A Scaleable and License Free 5G Internet of Radio Light Architecture for Services in Train Stations

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***Abstract*— In this paper we present a 5G Internet Radio-Light (IoRL) architecture for underground train stations that can be readily deployed because it utilizes unlicensed visible light and millimeter wave part of the spectrum, which does not require Mobile Network Operator (MNO) permission to deploy and which is used to provide travelers with accurate location, interaction, access to Internet and Cloud based Services, such as high resolution video on a Tablet PC. The paper describes the train station use cases and the IoRL architecture.**

Keywords—Train Stations, Visible Light Communications, mm Wave Communications, Network Function Virtualisation, Software Defined Networks, 5G System Architecture.

I. INTRODUCTION

Internet of Radio-Light architecture is a 5G Radio-Light multi-component carrier, Frequency Division Duplex (FDD) broadband system for buildings, shown in Figure 1, consisting of a VLC downlink channel in the unlicensed THz spectrum and mm Wave up/downlink channels in unlicensed 30-300 GHz spectrum, which allows wireless communication networks to be deployed in buildings that can provide bitrates greater than 10Gbit/s, 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.

The European Union funded IoRL research project's Software Defined Home Network (SDHN) Architecture, shown in Figure 1, not only allows network service providers to develop 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 Mobile Network Operators (MNOs).

Furthermore it does not require MNO approval for deployment [1]. This step change in performance and flexibility is a very attractive solution for building owners since it will increase their ability to promote their efficient operation thereby improving their profitability, which will incentivize them to raise capital to finance the upgrade of their building network infrastructure.

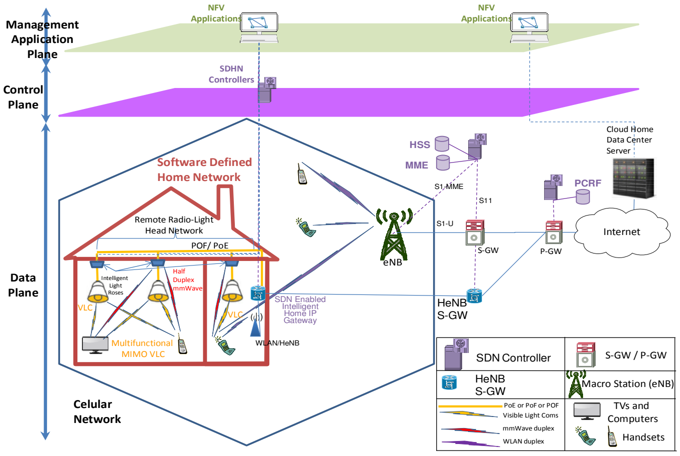

Figure 1: IoRL Network Architecture

There are 2,530 train stations in the UK [2] with 2.47 billion entries and exits every year for 2011/12. Waterloo Station is the busiest with 95.750 million entries and exits every year and just 4% (101 stations) of the busiest experiencing just over 50% of all entries and exits every year and 10% of the busiest carrying 67%. London Underground consists of 271 stations carrying 1.37 billion passengers every year with the 45% of network in tunnels [3].

Thus on average there are roughly 182 people entering and exiting Waterloo station every minute of the year and on average 2606 people in the London Underground system every minute of the year.

These are very large numbers of people who flow through the train station system that requires an information system that has the capacity to support such large numbers and whose behavior and habits are valuable information in marketing through big data analysis [4].

Railways are playing an increasingly important role in alleviating problems such as road congestion and air pollution and new plans for high-speed intercity railway links are being initiated around the world [5]. The objective of transport centers such as train stations and airports is the efficient management of the flow of very large numbers of people through the station to their destination safely, punctually and enjoyably.

The pursuit of customer satisfaction has led to the provision of more retail areas in stations. Inside railway stations, restaurants, book stores, convenience stores, fashion boutiques, and other retailers vie for attention, while station neighborhoods are well provided with hotels, shopping, and similar facilities. When passengers arrive at a station either at the start or end of their journey, they are often unfamiliar with its surroundings and so incorporating advanced information systems into stations and other parts of the railway network is important contributor to the free flow of people by informing them how to get to where they want to go.

The Mobile Internet is playing an increasingly important role in informing people but particularly important for passengers who do not have Mobile Internet access is digital signage to display service status, news, and guides to the station and surrounding areas of railway stations.

The pursuit of customer satisfaction has led to making access to station buildings barrier-free. Integration of smart card ticketing systems between different railway companies allows cards to be used interchangeably over a wide area of a country and improving the flow of passengers through train stations [6].

In addition to information systems for passengers, more sophisticated information systems are required for train operation management for ticketing, for maintenance, to enhance security and for disasters and emergencies to maximize operational efficiency.

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 [7]. 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 [8], 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..

II. USE CASES

This section presents underground train station use cases each one of which is a list of actions defining the interactions between a user and a system to achieve a goal, whereas a use case scenario is a single path through a single use case. The use cases can be subdivided into maintenance and passenger use cases.

A. *Accurate location and information provision under tunnel premises*

The Services Manager in the Control Office is able to exactly locate the maintenance workers that are performing activities in the tunnel. At the same time, there is the possibility for the Control Office to send information (procedures, guidelines, designs, videos and previous maintenance works reports) to a specific location where a maintenance activity needs to take place.

B. *Tunnel video conference communication*

The Services Manager in the Control Office is able to communicate directly with the worker through video conference. This way, some complicated activities can be overviewed by the Control Office and direct feedback can be obtained by the worker performing the maintenance activity on site.

C. *Carbon monoxide and smoke detection in tunnels*

Long tunnels without fans and with limited ventilation have the potential problem of exceeding the safe levels of carbon monoxide (CO) when maintenance activities are performed. Additionally in the case of a small fire in the middle of the tunnel, there are sometimes problems to detect it instantaneously. This use case installs sensors for detecting carbon monoxide and smoke that can send using IoRL devices, the status information of CO and smoke detectors to the Control Office instantaneously.

D. *Instant information and ultra-high bandwidth downloading*

Frequently passengers arrive at large stations where they do not know their whereabouts or the whereabouts of important facilities in the station and in its vicinity. IoRL devices are used to download information related to services and locations in the street above them (restaurants, how to reach the most appropriate exit for the place where they are heading, what are the most suitable touristic places around, etc.). This use case allows the downloading of all the information instantaneously making use of the ultra-high bandwidth of IoRL technologies.

E. *Ticket purchase and validation*

The intention of this use case is to go beyond current existing airport flight ticket validation machines that need to be cleared before entering the security check area. The security doors to enter the passenger platform will automatically open when holding the cellphone out of the pocket. The IoRL technology (intelligent light bulbs) will automatically detect those cell phones that are providing the information related to the ticket. No action from the passenger will be needed, only holding the cellphone in the hand. People need to first buy a ticket on their mobile in order to pass through VLC barrier.

F. Emergency videoconference communication

Security guards are the first ones to act when any type of emergency (medical conditions of passengers, missing or suspect objects, etc.) takes place at the station. If they can have a video conference with the appropriate emergency service that needs to arrive to the place, they can be better advice on what they need to do until the expert team arrives.

G. Commercial Signage

The digital sign could point out and show directions and routing info as well as more neighborhood related information such as exit routes from the station and local business offerings in and outside the station (for example at end of the day 1+1 sales offer in the neighborhood bakery);

Train station touch screen digital signage for both the services of the train station as well as to support the business (big and small) of the surrounding neighborhoods. This will show:

- Live train locations
- Commercials with hourly based offers (sales and last minute purchases) from the businesses around the station.

H. Rogue VLC Transmitter Placement and Denial of Service Attacks

The analysis of the initial IoRL system design and train station use cases reveals a number of potential cyber security threats, from which the two most interesting ones are: rogue VLC transmitter placement and DoS (Denial of Service) disruptive attacks. In the first scenario, an attacker places a VLC transmitter which sends malicious code infecting passengers` devices which are utilizing VLC transmission at the train station. In the second scenario an attacker intentionally leaves the device at the train station, which interrupts VLC communication thus preventing e.g. automatic ticket purchase and validation.

III. 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.

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.

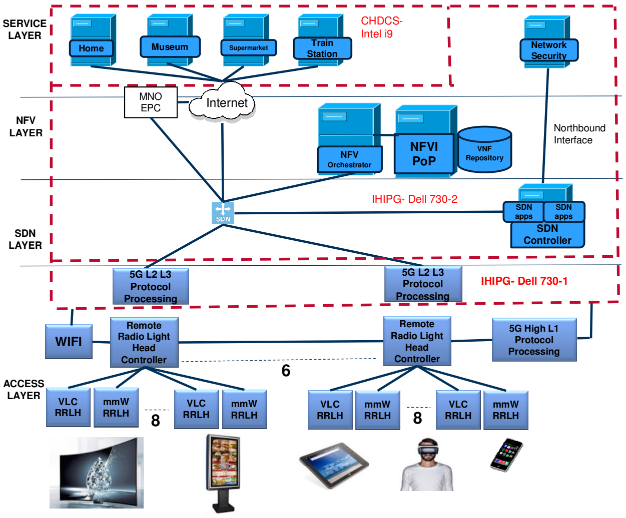

Figure 2: IoRL Layered Architecture

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 network functions (VNFs) required for an Intelligent Home IP Gateway (IHIPG) such as local access & mobility management, deep packet inspection, transcoding processes for video streaming and network security functions (e.g. firewall etc.).

The Access Layer 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.

A UE can obtain direct access to the Internet, by 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. Alternatively the UE obtains 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.

IV. RAN ARCHITECTURE

The Access Layer architecture uses a 10G Common Public Radio Interface (eCPRI) ring Ethernet, to interconnect a Upper Layer 1 processing on an FPGA with up to six Remote Radio Light Head (RRLH) Controller FPGAs 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 mmWave RF Duplex modules using a 1 to 8 RF splitter, as shown in Figure 3.

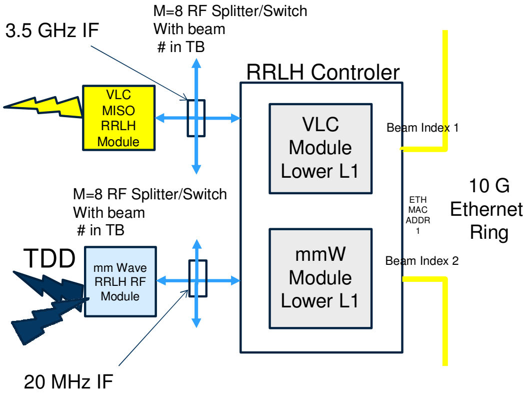

Figure 3: Radio-Light Head Controller

The functional split between the RRLH Remote Unit and the Central Unit in the Physical Layer 1 is at split 7 on the protocol stack [9]. The eCPRI Ethernet ring is 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 clock signal is sent to IHIPG, Upper Layer 1 Protocol Processor and RRLH Controller for use in 5G synchronization algorithms at these layers, thereby leaving just amplification and IF to RF up conversion to be performed at the RRLH.

As there is a limited amount of space available in Light Rose housing within which the VLC and mmWave RRLH is housed, the concept of Network Function Virtualisation (NFV) is adopted to off-load the complexity of the upper layer protocol processing of the communication systems required in the RRLH onto the IHIPG or CHDCS. This complexity consists of Network Layer 3, MAC Layer 2 and Physical Layer 1 processing.

DC-OFDM modulation is used for VLC transmission, which is compatible with the New Radio 5G frame formats [10]. 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 with 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 Table 5.3.2-1: "Maximum transmission bandwidth configuration N_{RB} for FR1" in [11], potentially providing maximum downlink bitrate of 691.2M bits/sec when 256-QAM and 100MHz bandwidth is used. 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. The NR FR2 frame format, as shown in Table 5.3.2-2: "Maximum transmission bandwidth configuration NRB for FR2" [11], can use much higher bandwidths of up to 400 MHz, using SCS of 60 or 120 kHz and operating in 60 GHz unlicensed spectrum thereby providing uplink and downlink bit rates ranging up to 2.7 G bits/sec, when using 256-QAM and 100MHz bandwidth, depending on the TDD frame type used. Since the IoRL project intends to use mmWave bandwidth of 100MHz and SCS of 60 kHz, then this will provide a maximum downlink or uplink bitrate of 675.84 Mbit/sec.

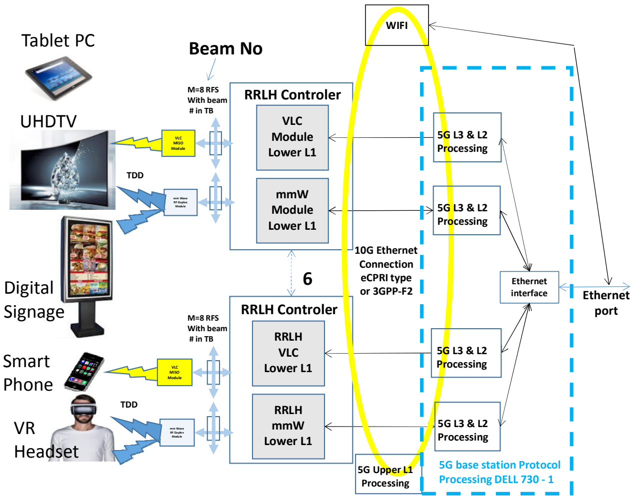

Figure 4: RAN Architecture

MISO diversity is used in the downlink where the same data is transmitted from different mmWave 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 mmWave paths is occluded then there is always the availability of the other paths to ensure continued communications, as shown in Figure 5.

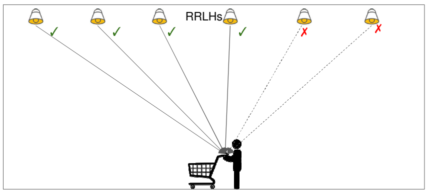

Figure 5: Downlink MISO and Uplink SIMO Diversity

SIMO diversity will be used in the uplink where the same data is received by different mmWave antennas at the RRLHs and maximum ratio combined higher up in the layered protocol thereby increasing reliability, as shown in Figure 5.

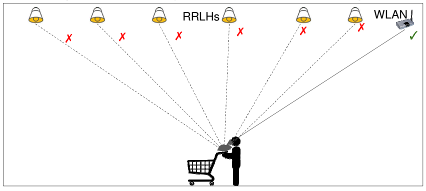

Figure 6: Multi Source streaming to ensure connectivity

In the case when all the paths are occluded, for example when someone conceals the Photo Diode (PD) receiver and mmWave antenna at the User Equipment (UE), then Multi Source (MS) streaming [12] is used to ensure that there is always the availability of another low frequency low capacity

WLAN path for continued communications and synchronization with the streaming audio/video, as shown in Figure 6. The Deep Packet Inspection VNF is used at IHIPG to identify video streams and a video transcoding VNF 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.

V. 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, MNO's billing rules etc. as shown in Figure 7.

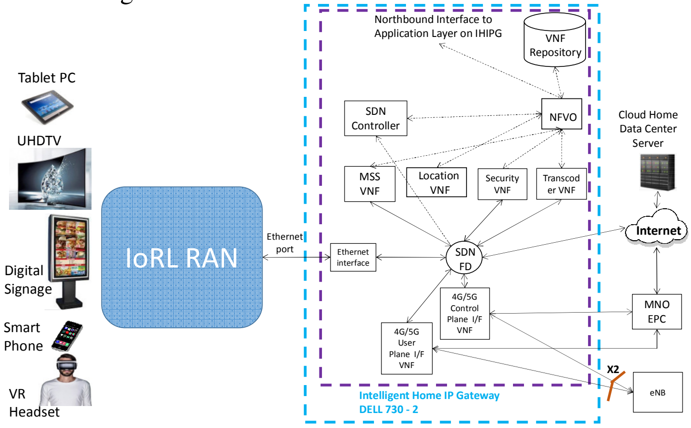

Figure 7: NFV/SDN Architecture

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 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).

A significant role of the SDN is to route IP packets within Ethernet MAC frames to/from the 5G L3 & L2 Processing cores in the IHIPG, shown in Figure 4, 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.

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. 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 8.

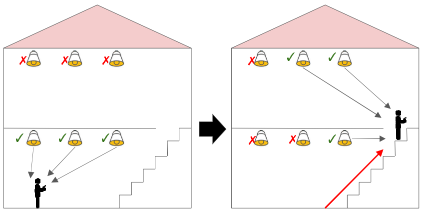

Figure 8: Intra Building Handover

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 could be measured by the UE and reported to the LTE's Mobility Management Entity (MME) to initiate a conventional inter (between outside and building) network handover procedure.

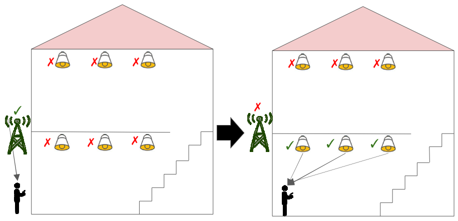

Figure 9: Outside to Inside Building Handover

VI. USER EQUIPMENT ARCHITECTURE

The user equipment (UE) design is similar to the RAN design described in Section III above but clearly with much less computer processing power as shown in Figure 10.

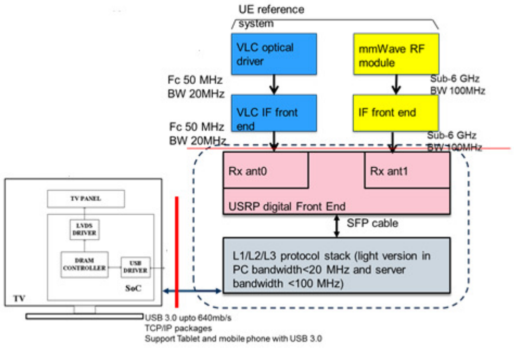

Figure 10: General scenario for VLC IPS

Using one RF chain of the RAN, a single VLC and mmWave antenna pair UE can be built with similar structure of the

RAN. The mmWave card is used to convert between mmWave and radio frequency. The NI RF card can switch the RF signal to baseband I/Q signal and transmit it into the L1/L2/L3 protocol stack processing server for signal processing. Several UEs can be located at different positions in a room for multiuser access.

VII. VLC BASED INDOOR POSITIONING SYSTEM

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.

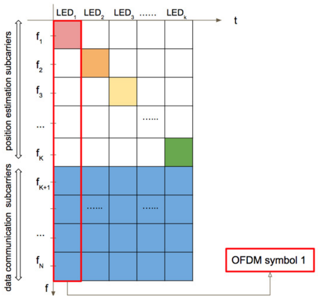

Figure 11: VLC Positioning System Reference TDM amplitude sub-carriers

The positioning system based on mmWaves uses electromagnetic waves to determine the location of UEs. The location relevant parameters can be 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 mmWave 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 mmWave 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.

ACKNOWLEDGMENT

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