheless the system can evolve to faster data rate transmissions. In Figure 10-2 a VLC-to-VLC transceiver is shown. There are two cards superposed, one of them is the receiver card that could be used in this project.

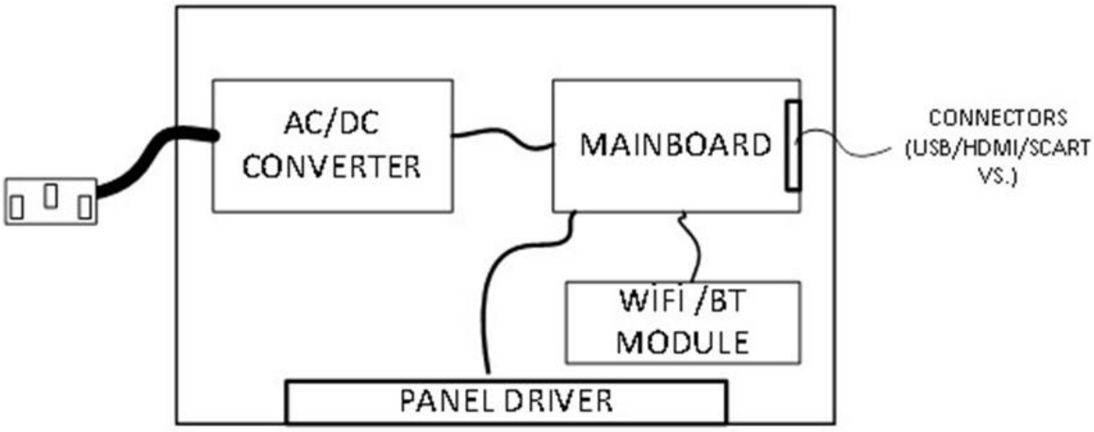


Figure 10-2 Current structure of Arçelik TV sets

Control and driving of the Panel, peripherals, input/outputs and special functions are done by a particular SoC (System on Chip) in each TV.

10.3 User terminal mechanical design

According to business case proposed or defined by Arçelik, the Arçelik TV will be the terminal user equipment.

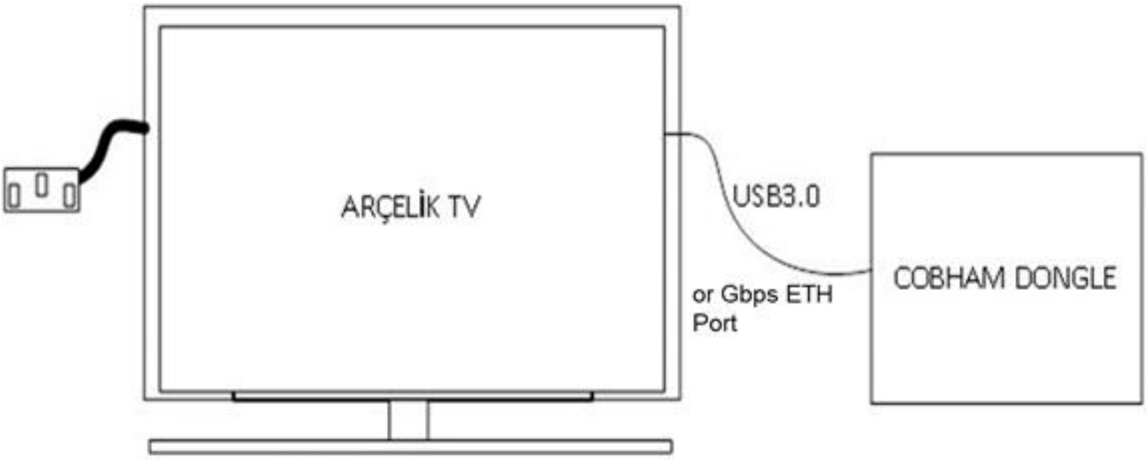


Figure 10-3 Terminal User Equipment View

Cobham Dongle will be handling the connectivity while Arçelik TV plays the content (or multiple contents) with USB 3.0 or Gbps Ethernet port. We will use 43" Screen Smart (Connected) LCD TV for the demo which will be decided later.

Table 9-1: UltraHD Smart Television Set Features

Arçelik UHD Smart TV Configuration	
Television Set	40” UHD 50 Hz GRUNDIG TV Smart Inter@active 4.0+
Model Number	40 VLX 8650 BP
Screen Dimension	40”/102cm
Main Processor	Quad-Core Processor
Resolution of TV	UHD (3.840x2.160)
Peak Luminance	%65
Ethernet	YES
USB 3.0	2
USB	1
HDMI	4 HDM1 (MHL), HDMI2, HDMI3, HDMI4 (ARC)
Common Interface	YES (CI1, CI2)
AppStore	YES
DLNA	YES
Miracast	YES (Dual-direction)
RC over IP	YES
Bluetooth (TV)	YES
USB Recording	YES (Dual Recording)
DVB Reception	2 x (DVB-T2/C/S2)
Picture in Picture (PIP)	YES

10.3.1 Museum scenario kiosk station production

Option A

First option is a stationary (can be with wheels) Kiosk that will be roughly 1.5m x 1.5m in size. It will be connected to the power grid in order to support the dongle, 4 Mini PCs and 4 55" touchscreens. It will be communicating with the IoRL system installed in the museum through the dongle and will constantly have a 4 interactions stations through 55" touchscreens that will enable two children to work simultaneously on each single screen.

When working, there is a constant eye contact between the people standing opposed to each other, these can be used for the interactions and activities that will be designed for the Kiosk. There is also a place in the center of the Kiosk that can hold a physical exhibit that might be related to the activity done on the screens.

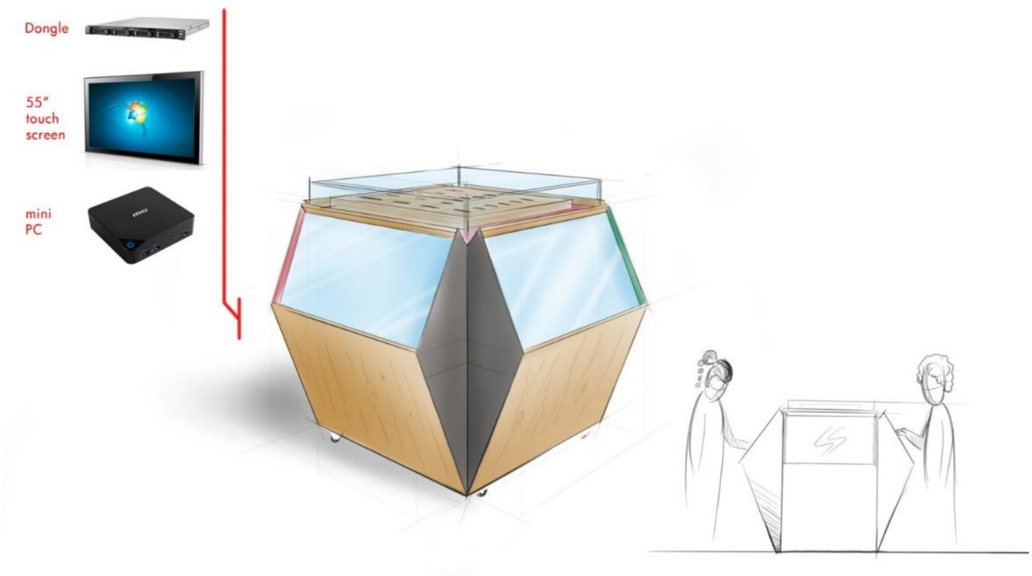


Figure 10-4 Stationary Kiosk Design

Manufacturing details:

- Manufacturing techniques: Carpentry and Metal working
- Materials: Laminated wood, Steel, Aluminum
- Estimated time for manufacturing: 6-8 weeks.
- Additional components needed: 4 55" touch screen TV, 4 Mini PC
- Estimated price (Additional components not included) 4000 euro

Option B

Second option is a Semi stationary wheeled working station also connected to the power grid to support all its component. This solution has an extension ability as well and when opened has a strong influence on its surrounding (will cover a space of around 1.5m x 3m) as opposed to a much smaller of roughly 1.5m x 0.4m when closed. It's room divider design doesn't permit communication between people working on different screens, but, can be used to invite people to walk around and explore what is found on the different screens (might be suitable for the treasure hunt use case). When closed it has 2 visible 55" touchscreens and 2 additional screens are added when the room divider kiosk is open. Each one of the 4 interaction stations is equipped with a 55" touchscreen that enable 2 children to be engaged with it simultaneously.

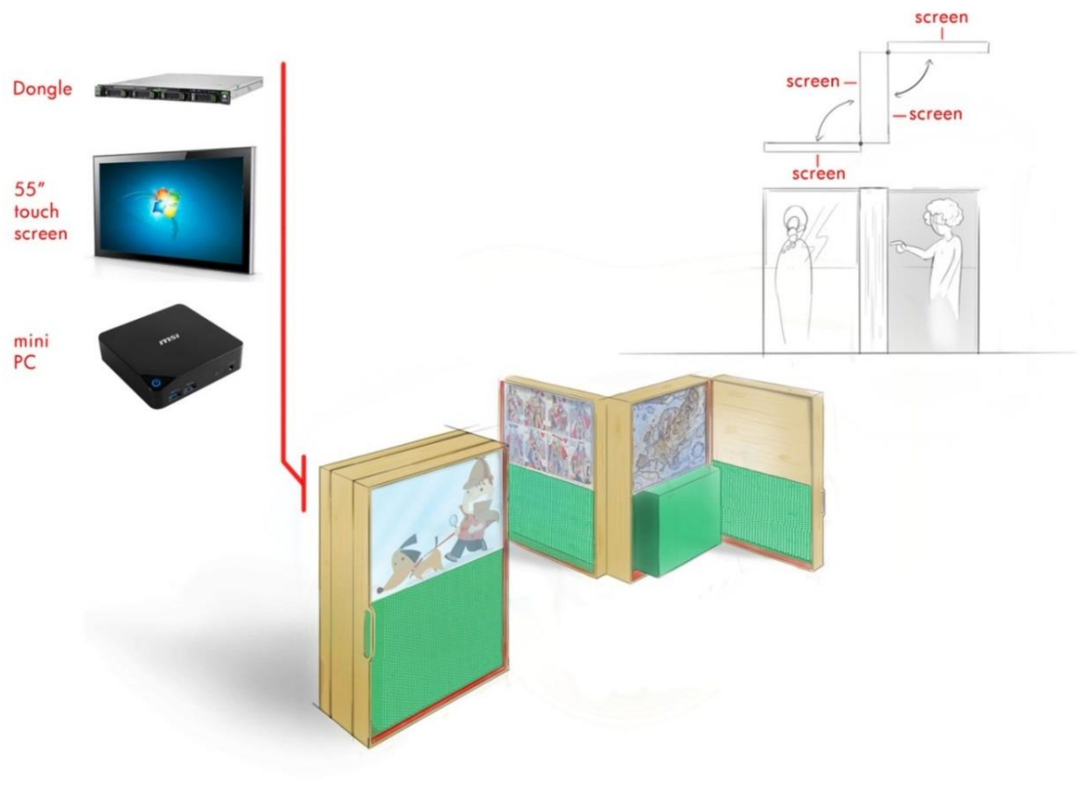


Figure 10-5 Semi Stationary Kiosk Design

Manufacturing details:

- Manufacturing techniques: Carpentry and Metal working
- Materials: Laminated wood, Steel, Aluminum
- Estimated time for manufacturing: 6-8 weeks.
- Additional components needed: 4 55" touch screen TV, 4 Mini PC
- Estimated price 5000 euro (Additional components not included)

Option C

This option is a mobile Robot-like Kiosk that is designed for interaction with a single visitor using a standard tablet in the kiosk. For the Kiosk to work we will have to buy a tablet since Arcelik has no tablets in its portfolio and ideally, we will also find a battery that can support the Dongle and tablet, so the station will be totally mobile and thus will enable its user to interact with it and with the space, moving between various IoRL lights and getting a different stream of data accordingly. For ideal usage by the museum it is preferable to have more than one kiosk at the end of the process.

Figure 10-6 Mobile Kiosk Design

Manufacturing details:

- Manufacturing techniques: Carpentry and Metal working
- Materials: Laminated wood, Steel, Aluminum, OEM wheels
- Estimated time for manufacturing: 6-8 weeks.
- Additional components needed: 4 Tablets, 4 Batteries.
- Estimated price 800 euro (Additional components not included)

10.4 Initial synthesis of system design and the manufacture capability

As the facility of Arçelik Electronic Company, we are designing Printed Circuit Boards, assembling components, configuring the user inputs and peripheral devices, designing the mechanical parts of the television sets, constructing LCD/OLED panels and Backlight Unit and we are collecting the television sets at the end of the production line in the factory. Except the electronic and mechanical design of Arçelik television sets, we are designing and developing the software stack and software modules of the television sets. Arçelik purchases electronic chips, Bare LCD/OLED Displays, Cables and Connectors from suppliers and design MainBoard, AC/DC Converter within the sources he holds.

Arçelik will be responsible from Multiple Content Display and Recording business case via Li-Fi connection in this project. We will connect to Li-Fi through USB3.0 via Cobham Dongle. While Cobham dongle handles the internet connection and high data rate communication, Arçelik TV will handle the display of incoming data which contains multiple content from multiple sources. The connection between the dongle and Arçelik TV will be provided by USB3.0. We will configure and modify our current television software to handle high data rates and to decode very big TCP/IP packages so we can drive the panel accordingly.

Appendix I Tables of Key Performance Indicators for IoRL Use Cases:

Use Case Key Performance Indicators

1. Peak data rate (10Gbps)
2. Peak Spectral efficiency (30bps/Hz down, 15bps/Hz up)
3. Bandwidth (mmW 100MHz, VLC 10MHz)
4. Control plane latency (1 to 20ms)
5. User plane latency (down/up 4ms)
6. Latency for infrequent small packets (1 to 20ms)
7. Reliability
8. Coverage
9. Area traffic capacity (50Mb/s/m2 - 1Gb/s/m2)
10. User experienced data rate (100Mbps - 5Gbps)
11. Connection density 4 -40 device/m2
12. Mobility (1m/s)

Table A-1: Key Performance Indicators of Home Use Cases

		Use case Key Performance Indicators												5G Service Type		
UC Number	UC Name	Peak data rate	Peak Spectral efficiency	Bandwidth	Control plane latency	User plane latency	Latency for infrequent small packets	Reliability	Coverage	Area traffic capacity	User experienced data rate	Connection density	Mobility	xMBB	uRLLC	Suitability Score
UC1.1	Away from Home	1Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	15ms	15ms	15ms	N/A	80dB pathloss for mmW, 90% for VLC	100Mbit/s/m^2	500Mbps	10 devices/sqrm	1m/s	Yes	NO	2
UC1.2	Welcome Home	1Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	15ms	15ms	15ms	N/A	80dB pathloss for mmW, 90% for VLC	100Mbit/s/m^2	500Mbps	10 devices/sqrm	1m/s		Yes	7
UC1.3	Multiple Contents Display and Recording	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	10ms	10ms	10ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	5Gbps	4 devices/sqrm	1m/s	Yes		6

UC1.4	Broadband Office in the Home	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	5Gbps	4 devices/sqrm	1m/s		Yes	7
UC1.5	Virtual Reality Tourism from your Living Room	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	5Gbps	4 devices/sqrm	1m/s		Yes	8
UC1.6	Real Time Gaming	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	5Gbps	4 devices/sqrm	1m/s		Yes	8
UC1.7	Follow me video watching experience in transit between rooms	1Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	10ms	10ms	10ms	N/A	80dB pathloss for mmW, 90% for VLC	100Mbit/s/m^2	500Mbps	4 devices/sqrm	1m/s	Yes		5
UC1.8	Follow me HiFi listening experience in transit between rooms	1Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	20ms	20ms	20ms	N/A	80dB pathloss for mmW, 90% for VLC	100Mbit/s/m^2	500Mbps	4 devices/sqrm	1m/s	Yes		3
UC1.9	Secure Home using Outside Monitoring	1Gbps	30bps/Hz DL, 15bps/Hz	100MHz for mmW	20ms	20ms	20ms	N/A	80dB pathloss for	100Mbit/s/m^2	500Mbps	4 devices/sqrm	1m/s	Yes		5

			UL	and 10MHz for VLC					mmW, 90% for VLC							
UC1.10	Broadband Media Handover in Home	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	5Gbps	4 devices/sqrm	1m/s		Yes	7
UC1.11	Assisted Living	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	5Gbps	4 devices/sqrm	1m/s		Yes	7
UC1.12	Eves Dropping and Rogue VLC Transmitter Security Threats	500Mbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	50Mbit/s/m^2	100Mbps	4 devices/sqrm	1m/s		Yes	1

Table A-2: Key Performance Indicators of Museum Use Cases

		Use case Key Performance Indicators												5G Service Type		
UC Number	UC Name	Peak data rate	Peak Spectral efficiency	Bandwidth	Control plane latency	User plane latency	Latency for infrequent small packets	Reliability	Coverage	Area traffic capacity	User experienced data rate	Connection density	Mobility	xMBB	uRLLC	Suitability Score
UC2.1	Children's Treasure Hunt	500Mbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	50Mbit/s/m^2	100Mbps	4 devices/sqrm	1m/s		Yes	5
UC2.2	Updating Information System for Exhibits in the Exhibition Hall	500Mbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	50Mbit/s/m^2	100Mbps	4 devices/sqrm	1m/s		Yes	5
UC2.3	Navigation Guide and Information System on Visitors' Activities in Museum	500Mbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	50Mbit/s/m^2	100Mbps	4 devices/sqrm	1m/s		Yes	5

UC2.4	Exploring Current and Past Museum's Expositions in the Restaurant or Externally	2Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	500Mbit/s/m^2	1Gbps	4 devices/sqrm	1m/s		Yes	5
UC2.5	Handover between Different Areas of the Museum Building	2Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	500Mbit/s/m^2	1Gbps	4 devices/sqrm	1m/s		Yes	5
UC2.6	Rogue VLC Transmitter Placement and Denial of Service Attacks	500Mbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	50Mbit/s/m^2	100Mbps	4 devices/sqrm	1m/s		Yes	1

Table A-3: Key Performance Indicators of Tunnel Use Cases

		Use case Key Performance Indicators												5G Service Type		
UC Number	UC Name	Peak data rate	Peak Spectral efficiency	Bandwidth	Control plane latency	User plane latency	Latency for infrequent small packets	Reliability	Coverage	Area traffic capacity	User experienced data rate	Connection density	Mobility	xMBB	uRLLC	Suitability Score
UC3.1	Accurate location and information provision under tunnel premises	1Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	100Mbit/s/m^2	50Mbps	10devices/sqrm	1m/s		Yes	7
UC3.2	Tunnel video conference communication	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	100Mbps	4 devices/sqrm	1m/s		Yes	8
UC3.3	Carbon monoxide and smoke detection in tunnels	1bps0Gbps	30bps/Hz DL, 15pbs/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	10Mbps	40 devices/sqrm	1m/s		Yes	1

UC3.4	Instant information and ultra-high bandwidth downloading	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	50Mbps	10 devices/sqrm	1m/s		Yes	7
UC3.5	Ticket purchase and validation	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	10Mbps	10 devices/sqrm	1m/s		Yes	5
UC3.6	Emergency videoconference communication	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	50Mbps	10 devices/sqrm	1m/s		Yes	8
UC3.7	Train occupancy	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	10Mbps	40 devices/sqrm	1m/s		Yes	1
UC3.8	Commercial Signage	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	20ms	20ms	20ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	50Mbps	10 devices/sqrm	1m/s	Yes		3
UC3.9	Passenger Usage Analysis	10Gbps	30bps/Hz DL, 15bps/Hz	100MHz for mmW	1ms	4ms	1ms	N/A	80dB pathloss for	1Gbit/s/m^2	50Mbps	10 devices/sqrm	1m/s		Yes	6

			UL	and 10MHz for VLC					mmW, 90% for VLC							
UC3.10	Rogue VLC Transmitter Placement and Denial of Service Attacks	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	10Mbps	40 devices/sqrm	1m/s		Yes	1

Table A-4: Key Performance Indicators of Supermarket Use Cases

		Use case Key Performance Indicators												5G Service Type		
UC Number	UC Name	Peak data rate	Peak Spectral efficiency	Bandwidth	Control plane latency	User plane latency	Latency for infrequent small packets	Reliability	Coverage	Area traffic capacity	User experienced data rate	Connection density	Mobility	xMBB	uRLLC	Suitability Score
UC4.1	Preparing a Shopping List	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	10Mbps	40 devices/sqrm	1m/s		Yes	1
UC4.2	Store Guide and Route from Shopping List	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	50Mbps	10 devices/sqrm	1m/s		Yes	5
UC4.3	Highlighting Product Features on Shelves	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	50Mbps	10 devices/sqrm	1m/s		Yes	5

UC4.4	Monitoring Baby in the Nursery	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	500Mbit/s/m^2	100Mbps	4 devices/sqrm	1m/s		Yes	8
UC4.5	Viewing Cartoons for Children on Shopping Cart Chair	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	50Mbps	10 devices/sqrm	1m/s		Yes	7
UC4.6	Virtual Shopping for the Disabled via the Carer	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	50Mbps	10 devices/sqrm	1m/s		Yes	8
UC4.7	Promoting the Sales of Products	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	50Mbps	10 devices/sqrm	1m/s		Yes	6
UC4.8	In Shop and Personalized Advertisements	10Gbps	30bps/Hz DL, 15bps/Hz UL	100MHz for mmW and 10MHz for VLC	1ms	4ms	1ms	N/A	80dB pathloss for mmW, 90% for VLC	1Gbit/s/m^2	50Mbps	10 devices/sqrm	1m/s		Yes	6
UC4.9	Rogue VLC Transmitter and Denial of Service	10Gbps	30bps/Hz DL, 15bps/Hz	100MHz for mmW	1ms	4ms	1ms	N/A	80dB pathloss for	1Gbit/s/m^2	50Mbps	10 devices/sqrm	1m/s		Yes	1

	Attacks		UL	and 10MHz for VLC					mmW, 90% for VLC							

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