Internet of Radio-Light: 5G Broadband in Buildings

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***Abstract*— Wireless networks in buildings suffer from congestion, interference, security and safety concerns, restricted propagation and poor in-door location accuracy. The Internet of Radio-Light (IoRL) project develops a safer, more secure, customizable and intelligent building network that reliably delivers increased throughput (greater than 10Gbps) from access points pervasively located within buildings, whilst minimizing interference, power consumption and harmful EM exposure and providing location accuracy of less than 10 cm. It thereby shows how to solve the problem of broadband wireless access in buildings and promotes the establishment of a global standard in ITU and 5GPPP. Building landlords will be incentivized to find funding to realize this solution for their properties to increase their value resulting in a stimulated market for broadband networking products in buildings, benefiting society and stimulating the world Gross Domestic Product. IoRL project provides solutions to develop this broadband networking solution in buildings using the existing joint VLC demonstrator at Tsinghua University & ISEP, the mmWave at Cobham Wireless and the NFV/SDN at NCSR-Democratos. The challenges are to develop broadband communication solutions for buildings by integrating these technologies to exploit the pervasiveness and accessibility of the existing electric light access points, the broadband capacities of mmWave and VLC technologies and the flexibility of SDN/NFV and to industrially design a radio-light solution that can be integrated into the myriad of form factors of existing electric light systems and consumer products.**

Keywords—Visible Light Communications; Millimeter Wave Communications; Software Defined Networks; Network Function Virtualisation; Networks in Buildings.

I. INTRODUCTION

The increased use of Wireless Local Area Networks (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 Mobile Network Operators (MNOs) due to their potential to interfere with the main transmitted signal from the main mobile network (eNB). However MNOs only have the capacity to analyse their largest customers' deployment requests thereby losing a large market opportunity. To complicate matters further, each building requires a HeNB deployment for each MNO that is providing coverage for it, which is very costly and inconvenient for the building owner. The IoRL project solves this problem by providing a broadband radio-light communications solution that operates in unlicensed millimeter wave and visible light spectra, does not suffer from interference because of the propagation characteristics of EM waves in this part of the spectrum and provides universal broadband coverage within buildings from radio-light access points that are pervasively located within the light roses in buildings. This technology can also be applied to other indoor environments such as Tube Stations, Underground Pedestrian tunnels etc.

The challenge that is addressed by IoRL project is to design Remote Radio Light Head (RRLH) electronics that can be elegantly integrated into the myriad of different types of electric LED lighting systems. The main benefit is the availability of broadband communications services greater than 10Gbits/sec ubiquitously available throughout buildings from pervasively located radio-light RRLH access points situated within light roses. A further benefit is that user equipment can be located to an accuracy of less than 10cm. Designing the radio-light communication system to fit into the confined space of a light rose requires a Network Function Virtualisation (NFV) solution, whose cloud computers can be variously located remote from the radio-light access points elsewhere in the Home Cell Site or in the external Cloud network, and a Software Defined Network (SDN) to intelligently manage and route data to the different parts of the radio-light network. Consequential benefits of this architecture are that its common building electric light network resources can be more easily shared between MNOs by network slicing and that the NFV solution provides an Application Programmers Interface (API), which allows third party service providers to write specialized network applications to manage multi-MNO networks in homes, businesses and public space buildings and environments such as tunnels, train stations and airports. IoRL project also significantly benefits 5G MNOs because it considerably reduces EM interference, which would have otherwise been generated by Home eNodeBs thereby increasing throughput in the wider 5G mobile network and improves mobile access to users within buildings without incurring interference with the wider 5G mobile network, thereby increasing the value of their customers' buildings.

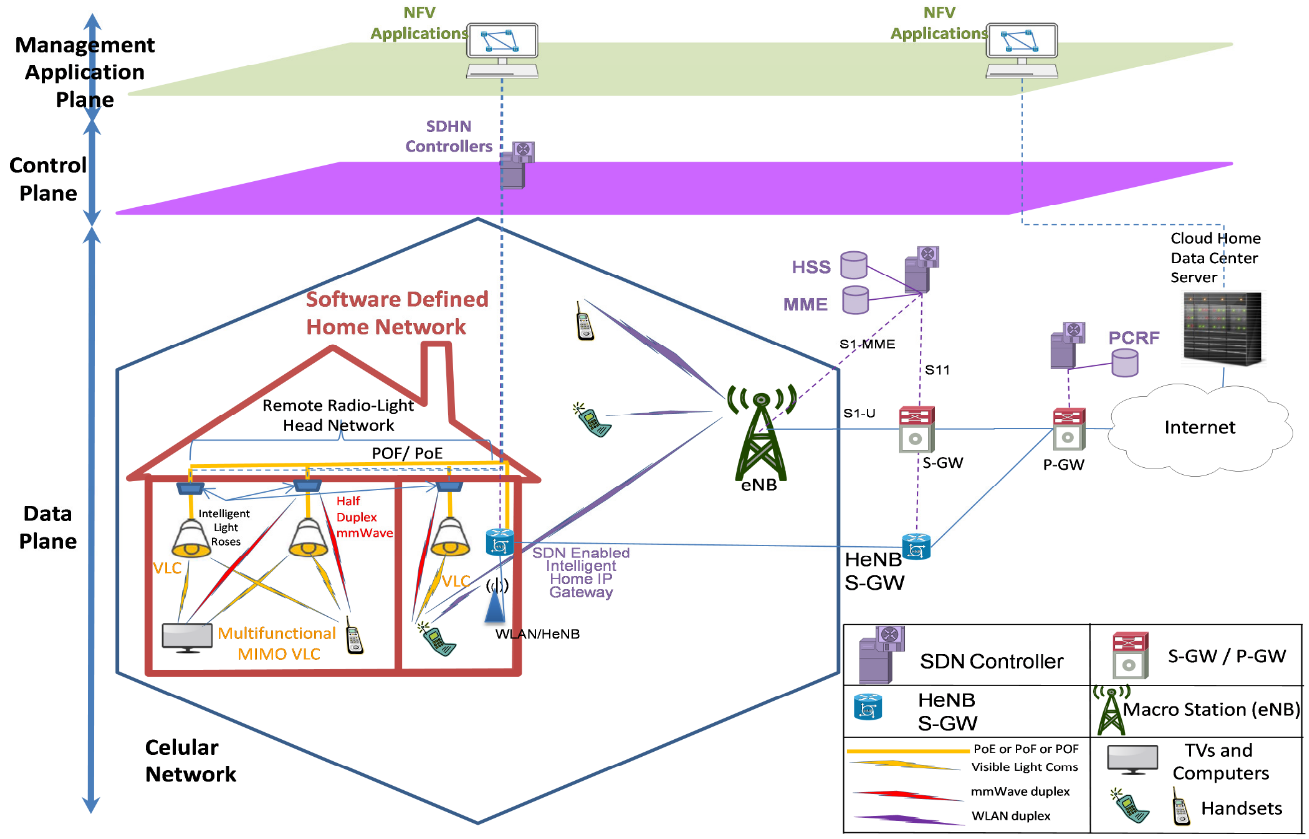

Figure 1 Software Defined Home Network Architecture

The net result is that there will be a considerable reduction of transmission power and EMF radiation levels, so the user equipment will potentially require to consume 10 times less energy, which would result in 90% energy savings, and a ten times increase in battery lifetime during use in buildings. The combined effects of a reduction in delay spread, due to smaller room geometries, the adapted 3GPP 5G transmission frame approach and the considerable reduction in propagation delays, is expected to result in a reduction in latency to within 1ms. 5G mobile network users will significantly benefit because they will have the choice of a wider range of network services from third party network and home services providers, who for example could provide substantially higher bit rates using RRLH in in-door environments, whilst also significantly reducing the level of EM exposure.

II. Network Architecture

The IoRL project's Software Defined Home Network (SDHN) Architecture, shown in Figure 1**Error! Reference source not found.**, not only allows network service developers to write Security Monitoring, Energy Saving, Location Sensing, Network Slicing, Lights Configuration, Video and Network Transport Configuration and Network Security applications but also provides the means to locate network operations and management functions between the Intelligent Home IP Gateway (HIPG) and the Cloud Home Data Centre (CHDC) server in a configurable way to meet the different OPEX and CAPEX needs of different MNOs. The concept of Network Function Virtualisation (NFV) will be applied to the VLC and mmWave RANs to off-load the complexity of the electronic systems required in the RRLH onto the CHDC or Intelligent HIPG because of the very confined space available in Light Rose housings. The design of strategies for configuring the video streams to be transported with different percentage proportions over the different available home networks and paths (WLAN, HeNB, VLC, mmWave etc.) is an important consideration for maintaining continued service connectivity in the presence of many Line of Sight (LoS) radio transmission paths. The SDHN will be realized from Open Flow enabled network elements: Home IP Gateway and Remote Radio-Light Head; by enhancing them with OpenFlow capabilities.

LTE based communication protocols will be used for providing a radio-light broadband indoor femto cell as an mmWave physical layer has been proposed with a 6.67ms OFDM Symbol duration, 200 MHz channel bandwidth per component carrier and a Bit rate @ 64-QAM of 0.96 Gbits/second [Zhe15]. Carrier aggregation that can combine up to five 200 MHz inter-band, contiguous and non-contiguous component carriers [Wan13] distributed between different mmWave bands can thereby provide 4.8 Gbit/sec bit rate. This could be extended beyond five component carriers to allow more than 10 Gbit/sec bit rate. Handover procedure consisting of hand-in, hand-out and inter-Femto handovers, which is based on 3GPP LTE specification and was reported in [Ulv10], could be considered for handover between radio-light broadband indoor femto cells in each room of a building. Since 3GPP 5G approach is the most advanced technology today and supports broadband, IOT and Ultra-Reliable and Low-Latency Communications (URLLC) with real support of networking, NFV etc. and no need to change operator while at home, it will most likely be adopted in the project.

The IoRL project will develop an API in its open source development environment to allow third party software developers to write management plane applications that adapt the operation of the Intelligent HIPG and NFV servers and use Meter, Flow and Group Tables data to tailor a range of resource management services for the needs of their different classes of customers e.g. commercial, industrial, residential.

The benefit of a RRLH wireless access networks is that it does not interfere with a range of different wireless systems in the home, namely: electronic equipment such as microwave ovens, cordless phones, wireless headsets, Zigbee, Z-Wave, Bluetooth devices, surveillance cameras and other wireless radio networks. Furthermore, since each room in a building contains one or more light roses accessed by already existing electrical conduit systems, transmission of the communication signal to all rooms in the building can easily be achieved, thereby overcoming the constraints to radio propagation within a building resulting from the use of metal clad thermal insulation and metalized windows.

The home network will consist of a plastic optical fibre (POF) or a power over Ethernet (PoE) wireline networks to distribute IP packets throughout a building to RRLH access points. Since RRLH home communications does not interfere with the main transmitted mobile signal, their deployment will no longer require the permission of MNOs, so MNOs will be able to quickly provide indoor mobile service to all homes and businesses as opposed to only their larger business clients as is currently the case.

IoRL will investigate the reuse of the same baseband (BB) MAC Layer Transport Blocks of 5G 3GPP New Radio (NR) RAN using the OFDMA based flavour (that will have high subcarrier spacing and lower Cyclic Prefix (CP) that may be good for the VLC channel) with all the adaptation of supporting the same NR RAN, and adding some improvements/adaptation for the VLC case. This may simplify and reduce prices of the terminals and the Access Point or network in case of Virtualization. The VLC will be only another carrier or component carrier frequency.

The OFDMA and the NR 5G will enable us to have a more reliable communication (due to adaptive bandwidth transmission, resource blocks etc. in the presence of the highly directional beam etc.) and better transmission granularity packet size, better management/coordination of interference etc. It will enable the use of the aggregation concept for different transmissions coloured at the same time, the use of the Energy Efficient Full Dimension (eFD)-MIMO (Massive multi-user MIMO mainly) and all the capability to support different types of vertical communications (Energy Efficient Mobile Broadband (eMBB), Ultra-Reliable and Low-Latency Communications (URLLC), Internet of Things – Machine Type Communications (IOT-MTC). In IoRL we may investigate the aggregation of VLC with mmWave transmissions.

III. Remote Radio-Light Head Architecture

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 mmWave and VLC multifunctional MIMO networks integrated within remote light roses, as shown in Figure 2.

MIMO diversity requires the same data to be transmitted from different mmWave antennas / VLC LEDs at the same time thereby increasing reliability, whereas MIMO multiplexing requires different data to be transmitted from different mmWave 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 mmWave antennas / VLC LEDs to operate using different configurations of MIMO diversity and/or MIMO multiplexing.

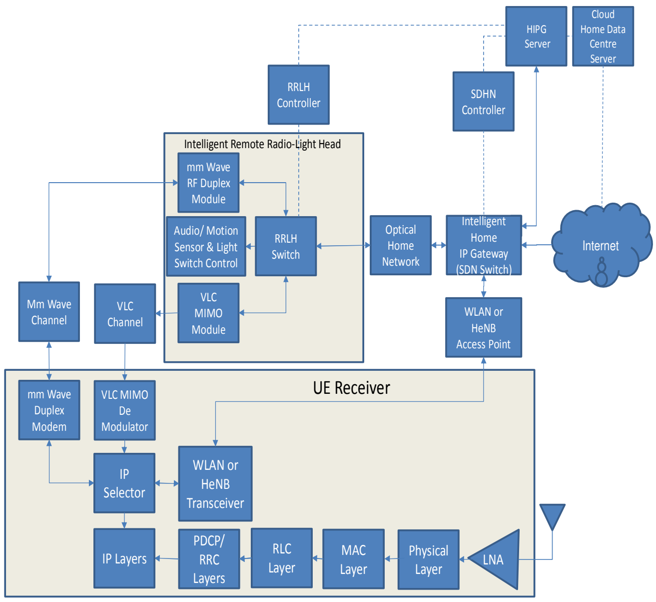

Figure 2: RRLH Architecture with External WLAN

IP packets destined for transmission over VLC network could be separately transmitted to all the RRLHs in a building using Wavelength Division Multiplexing (WDM) over POF. A sufficiently powerful signal processor on the RRLH should allow IP packets to be routed to one or more VLC MIMO modules and IP Layer processing performed on them.

The IP layer processing for packets, which are destined for transmission over the mmWave module, will need to be performed on the computationally powerful HIPG Server at the Intelligent HIPG. The HIPG could distribute the baseband signals that have been converted to IF (can be 6GHz) throughout the property using IF over POF and upconverted / downconverted at the rose head to mmWaves and/or VLC. This RF partitioning will enable a collaborative approach to be designed to cover the whole indoor space including dynamic resource allocation and aggregation between the VLC and mmWave.

Since buildings consist of only one set of lights powered by one power network, it will become the norm inside buildings for RRLH wireless networks to be required to function as a multi-operator network. In order for RRLH to function as a multi-operator network it will need to have the means of transmitting IP packets from all the network operators in a nation state. The IoRL project will develop SDHN functions to allow third party service developers to configure different types of multi-tenant SDHNs using the concept of network slicing with an API in its open source development environment under the control of a SDHN.

The IoRL project will enhance SHDTVs and Virtual Reality (VR) headsets UE architecture with Radio-Light interfaces so that third party network services can be developed for them.

IV. MMWAVE AND VLC MULTIFUNCTIONAL MIMO

In order for the radio-light network within the RRLH to transport IP packets for multi-network operators, Spatial Multiplexing MIMO is required to increase the throughput by the number of signals from RRLH antennas/luminaires in spatially different locations arriving at mmWave antenna or VLC Photo Diode (PD) image sensor receivers at UEs. In order for radio-light network within the RRLH to reliably connect to antenna and PD image sensor at UE, Spatial Diversity MIMO is required to increase the coverage of the light signals to all parts of a room.

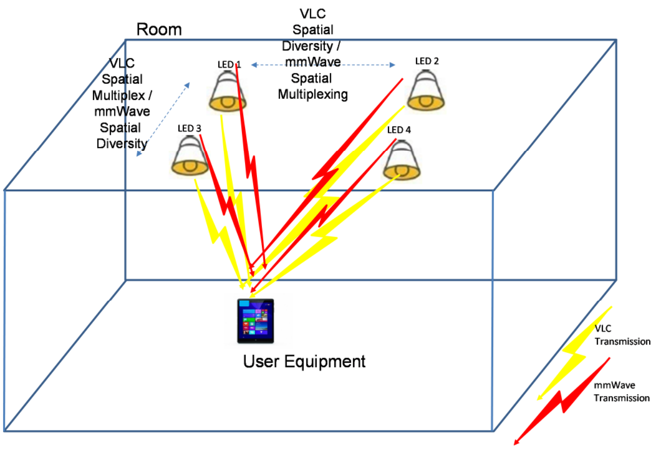

Figure 3: Exemplary Organisation of Spatial Multiplex and Spatial Diversity LED Locations in Room

IoRL project will design an API in its open source development environment to allow third party software developers to provide services that allow a mmWave / VLC Multifunctional MIMO system to combine both Spatial Multiplexing MIMO and Spatial Diversity MIMO in different ways. This will allow the number and placement of RRLHs in a room to be designed to obtain a throughput that is sufficient to support the number of network operators required to be accessed within a building and light coverage that is sufficient to support UE connectivity with multiple paths in the required locations in a room, as shown in Figure 3.

V. POF / POE HOME NETWORK

LED lights in buildings have traditionally been powered by an electric power network that can be accessed by electrical conduit system, as shown in Figure 4.

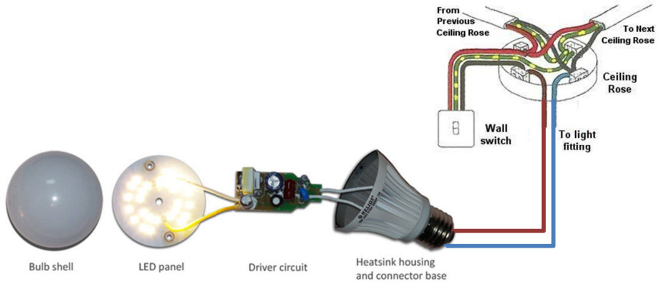

Figure 4: State of the art LED Light integrated in LED Rose

Visible Light Communications have used Power Line Communication (PLC) technique to deliver the modulated VLC signal to its LED lights [Kom04], [Gal11], [Kom03] [Son15]. However appliances such as electric motors, power supplies and radio signal interferences over power lines are the source of high noise injections in power lines, thereby making the BERs in PLC networks variable and sometimes typically high [Mel14].

Alternative approaches have kept the LED lights in buildings being powered by an electric power network and sent the modulated VLC signal to its LED lights over a separate wireline e.g. G.hn specification [ITU09] or optical fibre network e.g. Polymer Optical Fibre (POF) [Chr16]. A wireline network adjacent to a power network will simply induce unnecessary noise, which impairs its performance; therefore it is preferable to use a POF in parallel to the Power network. 100G optical transmission has been achieved over 100m GI-POF with dual-polarization and QPSK modulation transmission and Constant Modulus Algorithm with carrier and phase estimation for receiver [Sha12]. For existing buildings, whose LED lights are being powered by their existing electric power networks, there should be an option to continue its use and integrate the VLC network in the home by simply replacing the LED light rose. The Light Rose has been selected as the Radio-Light access point because it is ubiquitously located in convenient LoS access points positioned at a high and central positions in each room within buildings, which coincides with the location of the main light sources of a room.

The Ceiling Light Rose architecture will be designed to give the consumer a choice of two technologies for distributing the communications signal to the transceivers points, namely:

POF and PoE. The IoRL project will develop a broadband POF home network architecture that is interfaced to a network of RRLHs, which are integrated into the Light Roses of the light power network in the home as shown in Figure 5.

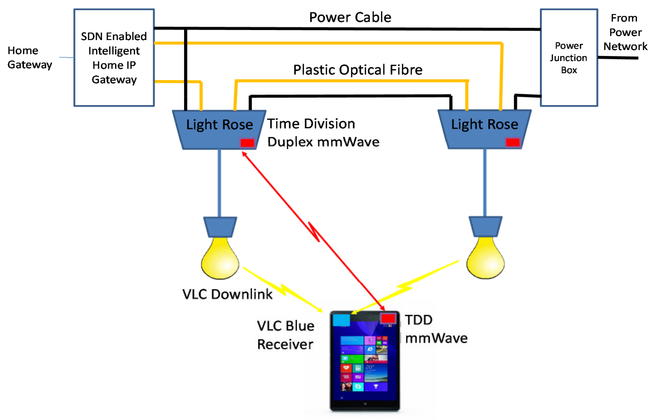

Figure 5: POF Home Network

VI. LED Ceiling Light Rose Architecture

The IoRL project will design the electronics for a generic Intelligent RRLH architecture that can be based on the traditional Pendant Light architecture, as shown in Figure 6, but which can be adapted for use in different types of light systems such as: Celling lights, Spot Lights, Strip lights, Wall lights, Chandelier lights etc.

The light rose architecture contains the AC-DC driver circuit as well as the VLC modulator and an mmWave modem circuit, see Figure 6, and requires the additional cable routing of an Optical fibre or Wireline network. Audio and Motion Sensor activated light switch could operate in parallel with a wall switch and could also allow security apps to be developed that switched lights on/off automatically for the whole house and sense if there is any audio and motion to alert intruder alarm system.

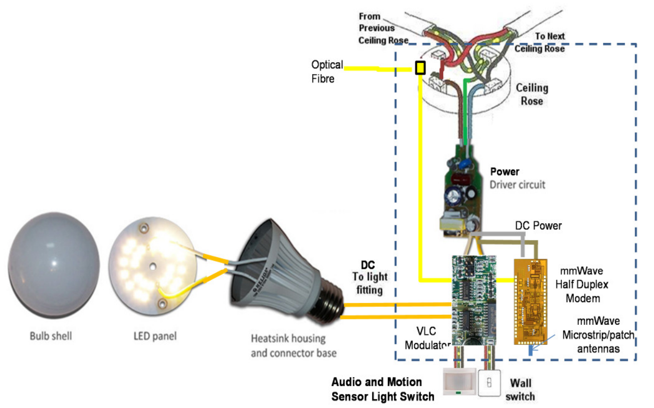

Figure 6: Beyond State of the Art POF RRLH

For new build properties the cost of implementation of a separate communication system over and above the existing electric power network is considerably high, due to the power consumption, wiring, and operation and maintenance aspects. IEEE 802.3af Power over Ethernet (POE) is a technology that lets network cables carry electrical power and data, which also has the advantage of keeping the cabling safe, no interference with concurrent network operation and requiring a much simpler Light Rose architecture since it obviates the need for a LED AC/DC power driver.

VII. Indoor Location Sensing Architecture

The IoRL project will use VLC combined with mmWave location methods to compute the positions of the UEs relative to the RRLHs to within 10 cm of accuracy and will assess from defined user and technical requirements candidate audio and motion sensing technologies for determining room occupancy detection to control the state of the lights for energy saving purposes under SDHN management.

An unidirectional VLC (without uplink) can be used as an indoor location system [Liu08] to obtain UE locations in-buildings to the nearest RRLH, namely: 2 to 3 meters depending on the size of the light spot or beam size; as opposed to 35- 50 meters using WLAN triangulation [Par16]. The mobile devices can determinate their position inside a building by detecting the ID received from each light and knowing in advance the map and light distribution. However, if we want to gather information about the mobile devices positions, as a bidirectional positioning service, an uplink has to be implemented. Knowing the position of each device also allows us to communicate with more than one device at the same time, as we know which light should be used to modulate the messages for each mobile device. VLC localization technology can provide positioning information with an accuracy of ~1 centimetre by joint-detection among multiple LEDs, using a PD image array, gyroscope, and together with a little intelligence.

For mmWave communications, the four main localisation methods are Time of Arrival (TOA), Time Difference of Arrival (TDOA), Angle of Arrival (AOA) and Received Signal Strength (RSS). TOA relies on the transit time between transmitter and receiver to determine the distance [Ben08]. The TDOA method uses the differences of the arrival times measured on pairs of transmission paths between the target and fixed terminals [Ben08]. Both methods require very precise clock synchronization. The AOA method provides the angle of the incoming signal, which requires an antenna array. Position estimation of UE can be quite accurate if AOAs are combined from more than one RRLH. The RSS method uses more than 3 receivers to measure the signal strength of the transmitter node, estimating the distance between the transmitter and the receiver. This method can be implemented without the need for additional hardware, timing synchronization and complex algorithms. Only the ability to read the Received Signal Strength Indicator (RSSI) is required. However, it can have significant variation in signal strength due to multipath effects, especially at larger distances [Fan10].

VIII. NETWORK SECURITY ARCHITECTURE

IoRL project aims at integration between different networking technologies namely WLAN, eNB/HeNB, mmWave, VLC and SDNs. Each of these technologies alone comes with specific set of characteristic features and with potential security threats and vulnerabilities that still are often not completely resolved and still need addressing.

Therefore for the case when all these technologies are integrated into the single, heterogeneous network special care must be taken to develop a dedicated security framework whose main aim will be to provide secure communication and preserve users' privacy. This will be achieved by addressing the existing security issues of each technology alone, but most importantly by predicting and offering mitigation techniques for attacks that could be possible or could be amplified because of the mentioned network technologies' integration and coexistence. The proposed security framework will be an integral part of the developed architecture following security-by-design rules.

Moreover, by introducing centralized SDHN controller for this integrated network the security manageability will be improved. Typically the information gathered on the security incidents and its associated analysis is a very challenging task in the distributed and diverse environment. To work effectively security measures must be able to correlate, aggregate and analyze security-related data from different sources in order to provide a complete network-wide view of the security posture. This will be the role of the SDHN controller and it will allow providing near real time awareness of network security status and effective enforcement of security policy.

Apart from that the proposed dedicated security framework will include mechanisms to:

- Identify rogue mmWave or VLC points (antennas, luminaires or RRLH) installations and position location especially for handovers and in the business or public building scenarios.
- Identify rogue mmWave or VLC receivers and position location using position estimation of malicious mobile devices.
- Detect, attribute and prevent/avoid Jamming/Interfering attacks that aim to disrupt the signal by overloading the (antennas, luminaires or RRLH).
- Ensure users privacy. It must be noted that when an attacker has an unauthorized access to the network he can discover what devices are activate and infer user presence/location/behavior (mass surveillance).

IX. CONCLUSIONS

This paper describes a project that proposes a novel broadband home networking architecture that has the potential to significantly contribute towards the core 5G PPP KPI's: 1000x capacity, 1ms latency, 90% energy savings, 10x battery lifetime, service creation in minutes, better/increased/ubiquitous coverage, 10 times to 100 times higher typical user data rate, 10 times lower energy consumption and Lowered EMF levels compared to 4G LTE solutions.

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