A 5G Radio-Light SDN Architecture for Wireless and Mobile Network Access in Buildings

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***Abstract*— The Internet of Radio-Light architecture provides both direct WLAN type access to the Internet using 5G RAN as well as access to the Internet via Mobile Networks using a 5G mmWave and VLC Radio Access Network (RAN) within buildings. A SDN is used to manage the various different packet flows between the RAN, the Internet Interface and the Mobile Network User and Control plane interfaces for SmartPhone, Tablet PCs, HDTVs and Virtual Reality headsets within buildings.**

***Index Terms* — 5G, VLC, mmWave, NFV, SDN.**

I. Introduction

Mobile data growth is forecast to have a 53% compound annual growth rate from 2015 to 2020 [1] and 80% of this is generated indoors and is growing 20% faster each year than outdoor wireless traffic [2] [3].

This growth has been driven by the use of smartphones, which have benefited from wireless networks because they let users perform a variety of tasks with Internet access ranking as one of the most important. The Internet allows users to check their mail, surf the web and download multimedia content. While Mobile Network Operators (MNOs) provide Internet access through their outside data networks, smartphones can also connect to Wireless Local Area Networks (WLAN) building networks. It is customary now when people enter building that they search for the most convenient wireless network from which they can access the Internet from their smart phones and when they leave the building they switch to using the mobile network. The Smart Phone user simply locates an open wireless network usually found in buildings such as coffee shops, hotels, airports, train stations and libraries, which can be either an Open Wireless Network or accessed via a password that is made available by the building's staff. Commercial organizations like these often feature free WLAN Internet for customers to promote business. Smart Phone users like using WLAN network whenever one is available because Internet access is faster and free. Also it does not consume their monthly data limits set by their Mobile MNO contract.

This increased use of WLAN communications in buildings is causing congestion and interference, whilst modern building materials are restricting the propagation of Radio Frequency (RF) waves within them. Therefore building owners have been increasingly turning to the deployment of cellular home networks (HeNBs) in their buildings because they operate in licensed spectrum that can avoid interference and congestion. Unfortunately these deployments require the permission of MNOs due to their potential to interfere with the main transmitted signal from the main mobile network (eNB). However MNOs have only had the capacity to analyse their largest customers' deployment requests thereby losing a large market opportunity. The result is fewer than 2% of commercial and public buildings are currently covered by dedicated wireless indoor solutions [4]. The introduction of a commercial and public buildings network solution for mobile networks could have an enormous impact on this market.

WiGig Wireless LAN IEEE 802.11ad technology is a backwards-compatible extension to the IEEE 802.11-2012 specification that adds a new MAC/PHY to provide short range, high capacity links in the 60 GHz unlicensed band. It could be considered as an interesting technical solution for Wireless Building networking protocol as it has been rapidly evolving to support the increasing demand for high data rates, with the standard providing 6.7 Gb/s using GHz of bandwidth at 60 GHz mmWave frequencies [5]. In current Wi-Fi systems, interworking between WiGig and LTE/LTE-A systems is not supported, although it is badly needed due to users' frequent mobility between the coverage areas of Wi-Fi access points and mobile networks. Therefore the solution, as proposed by [6], could be used to manage handovers between mobile network and the WiGig Home Network and between the different rooms within the WiGig Home Network. However the benefit of using 5G for buildings is that its multi-component carrier architecture allows for combining VLC and mmWave physical layer to provide higher bandwidths. The bimodal nature of visible light and mmWave channels depending on the presence or absence of line-of-sight allows buildings to be easily subdivided into rooms/floors cellular areas thereby increasing the total bitrate that can be provided to buildings. It can be seamlessly integrated with the wider 5G network with inter gNB and Home gNB handover.

Internet of Radio-Light project provides this 5G solution to the problem of broadband wireless access in buildings by developing a 5G Radio-Light multi-component carrier, Frequency Division Duplex (FDD) broadband system for buildings, consisting of a VLC downlink channel in the unlicensed THz visible light spectrum and mm Wave up/downlink channels in unlicensed 30-300 GHz spectrum, which allows wireless communication networks to be deployed in buildings without MNO approval that can provide bitrates greater than 10Gbits/sec, latencies of less than 1ms, location accuracy of less than 10cm, whilst reducing EMF levels and interference, lowering energy consumption at transmitter/receiver and increasing User Equipment (UE) energy battery lifetime.

II. System Architecture

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 1. It is an architecture that is more akin to a Radio-Light Home eNodeB suitable for a single building network rather than an EPC suitable for a whole country [7]. 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.

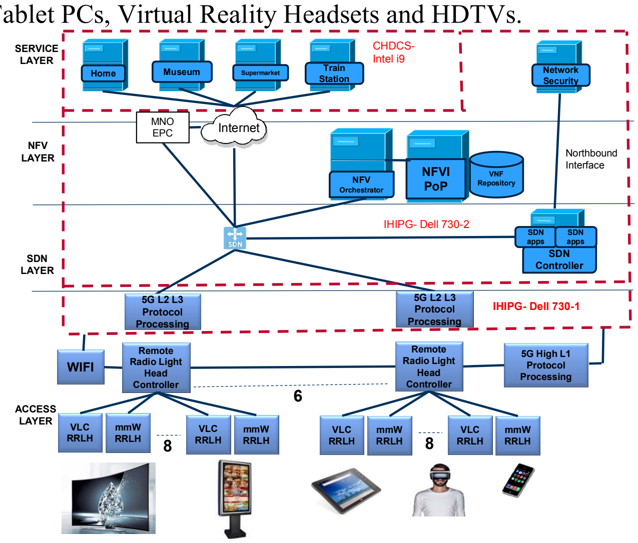

Figure 1: IoRL Layered Architecture

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 Internet or 5G Network Interfaces connected to the SDN Controller. The Network Function Virtualisation Orchestrator (NFVO) invokes various virtual functions required for an Intelligent Home IP Gateway (IHIPG) such as Access & Mobility Management, Deep Packet Inspection and Network Security Functions.

The Access Layer Radio Access Network (RAN) consists of six RRLH Controllers. Each RRLH Controller drives up to eight VLC and mmWave 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 area of a building. The 5G Layer 1, 2 and 3 processing is performed remote from RRLH at the IHIPG and at FPGA located in the RRLH Controllers.

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 via the Internet 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.

In IoRL project, the positioning system consists of two parts: VLC-based positioning system and mmWaves-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.

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.

In the mmWave positioning system, the UE is a transmitter and Multiple lamps (RRLHs) located at a priori known positions receive a signal transmitted from the UE at different times depending on distance. The RRLH controller performs measurements and estimates location relevant signal parameters using time-difference of arrival (TDOA) between different RRLHs. Combining a 10 MHz GPS synchronization clock with a 10 GHz Ethernet Bus clock could provide location accuracy of between 3cm to 6cm.

The user equipment (UE) design is similar to the RAN design described in Section above but using one RF chain of the RAN and clearly with much less computer processing power.

III. Software Defined Network Architecture

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.

The NFV Orchestrator (NFVO) is the top-level management entity of the IHIPG domain. The NFVO is the orchestration entity, which is responsible for the management

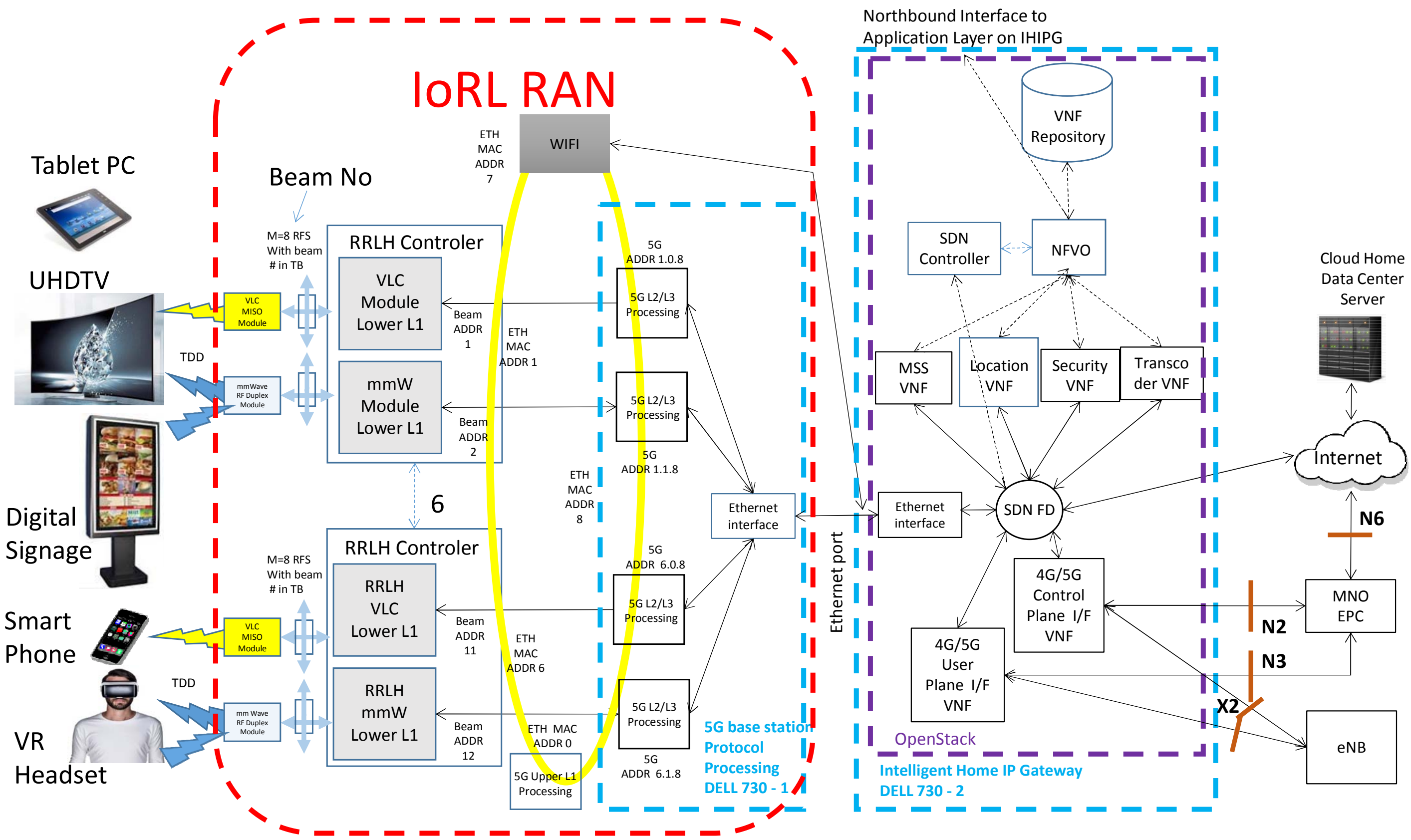

Figure 2: NFV/SDN Architecture - Note: All VNFs can have connections to SDN Controller and NFVO (sometimes not shown)

of the Network Service (NS) lifecycle, which includes NS instantiation, dimensioning and termination.

The NFVO 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 NS descriptors, which initiates the VNF instantiation with the appropriate network configuration internally in the IHIPG, which acts as a NFV Infrastructure (NFVI) Point of Presence (PoP).

The main role of the SDN is to route IP packets within Ethernet MAC frames to/from the 5G L3 & L2 Processing cores in the IHIPG depending on which RRLH Controller coverage area the UE is located and to/from Internet Bridge, 4G/5G Control Plane Interface and 4G/5G User Plane Interface depending on whether the IP Packets are Internet packets, 4G/5G Control packets or 4G/5G User packets, respectively. In the special case of video streaming, the SDN forwarding device is used to simultaneously route both higher and lower quality video streams to RRLH Controllers 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. Virtual Network Functions are used for transcoding the original high resolution video into lower resolution for transmission over the WLAN.

A. Internet Access

For direct Internet access, IP addresses are used by the L3 (Network layer) for end-to-end addressing. In the IoRL system for example, IP addresses of the UE device are used by the user web server in the Internet, for example www.google.com. Except the usage of Network Address Translation (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 is performed on the dedicated machine (DELL R730-1) and 5G L1 processing on dedicated FPGAs and circuits, which are 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 control or user data plane.

The control plane for Internet interface is local to the UE and RAN and is fixed with a single radio bearer within a single Protocol Data Unit (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 mmWave) which forwards this packet further.

Figure 3 presents an Ethernet frame which is sent from "5G L2 processing" unit to the SDN FD when the user UE located within the RRLH1 Controller's coverage area sends data to the Google search engine.

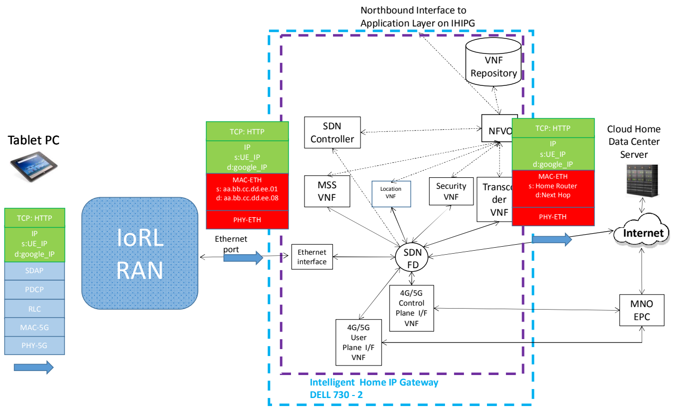

Figure 3: Ethernet frame to the SDN FD when the UE located below the RRLH1

Figure 4 presents the response packet from the Google web server which is sent to the appropriate VLC or mmWave module MAC address.

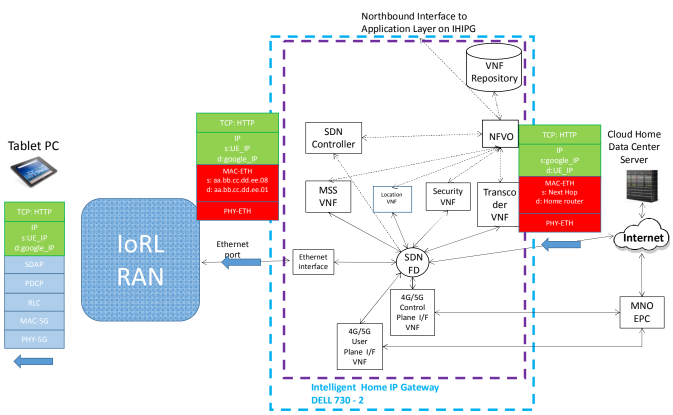

Figure 4: Response Ethernet frame from the SDN FD to UE located below the RRLH1

B. Intra Building gNB Handover with Internet Access

VLC and mmWave location estimation algorithms at the UE continuously report their location to the nearest 10cm to a Location Service linked to the SDN Controller.

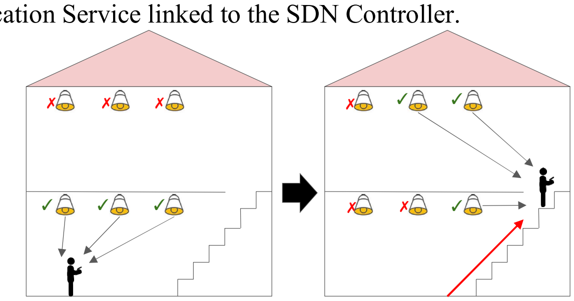

Figure 5: Intra Building Handover

Intra building handover between rooms or floors of a home network is either 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 at SDN Level by performing a handover between RRLHs depending on the measured location of the UE, as shown in Figure 5.

When, in the presented example, the user changes his location to e.g. the location with the RRLH 6 Controller's coverage area, the source MAC address of the Ethernet frame at changes. Now it is associated with the RRLH6 VLC or mmWave module, which later allows for appropriate routing of the frames. This situation is presented in the Figure 6.

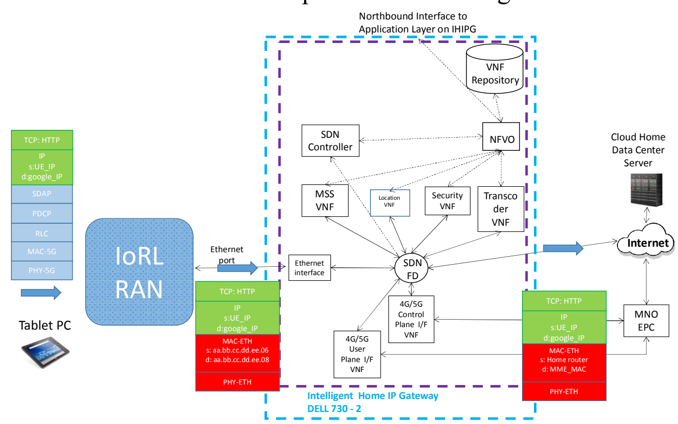

Figure 6: Ethernet frame to the SDN FD when the UE located below the RRLH6

C. Mobile Network Access

The IoRL 5G system control plane protocol flow is shown in Figure 7 and Figure 8. 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 Non-Access Stratum (NAS) data generated at the UE. In the EPC side, all packets destined to or sourced from EPC use single MAC address (EPC_MAC) via N2 interface. The addresses to or from the RAN part is associated with the exact RRLH or used module (VLC or mmWave) which forwards this packet further.

Figure 7 presents an Ethernet frame which is sent from "5G L2 processing" unit to the SDN FD when the user UE located within the coverage area of the RRLH1 sends data to EPC.

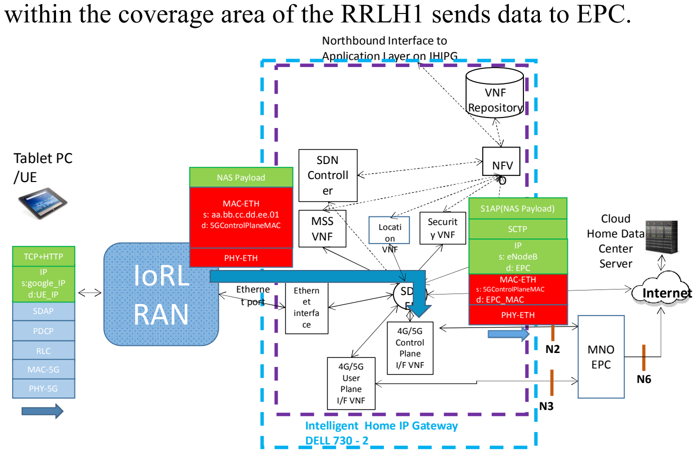

Figure 7: 5G system control plane protocol flow (Uplink)

Figure 8 presents the response packet from EPC server which is sent to the appropriate VLC or mmWave 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 mmWave module, which later allows for appropriate routing of the frames.

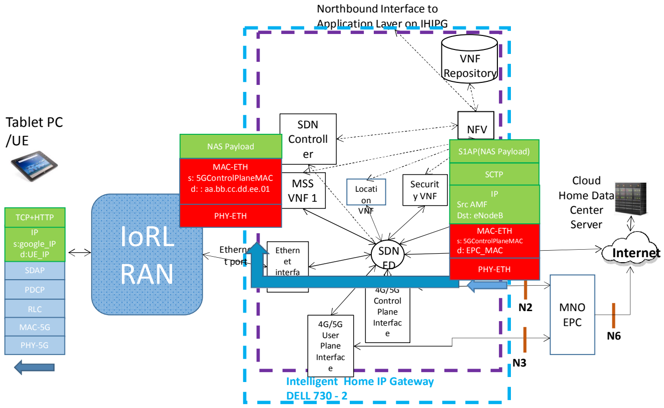

Figure 8: 5G system control plane protocol flow (Downlink)

The IoRL 5G system user plane protocol flow is shown in Figure 9 and Figure 10. 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 (S-GW_MAC) that is characteristic for the EPC User Plane Function (UPF) via N3 interface. The addresses to or from the RAN part is associated with the exact RRLH or used module (VLC or mmWave) which forwards this packet further.

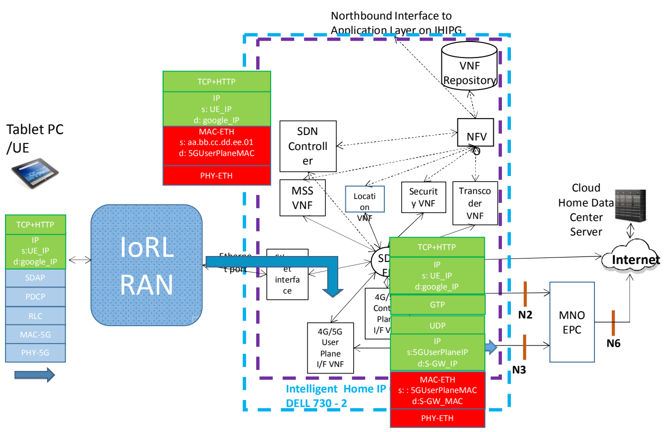

Figure 9: 5G system user plane protocol flow (Uplink)

D. Intra Building gNB Handover with Mobile Network Access

Figure 9 presents an Ethernet frame, which is sent from "5G L2 processing" unit to the SDN FD when the user UE located the coverage area of RRLH1 Controller sends data to EPC.

Figure 10 presents the response packet from EPC server which will be sent to the appropriate VLC or mmWave module MAC address. When, in the presented example, the user changes his location to e.g. the location within the coverage area of RRLH 6 Controller the source MAC address of the Ethernet frame at changes. Now it is associated with the RRLH6 VLC or mmWave module, which later allows for appropriate routing of the frames.

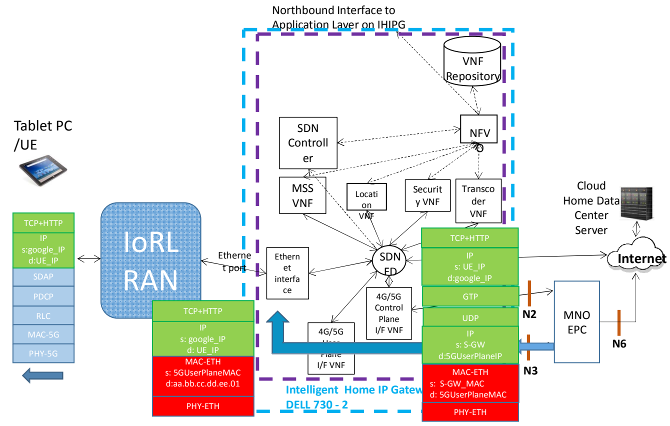

Figure 10: 5G system user plane protocol flow (Downlink)

E. Inter Home gNB and Outside Network gNB Handover with Mobile Network Access

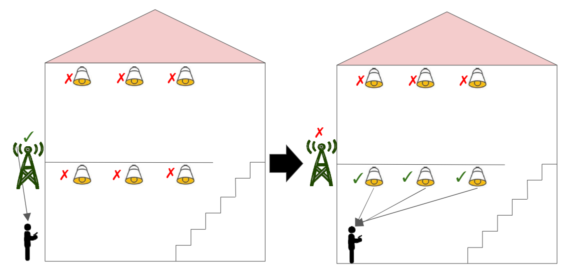

Figure 11: Outside to Inside Building Handover

In the case of inside IoRL (source) to outside gNB (target) handover, as shown in Figure 11, 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 gNB on the X2 interface, as shown in Figure 12.

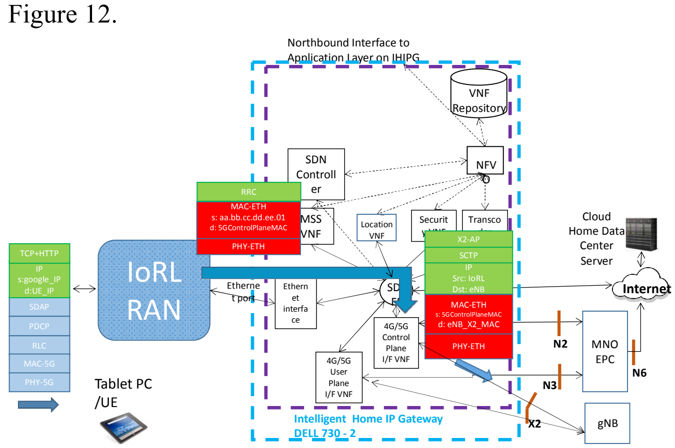

Figure 12: Control Plane protocol Flow IoRL to gNB Handover (Uplink)

Any subsequent user plane packets that are misdirected to the IoRL network then gets redirected to the target gNB over the X2 interface, as shown in Figure 13.

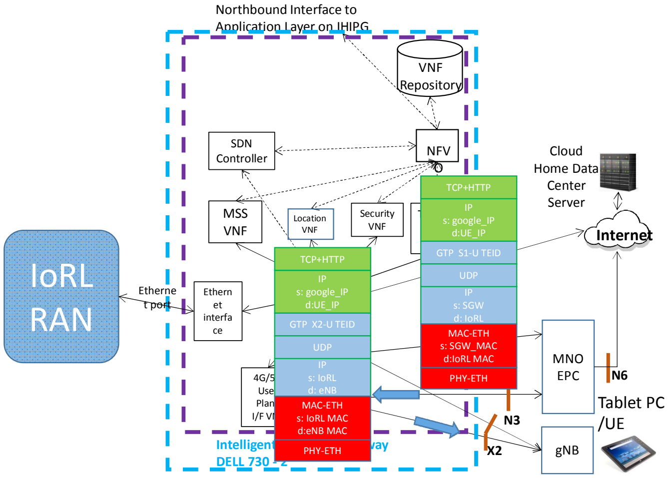

Figure 13: User Plane protocol Flow IoRL to gNB Handover

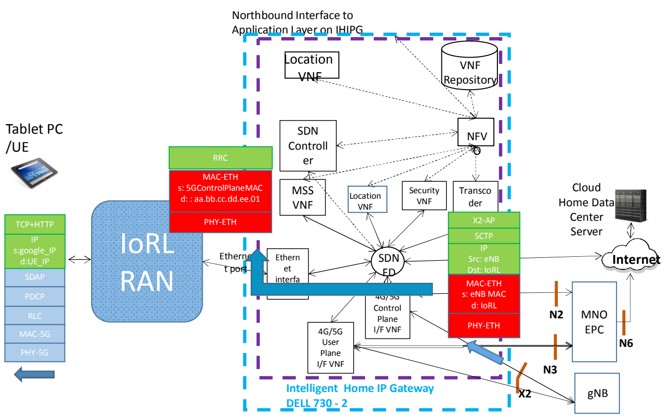

Figure 14: Control Plane protocol Flow gNB to IoRL Handover

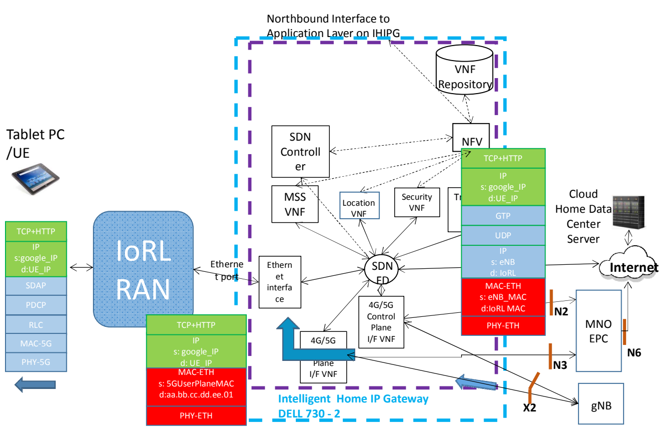

Figure 15: User Plane protocol Flow gNB to IoRL Handover

In the case of outside 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 gNB to the IoRL RAN on the X2 interface, as shown in Figure 14.

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 15.

IV. Conclusions

This paper presents an architecture that provides both direct WLAN type access to the Internet using 5G RAN as well as access to the Internet via Mobile Networks using a 5G mmWave and VLC Radio Access Network (RAN) within buildings. A SDN is used to manage the various different packet flows between the RAN, the Internet Interface and the Mobile Network User and Control plane interfaces for SmartPhone, Tablet PCs, HDTVs and Virtual Reality headsets within buildings.

From the operator's point of view the presented architecture 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 mmWave instead of their spectrum as an access mechanism to the network; however it will support larger number of users only by allowing the IHIPG to be connected to their systems and being registered with MNOs.

From the UE point of view, it will improve user experience as a user registered with one MNO by experiencing better coverage via VLC and mmwave 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. It will also allow the UE to obtain direct WLAN type access to the Internet using 5G RAN.

Acknowledgment

The authors gratefully acknowledge the European Commission for its financial support on the Horizon 2020 Internet of Radio-Light (IoRL) project No: 761992.

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