5G PPP Technology Board

Delivery of 5G Services Indoors – the wireless wire challenge and solutions

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Table of contents

Executive summary

The 5G Public Private Partnership (5G PPP) has focused its research and innovation activities mainly on outdoor use cases and supporting the user and its applications while on the move. However, many use cases inherently apply in indoor environments whereas their requirements are not always properly reflected by the requirements eminent for outdoor applications.

The best example for indoor applications can be found is the Industry 4.0 vertical, in which most described use cases are occurring in a manufacturing hall. Other environments exhibit similar characteristics such as commercial spaces in offices, shopping malls and commercial buildings. We can find further similar environments in the media & entertainment sector, culture sector with museums and the transportation sector with metro tunnels. Finally in the residential space we can observe a strong trend for wireless connectivity of appliances and devices in the home. Some of these spaces are exhibiting very high requirements among others in terms of device density, high-accuracy localisation, reliability, latency, time sensitivity, coverage and service continuity.

The delivery of 5G services to these spaces has to consider the specificities of the indoor environments, in which the radio propagation characteristics are different and in the case of deep indoor scenarios, external radio signals cannot penetrate building construction materials. Furthermore, these spaces are usually “polluted” by existing wireless technologies, causing a multitude of interreference issues with 5G radio technologies. Nevertheless, there exist cases in which the co-existence of 5G new radio and other radio technologies may be sensible, such as for offloading local traffic. In any case the deployment of networks indoors is advised to consider and be planned along existing infrastructure, like powerlines and available shafts for other utilities. Finally indoor environments expose administrative cross-domain issues, and in some cases so called non-public networks, foreseen by 3GPP, could be an attractive deployment model for the owner/tenant of a private space and for the mobile network operators serving the area.

Technology-wise there exist a number of solutions for indoor RAN deployment, ranging from small cell architectures, optical wireless/visual light communication, and THz communication utilising reconfigurable intelligent surfaces. For service delivery the concept of multi-access edge computing is well tailored to host virtual network functions needed in the indoor environment, including but not limited to functions supporting localisation, security, load balancing, video optimisation and multi-source streaming.

Measurements of key performance indicators in indoor environments indicate that with proper planning and consideration of the environment characteristics, available solutions can deliver on the expectations. Measurements have been conducted regarding throughput and reliability in the mmWave and optical wireless communication cases, electric and magnetic field measurements, round trip latency measurements, as well as high-accuracy positioning in laboratory environment.

Overall, the results so far are encouraging and indicate that 5G and beyond networks must advance further in order to meet the demands of future emerging intelligent automation systems in the next 10 years. Highly advanced industrial environments present challenges for 5G specifications, spanning congestion, interference, security and safety concerns, high power consumption, restricted propagation and poor location accuracy within the radio and core backbone communication networks for the massive IoT use cases, especially inside buildings. 6G and beyond 5G deployments for industrial networks will be increasingly denser, heterogeneous and dynamic, posing stricter performance requirements on the network. The large volume of data generated by future connected devices will put a strain on networks. It is therefore fundamental to discriminate the value of information to maximize the utility for the end users with limited network resources.

1 Introduction

The various fundamental aspects of delivering 5G services have been well studied and been captured and covered by a series of white papers prepared and issued by the 5G Infrastructure Public Private Partnership (5G PPP). However, up to now the technical focus has been on outdoor use cases in general, to support users on the move. At the same time, data consumption statistics tell us, that the vast majority of data consumption, and thus service usage takes place indoors. We also see that a number of verticals have strong focus and business interest in 5G services indoors. Indoor environments exhibit characteristic differences in comparison to outdoor environments often making them more challenging from the perspective of 5G services delivery, or simply just substantially different. Hence, we decided to dedicate this white paper to the particularities of delivering 5G services indoors.

The concepts and approaches presented in the following are stemming from the work performed within a range of European research projects receiving funding in the frame of the H2020 programme of the European Union and being part of the European 5G Public Private Partnership.

Wireless delivery of 5G services indoors should be competitive in comparison to using the wired infrastructure that are currently being used to deliver broadband connectivity to homes and businesses in terms of:

- Speed
- Latency
- Determinism
- Reliability

Obviously, these properties should be weighed against:

- Cost
- Ease of deployment
- Flexibility

When assessing available options for delivering 5G services indoors we should anchor any such evaluation in the requirements of vertical industries, to be an enabler for them.

A possible segmentation of indoor scenarios is by public and private spaces. Public spaces then would include museums, libraries, other public service buildings, shopping malls, sport halls, concert halls, railway and metro stations, etc., whilst private spaces would encompass private homes, office spaces, industrial private spaces (shop floors and warehouses, etc.), hospitals, etc. (Sometimes the classification of public versus private is difficult, or less clear, e.g., in case of theatres and concert halls, etc.). **We note here that we expect neither revolutionary services, nor exceptional demands originating from the traditional consumer segment.**

The structure of the document is as follows. Following the approach taken at the inception of 5G, we start from the requirements of vertical industries that are concerned with indoor use scenarios. We capture those in Section 2. We follow in Section 3 with describing the particular technical issues and challenges providing 5G connectivity and services indoors. In Section 4 we discuss the enabling technologies and solutions to provide and improve 5G connectivity and services indoors. Section 5 follows describing the achievements so far, contrasting those with ambitions in terms of 5G KPIs. In Section 6 we summarise representative use cases, their specific requirements, enabling technologies and KPIs followed by an outlook to beyond 5G and 6G.

2 Indoor use cases of 5G services

2.1 Vertical industries concerned

This section identifies the vertical industries concerned. It describes representative services and outlines the potential impact of the envisioned 5G services. A broad range of vertical industries are concerned with indoor scenarios including:

- Private homes (entertainment)
- Transport (railway and metro stations, etc.)
- Office environments
- Commercial spaces (supermarkets)
- Public buildings (museums, theatres, event venues)
- Manufacturing (Industry 4.0)
- Medical (hospitals)
- Public protection and disaster relief (PPDR)

In the following we provide example use cases being considered by various 5G PPP projects.

2.1.1 Private homes

The Home use case scenario is situated in the BRE Smart Home Lab, shown in Figure 2-1 below, and is concerned with the connectivity required at any place and at any time by humans and machines in home environments, including the transitions from indoor to outdoor environments and vice versa. The BRE Smart Home Lab showcases the latest technologies in Online Services, Office in the Home, Communications, Entertainment, Assisted Living and Tele-healthcare and Smart Home. 5G services include streaming to 4k/8k TVs, multiplayer gaming on virtual reality headsets and remote 360° tourism on virtual reality (VR) headsets.

This is a commercially important use case because there are over 220 million households in Europe and the over-the-air TV transmission systems does not have sufficient bandwidth to deliver sufficient 4k/8k TVs channels, therefore 5G indoor technology is needed to provide this. The 21 billion Euros computer games market in EU also makes this a very important use case because 5G can provide untethered VR headsets with lower latencies, higher resolutions and higher location accuracies provides gamers with a much higher quality of experience.

Figure 2-1 BRE smart home lab

2.1.2 Transport

Underground Train / Metro Station Platforms and Tunnels

The Train Station use case is concerned with performing intervention in Madrid's Nuevos Ministerios railway station tunnel and platform areas for the purposes of improving communications and safety of maintenance railway workers. Additional value can also be provided by installing 5G User Terminals in the Nuevos Miniserios platform offering service to public users.

5G services include location-based access and visualisation of data to the nearest 10cm for maintenance staff using AR glasses showing the presence of water, cracks, escape routes maintenance (cleaning), draining system maintenance, track geometry, tracks Kilometre Points and notice the presence of alien objects. It also includes video conference calls to maintenance staff and security guard first responders for any type of emergency incident (medical conditions of passengers, missing or suspect objects, etc.) that takes place at the station.

This is an industrially important 5G use case because millions of people across Europe use public transport, therefore safety and reliability of public underground transport services are of paramount importance for its efficient functioning. Therefore, 5G indoor access technology is needed to provide accessibility, reliability and location-based data and conference calls are very important to happen with low latency and packet loss.

Figure 2-2 Nuevos Miniserios railway

Figure 2-3 Madrid metro tunnel

2.1.3 Public buildings, museums

The Musée de la Carte à Jouer in Issy-les-Moulineaux near Paris, consists of two buildings: the new and the old, as shown in Figure 2-4 below. The New Museum building is an excellent use case because it was built on the side of a hill and the basement areas suffered from an underground water course running through the building causing dampness. For this reason, the basement areas of this new building were encased in stainless steel container to keep out the water but this also acts as a Faraday Cage that prohibits outside wireless signals from entering the building and vice versa.

5G services include location-based access and visualisation of data to the nearest 10cm for visitors using smart phone explaining exhibits to them on headsets to preserve silence as it is important to keep a quiet atmosphere to stimulate the visitors to look around them and to discover also artefacts that they were not expecting. The museum regularly constructs new exhibits in the Exhibition Hall on different themes and it has to improve or reshape their permanent collections. The curator needs to regularly and efficiently design new exhibits according to new collection hosted and taking into consideration many different information (number of artefacts, theme of artefacts, particular needs of any single artefact). Additionally, the curator is required to update different information (e.g., texts, descriptions, images and videos) related to the new exhibit artefacts to allow visitors to fully appreciate the exhibition.

This is a socially important use case because millions of people across Europe use museums, which are of places of leisure and socialising and of paramount importance for educating people about their culture. Therefore, 5G indoor technology is needed to provide accessibility and location-based data access that can be readily changed and updated.

Figure 2-4 Musée de la Carte à Jouer

Figure 2-5 Underground Museum exhibits

2.1.4 Commercial spaces

On the high street, price is no longer a competitive differentiator for retailers, rather, selling services, solutions and stellar shopping experiences are the ones which will deepen emotional connections with shoppers and encourage consumers to shop longer, spend more and stay loyal are needed. Personalization enabled by Big Data and analytics, more personalized grocery shopping experiences, which in turn could translate into increased sales and repeat visits by loyal customers is the focus of retailers.

5G services include location-based data access, routing and monitoring to the nearest 10cm for shoppers using smart phone. Location based data access can be used to explain product details to customers, location-based routing can be used to guide shoppers to products of their interest or products they may be interested in through personalised profiling. Location based monitoring can be used for monitoring if customers are adhering to social distancing rules in a virus pandemic such as Covid-19.

This is a commercially important use case to supermarkets on the high street because millions of people across Europe who have been using supermarkets and turning to the internet to order groceries direct to the home, therefore they need to think of using 5G indoor technology to make shopping in supermarkets a more than just a shopping experience.

Figure 2-6 Shopping Isle

Figure 2-7 Supermarket checkout

2.1.5 Manufacturing spaces

Industry 4.0 smart factories

Work is underway in [60] on the technical and business validation of 5G from the verticals' points of view, following a field-trial-based approach at manufacturing sites. The trial sites are the Automotive Intelligence Center of INNOVALIA (Amorebieta, Spain) and the Automation Systems and Robotics floors of COMAU (Grugliasco, Turin, Italy). The Automotive Intelligence Center is a European centre generating value for the automotive industry, based on the concept of open manufacturing production innovation in which companies improve their competitiveness through cooperation. The Automation Systems and Robotics floors is a site in charge of production for the whole European area of Robots and Automated production lines, and provides "body-in-white" solutions (i.e., car bodies production) for Original Equipment Manufacturers such as Fiat/Chrysler, Daimler, Jaguar/Land Rover, Volvo, Porsche etc. The aforementioned sites are organized as shown in Figure 2-8 and Figure 2-9, respectively.

Figure 2-8 Automotive intelligence centre (Amorebieta, Spain)

Figure 2-9 Automotive intelligence centre (Turin, Italy)

The diversity, heterogeneity, and critical nature of exiting processes within Industry 4.0 makes it a very challenging and complex environment. Each process is characterized by a different set of requirements that must always be fulfilled, not only to guarantee a safety operation but also to avoid significant losses caused by stalling events. The selected use cases try to cover different manufacturing processes, ranging from metrology, quality control, digital twinning, telemetry and monitoring, and remote tutorial support.

In this sense, 5G technologies are one of the key enablers for the digital transformation of manufacturing in the 4th industrial revolution, by providing enhancements on four main strands: (i) wireless connectivity, while guaranteeing strict constraints; (ii) reliable and secure machine-to-infrastructure communication; (iii) sharing of the resources using secure and scalable cloud computing to reduce hardware resources; and (iv) unified network across the plants. Moreover, different 5G services are required to satisfy the stringent requirements (e.g., latency, bitrate, packet loss, availability, reliability, etc.) of the selected use cases, while at the same time provide significant improvements regarding flexibility, device density and global device connectivity.

In particular, ultra-reliable and low latency services are used to enable digital twin applications and remote operation of physical machinery (e.g., quality equipment or robotic arm equipment) in real-time and with zero-perceived latency; massive machine-type communication services to promote machine-to-machine communications with minimal or no intervention from humans, allowing the (semi-)automation of different manufacturing processes (e.g., efficiency on the quality control processes towards zero defect manufacturing, and telemetry and monitoring of machinery, production line and factory); enhanced mobile broadband services to support the transmission of not only live and on-demand ultra-high definition videos (4K / 8K) to/from remote sites (e.g., feedback for remote operations and digital tutorials) but also the extremely high amount of data generated by the manufacturing processes (e.g., quality control processes of small batch of 5000 objects can generate over 1TB of information); finally, 5G network slicing capabilities must be provided to guarantee that all the aforementioned services can run simultaneously over the same and shared network infrastructure.

Finally, these are commercially important use cases for the manufacturing industry, as proven by the necessity of the vertical industry partners, as they allow (i) a more efficient share and use of resources across different production lines; (ii) cost savings by reducing the acquisition, management and deployment costs of the network, the required travels to the factory premises and the wasted material and scrap; (iii) improve time-to-market and product designs.

2.2 High density networks, devices and data

The internet of things (IoT) has enabled many low-cost and low-complexity devices to benefit from communication and this also introduces a huge volume of devices indoors which need to connect to the network with excellent coverage [1]. Examples of extreme density devices also known as massive IoT application include wearables, asset tracking, environmental monitoring and smart metering in smart city/home/buildings, etc.

Some main challenges for these applications are first to provide a sufficient and cost-efficient network capacity that can support these large number of devices, and second to provide coverage in very deep indoor environments in which some of these devices maybe located (e.g., in the basement). Third, for most of these applications, for example wearables used in the e-health, it is significantly important to have a trustworthy network both in terms of communication and also end-to-end data integrity. Using 5G networks has the potential of fulfilling all these aspects in an indoor environment.

However, while the number of IoT devices requiring network access may be large, they are not the only device categories which require network communication within different indoor spaces. This means that within an indoor space, we have devices with different capabilities in terms of throughput, latency and coverage demands and hence it is important to consider proper 5G deployment in which all the devices could be properly serviced, while avoiding any significant interference impact of each device on other devices in the vicinity.

Telemetry and monitoring

5G enables very efficient monitoring and telemetry systems that provide a relevant improvement in preventive maintenance. Using 5G technologies, many different sensors are connected wirelessly to an IoT Platform that performs a real-time accurate analysis of the “health status” of an entire plant. Temperature, pressure, vibrations, as well as levels of consumables such as lubricants or refrigerants, are among the monitored parameters. Connecting so large number of sensors and extend the monitoring to so such large variety of devices (e.g., vibrating sensors) is very complex (and sometimes impossible) with wired technologies.

This improves the quality of monitoring and increase the diagnostic capability of the production lines than can perform a preventive diagnose that allow reducing the interruptions of the production. Preventive maintenance allows planning the maintenance operations in suitable time slot that minimize the impact on production line. Monitoring and Telemetry, leverages on the Massive Machine-Type Communications (mMTC) or Massive IoT profile. This profile targets a massive number of low-cost, narrow-bandwidth devices with long battery life capabilities. In the 5Growth pilot, mMTC is used to connect multiple sensors with a remote digital platform that continuously supervises the factory and assumes immediate decisions to prevent failures as shown in Figure 2-10.

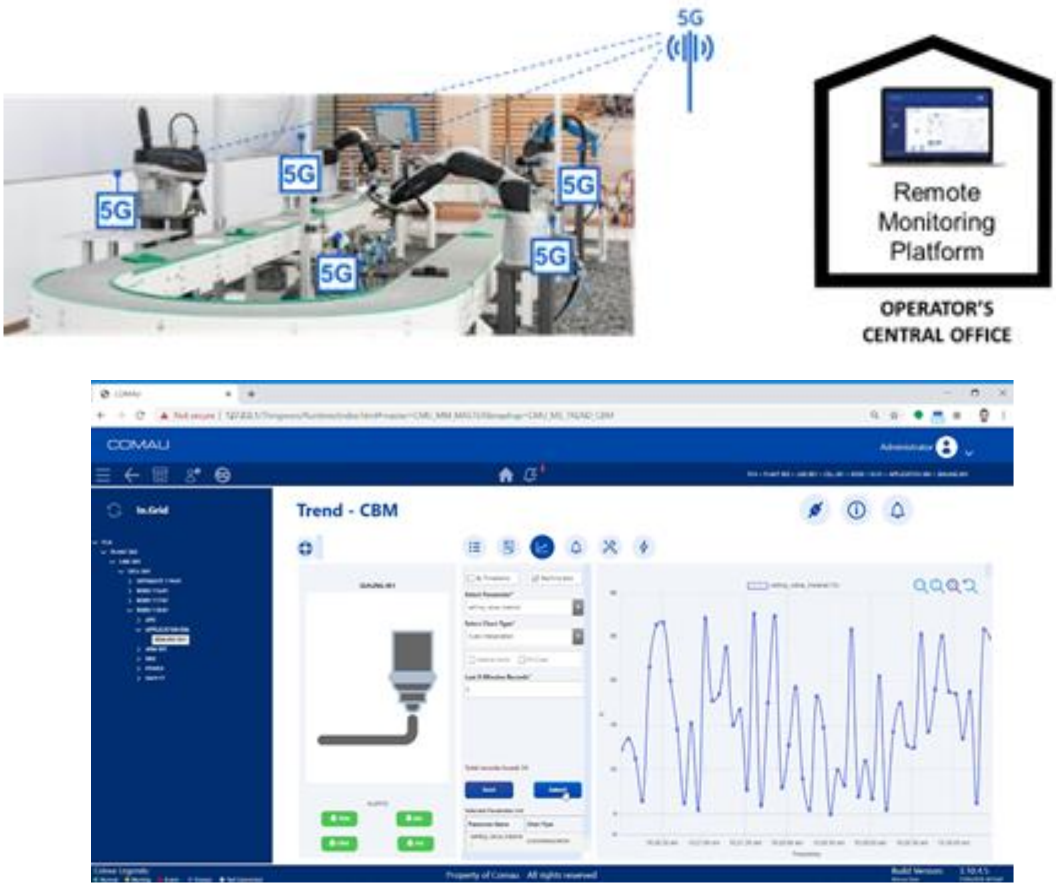


Figure 2-10 Telemetry / monitoring use cases

2.3 Time critical use cases, applications and services

While massive IoT and broadband IoT were already available for 4G networks, critical IoT would be only possible with advanced 5G networks. The critical IoT use-cases are mainly requiring data delivery with guaranteed reliability levels within a specified time duration; for example, providing a data delivery within 50 ms with 99.9% reliability [2]. In 5G, this type of communication is also known as Ultra Reliable and Low Latency Communication (URLLC).

Among different classification categories within time-critical use-cases, remote-control, real-time media and industrial control are the ones which are mainly concerns the indoor 5G services. Remote control use-cases refer to human control of remote devices, while industrial control refers to open or closed-loop control of industrial automation systems. The potential of remotely controlling an equipment can significantly improve some work environments and productivity by omitting the need of human presence in hazardous and improper environments (e.g. remotely controlling mining equipment).

Another one important time-critical use-case than can be enabled by 5G networks are real-time media in which media is both produced and consumed in real-time. The already available gaming and entertainment industry including AR and VR proves the fact that the delay in communication would result in negative quality of experience, and while in these use-cases the rendering and processing of media data are done locally in the device, with time-critical communication it is possible to offload parts of these process to the cloud. This would not only improve the quality of experience but also enables more lightweight devices which is much more favourable for the gaming application.

Time critical use cases in Industry 4.0

Digital twin and remote operation of machinery (also known as teleoperation) are emerging applications within manufacturing industries, which, due to the COVID-19 pandemic, are attracting additional relevance to support a ubiquitous and remote replica and access to facilities' environment. The concept of the digital twin refers to a digital replica of physical assets, processes and systems that mimics changes as they occur in an actual physical system. The digital twin is a powerful, new, digital environment that perfectly mirrors the manufacturing line, thus facilitating the optimization of complex processes and production scenarios. At the same time, it enables novel interactions with the underlying systems by enabling the remote operation to be performed by means of these digital replicas. Nonetheless, other means of feedback for remote operation can be achieved by using high resolution video streams, which tracks all the physical movements/operations.

In doing so, by relying on a cyber-physical convergence, these applications are providing a new way to execute smart manufacturing, management, and control of the manufacturing processes. However, these extremely critical and precise processes. Safety concerns must be ensured at all times and stalling events must be prevented, thus imposing stringent time constraints. Latency and jitter can then impact the feasibility of such applications. For example, remote operating machinery over an unreliable communication link with variable latency and jitter can lead to its maloperation. In extreme cases, it might lead to damage of goods and the machine itself. As another example, if information is delivered to the digital twin applications without any time guarantees, analytics and decisions might act on outdated information. The ultra-reliable and low latency communication capabilities offered by 5G will greatly contribute to meet the time requirements of the aforementioned applications.

In this perspective, EU projects related to 5G are defining a variety of use cases for showing how 5G technologies can enable remote operation and digital twin applications in Industry 4.0 environments.

In Figure 2-11, the digital twin use case is shown, which leverages on the Ultra-Reliable Low-Latency Communications (URLLC) or Critical IoT profile. For the specific application, URLLC ensures a stable and low delay in the connection of a real robot with its digital replica. Such application, as deployed in 5Growth, consists in a robot remotely controlled by a computer. A robot controller estimates the actual position of the robot via the encoders installed on the axes motor. As such, the robot controller sends, in real-time, the robot status and position to a computer that builds the digital replica and feeds an AR device with information for a supervisor who is in front of the real robot. In one of the other use cases addressed by [60], the remote operator controls a physical quality control machine using a remote joystick. Unlikely, the visual feedback of the actions being executed in the physical machinery are provided by two live video streams, one providing a general view and another a detailed view. In such scenario, for a real-time control experience, a complete synchronization between the video streams and the remote joystick instructions is required.

The latency requirements of the selected use cases range from 5ms to a maximum of 15ms with a jitter no higher than 100us, in order to enable a synchronized alignment of the robot with the feedback mechanisms (either virtual replica or video stream).

Figure 2-11 Digital twin use case

2.4 Coverage and service continuity

Remote operation, remote support, and digital tutorial support are expected applications within Industry 4.0 to implement multi-experience and multi-communication channels and platforms. By extending the coverage and service continuity across different locations (e.g., different manufacturing sites), a remote paradigm becomes available to manufacturing industries. The relation between customer and supplier is tighten through a faster, more interactive, and less costly support. Specialized personnel do not require to travel to the manufacturing sites, providing supporting services remotely from their headquarters facilities. The main objective is to reduce the mean time to repair, using remote processes and real-time streaming with specialized personal from remote locations to support maintenance and repair operations in the production line of the factory. This includes the remote operation of manufactory machinery for configuration and calibration purposes, as well as providing in-field technicians and maintenance staff with digital tutorials and remote support for troubleshooting.

In a typical scenario, a machinery is affected by a fault, but the local staff requires advanced support to rapidly fix the problem. Technicians in the remote factory can use a tablet or augmented reality devices connected via 5G. On the other side of the connection, geographically far from the factory, there is an expert with a remote maintenance application. Such expert has the "full picture" of the fault and can provide remote support to the in-field technician. As alternative the technician can access to step-by-step digital tutorials and instructions. Additionally, the expert can remotely control the machinery to proceed with its configuration and calibration, avoiding the need to ship the machinery to the supplier or the travel of the expert to the manufacturing site.

Still, one of the main challenges is the orchestration of a full E2E service that crosses different locations, as different network slices with different requirements might need to be provisioned over a shared heterogeneous infrastructure that might belong to different organizations. Isolation must also be guaranteed due to the critical nature of the manufacturing processes, especially when relying on the infrastructure of a third-party organizations. In this sense, E2E solutions are needed to facilitate the deployment of private 5G networks, known as 5G non-public networks (NPNs), integration with the public networks of the MNOs. Related aspects are further discussed in sections3.4 and 4.2.

2.5 5G location-aware applications

Context-awareness is essential for many existing and emerging applications, and it mainly relies on location information of people and things [3]. Localization, together with analytics, and their combined provision “as a service” will greatly increase the overall value of the 5G ecosystem [77], allowing network operators to better manage their networks and to dramatically expand the range of offered applications and services, especially in indoor scenarios.

5G will be a key enabler for context-aware indoor applications due to the level of location awareness offered by integration of RAT-dependent (5G New Radio) and RAT-independent technologies as well as to the capability of interconnecting a massive number of devices. GNSS, Wi-Fi and Bluetooth are RAT-independent technologies under consideration in 3GPP, while UWB is currently not under consideration. In this perspective, EU projects related to 5G are defining a variety of use cases for showing how 5G can enable new indoor services and applications in various field including emergency, industrial IoT, and device-free flow monitoring.

2.5.1 3D indoor localization for emergency scenarios

There are many scenarios requiring indoor emergency localisation, like building fire, kidnap/terrorism incident, medical emergency and building evacuation in emergencies. Novel localization mechanisms are required, as indoor locations are not well supported by GNSS and we might not rely on the existing wireless infrastructure (like Wi-Fi nodes, femto cells) within the premises. Therefore, indoor localization presents many challenges in respect to the radio environment, including multipath, blocking and non-line of sight (NLOS) conditions. For an emergency support service high levels of accuracy, service reliability and availability needs to be achieved in situations where other human senses might be challenged severely. The localization accuracy and reliability can be enhanced using fusion techniques in an opportunistic manner, integrating any usable wireless technology - on top of the baseline localization technology.

Figure 2-12 depicts the 3D indoor localization for emergency scenarios under development in [4]. Victims and emergency service personnel are localized within an indoor ‘incident’ environment. This localisation capability will be provided to the emergency crew as a service, with guaranteed levels of accuracy, reliability, service availability and other agreed KPIs. The emergency crew will use this localisation service to manoeuvre their operations and ensure safety of victims as well as emergency crew attending the indoor ‘incident’. In such a scenario, 5G is essential to obtain the required level of accuracy (meter level, both horizontal and vertical, in 99% of times) and latency. For buildings with a lot of small rooms, this level of horizontal accuracy is needed to identify victims and emergency crew within the right room, saving precious time. Vertical accuracy is critical to ensure identification is done at the correct floor level, as movement between floors can be difficult and restrictive.

One of the main challenges in developing a 5G based emergency localisation solution is how to guarantee the service availability across the operational area (likely to be city-wide) of the emergency response agency. 5G is very likely to be deployed only in the capacity hotspots in the beginning, relying on the LTE networks for wider coverage. Within this context, drone-based ad-hoc 5G deployments, which can relay the 5G signal from the emergency site to a pre-assigned 5G or 4G ground base station, can be effective in stretching the 5G based solution to any site within the operational area.

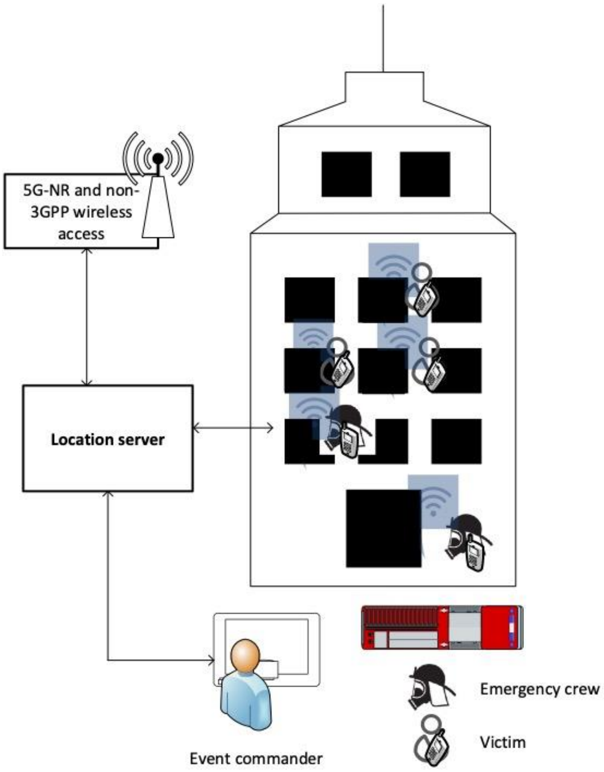


Figure 2-12 3D indoor localisation for emergency scenarios [4].

2.5.2 High-accuracy indoor positioning for industrial IoT

Industries have automated many processes, secured wireless connectivity which empowers factory automation, making industrial automation possible on a much larger scale. These applications have extremely demanding connectivity requirements and require very accurate indoor positioning and distinct architecture and security attributes. These varying use case requirements range from environmental sensors and trackers for inventory and supply management to more demanding connectivity for Automated Guided Vehicles (AGV), to the most demanding real-time sensors and robotics on the assembly line which are typically wired.

Industrial IoT (IIoT) is characterized by challenging system requirements for positioning accuracy. For example, on the factory floor, it is important to locate assets and moving objects such as forklifts, or parts to be assembled. Similar needs exist in transportation and logistics. Positioning integrity is also a key input to determining whether an AGV in a factory such as a forklift is travelling on the trust assigned path or not.

Figure 2-13 illustrates an industrial IoT scenario in which autonomous forklifts and many other facilities in the factory require high accuracy (submeter in 99% of times) and low latency (100ms or less). Such level of requirements need 5G network capabilities and integrated communication and sensing through both RAT-dependent (multiple gNB nodes) and RAT-independent (UWB and VLC sensors) technologies.

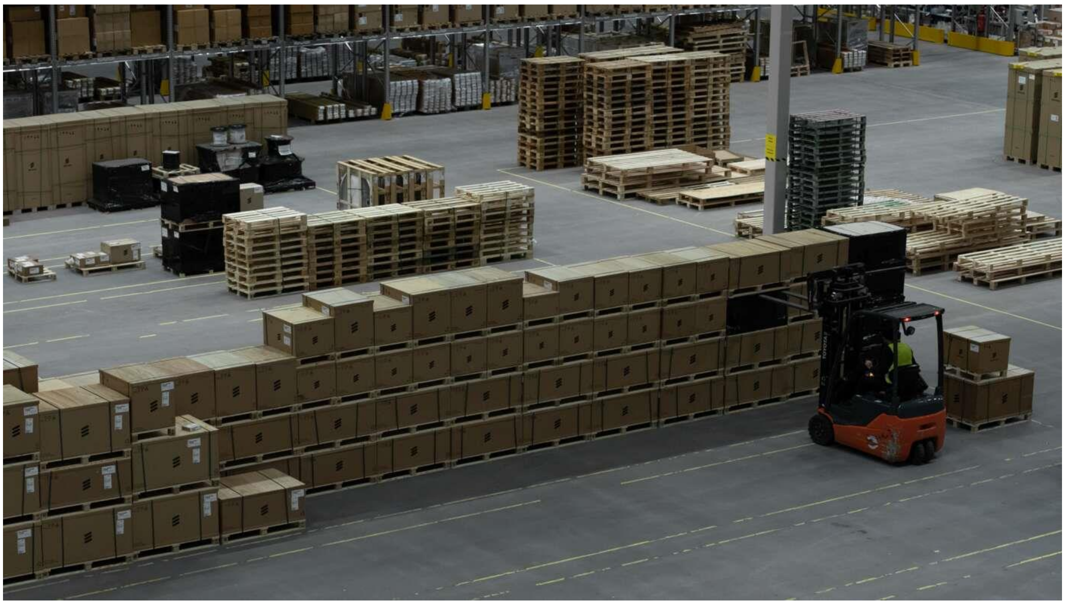


Figure 2-13 Illustration of an industrial IoT scenario

2.5.3 Indoor device-free localization

There are many scenarios where one needs to detect, localize, or extract analytics related to people and things (targets) not equipped with communicating devices. In many of such scenarios there are communication systems emitting signals for other purposes. Device-free localization consists in processing such signals after targets backscattering/reflection at one or multiple nodes to extract information about presence, range, location that may serve as input for the extraction of analytics. Device-free localization presents many challenges as clutter, multipath and NLOS conditions.

Figure 2-14 sketches a device-free localization scenario considered in [4]. The figure illustrates sensor radar with one transmitter, one receiver, and two targets. The lines represent the signal transmitted, reflected by the target, and measured at the receiver. The detection and localization of the targets is performed by processing signals at a network of receivers (through their UEs). Of particular interest to understand the benefits provided by 5G technology is to consider a situation in which a 5G emitter emits the signal in the environment (broadcast, positioning signal); targets backscatter the incident signal, which is received at the network of receivers and then processed to infer information about the presence and location of the targets. The service provider ensures that the device-free localization meets the necessary accuracy (a few meters in 90% of times). The 5G ecosystem will benefit such application by integrating the network of 5G receivers with sensor radar networks where sensor radar utilizes other technologies such as UWB.

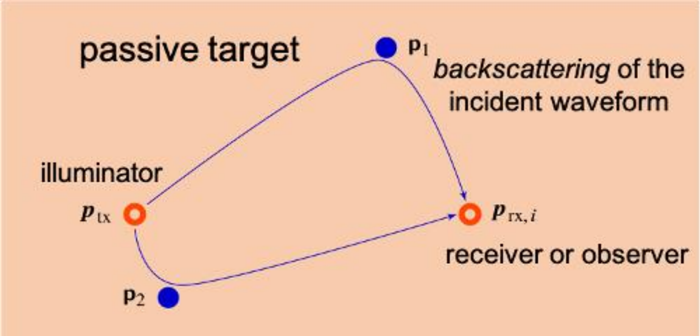


Figure 2-14 Device-free localization scenario

2.5.4 Dynamically extensible location database

A dynamic database was designed and deployed by [61] as a virtual network function (VNF) service on a software defined network (SDN). The VNF offers a flexible and quickly accessible location database in the MEC, resulting in speed of access and a reduced power consumption. The requirements were the following:

- Develop a dynamic database that display content.
- Develop a GUI that allows managers to edit, add, and delete content of the database.
- Create a dynamic system that allows the interaction between the user's browser and the database.

The dynamic location database was deployed using the Django framework and is easily customizable anf scalable by making changes to Django's decoupled components.

2.5.4.1 System architecture

A database driven application with the requirements as mentioned above requires two interfaces. A front-end and back-end, where the front-end is the GUI for users and managers. The back-end is the database engine, which is for developers and managers. Both interfaces were developed using the Django's framework.

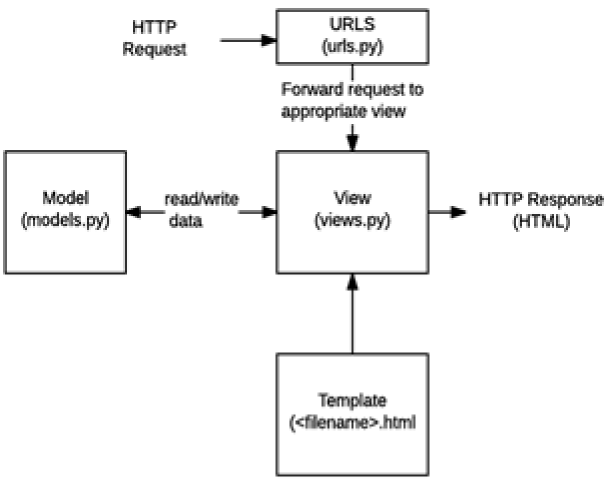


Figure 2-15 Front-end of dynamically extensible location database

Django's architecture operates using python modules as shown in Figure 2-15, each of the different modules inside Django's web server is vital for provide the information to the front-end. The client requests a webpage from the web server, the web server receives the request and send it to the controller (URLs). The controller checks if the requested URL is a match with REGEX registry; once matched it requests a view for the URL from the view's module. Then, the view's check inside the template module (.html) for the template as it holds information needed from the database. The template then sends the information back to the views. The views then check model module for the requested objects from the template. The model creates objects and fills it up with the information given by the database and sends it back to the views. The views then send the web page to the client, where it will be displayed on their web browser.

2.5.4.2 System design

The front-end system has been designed using several different programming languages. The following languages were needed to keep the front-end user friendly.

- HTML5: Allows it to be universal to all the different browsing platforms.

- JavaScript: Makes elements in the website interactive without the need to keep reloading the webpage.
- CSS3: Provides the website with an appealing look. It controls the fonts, sizes and colours.
- Bootstrap: To provide flexibility to the website as it lets elements to resize depending on the screen size.

Figure 2-16 shows the different webpages that were created to serve as the front-end and how it is interactive and user friendly. Also, it shows

Figure 2-16 Django web server

The back-end consists of the MySQL and Django frameworks. MySQL is the database engine, which allows the storage of information by the curator. The Django framework interlinks the different platforms used, and controls the whole system. Figure 2-17 shows, the back-end of the system, where the managers have access and add, edit, and delete content from the database.

Figure 2-17 Back-end of dynamically extensible location database

2.5.5 High-accuracy indoor localization for Industry 4.0

2.5.5.1 AGV positioning

This use case focuses on providing high precision multi-WAT positioning of the movement of goods within a factory (e.g., Bosch factory [17]). For example, an Automatic Guided Vehicle (AGV) moves material ordering or products from the production line to the warehouse. To date, mainly a driver delivers the goods to the production area with a train (called milk run) driven by a tractor head, to then pick up the finished product and return with the empty boxes.

The system deployed in [62] involves several Wireless Access Technologies (WATs), e.g., Wi-Fi, Li-Fi and mmWave, deployed in this indoor scenario at the factory. The WATs Access Points (AP) are installed in suitable places along the factory infrastructure to provide connectivity to those installed at the AGV User Equipment (UE). Each technology is able to deliver positioning information to a centralized localization server with different levels of positioning accuracy. This server generalizes the positioning problem in a multi-connectivity framework, and fuses or combines different algorithms targeting an enhanced position estimation of the AGV.

The particularities of the different technologies and the chosen scenario e.g., line of sight (LOS) or non-line of sight (NLOS) conditions, determine the degree of availability of wireless connectivity and favour the use of certain technologies. Technologies that are more robust to reflections and changes in the environment could support those offering a more accurate position estimation (e.g., mmWave) but which are prone to blockage. A key objective of the use case is to avoid the lack of connectivity between AP and UE, reaching seamless connectivity along the path to be followed by the AGV. Machine learning (ML) algorithms are used to detect the LoS/NLoS condition, and to fuse different positioning technologies in order to enhance the estimate accuracy. Additionally, various data available from the AGV, such as speed, acceleration, deceleration, track identity, incidents detected, etc., are used to assist the deployed ML algorithms.

Depending on the available technologies deployed in a given Industry 4.0 scenario, in the best case (e.g., mmWave technology available and densely deployed), the positioning accuracy is expected to be better than 10 centimetres, availability better than 99.9% and latency 10 milliseconds or better.

2.5.5.2 5G new radio positioning

5G NR should enable enhanced positioning services. The requirements for the performance targets are split into regulatory and commercial use cases. The regulatory use case requirements specify the minimum performance targets. The horizontal and vertical positioning error for the regulatory use case are less than 50 and 5 meters respectively for 80% of UEs, and latency and Time to First Fix (TTFF) less than 30 seconds. For commercial use cases, requirements for horizontal and vertical positioning error in indoor environments are less than 3 meters for 80% of UEs. For outdoor deployment scenarios, the horizontal and vertical positioning error should be less than 10 and 3 meters respectively for 80% of the UEs. The end-to-end latency should be less than 1 second. An additional use case, called “high accuracy positioning” for NR is defined in [17]. The positioning accuracy for this use case is better than 1 meter in 95% of service area.

Two main groups of positioning technologies are envisioned in 5G NR. The first group includes RAT-dependent technologies like: Cell-ID, E-Cell ID, DL-TDOA, UL-TDOA, etc. The second group includes RAT-independent technologies like: GNSS, Bluetooth, WLAN, Terrestrial Beacon Systems (TBS), motion sensors, Li-Fi, UWB, etc. The NR positioning should exploit the high bandwidth, massive antenna array systems, mmWave technology, heterogeneous networks, broadcasts, Multimedia Broadcast Multicast Services (MBMS) and the large number of deployed devices in order to offer a high precision, low latency, indoor and outdoor, reliable positioning service.

Some of the RAT-dependent positioning techniques were first standardized in LTE. These techniques are agreed to be supported in NR Rel-16. They are additionally extended in order to support new technologies, like mmWave, available in 5G NR. With bandwidths of 100 MHz, or more, available in FR1 and FR2, positioning precisions of better than 1 meter would be available. In order to achieve this high precision using techniques such as DL-TDOA or UL-TDOA, strict synchronization of a few nanoseconds between gNBs is required. Therefore, having a nanosecond synchronization solution for neighbouring gNBs would enable high precision positioning, especially important in indoor application. Additionally, 5G NR should support round trip time (RTT) ranging. This means that each gNB should measure the RTT with UE. Having the RTT values would enable UE position estimation using trilateration. This approach does not require precise synchronization, but introduces additional overhead for position estimation of each UE and, therefore, it is not a favourable solution for high density scenarios.

RAT-independent technologies are complementary to RAT-dependent technologies and should offer high precision positioning in scenarios where RAT-dependent technologies are either not available or cannot offer the required positioning precision. Even low precision positioning technologies like Bluetooth or motion sensors can be beneficial since different precision classes are envisioned in 5G positioning. The most promising technologies to enable high precision indoor positioning are Wi-Fi and UWB. UWB is unfortunately not standardized and mainly proprietary solutions exist. Wi-Fi on the other hand, is well established and standardized. Additionally, a Wi-Fi positioning standard, IEEE 802.11az, is developed. According to this standard, RTT with multiple Wi-Fi APs is used to estimate the distance to these APs and to estimate the UE position using trilateration. The IEEE 802.11az uses the fine timing measurement (FTM) protocol to estimate the RTT. The FTM protocol is already available in some COTS devices. In order to perform a high precision ranging in positioning using Wi-Fi, a large bandwidth would be need. This large bandwidth is available using channel bonding, for example in IEEE 802.11ac, or in the mmWave IEEE 802.11ad Wi-Fi.

The positioning data obtained using RAT-dependent or RAT-independent technologies is usually not sufficient for UE position estimation in gNBs. Therefore, special control channels in the control plane are used to transfer this information to the localization server. The localization server estimates the position of the UE and returns it to the client, which requested it.

RAT-dependent localization cellular localization techniques are primarily limited by the sampling time (Ts). In LTE, with the fixed sub-carrier spacing of 15 kHz and a maximum FFT size of 2048 bins, the maximum achievable localization resolution (related to a Ts) is expected to be around 9.8 m. In contrast, 5G-NR provides higher localization accuracy as it offers larger sub-carrier spacing and larger FFT sizes. Location accuracy depends on many system parameters. At sub-6 GHz, the maximum resolution is 2.44 m (sub-carrier spacing of 60 kHz and FFT size of 2048 bins). At mmWave, the maximum resolution increases to 0.61 m (sub-carrier spacing of 120 kHz and FFT size of 4096 bins).

The aim with RAT-independent localization is to leverage the fact that the User Equipment (UE) has several radio interfaces such as Wi-Fi and Bluetooth that could be accessed and exploited by 5G. The solutions must also take into account that the 5G Radio Access Network (5G-RAN) does not have any control on any RAT-independent infrastructure deployed. This implies that there is no direct communication between the 3GPP location server (e.g., the Enhanced Serving Mobile Location Centre in LTE, E-SMLC, or the Location Management Function in 5G, LMF [22]) and Wi-Fi APs or Bluetooth APs devices.

All localization solutions are expected to meet one of the seven 3GPP positioning service levels defined in Release 17 [18]. Among the seven service levels, levels 1-6 aim to provide absolute positions in the order of 0.3-10 m, and latencies from 1 second down to 10 milliseconds, depending on the scenario, whereas level 7 targets relative position between two 5G devices, such as mobile devices, with accuracy in the order of 0.2 m. For each technology, we indicate the positioning level it can reach as standalone method. The main insights of the table are reported here for completeness.

Table 1 Positioning service levels as defined in TS 22.261

Positioning Service level	Absolute (A) or Relative (R)	Horizontal Accuracy (95% confidence)	Positioning latency
1	A	10 m	1 s
2	A	3 m	1 s
3	A	1 m	1 s
4	A	1 m	15 ms
5	A	0.3 m	1 s
6	A	0.3 m	10 ms
7	R	0.2 m	1 s

As originally defined in LTE [19], [20] and further adopted in 5G [21], [22], there exist three positioning modes for integration of RAT-independent technologies:

- *standalone*: UE localizes itself without any aid from the network
- *network-assisted*: UE position is calculated by UE with assistance from the network
- *network-based*: UE position is calculated in the network side with measurements sent from the UE

For this reason, for each RAT-independent technology, we indicate the most suitable operation mode and its feasibility. Furthermore, each of these technologies has different requirements for deployability which could make feasible or not reaching the target accuracy in practical scenarios.

In the following table, we compare the technologies studied in this work.

Table 2 High-level comparison of RAT-independent positioning methods

Technology	Positioning service level	Best operation mode	Integration with cellular vs. standalone operation	Comments
A-GNSS	5	Standalone, network-assisted	Both	Mainly for outdoor scenarios. Network-based is currently not supported by 3GPP, but it could be beneficial for localization performance. Integration with cellular can be beneficial in certain scenarios.
Wi-Fi (sub-6 GHz)	5	Network-assisted or network-based	Integration	Network-assisted and network based are supported, and both of them are beneficial depending on the context. Integration with cellular can be beneficial in several scenarios as the two technologies compete in terms of localization performance.
mmWave	6	Standalone	It may work standalone if RAT-dependent operates in Frequency Range 1 (FR1); else it can be integrated	As discussed in Section 6, mmWave can work without any aid from the network. Furthermore, sending raw data to the location server could be too expensive in terms on network throughput
Ultra-Wide Band (UWB)	6	Standalone, network assisted	Standalone	UWB works at short range, and thus the deployment of dedicated APs is limited to few scenarios

2.5.5.3 Positioning protocols

Positioning in 3GPP LTE was initially introduced to provide the means for operators to meet the UE Federal Communication Commission (FCC) emergency call positioning requirements in adequate deployments. At a high level, the location server (E-SMLC in 4G, and LMF in 5G infrastructure), initiates the process of locating the mobile device. The E-SMLC and LMF request measurements to the UE using the LTE Positioning Protocol (LPP) [19] messages. LPP was introduced for point-to-point communication between the location server (E-SMLC) and the mobile device (UE) in order to position the mobile device using position-related measurements obtained by one or more reference sources. While the term LPP originated from LTE and 4G, the same term is being used for 5G networks. One should notice that the specification TS36.355 has been enhanced to TS37.355 for 5G-NR. However, since the beginning of 5G positioning, the protocol between the location server (i.e., LMF) and the radio network node (i.e., gNB) has been defined as NRPPa [23] which is similar to LPPa protocol in LTE.

LPP/NRPP messages are used not only for positioning with cellular data but also for requesting the mobile device to collect passive or active measurements of RAT-independent infrastructure. The mobile device collects measurements for a given amount of time from Wi-Fi and Bluetooth devices in range operating in Access Point (AP) mode and sends the report to the E-SMLC or LMF. It can also provide the position as estimated by the embedded GNSS chipset in the mobile device. The E-SMLC or LMF will then fuse all the received results and determine the location estimate for the target mobile using the available technologies.

An *LPP session* is used between a location server and the target device in order to:

- receive target device capability
- obtain location related measurements
- obtain location estimate
- transfer assistance data

A single LPP session is used to support a single location request. Multiple LPP sessions can be used between the same endpoints to support multiple different location requests. Each LPP transaction involves the exchange of one or more LPP messages between the location server and the target device. The general format of an LPP message consists of a set of common fields followed by a body. The body (which may be empty) contains information specific to a particular message type. Each message type contains information specific to one or more positioning methods and/or information common to all positioning methods.

LPP procedures enable the transfer of capabilities from the target device to the server. In this context, capabilities refer to positioning and protocol capabilities related to LPP and the positioning methods supported by LPP. Relevant information about the Message Body Information Elements (IEs) are:

- *RequestCapabilities*: the *RequestCapabilities* message body in an LPP message is used by the location server to request the target device capability information for LPP and the supported individual positioning methods.
- *ProvideCapabilities*: the *ProvideCapabilities* message body in an LPP message indicates the LPP capabilities of the target device to the location server.
- *RequestAssistanceData*: the *RequestAssistanceData* message body in an LPP message is used by the target device to request assistance data from the location server.
- *ProvideAssistanceData*: the *ProvideAssistanceData* message body in an LPP message is used by the location server to provide assistance data to the target device either in response to a request from the target device or in an unsolicited manner.

- *RequestLocationInformation*: the *RequestLocationInformation* message body in an LPP message is used by the location server to request positioning measurements or a position estimate from the target device.
- *ProvideLocationInformation:* the ProvideLocationInformation message body in a LPP message is used by the location server to provide positioning measurements or a position estimate from a target device to the location server.

Once the capabilities of the target device are known through *RequestCapabilities* and *ProvideCapabilities* messages, subsequent procedures enable the location server to request location measurement data and/or a location estimate from the target. The main procedure is as follows:

1. The server sends a *RequestLocationInformation* message to the target to request location information, indicating the type of location information needed and potentially the associated QoS.
2. The target sends a *ProvideLocationInformation* message to the server to transfer location information. The location information transferred should match or be a subset of the location information requested in step 1 unless the server explicitly allows additional location information.
3. If requested in step 1, the target sends additional *ProvideLocationInformation* messages to the server to transfer location information. The location information transferred should match or be a subset of the location information requested in step 1 unless the server explicitly allows additional location information.

Procedures are also defined to enable the target to transfer location measurement data and/or a location estimate to a server in the absence of a request.

2.6 Rich media applications

2.6.1 Ultra-High-Definition TV Streaming

Video contents are accessible on essentially every gadget with a screen; additionally, the number of gadgets in the home increases to 4 or 5 including PCs, smartphones, tablets, VR headsets and most importantly smart 4K & 8K TVs.

The transmission necessities for the home network have increased radically with the developments in the quality of the video contents and the pixel technology in the screens. Additionally, very high-resolution video capturing, storage and viewing technologies are also developing very fast. Unlike satellite or cable broadcasting popular services like Amazon Prime, Netflix, YouTube and additionally the new trend IP-TV all depend on the internet connection used as a way for reaching the high-resolution video contents. Thus, one of the most important things in this new decade of video streaming is the bandwidth and speed requirements which generally causes packet loss and latencies.

2.6.2 Tetherless augmented and virtual reality

2.6.2.1 Virtual and augmented reality

Since Ivan Sutherland famously described “the ultimate display” in 1965 [3], there has been a widespread desire to immerse a user within a realistic virtual environment. Modern technology has led to significant innovations within this new field, allowing users to interact and even sense virtual environments like never before.

Modern Virtual Reality (VR) commonly involves exposing a user to visual and auditory systems designed to imitate the senses of a completely virtual environment. Alternatively, Augmented Reality (AR) attempts to overlay virtual objects within the users' physical environment.

Both VR and AR systems typically consist of a Head-Mounted Display (HMD) used to present the user with the image of their chosen virtual environment. For AR, the user's surrounding physical environment must remain visible through the display. In most VR and all AR systems, a form of head tracking alters the user's display with respect to its movement. Additional tracking of various user body parts, such as hands and legs, can increase interactivity and user experience.

2.6.2.2 Tetherless systems

Systems can differ in regards to where the tracking data is processed, and the respective media rendered; those that offload this operation to an external device conventionally use a cable to transmit and receive data. In these circumstances, the cable forms a physical tether between the user and the external processor.

Not only can this restrict the user freedom to explore a more significant amount of space, but the cable can also interrupt the experience or present itself as a trip hazard. Various work to remove these data cables for external processor systems implement the use of high-speed wireless transmission. The need for high-speed data rates stems from the principle that VR and AR systems must maintain ultra-low latency and demand large amounts of data, for the high-resolution displays required to immerse the user [63] Ultra-low latency is critical within VR/AR systems as a slight disparity between the users' movement, and the correct visual response can lead to simulation sickness, a form of motion sickness [64]. Any added wireless method must therefore not induce too much extra latency.

Early trivial tetherless solutions involved users carrying computer backpacks presenting a usable but non-ideal solution. Entirely wireless solutions commonly employ mmWaves for their potential multi-Gbps data rates. A study on mmWaves for this application considered the occlusions of such signals and presents a 'configurable mmWave reflector' [10] to reduce signal loss. A simulation in [11], with a focus on latency and reliability, considers mmWaves along with edge computing to facilitate multiple wireless VR users. Commercial Wireless VR adapters from TPCAST [12] and DisplayLink [13], employing mmWaves, have since been developed and evaluated with almost negligible effects on latency and resolution [14], [15].

These studies and existing adoption into commercial systems highlight the usability of mmWaves for tetherless VR and potentially AR. While new tetherless VR systems like the Oculus Quest [16] continue to develop, the computational benefits of external processor VR/AR systems remain present, as such, mmWave technology integrated into future HMDs will provide improved tetherless VR experiences.

2.6.3 Location monitoring & guiding Follow-Me TV service

A flexible design of the Intelligent Home IP Gateway, enables hosting intelligent services and NFV technology enables the deployment of network functions in the form of VNFs, e.g., location servers, cache servers, etc. Integrating NFV and SDN with digital TV in the home has the potential to provide smart TV services to users. The Follow-Me Service (FMS) is an example of such an intelligent service.

Follow-Me Service (FMS) architecture

The system architecture for the FMS is shown in Figure 2-1. It consists of end user application installed on UE smart phone, SDN Follow ME Application (FMA) interacting with other platform entities (location server and SDN controller) and proxy/cache server. The focus of FMA is to manage the proxy server downstream destination according to the UE's location information acquired from the location server. The proxy server and location server are fully accessible by the FMA within the Intelligent Home IP Gateway, enabling efficient service operation to optimally forward the data to the correct TV destination within the coverage area.

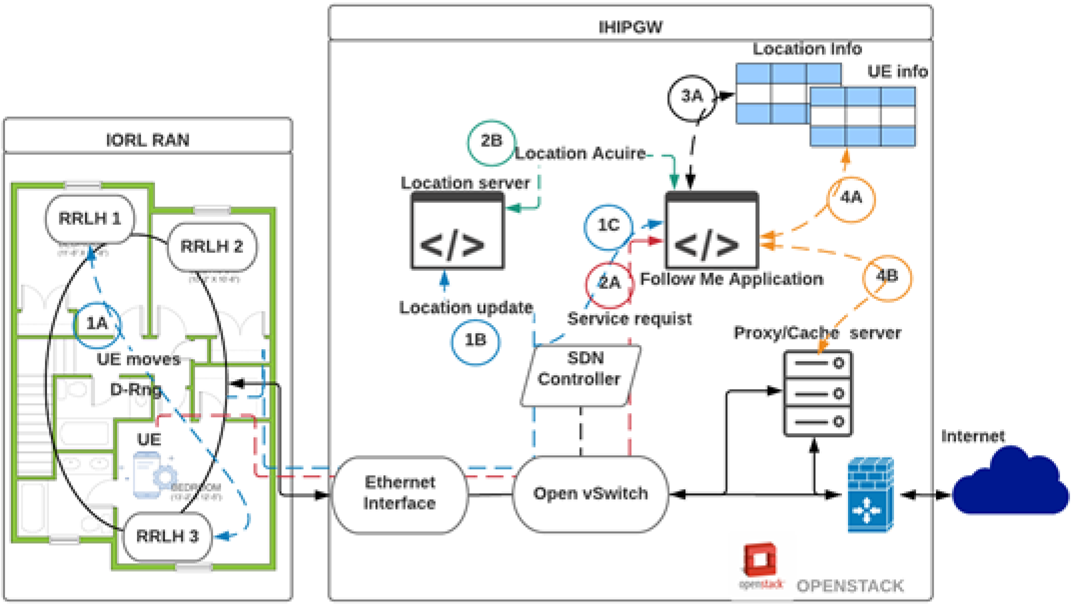


Figure 2-18 Follow-me service architecture

FMA interactions with location server and proxy server is transparent to the UEs registered for this service, and it only requires the UE to initialize the service by requesting a video content to be displayed on specific TV set or multicast the video to all TV sets. FMA configures the proxy server to establish a UDP unicast session to the end TV device or multicast sessions to all TV devices. The proxy server intercepts the TCP connection request originated by the UE, and fetches the video content from the content server, then passes downstream the content to the end destination using UDP sessions.

3 Specificities of indoor environments

In this section we provide a high-level outline of the specificities of indoor environments. Indoor environments are characteristically different from outdoors – to which mobile system solutions are primarily optimised – in a number of aspects. The differences include:

- radio propagation and approaches to its handling, including distributed antenna systems, deep indoor scenarios
- use of and coexistence of a multitude of wireless technologies, and subsequent interference issues
- existing / alternative infrastructures (such as Wi-Fi/Li-Fi and wired, including powerline, Ethernet and fibre)
- cross-domain ownership and control issues – the ownership and control of the alternative indoor infrastructures is by other stakeholders than MNOs
- the number of UEs and their density, which includes wired interfaces in addition to wireless interfaces
- a much wider variety of UEs, than common mobile handsets. Very large, high-resolution displays and TVs (fixed, due to their size), a large number of sensors and IoT devices - some with low or very low data rates, some, potentially requiring very high data rates. AR/VR headsets, game consoles, etc. Industry and e-health - potentially huge volumes of data to be transferred uplink. Drones and robots as well as connected cars.
- indoor radio / wireless access characterised mostly by short distances, in any case shorter than in 5G outdoors (but generally longer than what is commonly referred to as personal area network).

3.1 Effects of building materials on radio propagation

Generally speaking, building materials represent an obstacle for the propagation of electromagnetic waves. Concerning indoor - in building scenarios, we can distinguish a particularly difficult type, the so called deep indoor. Deep indoor refers to indoor environments in the centre of buildings, without windows to the outside world, as well as cellars and underground environments.

Radio waves impinging on a building enters the building by various mechanisms. The influence of the electrical properties of building materials on each mechanism is different. Material properties have a dominant effect on the reflection from, and transmission of, radio waves through building materials and on the absorption of radio wave energy in those materials. These effects give rise to attenuation of the signal. Other mechanisms include diffraction from the edges of materials and scatter from rough surfaces.

The ability to treat propagation mechanisms such as reflection separately from diffraction and scatter arises from the fact that building elements such as walls, windows and doors are generally quasi-two-dimensional structures with sharply defined edges and faces that are planar and smooth on the scale of a wavelength. Whilst this is only approximately true, and is frequency-dependent, all detailed computational models for propagation into and within buildings make these assumptions.

All normal building materials are non-magnetic and non-ionised. This means that we only need to consider the dielectric properties of building materials. Most building materials behave as lossy dielectrics. Even metals can be characterised in this way, although the RF losses through metal are very high.

When a radio wave propagating in the atmosphere impinges on a dielectric material such as a wall or window it will be refracted by the material. Part of it will be reflected and part will be transmitted through the material into the building. The magnitude and phase of the reflected and transmitted components are given by the well-known Fresnel reflection and transmission coefficients. These in turn depend on the dielectric properties of the material, on the wavelength of the radio wave, and on the angle of incidence of the radio wave to the material.

Diffraction of radio waves occurs where two different materials meet, or where there is a sharp change in the shape of the surface of a material. Practical examples in buildings are at corners and edges where two or more walls/ceilings meet, and at the edges of window and doors where wood or glass panels meet walls. Diffraction is generally a "weaker" mechanism than transmission for getting radio signals into a building. On the other hand, it can be the dominant mechanism for providing coverage at certain location inside a building.

Scatter occurs when a radio wave impinges on a rough surface. Whether a surface appears rough or smooth at radio frequencies depends on the relative sizes of surface irregularities compared to the wavelength, and on the angle of incidence of the radio wave. If the irregularities are less than a tenth of a wavelength the surface can be considered smooth at all angles of incidence.

The effect of compound building materials on the attenuation of radio waves is readily derived from the electrical properties of the homogeneous constituent parts. The fundamental quantity of interest is the electrical relative permittivity, ε_r^c. "Relative" means that it is measured relative to the free space value ε_0 , and is a dimensionless quantity. ε_r^c is a complex number, the imaginary part being responsible for absorption of radio waves by the material: $\varepsilon_r^c = \varepsilon_r' + j\varepsilon_r''$.

At the molecular and atomic level, permittivity is caused by the polarisation of the charge carriers in the material in response to an applied electric field. Several different mechanisms occur, at different scales in the material. For example, polar molecules such as water have a permanent dipole moment which causes the dipole to rotate slightly from its rest position in an applied electric field. When the electric field is removed, the molecule "relaxes" back to its normal state. In an applied radio frequency field, the molecules will oscillate. The oscillation is lossy, giving rise to the ohmic losses in the material [26].

Holographic mMIMO refers to the large intelligent surface with (approximately) continuous aperture used for wireless data transmissions. The surface can generate beamformed signals or control reflections from other sources. H-mMIMO can be integrated into any surface, including walls, windows and even fabrics. Extreme spatial resolution enables very low transmit powers and high spatial multiplexing capabilities.

3.2 Reconfigurable intelligent surfaces

Motivation in indoor scenarios

The conventional way of circumventing non-line-of-sight (NLOS) limitations is by providing alternative line-of-sight (LOS) routes through relay nodes. Although such an approach is a well-established method to enhance coverage in poor quality direct connections, it is argued that it is unlikely to constitute a viable main-stream approach, especially in networks employing high-frequencies, mainly because of the increased power consumption, the lower spectral efficiency of the most commonly used half-duplex (HD) relay protocol and the technical challenges of an alternative full-duplex (FD) relay protocol.

When the quality of the direct link is poor and in cases where highly dynamic blockage situations appear (e.g., at high frequencies), the employment of reconfigurable reflectors that can shape the impinging waves in an adaptive and agile fashion could offer substantial benefits. This is the main reason behind the fact that the RIS paradigm has received a huge amount of research attention over the last couple of years. RISs are artificial electromagnetic-material surfaces that are engineered to possess specific desirable properties, that cannot be found in naturally occurring materials. They are based on meta-surface technology, which is the 2D equivalent of metamaterials. More specifically, a meta-surface is comprised of periodic sub-wavelength metallic or dielectric scattering particles that are called unit cells or meta-atoms [32], [33].

It can be described as an electromagnetic discontinuity that is notably sub-wavelength in thickness, with typical values ranging between $\lambda/10$ to $\lambda/5$, where λ is the wavelength, and electrically large in transverse size. Its unique properties lie in the shaping of an electromagnetic wave according to the generalized Snell's laws where ordinary as well as anomalous reflection and refraction phenomena are observed. In a non-reconfigurable meta-surface, the unit cells have fixed structural and geometrical arrangements, which results in fixed refraction index, and hence, a static interaction with the impinging electromagnetic wave. On the other hand, in the reconfigurable case, the unit-cell arrangements can be modified based on external stimuli. This can be enabled by electronic phase-switching components, such as PIN diodes, radio frequency (RF)-microelectromechanical systems, and varactor diodes, that are introduced between adjacent unit cells. In such a way, the wavefront can be shaped arbitrarily so that the electromagnetic wave can be either reflected, refracted, or absorbed [34], [35], [36].

3.3 Co-existence of wireless technologies

One of the growing problems in homes and businesses is interference between the range of different wireless systems in the home, namely: electronic equipment such as microwave ovens, cordless phones, wireless headsets, Zigbee, ZWave, Bluetooth devices, surveillance cameras and other wireless radio networks. These, further compromise the performance of licence-exempt broadband (Wi-Fi) that is best-effort quality and has listen-before-talk protocols to mitigate interference. Thus, the main motivation for home and business owners has been to switch to home networks that use regulated spectrum such as Home gNBs (HgNBs) to avoid interference problems and provide more deterministic quality of service.

However, many modern buildings are built with thermal metal clad insulation that severely restricts the propagation of RF waves and with metal coated windows, which restrict the propagation of RF waves within and to/from outside the building. In the extreme, some buildings are made from steel shipping containers such as the Starbucks building in Tukwila, Washington USA [27]. Therefore, the introduction of modern building materials is making it increasingly difficult for the radio signal from wireless transceivers to provide sufficient coverage inside buildings and so many organizations are attempting to deploy HgNBs on their premises. Furthermore, although outside to in-door mobile solutions are trouble free for the consumer to set up, they do not work for all locations inside a building, since it does not make sense to illuminate the inside of a building from outside gNB macrocells.

The deployment of HgNB small cells requires the permission of MNOs, due to their potential to interfere with the main gNB transmitted signal, but the MNOs only have the resources to approve installation for their larger business clients (with 100 employees and above) and neglect their smaller clients, who are by far the largest group in the market place. These smaller clients then become frustrated and return to using Wi-Fi! This trend is being experienced worldwide.

Furthermore, larger clients, who wish to use HgNB small cells in their premises, require separate infrastructure for every MNO that is providing coverage in a building, which is very costly and inconvenient to the client. This has led to the concept of the sharing of mobile network resources, such as with Multi Operator Radio Access Network (MORAN) HgNB systems, and the concept of improving the coverage within buildings such as with Distributed Antenna Systems (DAS), both of which continue to be costly options for the client.

The status quo between mobile network providers and wireless network providers has been that the former has operated their networks in licensed spectrum whereas the latter in unlicensed spectrum. However recently this status quo has been disturbed by the concept of LTE-Unlicensed, License Assisted Access (LAA) and LTE Supplemental Downlink (SDL), which enables network operators the use of the 4G carrier aggregated LTE radio communications in unlicensed spectrum used by Wi-Fi equipment as well as licensed spectrum.

Recently MuLTEfire has been proposed by Qualcomm, which uses LTE in unlicensed spectrum that does not require an anchor in licensed spectrum, so opening up LTE to organisations that do not own licensed spectrum like Internet service providers (ISPs) and stadia or conference venue owners. MuLTEfire does not adhere to the European requirement to listen before talk and hence faces regulatory issues about interference to other license-exempt users and to radar services in the 5 GHz band. Furthermore, the Spectrum Access System (SAS) has been proposed by Google, which uses both 802.11 Wi-Fi and/or LTE in unlicensed 3.5 GHz spectrum for Internet of Things (IoT) devices, which need low latency, high-performance wireless networks typically over a very short range that can handle up to ten million devices under management.

3.4 Existing indoor infrastructures and facilities that can support 5G networking and service delivery

Indoor environments are characterised by the existence of various standard infrastructures, including:

- electric power
- lighting
- water and sewage

In new and recent buildings dedicated wired communication infrastructures, such as Ethernet, and/or fibre optical cabling can also be present. The presence of such wired communication infrastructure is probably still less common even in newly built private homes, as in any industrial or office environments, where they had become almost standard.

In Europe, the electric power distribution network in buildings uses alternating current (AC) operating at 230V. It serves both lighting and offering access to electricity for various devices and machines through standard (electric) power outlets distributed across the building. Usually, the lighting and powering circuits are separated.

In the last twenty years or so, power-line communication technology has been developed offering wired connectivity as a secondary use of the AC electric power distribution network. Power-line communication (PLC) carries data simultaneously on a conductor that is used for AC electric power distribution. Most PLC technologies limit themselves to in premises wiring within a single building. Various data rates and frequencies are used in different situations. Power-line communication is prone to radio interference problems causing concerns. Nevertheless, simple to use consumer grade solutions are available and are widely used.

With the successful commercialization of the InGaN based light- emitting diode (LED), the white LED has been widely deployed in the public illumination systems (such as transportation, hospitals, etc.) to replace the current incandescent and fluorescent lights due to its better energy efficiency, smaller size, and longer lifetime [55]. In fact, LEDs can be utilized not only for illumination but also for visual Light Communication (VLC) [56], [57], [58]. VLC technology has many attractive features, such as among others the worldwide available and unlicensed bandwidth, non-interference with RF bands, no electro-magnetic radiation and high data rates. These exciting assets have generated considerable research and industrial interests for VLC, especially with the approval of the IEEE 802.15.7 standard in 2011 [59].

VLC is an effective solution to satisfy the strict communication requirements of indoor hospital applications. However, VLC must access the backbone network to avoid becoming the so-called *information isolated island*. The integration of VLC and PLC comes from the fact that all the LED lamps have to be connected with the power line, and power line can naturally act as the backbone for VLC while powering the LED lamp. In this way, it can save the additional communication lines, avoid the layout modification, and hence be easier to install compared to other access solutions.

Building practice in the UK dictate that there is always a space between the ceiling and floor above it, along which power cables, water and drainage pipes can be routed. In other parts of Europe this is not necessarily the case with some buildings constructed from concrete using conduit within which to route the power cables whereas other buildings embed the cable within the concrete. The lighting and power circuits are ring networks in some parts of Europe e.g., UK that are usually separate from each other due to different rating requirements. In other parts of Europe these are star networks e.g., in Germany. Since all VLC and radio wireless communications access points require power, position and backhaul to operate, co-locating these access points with lighting network access points and adopting a similar topology to power network e.g., ring network in UK, means that all three requirements are readily provided thus making it cost efficient to deploy.

All the above utilisation of various indoor infrastructures complements and supports the ever more widespread use of wireless technologies – most notably Wi-Fi – to connect an increasing number of potentially mobile devices. The wireless connectivity, or access representing usually the last, short hop.

Finally, all the above indoor communication infrastructures are used in combination with the standard presence of a central hub, a broadband router, in case of private homes, which is connected to the broadband access provider network, be it cable, or DSL.

In the following we give examples showcasing how the indoor lighting infrastructure can support 5G connectivity.

3.4.1 Ceiling Light

The ceiling light consists of illumination LEDs, communication LED and two (vertical and horizontal polarised) mmWave antennas, as shown in Figure 3-19 below. Since the illumination LEDs were arranged in a complex parallel-serial circuit with significant impedance, they were not suited to be driven by the VLC driver. The communication LED is situated in the centre of the Ceiling Light with a large lens in front of it and a clear circular aperture, whereas the illumination LEDs are situated in the remaining area with diffuser. In the two diagonal corners are two square apertures through which the vertical and horizontal polarised mmWave antennas are exposed. The VLC and mmWave drivers are located behind the illumination LEDs circuit and high frequency SMA cables must be used to connect them to their communications LED and mmWave antennas.

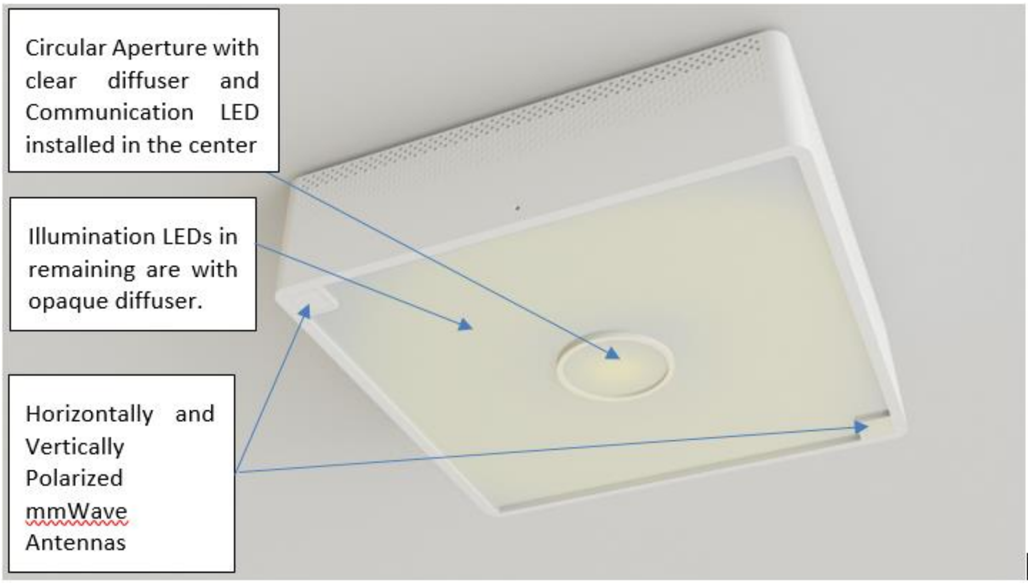


Figure 3-19 Ceiling light

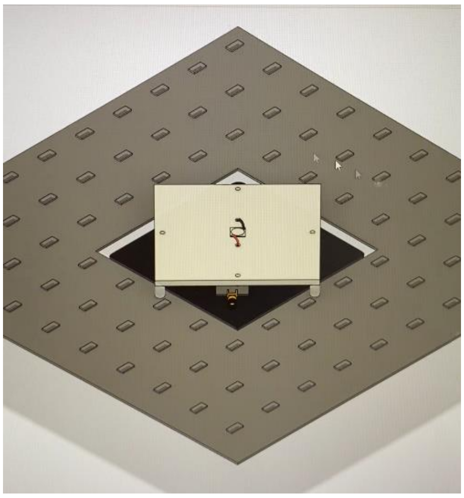


Figure 3-20 Communication LED and illumination LEDs

Figure 3-21 Communication LED with circular aperture lens

3.4.2 Spot Light

The spot light consists of a communication LED (which also acts as the illumination LED) and two (vertical and horizontal polarised) mmWave antennas, as shown in Figure 3-22 below. The communication-illumination LED is situated in a separate circular housing which can be swivelled to point to the illumination subject. In the two diagonal corners of a RRLH housing are two square apertures through which the vertical and horizontal polarised mmWave antennas are exposed. The VLC and mmWave drivers are located within the housing and high frequency SMA cables must be used to connect them to their communications LED and mmWave antennas.

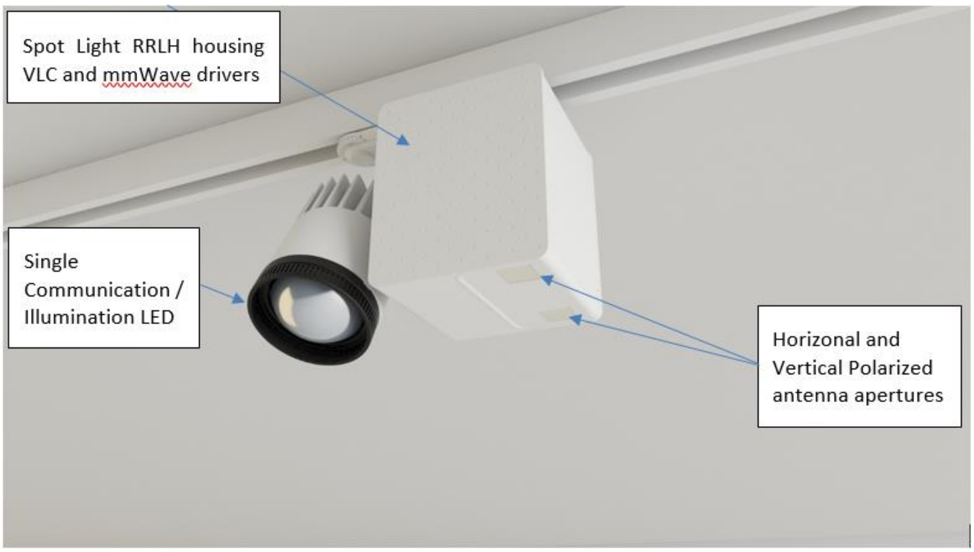


Figure 3-22 Spot light

3.4.3 Pendant Light

The pendant light consists of a communication LED (which also acts as the illumination LED) and two (vertical and horizontal polarised) mmWave antennas, as shown in Figure 3-24 below. The communication-illumination LED is situated at the end of a pendant which consists of a high frequency SMA cable. In the two diagonal corners of the light rose RRLH housing are two square apertures through which the vertical and horizontal polarised mmWave antennas are exposed. The VLC and mmWave drivers are located within the light rose housing.

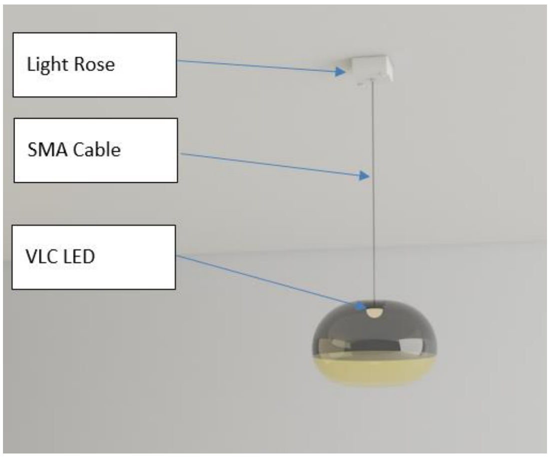


Figure 3-23 Pendant light system

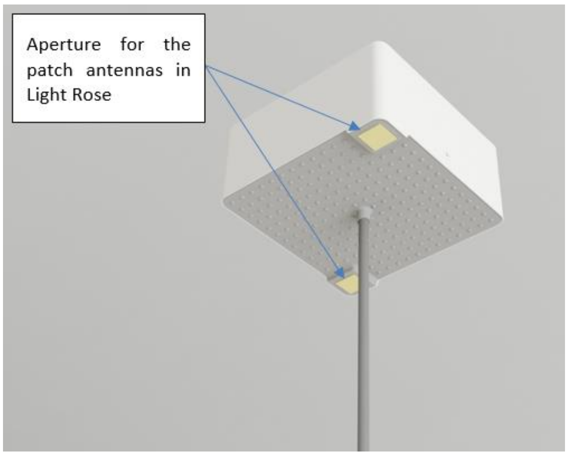


Figure 3-24 Light rose with apertures for LED at the end of the pendant mmWave antennas

3.4.4 Accessory Light

Three options have been designed for accessory light, namely: ceiling light without communication LED but with illumination LEDs, ceiling light without communication LED and without illumination LEDs, ceiling light with communication LED and without illumination LEDs, as shown in the figures below. These were required for train station platform and tunnel requirements.

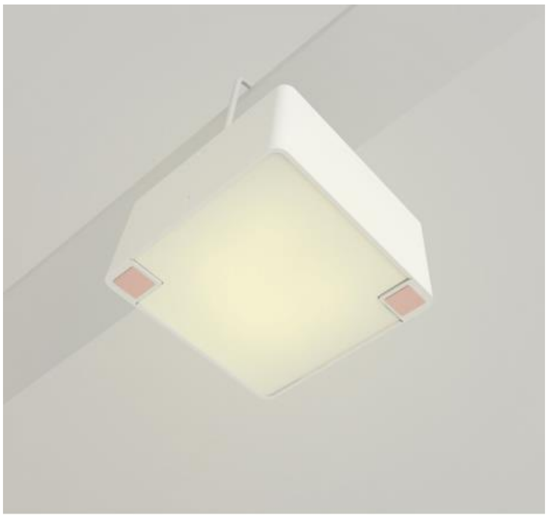


Figure 3-25 Accessory light without communications LED

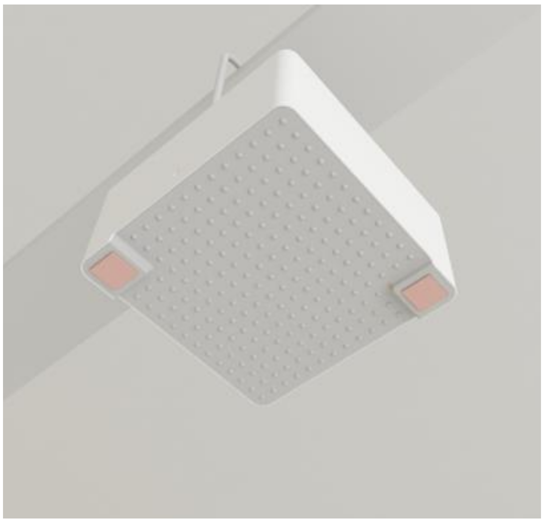


Figure 3-26 Accessory light without communications and illumination LEDs

Figure 3-27 Accessory light without illumination LEDs

3.5 Administrative domains and ownership issues

The broadband service provider provides its service through broadband access network, be it cable, DSL or wireless. Such a broadband connection is accessed through a router, in most cases the router being selected by and under the control of the customer, in case of private homes. In case of industrial, medical premises or institutions, private networks are present on premises and on site, under the control and administration of the organisations operating there, or under the administration of a property manager organisation,

In certain cases, such as for example public transport the public network of the mobile network operator is present, for example in deep indoor situations, in the underground and metro.

3.5.1 Private 5G networks in smart manufacturing indoor environments

The evolution towards Industry 4.0 implies that the number of connected devices in the plant will increase exponentially: assets, equipment, vehicles and processes, all of that will be massively connected through a private 5G network which guarantee stable and secure performance.

To understand from where the need for a private network comes from, in a smart manufacturing scenario, let’s consider the most relevant use cases:

- The process of integrating private 5G networks in a manufacturing plant is typically triggered by a need to replace legacy networks or the increasing mobility requirements of their operations. The goal is a significantly reduced infrastructure cost by replacing cables with industry-grade 5G cellular connectivity able to support latency-critical, massive, enhanced broadband, and security needs. Less cabling in the factory also implies increased floorplan, layout flexibility, and easier deployment of new factory equipment.
- The second step, once a 5G private network is in place, is removal of in-field distributed control logic (local PLCs and some functions in robot controllers), moving control into the cloud in the form of virtual machines (e.g., soft PLCs). Virtual and remote control save space in the plant, reduce energy to cool the plant, provide redundancy, enable easier implementation of new control features, facilitate cooperative device control and finally, reduce maintenance costs. A latency of a few milliseconds is required at the wireless network to support transport of industrial protocols like ProfiNet and Ethernet/IP.
- The same 5G network can also ensure massive machine type communication which is a pre-requisite for the supervision in real time of the factory and of the production. This use case, performing predictive and preventing maintenance, is enabled by a multitude of wireless sensors, with pre-emptive analytics to detect anomalies, predict and prevent failures, thereby reducing unscheduled downtime for maintenance or repair. A modern plant produces and assembles about one car every minute. Five minutes of downtime for maintenance corresponds to the loss of value of five cars.
- The 5G network, with the clear flexibility advantage vs. cable, enables the use of Autonomous Mobile Robots (AMR), an evolution of the AGVs. These mobile robots are trolleys that enable *multidirectional layout* of the production line instead of the *linear layout* enabled by conventional conveyors. AMRs *understand* the surrounding environment and ensures the shuttling of the various components inside and among the work cells in the plant and between the line and the warehouses/loading bays. Most of the processing, for example for collision avoidance and visual navigation, is migrated in a cloud on premises.

These use cases require a private network as they demand the industry-grade, guaranteed, performance that is summarized in the following:

- Data rates to be supported are very use case specific and will vary from a few kbps to tens or even hundreds of Mbps. Some use cases require massive data transfer with Gbps throughput. Moreover, differently from traditional consumer mobile traffic, which is typically downlink unbalanced, the data traffic from the industrial shop floor is generally uplink intensive (due for instance to massive distribution of sensors and high-definition cameras on the field).
- Latency down to one millisecond for specific use cases is required. In addition, latency with a guaranteed upper bound, i.e., deterministic latency, is essential for critical automation use cases; packets need to arrive on time, otherwise they are considered lost. Robots cannot stay without instructions!

- A need to guarantee traffic separation and quality of service assurance per device and per service, and even per location of the device (positioning with high accuracy, down to millimetre, and low latency positioning could be relevant).
- Mobility is required for some devices to move freely within the coverage of the private 5G network as well as outside of the private network to public networks. E.g., for tracking and software updates of produced goods, for manufacturing equipment that moves outside the local industry plant such as trucks, and personnel.
- Scalability, since the number of supported industrial devices by the connectivity solution needs to be able to scale from few devices to thousands.
- Some industries show particularities as well on the network roll-out and planning requirements due to special conditions like metal walls, high ceilings, heavy electromagnetic interferences etc.
- Finally, reliability and availability of the connectivity layer are crucial in the industrial environment since any single network downtime can lead to sensible production lags with consequent economic damage. To this extent, independently from the specific radio access technology (4G or 5G), special care must be given to network and system design, often requiring dedicated coverage and equipment redundancy schemes as well as proper fault management procedures. This is in order to increase network availability to levels not normally assured in traditional commercial networks for retail services.

3.5.2 Deployment options for non-public networks

5G private networks can cover multiple industrial sites (e.g., manufacturing plants), serve an industrial district where several small-medium enterprises operate or be envisioned as region-wide. In any of these cases, the 5G private network, called Non-Public Network (NPN), can operate in conjunction with a public network (PN) of the MNO.

The integration between the NPN and PN can embody different levels of interaction as proposed by 5G-ACIA and depicted in Figure 3-28:

- a fully “isolated” private network where the whole network is deployed on-premises as a standalone network, without any bond to the public network
- an intermediate case in which the radio access network (RAN) and (part of) the control plane elements are shared with the public network. Nevertheless, the private network preserves its own local services
- a network where the only “private” element is the coverage, while all user plane and control plane elements are provided by the public network

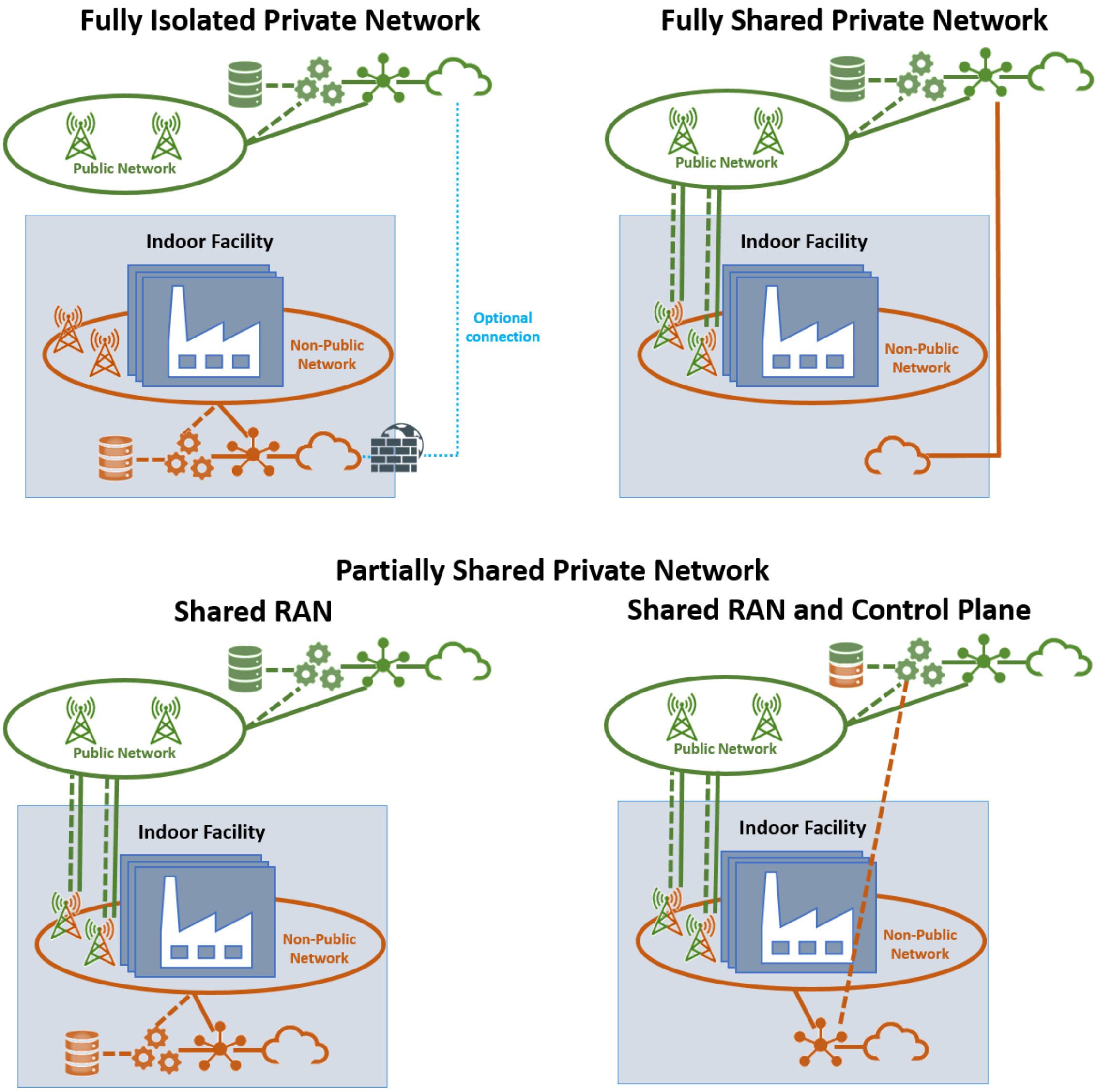


Figure 3-28 5G NPN-PN deployment options according to 5G-ACIA

Taking into account the aforementioned three-levels of integration, an industrial environment can either (i) deploy, at the internals of the industrial sites, a fully and complete operational 5G network (i.e., standalone NPN approach); or (ii) leverage on capabilities available at the MNO public network to complement its own deployment (i.e., the NPN-PN integration approach). While the former is a totally isolated deployment without any dependency on the MNO public network, the latter relies partially or totally on the infrastructure and functions of the MNO.

The best deployment approach must be selected on a case-by-case basis, since it depends on several factors that might not be common to all industrial environments. Different industries might have different requirements and needs, which would impact e.g., the level of QoS customization and control required, autonomy towards the MNO, security, and isolation of their internal processes. Additionally, aspects such as the support of mobility when outside the factory premises, the need for know-how and specialized personnel to manage the NPN, and costs of deployments are other entry barrier aspects that might influence the choice of a specific NPN deployment approach.

A proposal of the shared transport solution to connect such a NPN with the PN is explained in Section 4.2. For a thorough discussion on Non-Public-Networks refer to the related 5G PPP whitepaper [76].

4 Solutions and enablers for delivery of 5G services indoors

Two major challenges in providing indoor connectivity which needs to be addressed by mobile systems and economics are: how to provide deep indoor coverage in a way that benefits both the deployer and the building owner or the enterprise; and how to deliver the wireless connectivity which is optimal and fulfils the user needs, if it is a home or a vertical with its specific requirements.

It is well known and repeatedly said that we spend 90% of our time indoors, and then correlated to this an increasingly higher percentage of overall mobile data around, three-quarter or more, is generated indoors. Wi-Fi is the most widespread wireless technology used for indoor, and Wi-Fi 6 is well suited to indoor and use cases requiring high speed and best effort traffic. But since Wi-Fi operates on unlicensed bands and its reliability and availability cannot be guaranteed, 5G comes into the picture to deliver crucial services indoors.

Furthermore, it is noted that the 5G *Vertical_LAN* in 3GPP Release-16 introduces three new 5G enablers for emerging use cases especially in Industrial IoT applications such as Industry 4.0 and factory automation to provide support for Time Sensitive Communications, Non-Public Networks and 5G-LAN type services respectively. Compared with Wi-Fi-based solutions, these Vertical_LAN services can all contribute to indoor use cases by offering extra benefits in mobility, security, coverage and performance.

Small cells, e.g., femtocells and picocells, are localised mobile networks in home/offices to access the MNO's network via user's broadband connection, i.e., they act similar to Wi-Fi but use frequency bands that are licensed to the MNO (and then are directly connected to the mobile network). 5G small cells can bring benefits through mmWave 5G, i.e., high throughput, increased capacity, high reliability and simultaneous service to large number of users, to the indoor use cases.

Yet the other trend in indoor connectivity with 5G, especially for enterprise, is the private (non-public) networks. These can offer a wide range of benefits compared to the other options. In contrast to Wi-Fi, a private 5G network can deliver required coverage and capacity with high quality and reliability to realise the 5G *Ultra Reliable, Low-Latency Communications*. Moreover, strict security, privacy and data isolation requirements can be met particularly through the advanced range of features available with 5G network solutions. 5G network slicing can be equally applicable to the private networks to allow partitioning of devices and applications which allows for further enhancements to data security and containment especially with the deployment of on-site edge computing.

Transmission latency can be reduced when local edge equipment is installed for the private or dedicated network which enables *real-time* or *near real-time* services particularly with improvements delivered by 5G ultra-low latency services when used with edge computing.

Distributed antenna systems (DAS) are an infrastructure of cables and antennas installed within a building to connect a range of wireless devices, e.g., mobile phones, tablets, public safety radio, etc., without interfere to each other. DAS are mainly deployed in public environments, e.g., airports, sport complexes, shopping malls, etc. This technology however requires network planning which may be lengthy for large venues, and overall, the market prediction does not show a large growth [65] and hence 5G deployments cannot rely on this technology. DAS cabling cannot serve the new 5G frequencies, especially mmWave, which means that one would need to rewire existing DAS enabled sites to deliver 5G. DAS is not a good architecture in the case of massive MIMO [66].

This section presents a comparative analysis of 5G against Wi-Fi 6, a number of options for indoor RAN deployments, integration possibilities of non-public networks with public networks and shared transport networks for connectivity, as well as various edge computing solutions for supporting indoor 5G services. Finally, it provides an overview of existing indoor localisation solutions.

4.1 Wi-Fi 6: a comparative analysis

The boost given to Wi-Fi 6 in terms of capacity, efficiency, and flexibility has aligned it with emerging 5G priorities. Unlike its predecessor, IEEE802.11ac, the standard can support up to 12 simultaneous user streams from a single Wi-Fi access point, 8x8 multiuser MIMO for both uplink and downlink, and offers greater flexibility to deploy channel sizes from 20MHz to 160MHz, accommodating specific use case requirements. The addition of OFDMA improves Wi-Fi performance, driving greater efficiency, and lower latencies in arenas, auditoriums, and other high-density environments. Wi-Fi is certain to remain popular, providing last-hop access to wireless devices in people’s homes. It will also continue to serve enterprises’ non-critical use cases effectively in mainly indoor deployments.

5G, on the other hand, is a complete solution for enhanced mobile broadband (eMBB), fixed wireless access (FWA), massive machine-type communication (mMTC), and critical machine-type communication (cMTC). It supports both the wide-area and indoor connectivity needs of consumers, enterprises and the public sector alike.

Wi-Fi 6 and 5G will co-exist, and work better, together to support different use cases, and will expand opportunities for digitization across all industries. The reality is that the two are largely complementary with an overlap for some use cases.

5G NR has given dramatic capability boost to cellular communication leveraging wide range of frequencies (sub-1 GHz to 100 GHz) with very large bandwidths, seamless carrier aggregation across multiple bands, massive number of steerable antenna elements, flexible and scalable physical layer for handling diverse scenarios, ultra-lean design for energy efficiency, advanced critical MTC features for ultra-reliability, ultra-low latency, interruption-free mobility, and Time-Sensitive Networking (TSN), and fully flexible end-to-end network slicing and QoS framework. With these capabilities, 5G NR is much more attractive technology for addressing demanding indoor connectivity requirements than the earlier generations of cellular systems.

When operating on licensed spectrum, 5G offers superior reliability and better predictability to meet critical communication needs. Here is a list of its advantages:

- 5G is designed to fulfil QoS requirements for a much broader range of use cases than Wi-Fi (5G has full support for mMTC, eMBB, critical IoT and TSN).
- 5G supports fully flexible end-to-end QoS differentiation and per-user policy control with a single network, which is not available in Wi-Fi 6.
- 5G provides end-to-end security and global identity management.
- 5G has end-to-end specifications covering a complete system architecture (in contrast to Wi-Fi which specifies primarily L1 and L2).
- In general, cellular technology uses licensed spectrum which largely eliminates potential interference that may occur with unlicensed Wi-Fi spectrum. Like 4G LTE technologies, 5G can be supplied by cellular wireless carriers or built as a private network.
- 5G can also use unlicensed spectrum to offload non-critical traffic. For example, New Radio Unlicensed or NR-U (part of 3GPP Release 16) can be used, or Wi-Fi can be integrated within a 5G system as a complementary access technology.

- 5G provides both wide-area and local coverage with full mobility, while Wi-Fi 6 is limited to local coverage and more basic mobility. Movement and handover between cells are intrinsic in cellular systems, whereas there is no such a thing in Wi-Fi. However, it is anticipated that much of the growth in traffic and usage models for both 5G and Wi-Fi 6 will be associated with quasi-fixed, nomadic use cases.
- 5G offers the combined merits of the mid-band and low-band for good coverage, and high band in mmWave for extreme capacity, low predictive latency, and highly accurate positioning. Wi-Fi 6 is limited to the mid-band and finite bandwidth per access point or device.
- 5G Supports rigorous device interoperability testing and certification process.

As a technology option, Wi-Fi has been far more widely adopted by non-smartphone device manufacturers and is established in more ecosystems than 5G. The following advantages can be identified for the technology:

- Wi-Fi 6 modems are less expensive than their 5G counterparts.
- Wi-Fi deployments are often easy and require limited technical competence (users can establish one or a few access points themselves).
- Wi-Fi is preferred over cellular by some operating systems such as Apple iOS, which connects the device to the Wi-Fi network automatically.
- Wi-Fi operates on unlicensed spectrum (as well as NR-U, but usage rights are limited with 5G NR, which operates on licensed spectrum).
- Enterprise IT integrators and procurement departments may prefer Wi-Fi as Wi-Fi competence is common, relationships with vendors are well established, and users with data-limited packages are accustomed to offloading to Wi-Fi.

4.2 Indoor RAN deployment

Cellular coverage in indoor areas has been a long recurring problem, more so as mobile data capacity and pervasiveness of smartphone usage continued to increase. This coverage (and capacity) problem has been worsening continuously due to different causes: exhaustion of low spectrum frequencies which were best for building penetration were replaced with higher operating frequencies with worse penetration characteristics, the use of efficient and environmentally friendly materials in buildings (ex. use of glass to reflect infra-red radiation to keep the heat in or out) causing higher attenuation also to radio waves) and the sole expectancy by users of having cellular coverage and higher capacity rates (requiring better signal to noise ratios) in indoor *not-spots* or *bad-spots* including underground areas, parking lots, basements, etc. There are different indoor solutions that MNOs have traditionally tried to use mainly with 3G and 4G technology to address the indoor coverage challenge:

- Classical Distributed Antenna Systems (DAS): this approach requires large space, power and cooling requirements and has traditionally been used for large venues
- Advanced Distributed Antenna Systems: enhancement easier to install (Fibre and CAT6) and with reduced space and power requirements to address the issue with expensive classical DAS
- Fully integrated Small Cells: all-in eNB solutions deployed either in residential or enterprise environments and normally connected back to the EPC through unmanaged backhaul[1]. The residential solutions were normally based on single operator platforms

[1] The backhaul is a network segment between the network edge (RAN) and the core network.

deployed by the operators in the homes of their customers (Home eNodeB) or at the most some neutral host approaches via multi-operator core networks with single carrier or MORAN with multicarrier platforms in the enterprise space. These were mostly, like DAS, addressing licensed frequency spectrum belonging to the incumbent MNOs.

Green Femtocell architecture was demonstrated in [49]. The architecture is based on hybrid wireless-wired home infrastructure, with the aim to limit drastically the radio signals in-house. The architecture named very-low radiation distributed antenna system (VLR-DAS) was demonstrated for the distribution of various radio-protocols including UMTS, 3G, LTE, WiMax over multiple rooms. Home access nodes (HAN) were developed to enable transmission of the signals with minimum delay and negligible distortion.

A further extension to the VLR-DAS architecture was published in [48], [47] targeting the distribution of combined 5G and VLC signals. The data rates requirements for indoor DL were 1.5Gbps and 500Mbps in the UL. The main ideas were carried forward to [61] and include:

1. Fronthaul[2] architecture, which includes the baseband unit (BBU) at the logistic centre (i.e., Radio Cloud Centre, or Cloud-RAN and the remote radio head (RRH) installed at home/office, to comply with the required coverage while keeping the operational expenditure minimal.
2. Connecting the BBU and the RRH with optical fibres: single-mode fibre between the logistic centre to the customer’s building and with Plastic Optical Fibre (POF) inside the building. Using the digital radio-over-fibre (D-RoF) technique for leveraging the decentralization of the RRH concept without any degradation in the potential of the quality-of-service level from the small-cell and with minimal cost.
3. Taking advantage of the front haul architecture for indoor coverage improvement allows to effectively reduce the transmission power dramatically (~40dB), while maintaining the quality and reliability levels of the communication.
4. Flexible and dynamic RRH architecture to support 5G concepts of SDN and NFV.
5. Multi-Radio Access Technology (RAT) based RRH for low-power, high speed, flexible and reliable Radio Access Network for meeting the 5G indoor requirements.

With the advent of the new 5G architectures with efficient and flexible splits between CU, DU and RUs, new regulatory regimes enabling spectrum for private enterprise use via local or shared access licenses and the inclusion in 3GPP on its own right of unlicensed spectrum operation and support for NPN (whether SNPN or PNI-NPN), the mass deployment of indoor solutions enabled with neutral host business models will enable the densification needed also indoors.

[2] The following definition of *fronthaul* is borrowed from the 5G Architecture white paper [37], although the 5G Architecture white paper stops short of providing a formal definition of fronthaul).

The RAN architectures adopting the Cloud-RAN (C-RAN) concept require infrastructure connectivity within the RAN, for example between centralized units (CUs) and distributed units (DUs), and such infrastructure connectivity is commonly referred to as fronthaul (FH).

4.2.1 Indoor 5G small cell architectures

As discussed in Small Cell Forum SCF 238 *5G architecture and product definitions* the SCF market analysis categorised 5G small cell environments to meet the 5G use cases in 2020-2025 as follows:

- Residential/SOHO → indoor
- Indoor Enterprise (small, medium and large) → indoor
- Private Industrial → indoor/outdoor
- Campus environments venues, manufacturing complexes, educational institutions and stadiums → indoor/outdoor
- Outdoor dense urban public
- Outdoor rural

These are all based on the same 5G architectural principles. To take advantage of the RAN virtualization benefits in terms of scalability and centralization, 3GPP NR allows splitting the gNB functionality into three logical modules: Radio Unit (RU), provisioned with RF circuitry; the Distributed Unit (gNB-DU), hosting gNB real-time functions; and the Centralized Unit (gNB-CU), hosting gNB non-real-time functions. The distribution of gNB functionality (see Figure 4-29) across these three modules has been in discussion within 3GPP and the industry in general for some time. Eight split options were identified. The critical question here was where to make the necessary splits between gNB-CU, gNB-DU and RU: High-Layer Split (HLS), between gNB-CU and gNB-DU, and Low-Layer Split (LLS), between gNB-DU and RU.

The industry has settled around split option 2 for the HLS. This is now the standard and normative 3GPP F1 mid-haul interface defined to connect the gNB-CU and gNB-DU. For the LLS between gNB-DU and RU, 3GPP has recommended either Split 7-2 (which is specified in O-RAN Alliance as the Fronthaul 7.2 interface) or Split 6 (which is defined in Small Cell Forum as the 5G FAPI/nFAPI). The initial ecosystem of disaggregated RUs (white label, low cost, commoditised and interoperable RUs as O-RAN pursues) seem to be developing towards the O-RAN Fronthaul 7.2 based RUs, although other deployments based on SCF nFAPI could also be available, particularly for combined DU/RUs with internal interfaces based on SoCs interfaces compatible with the former 4G FAPI interface.

The 2 main splits introduced with the mid-haul interface based on HLS and the fronthaul interface based on LLS, enable a flexible toolset for deployments according to different transport characteristics such as bandwidth, latency and jitter. HLS Split 2 allows the virtualization of the CUs components of the RAN in either DC or Edge-based COTS servers (including enterprise servers) with not so demanding latency requirements. The LLS based on Split 7.2 allows the deployment of DUs connected through RUs with transport technology based on 10 Gbps (or more) Ethernet/Fibre connectivity. Specifically, Split 7.2 unlike other lower layer splits, enable efficient scheduling and latencies while at the same time allowing reasonable and scalable transport capacity requirements for the support of massive MIMO and mmWave based capabilities.

The project [62] follows the above industry recommendations, providing the gNB decomposition as illustrated in Figure 4-30. On the one hand, the RU corresponds to the 5G physical access node, and therefore will be deployed as Physical Network Function (PNF) in the project's infrastructure stratum. On the other hand, with regards to gNB-DU and gNB-CU, different variants can be selected:

1. Both gNB-DU and gNB-CU executed atop the NFVI's RAN resource zone, but deployed separately. In this scenario, gNB-DU and gNB-CU can be modelled as (monolithic) VNFs.

2. Both gNB-DU and gNB-CU executed atop the NFVI's RAN resource zone, but deployed as a single (monolithic) VNF. The co-location described in this scenario corresponds to classical C-RAN, with this VNF providing Base Band Unit (BBU) functionality.
3. gNB-DU co-located with the RU, and gNB-CU running on the NFVI's RAN resource zone. In this scenario, gNB-CU is deployed as a (monolithic) VNF, and the gNB-DU and RU are integrated into a single PNF (combined DU/RU).

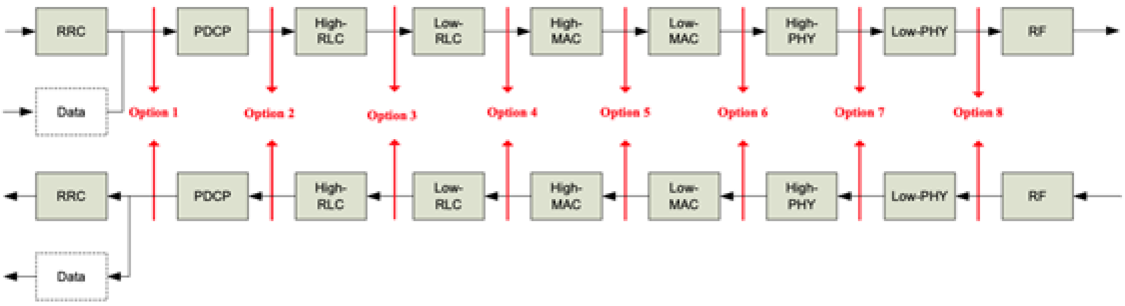


Figure 4-29 RAN decomposition options

An alternative, corresponding to the traditional fully integrated gNB with CU, DU and RU combined functions running as a single PNF (traditional fully integrated Small Cell with NG backhaul interface) could be another variant available in the market for low complexity deployments, included residential or SOHO.

In general variants 1/2 are more suitable for big deployments (high number of RUs) where scalability is achieved via hierarchical topologies where a CU can control a certain number of DUs (ex. 8 DUs per CU) with each DU controlling a certain number of RUs (ex. 8 RUs per DU) which at the same time support a certain number of RUs depending on the computing and transport characteristics. For smaller deployments (low number of RUs) a simplified approach based on variant 3 could be sufficient and less complex to deploy while still enabling scaling to a reasonable number of Small Cells in the cluster.

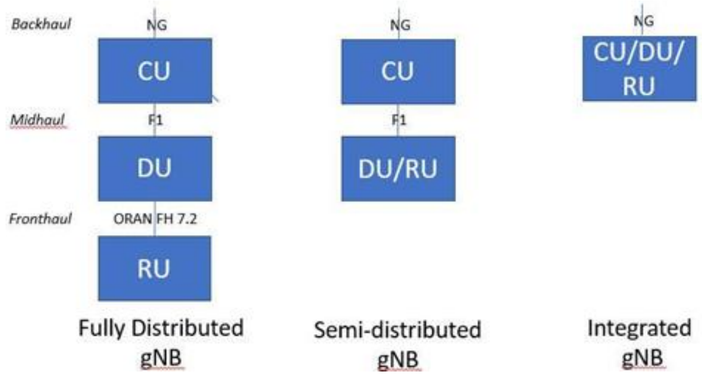


Figure 4-30 gNB deployment options

4.2.2 Multi-wireless access technologies reference architecture

In addition to the indoor 5G Small Cell RAN functional splitting principles discussed in the previous section, [62] also leverages on two further architectural pillars: integration of the O-RAN Alliance framework and integration of multi-WAT protocol stack.

4.2.2.1 Integration of the O-RAN Alliance framework

The O-RAN Alliance [46] is a world-wide community of more than 170 mobile network operators, vendors and research & academic institutions founded to accelerate the adoption of virtualized RAN on white box hardware, with embedded AI-powered radio control and SDN/NFV mechanisms. The mission of O-RAN is to re-shape the industry towards more intelligent, open, virtualized and fully interoperable mobile networks. O-RAN has defined an architecture based on well-defined, standardized interfaces in full support of and complementary to standards promoted by 3GPP and other industry standards organizations (e.g., ITU-T, Small Cell Forum). Figure 4-31 provides a simplified view of O-RAN architectural framework. As it can be seen, the O-RAN architecture follows the 3-split solution discussed in previous sections, with Open Fronthaul implementing the option 7-2 for LLS. Indeed, the definition of this option 7-2 is one of the key outcomes attributed to the O-RAN alliance.

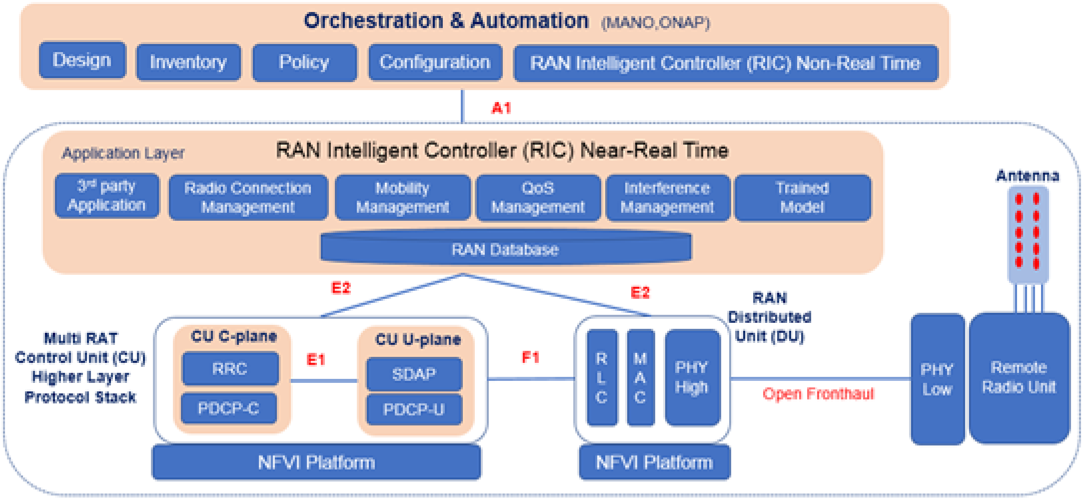


Figure 4-31 O-RAN alliance architecture framework

The 5G system developed in [62] and described in [67] incorporates relevant (beyond 3GPP) O-RAN architectural components, including both RAN Intelligence Controller (RIC) types: RIC near-RT and RIC non-RT. On the one hand, RIC near-RT provides millisecond-level Radio Resource Management (RRM) functionality with embedded intelligence, including per-UE controlled load-balancing, radio bearer management, interference detection and mitigation, QoS management, connectivity management and seamless handover control. It also delivers a robust, scalable and secure platform that allows for flexible on-boarding of 3rd party control-applications. On the other hand, RIC non-RT provides non-time-critical functionality, including service and policy management, RAN analytics and model-training for the RIC near-RT. RIC near-RT is imbued in the network function and application stratum, while RIC non-RT is logically positioned in the management and orchestration stratum [67].

4.2.2.2 Multi-WAT protocol stack

This principle is about ensuring a unified traffic processing when coming from multiple WATs, each having a different protocol stack. Different WATs have traditionally been used in a disjoint manner. As society increasingly depends on fast and reliable data connectivity, an important capability for the industry is the convergence between 5G and Wi-Fi, so that unique and complementary capabilities of both WATs are leveraged to provide innovative network services. New set of 5G use cases may require combined resources from both 3GPP and Wi-Fi networks in providing cost-effective solutions that meet diverse sets of requirements on throughput, latency, connection density, coverage and reliability. The 5G system in [62] leverages the principle of multi-WAT protocol stack to design an architecture solution based on the convergence of the two WATs mentioned above (i.e., 5G, Wi-Fi, Li-Fi). The combined use of these three WATs allows for enhanced data rates (e.g., by means of bandwidth aggregation) and improved reliability (e.g., by setting up back-up sessions). To that end, advanced 3GPP mechanisms based on the use of specific VNFs are considered in the proposed architecture design [67].

4.2.3 Indoor multi-WAT realisations

4.2.3.1 Wi-Fi/Li-Fi integration using N3IWF/TNGF

As described in section 3.5.2, the integration of a NPN is proposed as a non-3GPP access network. Since some of the key performance targets of 5G networks require extremely dense network deployments in order to provide enhanced mobile data speeds as well as area spectral efficiencies, non-3GPP access networks such as Wi-Fi and Li-Fi have a great importance to complement 5G networks. For example, in a user dense environment such as airport, stadium, factory, etc., deploying a non-3GPP access network as a private network will decrease the burden on 5G networks. Seamless integration of such networks to public 5G network needs (i) establishment of secure connection; (ii) connection/service continuity; and (iii) careful distribution of network traffic flows.

Secure tunnels between 5G core and a serving user that is connected to a non-3GPP based NPN can be established via either N3IWF or TNGF depending on whether the non-3GPP network is listed as untrusted or trusted, respectively. When a user establishes a connection to the non-3GPP access network, it also sets up a secure tunnel against N3IWF or TNGF which is then mapped to a per-user, per-access network tunnel for the user and control plane interfaces against the 5G core. This can be translated as such N3IWF/TNGF terminates the user and control plane interfaces to the 5G core network.

Currently, N3IWF/TNGF can be used to integrate single non-3GPP network. Therefore, it is proposed to have an integrated Wi-Fi/Li-Fi network using an SDN-based layer 2 (L2) network to utilize both technologies for indoor private networks [68]. The proposed integrated Wi-Fi/Li-Fi network provides a self-contained L2 network where the user devices are equipped with Wi-Fi and Li-Fi interfaces and each interface has one MAC address. As each interface has its own MAC address, the L2 network will perceive them as two different devices, hence, handover within Wi-Fi and Li-Fi APs are independent. In other words, while a user is connected to a Wi-Fi AP, it can execute handover within Li-Fi APs. Once a user is handed over from one AP to another (either in Wi-Fi or Li-Fi network), the proposed SDN-based L2 network maintains bindings between the MAC address of the user device and APs, and maintains IP address of the user. Maintaining IP address of the user is crucial as it provides continuity of the established secure tunnels between the user and N3IWF/TNGF. This is critical as high mobility scenarios for NPNs, e.g., an Automated Guided Vehicle (AGV) that carries goods in a factory or unmanned ground vehicle (UGV)/drone that operates within a factory, require service continuity for an ongoing transmission which is established via secure tunnels.

The proposed SDN-based L2 network can also gather telemetry data from Wi-Fi and Li-Fi APs. This telemetry data can be utilized to distribute the ongoing traffic flows onto available access networks effectively. The described NPN integration to 5G networks can also make use of the recently defined function for 5G systems, namely access traffic steering, switching and splitting (ATSSS) [68]. ATSSS enables simultaneous utilization of user plane resources of 3GPP and non-3GPP access network. As its name indicates, ATSSS considers three different procedures, namely:

- **Traffic steering**: selects an access network for a new data flow and transfers the traffic of this data flow over the selected network, which can be 3GPP or non-3GPP network. There are five steering modes described, namely, active-standby, smallest delay, load-balancing, redundant and priority-based. These steering modes can be used to balance/prioritize the load between the access networks or improve reliability by duplicating the traffic flows.

- **Traffic switching**: moves all ongoing data flows from one access network to another. It can be used to provide data traffic continuity.
- **Traffic splitting**: divides the data traffic flows onto 3GPP and non-3GPP access networks. It can be used to aggregate traffic flows to improve throughput by utilizing user plane resources of 3GPP and non-3GPP networks.

The traffic steering, switching and splitting policies are provided by 5G core (generated by the Policy and Charging Function, translated to rules by Session Management Function, and pushed by UPF/UE), and they are based on pre-defined values for either all traffic types or some specific traffic type such as UDP/TCP to a specific IP address/port. The ATSSS rules are ordered in a way that as long as a data flow matches a rule, the data flow gets routed according to the rule and the remaining rules are not considered. The performance of the enforced policies is monitored by path performance measurements. If the targeted service performance is below its threshold, an ATSSS policy/rule change is initiated.

4.2.3.2 Indoor (home) gNB

The increased use of wireless 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. 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 project [61] solves this problem by providing a 5G HgNB (home gNB) broadband radio-light communications solution that operates in unlicensed 60 GHz mmWave and visible light spectra, does not suffer from interference because of the propagation characteristics in these bands and provides universal broadband coverage within buildings from radio-light access points that are pervasively located within the light roses in buildings. As a consequence of difficulties and high cost of obtaining electronic components for a 60 GHz system, which would have restricted the development of a demonstrator system to a single Remote Radio Light Head (RRLH), a much cheaper 40 GHz system was developed with more readily available electronic components that could provide a proof of principle solution with four or more RRLHs. This technology can also be applied to other indoor environments such as tube stations, underground

Visible Light Communication-based HgNB (VLC-HgNB) is a 5G small cell solution for indoor environments as shown in 4.4, consisting of two main subsystems linked together: the radio access network subsystem and the networking and services subsystem. The radio access network subsystem consists of mmWave and VLC modules which are utilizing 60 GHz unlicensed or 40 GHz licensed bands, and visible light communication to release the radio resources for the indoor environments. These technologies enable the HgNB to provide Gbps data rate and sub-meter location accuracy indoors. The networking and services subsystem consists of the Multiple-access Edge Computing (MEC) cloud which hosts the Virtual Gateway (VGW). It offers intelligent management, flexible deployment, and add-on services for the VLC-HgNB. The intelligence and flexibility are offered by use of SDN and VNF technologies, which enable the system to deploy UE's location server with sub-meter accuracy, which in-turn supports the deployment of add-on services such as smart TV services location-based data access services. Unlike the traditional Dual

Connectivity (DC) network architecture, where the Master eNB (MeNB) is responsible for the control plane processing for all 5gNBs in its coverage area. In VGW-based architecture, each VLC-HgNB has only RLC layer, MAC layer and Physical layer at each DU, while the Centralized Unit (CU) for a group of the VLC-HgNB DUs are kept as a VNF at the gNB, named Virtual Gateway. VGW connects to VLC-HgNB DUs using F1 interface. gNB uses NG interface to connect to 5GC and Xn interface to connect to the other gNBs. VGW is implemented as a VNF residing within gNB to optimize the signalling and the operation of the VLC-HgNB DUs, by providing one point of interaction with gNB to all connected VLC-gNB DUs. Also, it enables the VLC-HgNBs to provide intelligent services since it utilizes NFV technology to offer virtualised network entities such as V-proxy/cache servers. Adopting DU-VLC-gNB deployment makes the cost, flexibility and the handover signalling relatively low, while making the latency relatively higher. VGW solution eliminates the need for signalling messages for the CN (Core Network) to update the traffic tunnels. VGW-architecture enables all of the Indoors HgNBs to appear as a single HgNB to the rest of the network entities. It helps the realization of the HgNB system within the overall mobile network architecture without burdening it with unnecessary additional signalling overhead.

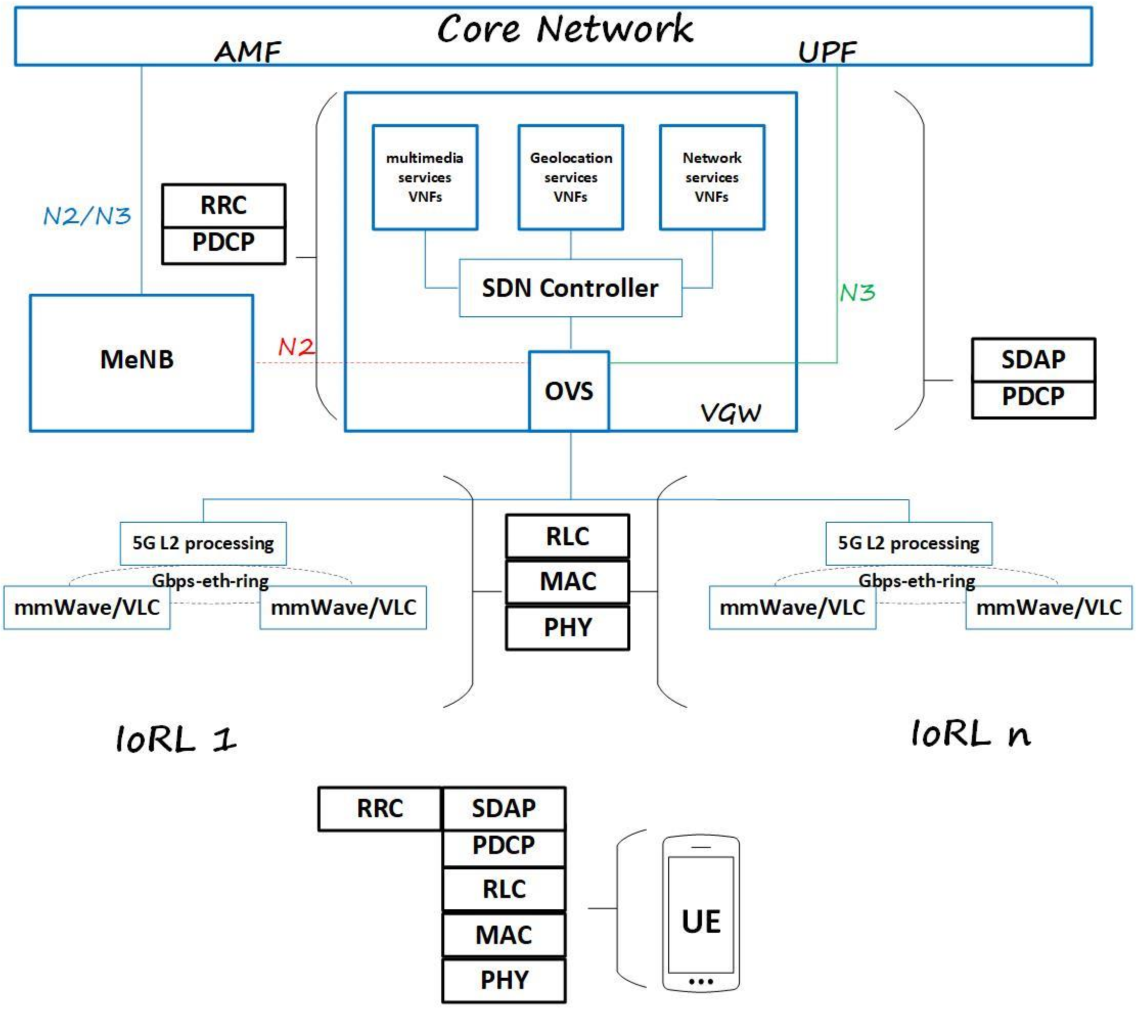


Figure 4-32 Indoor home network architecture [61]

Building owners who deploy cellular home networks (HgNBs) in their buildings that operate in licensed 26GHz/28GHz/40GHz or unlicensed 60GHz spectrum avoid interference and congestion but require the permission of MNOs due to their potential to interfere with the main transmitted signal from the main mobile network (gNB). A multi-component carrier solution which operates in unlicensed millimetre wave and visible light spectra, does not suffer from interference because of their propagation characteristics and provide universal broadband coverage within buildings from radio-light access points that are pervasively located within the light roses in buildings and does not interfere with the main transmitted signal from the main mobile network (gNB).

One advantage of the HgNB over its predecessor HeNB is that much higher bit-rates can be provided (e.g., greater than 10 Gbit/sec for a building), with much lower latencies (e.g., < 1ms from the user terminal to the Home Gateway). The second advantage is that multi-access edge computing server can be located near the HgNB to support services such as location estimation, multisource streaming, follow-me TV, security monitoring and load balancing services. The VLC and mmWave location estimation technologies can provide location accuracies of less than 10cm.

The RAN part of the HgNB includes the RRLH (Remote Radio Light Head) and Distributed RAN (DRAN). RRLH and DRAN system diagram with its main modules depicted in Figure 4-33 below. These include Layers-1 2 and 3 elements and interfaces northbound with the Intelligent Home IP Gateway and Southbound with the mmWave and VLC user terminals.

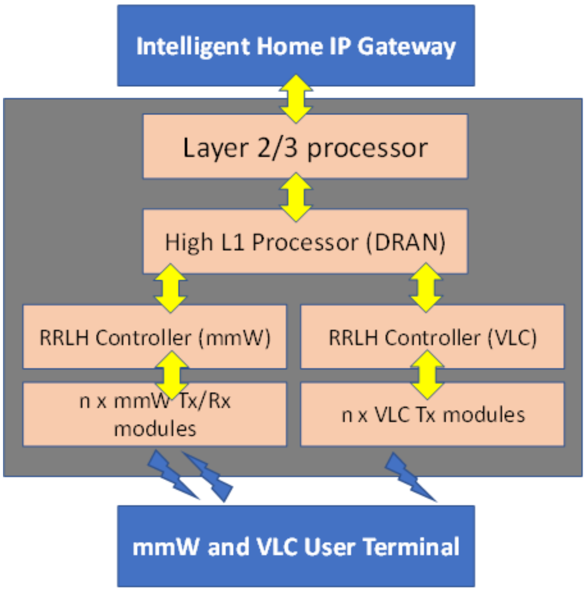


Figure 4-33 Home gNB (HgNB) architecture

Layer 1, the Physical layer, is comprised of the DRAN processor and the RRLH mmWave and VLC controllers. Physical Layer Central Unit, named DRAN (Distributed RAN) is carrying out the tasks of the upper L1 layer, which mainly include the FEC encoding and decoding, beam management and distribution of the data and control to the RRLH units over 10 Gbps Ethernet rings. The DRAN has an interface with the MAC and higher layers over a GB Ethernet connection. The design philosophy of the RRLHs is to keep the electronics circuit footprint in the RRLHs as small as possible to fit within different light system form factors by restricting their functionality to up/down conversion and amplification before transmitting on visible light LEDs or mmWave antennas. The 5G Layer 1, 2 signal processing is performed on a parallel processing pipeline between the Layer 2 Processor, DRAN and RRLH Controller for the real-time processing of the 5Gtransmission signal and Layer 3 signal processing is performed on the intelligent home IP gateway (IHIPG). The form factors were chosen to be representative of the type of light systems common in the market, namely: ceiling, sport, pendant and accessory.

The mmWave module in RRLH includes a RF board, a power supplies board and a low-cost antenna. To reduce the risk for non-working mmWave module the realisations are separate Tx and Rx layouts with two channels in each module to provide a dual polarized mmWave link. As for the up/down conversion, the intermediate frequency (IF) method is used. The modules open the possibilities of power control at Tx and Rx side and a flexible location of the used frequency band between 24 - 44 GHz which provide a fully compatibility to the 3GPP FR2 frequency bands.

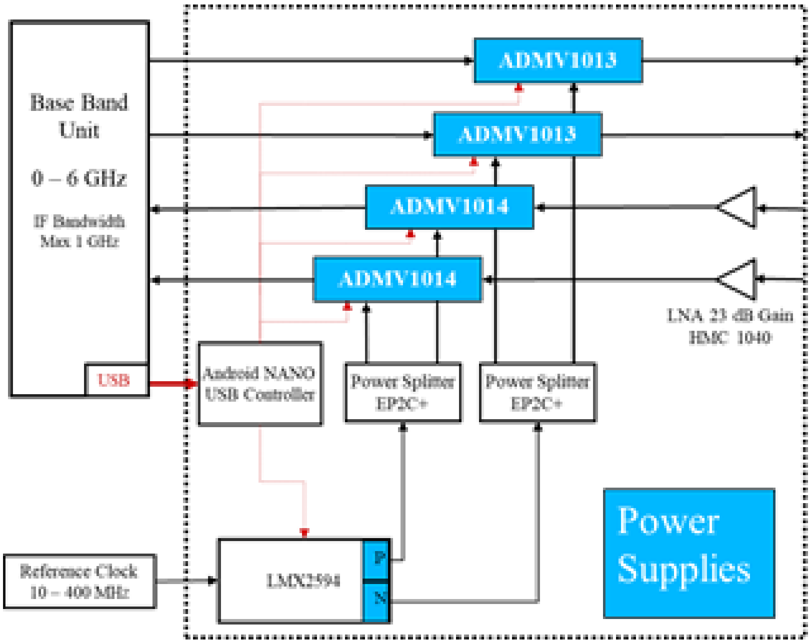


Figure 4-34 Internal architecture for the compact mmWave transceiver module

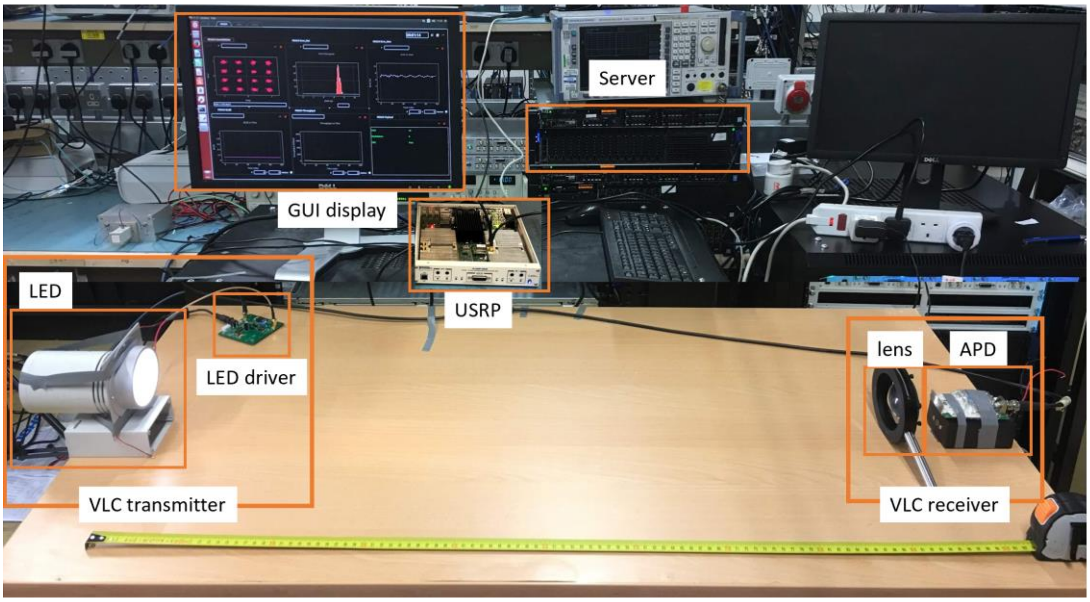
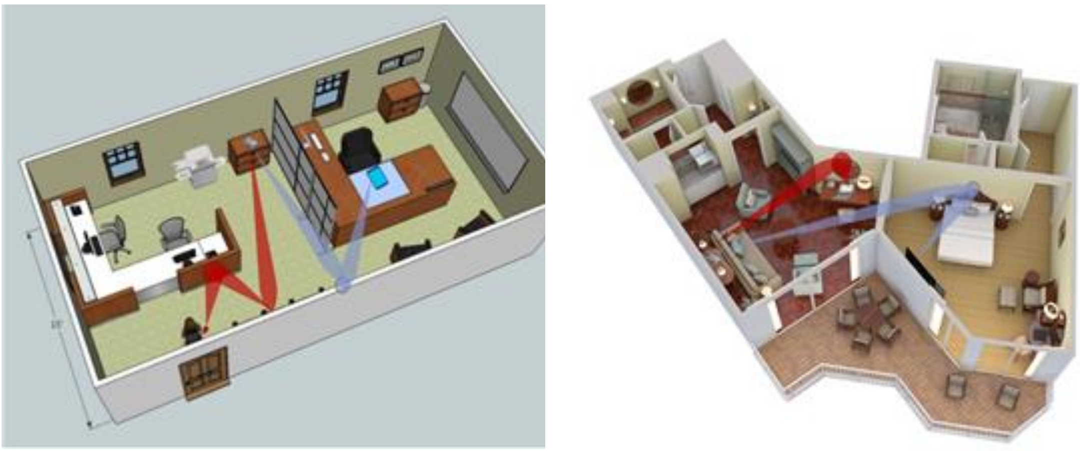


Figure 4-35 Experimentation environment of the VLC transmitter-receiver

4.2.4 Indoor RAN with smart surfaces

Reconfigurable Intelligent Surfaces (RIS) are expected to significantly improve wireless systems performance when the LOS path is either permanently or temporarily blocked. RISs are studied in two main scenarios [69]: indoor scenario and data kiosk scenario. The former focuses on indoor links where NLOS is highly probable, for instance when the LOS path is not available, which is quite common in high frequency communications where signals are attenuated fast and blocked severely by objects in the environment. The data kiosk scenario is focusing on maximizing the D-band performance on short distance links, usually in the case of extremely high data rates. In this scenario, the challenge is to maximize the throughput while maintaining the connection via RISs even when the primary LOS channel is blocked. The Indoor scenario focuses on slow movement and indoor coverage by RISs, whereas the data kiosk considers faster movement as the data kiosks can also serve cars and pedestrians. Thus, the tracking and connection setup needs to be faster and smarter.

One of the greatest challenges as far as the reconfiguration of the RISs is concerned, since it often needs to be realized in a much faster pace due to the possible movement of the users, is beam tracking. In addition, due to the challenging nature of pencil-beam tracking in scenarios involving movement of users, it may be necessary that the beamwidth of the transmit and receive antennas is increased so that the possible misalignments do not cause a substantial drop in signal quality.



(a) (b)

Figure 4-36 Indicative examples of possible applications of RIS

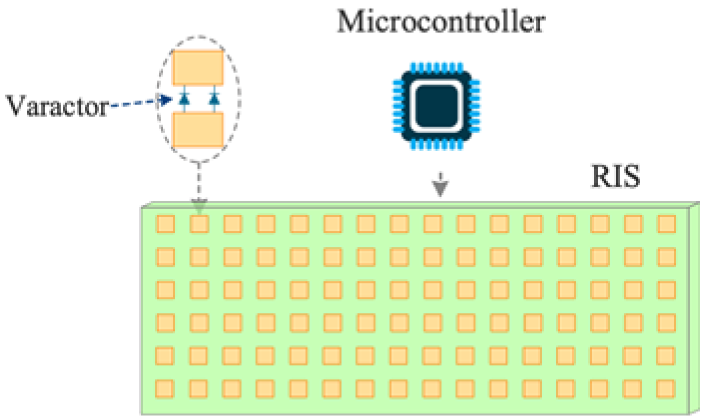
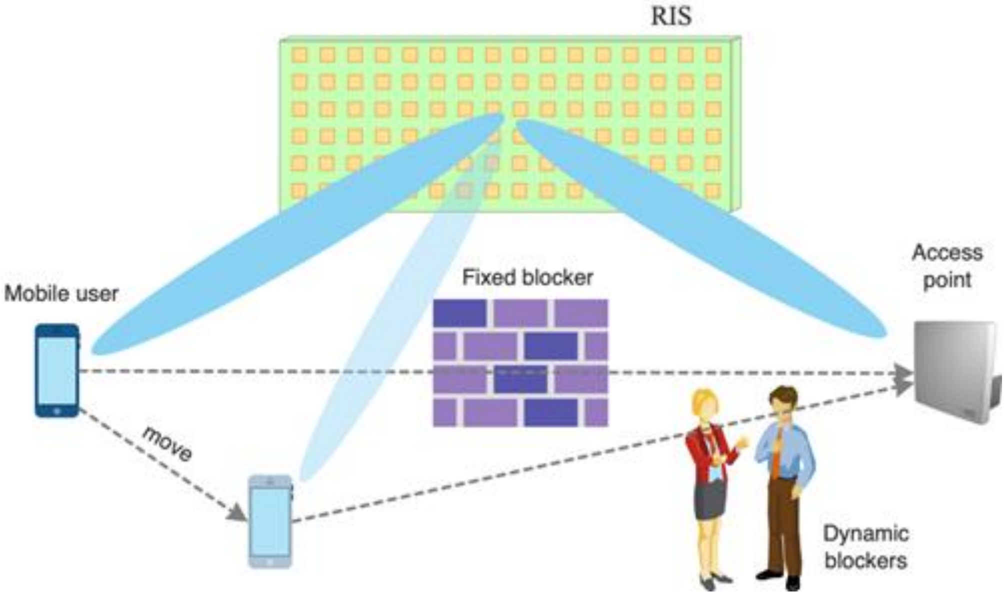


Figure 4-37 RIS structure

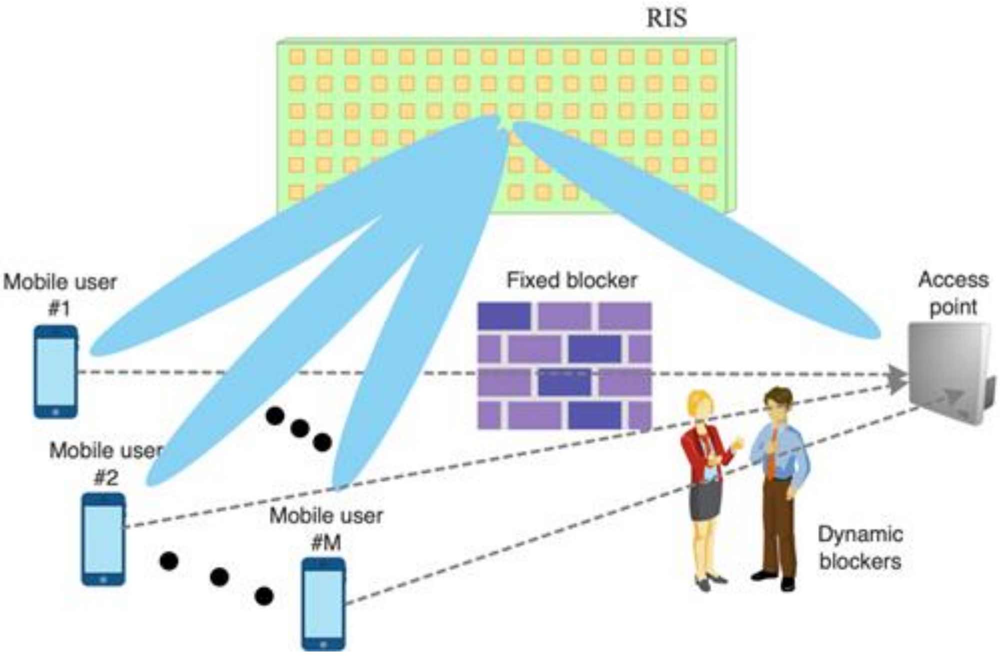
Scenario 1: Indoor advanced NLOS connectivity based on meta-surfaces

This scenario aims to provide reliable, uninterrupted connectivity in continuously changing indoor wireless environments. Note that D-band links (assumed in [69]) experience high path and penetration loss. To counterbalance pathloss, pencil beamforming is employed in all the networks nodes, which demands almost perfect beam alignment between transmitter (TX) and receiver (RX). Moreover, to deal with blockage that is caused by the high penetration loss, RISs are employed, which enable the development of advanced NLOS schemes.

As depicted in Figure 4-36, in wireless communication networks operating in high-frequency bands, such as D-band, the establishment of a LOS link is often difficult or even impossible. As a remedy, the exploitation of the implicit randomness of the propagation environment through RISs attracted the attention of both academia and industry. As illustrated in Figure 4-37, a RIS is represented as a two-dimensional (2D) array controlled by at least one microcontroller. One of the possible realizations is by using meta-surfaces. RIS can independently configure the phase shift of the incident electromagnetic (EM) signal. This motivates the investigation of two key functionalities of RIS, namely (i) beamforming, and (ii) broadcasting. An illustration of the scenarios corresponding to these functionalities is provided in Figure 4-38. Even without reconfiguration of meta-surfaces, they can be used to overcome the limitations of the NLOS scenario by reflecting and focusing waves to the desired areas. Moreover, they can be used for enhancing multipath propagation by reflecting waves into several directions behind obstacles, creating multiple reflections in the indoor scenario.



(a)



(b)

Figure 4-38 (a) RIS-assisted beamforming, and (b) RIS-assisted broadcasting

RIS-assisted beamforming scenario: In this scenario, a single TX communicates with an RX through a RIS. The TX and RX are equipped with N_t and N_r antennas and $M_t$and M_r radio frequency (RF) chains, respectively. In other words, they can perform analogue, hybrid, or digital beamforming, based on the number of the RF chains. Additionally, RIS consists of MxN similar unit cells. Each unit cell can independently phase shift the incident EM wave. The signals reflected by all the unit cells of the RIS to the RX are aligned in phase in order to enhance the received signal power. In other words, the RIS can operate as an analogue beamformer, whose characteristics depend on the RIS unit cell dimensions, radiation pattern, and number.

When a UE initially requests access to the RIS-assisted system, an initial access procedure needs to begin in order for the RIS to acquire knowledge concerning the TX-RIS and RIS-RX channels and to decide which unit cells should be turned ON and OFF. However, conventional RIS structures are passive units without any sensing capabilities; thus, channel estimation is not an easy task. A possible approach to channel estimation might be to divide the total estimation time into a number of periods. During each period, a different subset of unit cells will be ON, while all other unit cells subsets will be OFF. Energy detection will be performed at the RX, in order to determine the optimum RIS configuration. The main problem of such an approach is that as the number of unit cells increases, the channel estimation time also increases. Inspired by this, this scenario motivates the use of *machine learning* approaches that may limit the *initial setup latency*.

The indoor wireless environment constantly changes due to the existence of dynamic blockers and UE movement. As a result, the RIS should be continuously fed with new configuration parameters, in order to provide almost-uninterrupted connectivity with almost zero *adaptation-latency*. As in the initial access phase, the use of exhaustive search approaches would result in unacceptably high latency. Therefore, ML-based approaches need to be introduced. Apart from latency, these approaches need to guarantee high reliability, by minimizing the beam misalignment and the probability of blockage.

In such a scenario, apart from reliability and latency, critical parameters are also the communication range, data rate and availability. In particular, as in most practical implementations of RIS-assisted indoor wireless systems in high frequency bands, the TX-RX transmission distance is not expected to surpass 10 m (see e.g., [32], [33] and reference therein). Furthermore, an initial setup latency that is lower than 10 ms is a key requirement of high-frequency systems (mmW and THz) [34], while, an adaptation latency that is lower than 1 ms is requested for novel beyond 5G “killer applications”, such as augmented and virtual reality [35]. Of note, as initial access latency, we define the time that is needed for the BS and UE to identify and authenticate each other, while as an adaptation latency, the one that is required to determine the new direction of a moving node and appropriately perform beam steering. The wireless system reliability is quantified in terms of outage probability and uncoded error rate, which should be respectively lower than 10^{-4} and 10^{-5}. Finally, the throughput should even reach 100 Gbps, since this is one of the key targets of beyond 5G systems[36].

RIS-assisted broadcasting: In this scenario, a single AP is used to serve several UEs through a RIS. This setup can be used for both uplink and downlink applications. Especially, a possible application in the downlink might be for a scenario in which the same content needs to be delivered to several UEs. In what follows, without loss of generality, the downlink case is discussed. We assume that the AP and the n-th UE are equipped with N_t and $N_{r,n}$ antennas and M_t and $M_{r,n}$ RF chains, respectively. In other words, they can perform analogue, hybrid, or digital beamforming, based on the number of RF chains. Additionally, RIS consists of MxN similar unit cells. Both the AP and the UEs point at the RIS. Initial access and localization procedures are performed for each UE, in order for the AP to acquire knowledge concerning the UE positions and channels. As in the previous scenario, this procedure will require the use of ML. Next, a clustering problem is formulated and solved by the AP. The solution of this problem is the RIS configuration that determines the RIS half power beam width. This setup is of high interest since it can enable access schemes, such as frequency division multiple access (FDMA) and non-orthogonal multiple access (NOMA).

Expect from the aforementioned KPIs, in this scenario, we are also interested in the cluster radius, the number of users that can be served, as well as the coverage probability that is required to be higher than 99.99% in most B5G applications.

Scenario 2: Data kiosk

The data kiosks are envisioned to be network entities that are utilized in transferring large chunks of data during a short cell visit of a user or a device. The basic concept is the following: the data kiosk is a network edge repository that contains user requested or saved data or popular content similar to a network cache. Contrary to the network cache, the user communicates directly with the data kiosk upon data request. Since the data kiosks are often depicted as devices located in city centres or indoors, close to the users, the data rate required towards the users is very high to be able to transfer the requested data while the user is momentarily passing by the data kiosk. The other possible definition for a data kiosk is an ultra-high-speed hot spot with limited range. Thus, the operation is similar to the above with the exception of lack of edge storage. In any case, the data kiosk provides short range high data rate connectivity. The higher frequencies and large available bandwidths provide very large capacities due to large spectral resources and a possibility for very high instantaneous data rates. This is utilized in the data kiosk applications to achieve fast download of even large files, such as movies, games, or applications. However, there are other technical challenges to be addressed, such as beamforming, beam acquisition, beam tracking, and fast connection setup to mention a few.

The major problems associated with the utilisation of higher frequencies of the order of 100 GHz or THz frequencies (>300 GHz) is the very high path loss, which calls for the employment of high gain antennas and beamforming techniques. Also, very high bandwidths in general mean low power spectral density due to limited transmit power and at the same time high noise level due to the bandwidth. Nevertheless, the resources can be shared spatially more efficiently in high antenna gain systems because of limited interference among users. These issues also have impact on the data kiosks by limiting the range of the service area. The small service area means tight requirement for establishing the connections, handling the data requests, and finally delivering the data. Also, the possible blockage may require establishing the high-speed communication link via RISs, which brings another degree of difficulty, considering the fast link establishing speed and the high data rate. The communication via RIS relies on fast connection setup, especially in the case that the service is provided to passing by cars. Simultaneous tracking and connection setup of several moving users requires intelligence. This problem can leverage from machine learning, to better serve the users during the brief cell visits and during the initial connection setup and tracking.

At the same time, the beam tracking needs to be fast and efficient to maintain the connection during the cell visit. The generic data usually does not impose hard limitations on the outage or availability, but the short cell visit time requires reliable connection, in order to guarantee service. As a pure data source, the reliability does not have extremely high requirements. However, from the quality-of-service point of view for very large chunks of data, BER must be at a sufficiently low level to allow coding to fix most of the erroneous bits.

The hardware solutions and imperfections play a key role in understanding the real-world communication problems and limitations. Machine learning can be utilized in predicting the user movement and data requests to mention a few. The propagation research helps the quantification of the real channel and environment limitations, while the theoretical studies provide insightful performance bounds.

4.2.4.1 Indoor 5G small cell regulatory and environmental considerations

Changes in certain regulatory aspects affecting the deployment of Small Cells will enable the mass market deployment of small cell solutions (also the indoor ones) that until nowadays has been restricted to a low number of indoor residential/SOHO or indoor large office/venue deployments, which were in almost all cases driven by incumbent MNOs.

On one hand, light deployment regimes with permit exemptions or development rights are being harmonised in different regulatory jurisdictions to enable mass deployment of 5G small cells. Examples of such deployment regimes are the European Commission's Small Area Wireless Access Point (SAWAP) scheme [41] and the FCC's small wireless facility deployment rulings [42].

As indicated in Small Cell Forum SCF012 "Simplifying Small Cell Installation" jointly developed with GSMA, the recommendation was the adoption of the installation classes specified by the IEC 62232 Ed.2.0 standard [70] that were applicable to exposure limits based on international guidelines by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) as shown in Figure 4-39. Adoption of these harmonized and simplified rules by regulators and policy makers would reduce administrative overheads for both planning authorities and mobile operators. Regions using the IEC installation classes would benefit from faster small cell rollouts.

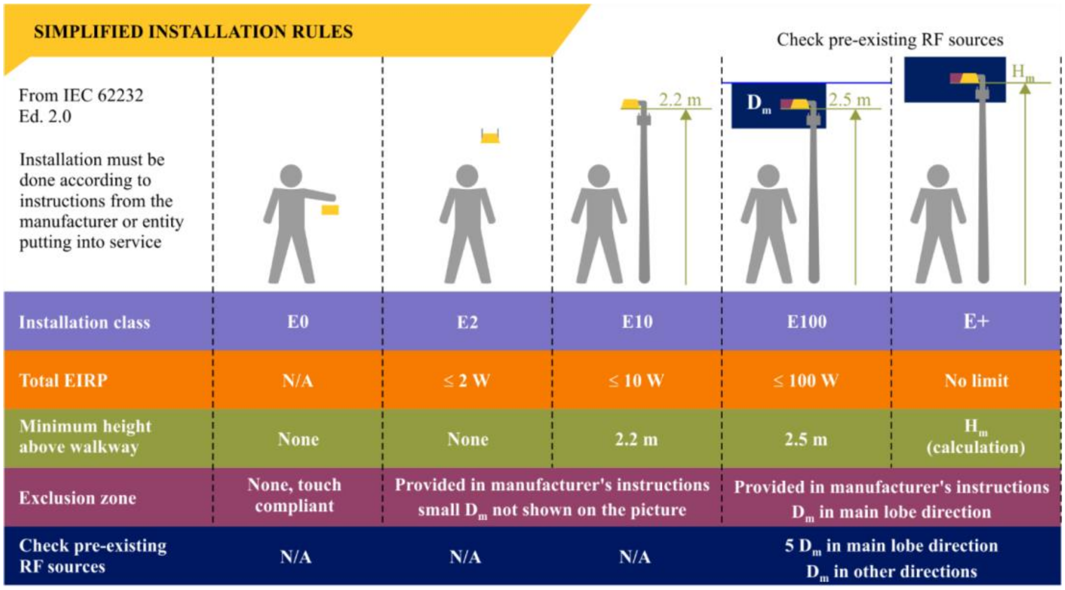


Figure 4-39 Simplified installation rules (Source: IEC 62232 Ed.2.0 [70])

On the other hand, access to specific parts of spectrum is being "liberalised" in certain geographies to foster innovation and private deployments beyond the traditional use of licensed spectrum open to incumbent MNOs. Countries such as France, Sweden and Germany have set aside spectrum allocations for local licenses for private deployments or vertical industries. UK Ofcom [43] regulated two new licence schemes to make it easier for a wider range of users in the UK to access radio spectrum on a shared basis and to improve wireless connectivity in enterprise sites as well as underserved areas. These two schemes are: shared access licence which gives access to four spectrum bands which support mobile technology and local access licence, which provides a way for other users to access spectrum which has already been licensed to the UK's Mobile Network Operators (MNOs), in locations where an MNO is not using their spectrum. In US the FCC established the regulatory grounds for Citizens Broadband Radio Service [44] a novel three-tier sharing paradigm coordinating spectrum access among the incumbent military radars, satellite ground stations and temporarily protected FWA legacy stations and new commercial users.

The flexibility of 5G architecture, its support for NPN, the availability of local/shared spectrum, light deployment regimes and the integration of unlicensed spectrum wireless access technologies into 3GPP, will foster not only private network deployments, but also new neutral host business models with new stakeholders, particularly when it comes to indoor wireless solutions.

4.3 5G non-public networks and their integration to the public 5G network

This section provides a description of the different approaches to interfacing and integrating indoor (private) networks with the public 5G Network. Most (if not all) indoor installations could be perceived as Non-Public Networks (NPNs).

The type of indoor networks of interest are those based on 3GPP 5G technologies, which are independent from the public 5G network provided by a Mobile Network Operator (MNO). 3GPP refers to this type of networks as Non-Public Networks (NPN), as opposed to the Public Land Mobile Networks (PLMN) traditionally used to deliver broadband mobile communication services.

In Release 16 3GPP [71] two types of NPNs are described, namely Standalone NPNs (SNPNs), which are completely isolated from a PLMN, and Public Network Integrated NPNs (PNI-NPNs), which are implementations of an NPN serving for example an indoor space of a private venue that are integrated with a PLMN. In the sequel we describe the mechanisms that 3GPP has put forward to enable the implementation of PNI-NPNs.

Indoor connectivity wireless links typically utilise unlicensed spectrum and unplanned deployments (such as Wi-Fi), meaning that the quality of service is best-effort only and not guaranteed and this is not compatible with the concept of network slicing where the service slices are meant to provide end to end deterministic latency and throughput. Mechanisms such as carrier-sense or listen-before-talk are employed to keep interference under partial control, which introduces variable delays. An exception is 5G home gNBs or small indoor cells managed by MNOs and using their spectrum, that will build neighbour lists and use them for mobility and diversity management.

Indoor connectivity needs to support service slices of various types, including low latency ones to support use-cases such as robotics, heath and interactive gaming. Currently, buildings are typically connected to an access network that is copper or fibre, and services are supplied by one service provider. That service provider typically has a contract with a single network operator who provides network connectivity to a point on the periphery of the building. The network management boundary is typically a connection point on an inside wall. Going forward, it will be necessary to support multiple service slices within buildings that are managed by multiple network operators on contract to service providers.

For a thorough discussion on Non-Public-Networks refer to the related 5G PPP whitepaper [76].

4.3.1 Public network integrated NPNs (PNI-NPNs) in 3GPP

3GPP in Release 16 [71] defines the following means to implement a PNI-NPN:

- Mode I. Setup of a dedicated APN or PDN to serve the NPN
- Mode II. Setup of a dedicated 3GPP network slice to serve the NPN
- Mode III. Integration of an NPN as a non-3GPP access network

The previous modes differ on the required functions that need to be hosted by the private network and on the level of dedicated service that the public network can offer to the NPN. Figure 4-40 provides an overview of the three modes, which we discuss next.

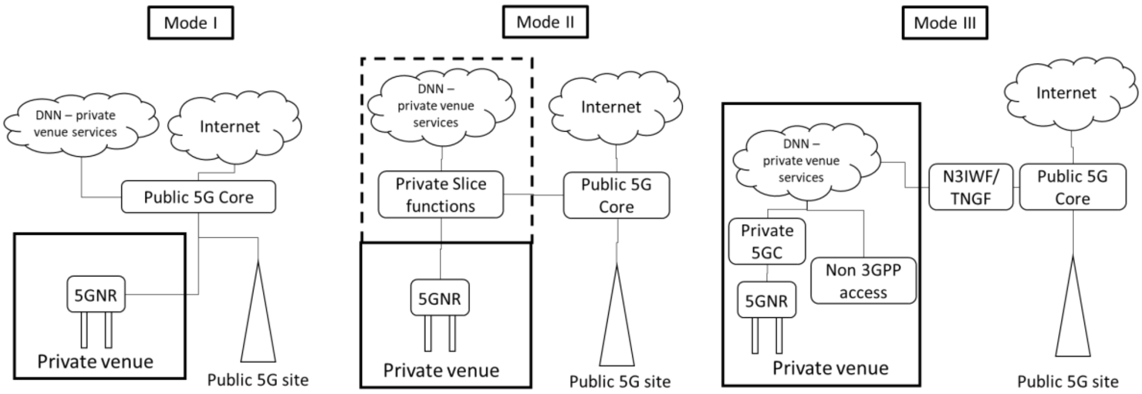


Figure 4-40. Interconnection modes between NPN and PLMN

Mode I is applicable to both 4G and 5G Non-Standalone (NSA) networks working with an Evolved Packet Core (EPC) and to 5G Standalone (SA) networks working with a 5G Core (5GC). In this mode a dedicated Access Point Name (APN) or Packet Data Network (PDN) is provisioned to serve the customers from the NPN, which are equipped with SIM cards from the MNO. Thus, NPN customers make use of the same radio access network and core network as public network customers, but their traffic is identified within the network using a differentiated bearer, if an EPC is used, or PDU session if a 5GC is used. In both cases, EPC and 5GC, bearers or PDN sessions can be offered a differentiated treatment using the QoS Class Identifier or Flow ID. In addition to traffic differentiation at the bearer/PDU session level, additional isolation guarantees can be obtained in Mode I if the MNO deploys a dedicated base station, e.g., in small cell form factor, within the NPN premises, which cannot be accessed by the customers of the public network. However, this isolation is not possible on the core network side, where signalling processing functions, e.g., MME in EPC and AMF (Access and Mobility management Function) in 5GC, are shared between the public and the private networks.

Achieving isolation at the network function level is the goal of Mode II, where the MNO defines a slice of the public network to deliver the required functionalities to serve the NPN. Defining a slice implies that dedicated core network components will be instantiated only to serve the NPN, i.e., dedicated UPF, which are completely separated from the functions serving the public network. The dedicated functions could be deployed inside the private venue or hosted by the MNO. In addition, the radio access nodes radiate a dedicated identifier to identify the network slice referred to as the Single-Network Slice Selection Assistance Information (S-NSSAI), which will be provisioned in the SIM modules used by the NPN subscribers. As in Mode I, both the base stations from the public network or a dedicated indoor base station, can be deployed to serve the NPN customers. Closed Access Groups (CAG) can be used to restrict the geographical location over which NPN customers may connect.

Finally, Mode 3 differs from the previous two modes in the sense that a full access network needs to be deployed within the private network, which does not need to be necessarily based on 5G technology. For example, an NPN can provide a Wi-Fi based network which is then integrated with the 5GC of an MNO. The integration between the non-3GPP networks and the 5GC can be implemented either through the Non3GPP Interworking Function (N3IWF) or the Trusted Network Gateway Function (TNGF), which make the whole NPN appear as a single gNB towards the MNO’s 5GC. In this case, the NPN subscribers are also authenticated by the public 5G network, but an initial authentication with the NPN may also be required. Interestingly, Mode III allows for a case where the NPN deploys a full 5G network, including wireless access and a local 5GC, which is then integrated with the public 5GC again through the N3IWF/TNGF gateway functions.

4.3.2 Shared transport network for connecting NPN

In order to enable new use cases for the factory of the future, [60] is experimenting all the industrial use cases described in Section 2.1 deployed in a shared RAN and control plane according to 5G-ACIA [72] scenario overlaid on a shared transport network. 5G-ACIA scenarios do not detail the transport network requirements, and, in general, a generic public transport network cannot assure low and deterministic latency requirements required for some URLCC use cases. Hence [60] aims at providing specific transport network solutions that enable the use of shared scenarios in critical use case as well.

The qualifying elements for realizing such shared networks are a supreme performance transport network and transport aware slicing mechanisms. The shared transport network allows to reduce total cost of ownership (TCO), but it has to guarantee the same performance of dedicated network including low latency requirement for URLLC. The transport aware slicing increases the level of automation in the management of the infrastructure to concurrently serve industrial use cases, and enabling high level of optimization of radio-cloud and transport. The selection of PNF/VNF to be assigned to a slice are performed considering the QoS of the transport that connect such network functions. This allows to better optimize the placement of the PNF/VNF and assure QoS of the service.

As shown in Figure 4-41, the network will evolve from a scenario completely isolated from public networks (named "standalone") towards a shared network thanks to the use of an innovative transport with low and controlled latency. On the top left corner of the figure, the pilot area of a manufacturing site is illustrated, where a standalone NPN radio network offers 5G connectivity to robots, machineries, sensors, and devices. Both baseband (BB) and virtual Evolved Packet Core (vEPC) are located on premises. This cellular coverage is an evolution of a previous indoor and private LTE network.

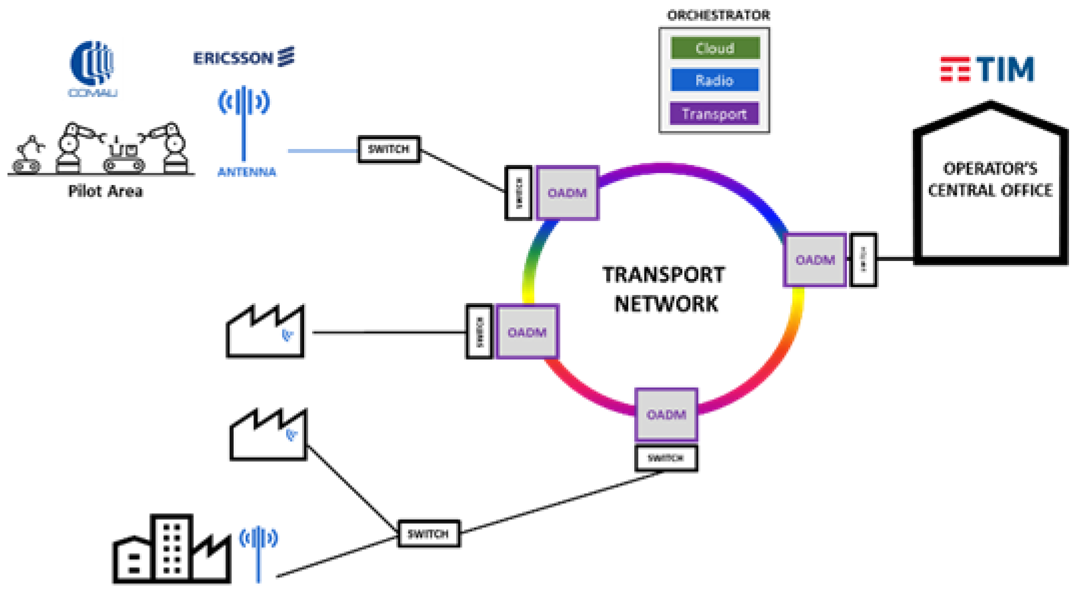


Figure 4-41 Example configuration for shared transport network for connecting NPN

The transport network is an optical infrastructure, which includes dedicated agnostic framing, a deterministic switching module, and a flexible control entity. The optical transport architecture is, basically a C-RAN scenario with the transmission of CPRI/eCPRI traffic. CPRI is the most demanding traffic profile for radio transmission both in terms of bandwidth and latency. Hence, such an experimental set-up allows stressing the optical network especially for the latency requirement. A dense wavelength division multiplexing system and deterministic framing are used and a single lambda connects the central office with the antenna sites. Such a configuration essentially provides a point-to-point connection with deterministic delay due only to transmission in fibre that is of the order of ms. The fibre length between the central office and the remote site where the robot is connected is 15 km. The upstream and downstream transmissions are on two different wavelengths on the same arc of the ring to guarantee symmetric latency. The use of deterministic framing ensures a certain level of flexibility because it is possible to aggregate in the same wavelengths more traffic flows and, if necessary, dynamically move the wavelengths from the central office to multiple remote nodes (i.e., optical add-drop multiplexer on the optical ring). The proof-of-concept setup includes a platform to orchestrate the radio and transport infrastructure with the applications running in the cloud in an automatic fashion. The E2E measurements showed that the latency of the transport network is negligible with respect to the E2E service latency. The latency of the transport network is essentially due to the fibre span (44 µs) and the additional delay due to digital processing (switching and framing) is below the 1 µs. Latency is independent of packet size or line load.

The orchestrator oversees the automation of radio, transport and cloud resources and it is able to setup and operate each vertical service. It also handles the 5G network slicing, which is used to support different traffic profiles over the same physical radio network.

4.4 Edge computing for providing 5G services indoors

In general, the benefits that multi-access edge computing (MEC) resources for indoor buildings provide are: service scalability, service selectivity and context awareness as elaborated in the separate whitepaper on Edge Computing for 5G Networks [73]. These can be used by intelligent network services and user applications to derive their intelligence by using these features. Context awareness provides the knowledge about the exact location of user terminals indoors. Service scalability and selectivity are provided by a MEC solution, whose Network Function Virtualisation (NFV) cloud computing, storage and networking resources can be provided as required as Virtual Network Functions (VNFs) and whose accompanying Software Defined Network (SDN) can be used to intelligently manage and route data to the different parts of the network. These features are essential for a variety of existing and emerging vertical sectors requiring continuous (indoor/outdoor) high-accuracy localization to not only fulfil the demanding QoS of 5G and beyond 5G new services but also enhance the intelligence of user applications. Multi-access edge computing resources for buildings can be located within the building premises itself, if the building size is sufficiently large to merit it, or in the cloud to support a number of small properties for example on the same road with a common post code or flats within the same building.

Designing the radio and light communication systems to fit into the confined space of a remote radio or light head also requires a MEC solution, whose NFV 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 an accompanying SDN to intelligently manage and route data to the different parts of the radio-light network. The benefit of this architecture is that the electronic footprint of the radio-light access points is small and unobtrusive, since all the heavy signal processing is performed in the cloud.

Further benefits of this architecture are that its common building radio light network resources can be more easily shared between MNOs by slicing using SDN and that the NFV solution provides an API, which allows third party service providers to write and support specialized network applications to manage multi-MNO networks in homes, businesses and public space buildings and environments such as tunnels, train stations and airports. 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.

4.4.1 Multi-access edge computing cloud

The Multi-access Edge Computing (MEC) cloud exploits SDN and NFV technologies to create agile and intelligent platform to drive the 5G network effectively. The MEC platform can be technically connected to more than one access network for example three external networks namely: the provider, Wi-Fi and VLC/mmWave networks. The network architecture is depicted in Figure 4-42. The figure highlights the external networks driven by the MEC as well as the provider network. There are more networks configured internally, one for platform management and others for attaching the deployed VNFs.

The network topology depicted in Figure 4-43. The terminologies refer to the actual purpose of the subnets, e.g., the uplink network refers to the Wi-Fi link, which is used for routing uplink traffic during the development phase, while the L2 subnet refers to the link to the L2 processing server and eventually L1 processing and VLC/mmWave transmission links and R1 refers to a SDN Open Virtual Switch (OvS) which can be dynamically controlled using programmable routing tables.

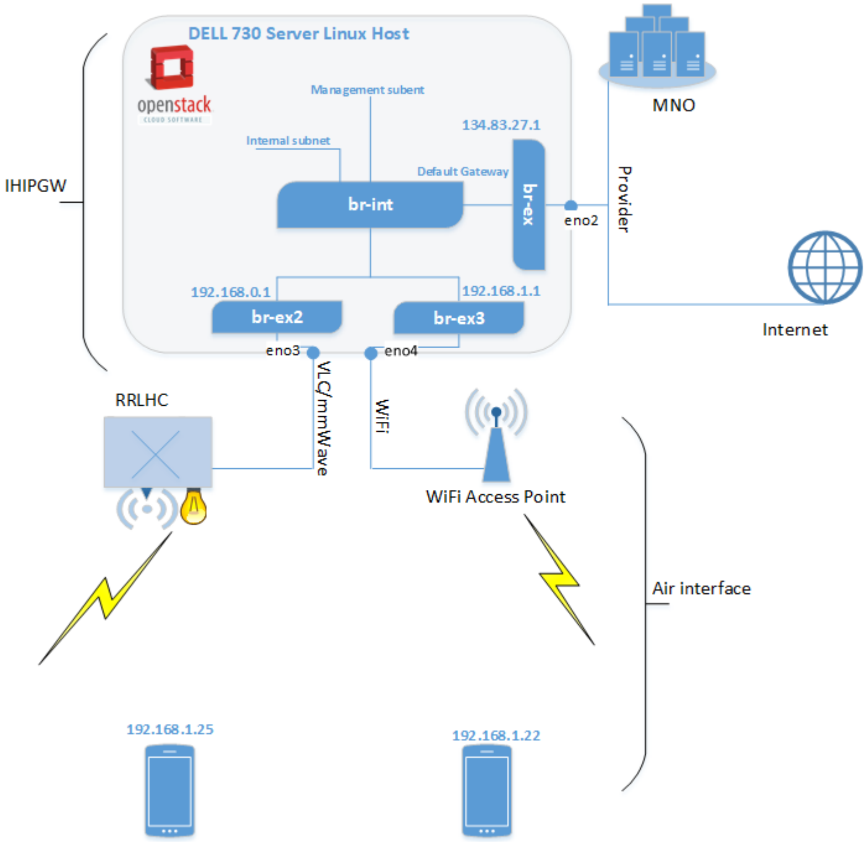


Figure 4-42 Illustration of the network architecture including MEC cloud

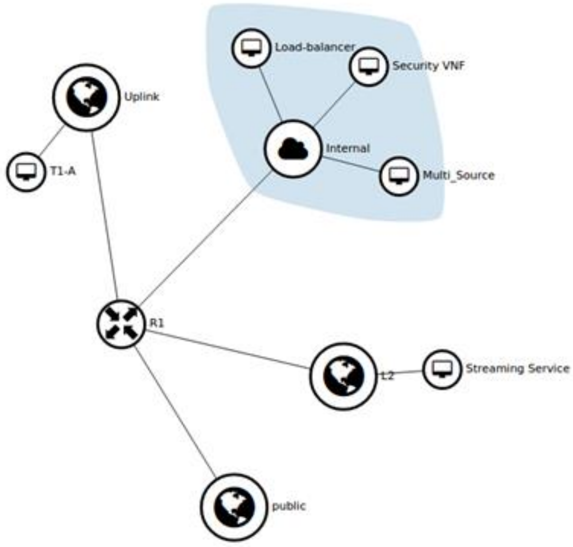


Figure 4-43 snapshot of the network topology at the OpenStack dashboard

4.4.2 Localisation service on the MEC

The indoor positioning protocol involves interaction between the four main components of the proposed 5G visible light positioning system namely: MEC, location database, location server, location service client (LSC) and the UE, which are illustrated in Figure 4-44. The benefits of using localisation service on the MEC is that location data fusion of indoor location data from more than one transmission technology (e.g., Receive Signal Strength (RSS) from VLC and Time Difference of Arrival (TDoA) from mmWave) can potentially take place improving the location accuracy/resolution and increasing the measurement frequency of overall indoor location estimates. The benefits of providing localisation service for indoor 5G Network Services to use is that 5G network management services (e.g., routing and handover) can be performed based on knowledge of the indoor location of users. The benefits of providing localisation service for indoor 5G Applications to use is that 5G user Applications (e.g., location data access, user monitoring and guiding) can also be produced based on knowledge of the indoor location of users.

The protocol is composed of the following aspects:

- Measurement of location relevant parameters (see the red lines)
  a. The UE sends the positioning request to the MEC;
  b. The MEC sequentially broadcasts a series of LEDs' IDs at Time Division Multiplex (TDM) mode;
  c. The UE receives the IDs from all LEDs in one room and reports them to the location datebase by using TCP/IP packages.
- Position estimation (see blue lines)
  a. corresponding LED from the location database performs the UE's position estimation; The normal operation of the 5G VLC system is that all LEDs transmit 5G OFDM symbols simultaneously in order to provide a man-made multipath environment but this does not allow RSS to be measured from any one LED. So for the purposes of location estimation only one LED transmits 5G OFDM symbols for selected symbols in a 5G Radio Frame.
  b. The location server writes the UE's position estimation results to the location database.
- Exploitation of position estimation

a. The LSC provides location-related broadcasting service to UE by retrieving the UE's position estimation from the location database.

Each geographic data represents one LED's ID. This ID is generated by 5G RAN and broadcast through VLC link. The geographic data and location-related data are integrated in 5G NR frame, which is illustrated in Figure 4-45, where one frame consists of 10 sub frames, each sub frame has two slots and each slot has 14 OFDM symbols. In the frequency domain, the subcarrier spacing is 30 kHz. They are allocated in the Physical Downlink Shared Channel (PDSCH) slots. In each slot, the where to 10^{th} OFDM symbols are used to transmit the location-related data such as the multimedia contents. The last four OFDM symbols transmit four geographic data, where only one particular subcarrier frequency f is used to carry the respective geographic data. Since one time slot duration is 0.5 ms, each data is obtained by UE every 36 us (0.5 ms / 14) at least.

MEC Cloud is required for storage and processing of location data of each UE for any application to use position data in their algorithms (e.g., security, handover, location-based databases etc.).

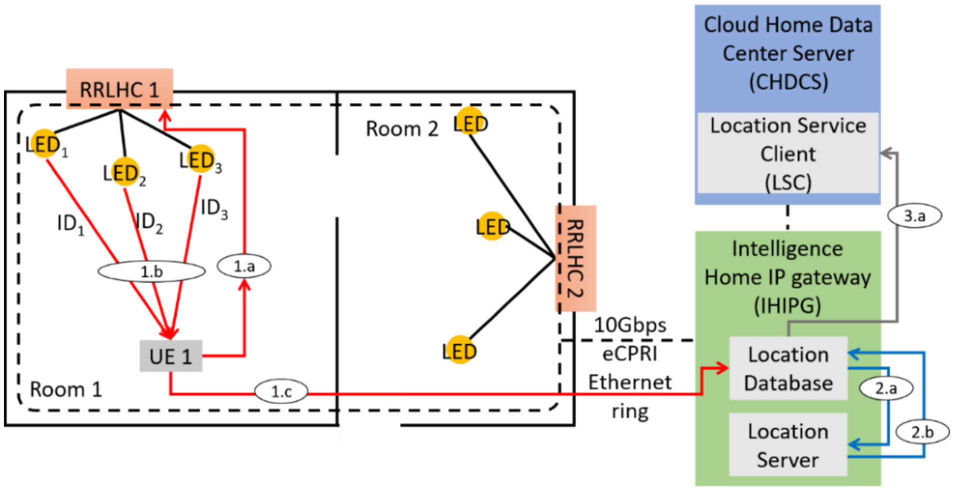


Figure 4-44 Indoor 5G visible light positioning protocol

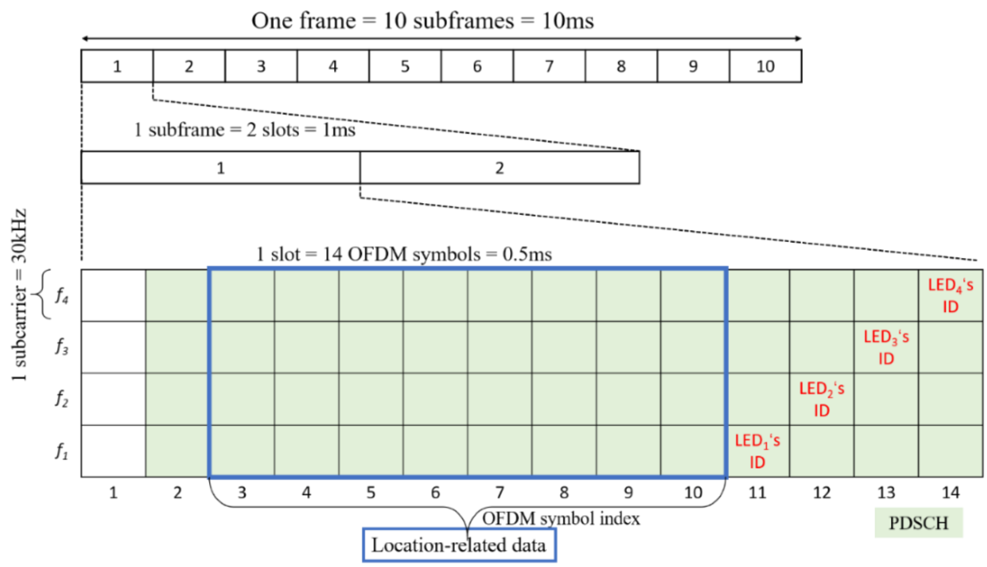


Figure 4-45. Definition of the geographic data and location-related data in 5G NR frame

4.4.3 Multisource streaming VNF

More and more users are consuming high bitrate contents like ultra-high definition (UHD) video or immersive media from both mobile and desktop devices. The objective is to achieve the same goals as future 5G networks in terms of video delivery, i.e., being able to reliably send UHD live and on-demand videos with a good Quality of Experience (QoE) to the end user. Considering the plurality and the heterogeneity of 5G MEC network architecture, the reliability can be tough to ensure using state-of-the-art single-path video streaming system because the video playback can be stalled in case of a signal loss if a specific wireless path (i.e., a light or a mmWave connection) is temporarily occluded.

By taking advantage of the plural network paths available by design in the 5G architecture, we propose multiple-source streaming (MSS) over RRLH, a DASH-compliant (Dynamic Adaptive Streaming over HTTP) end-to-end multipath streaming system [62] increasing both the reliability and the QoE of streaming sessions. MSS-RRLH is an evolution of over-the-top HTTP Adaptive Streaming solutions [63] (such as the MPEG-DASH and HTTP Live Streaming [64]) derived from previous work on MSS. The system simultaneously uses several paths to download the video segments over HTTP. The proposed end-to-end solution is composed of a MSS-RRLH server, deployed as a VNF inside of an intra-building home IP gateway (HIPG) and a MSS-RRLH client running at the UE, as shown in Figure below.

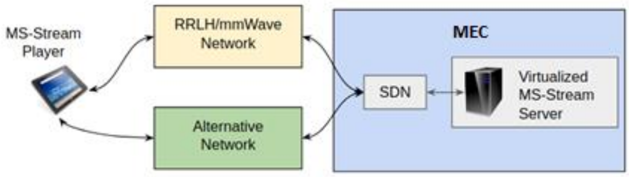


Figure 4-46 Multiple source streaming in MEC

Preliminary works on MSS-RRLH have been presented in [59] and [60]. The enhancements of MSS/RRLH and the principal mechanisms of the solution are presented in [61].

4.4.4 Security monitoring VNF

Security at the mobile edge has the advantage of being far more scalable and selective to the needs of end users within a building and would typically act as a first line of defence in a security architecture performing tasks such as Scanning Security, Denial of Service Security and Sniffing Security.

According to the recommendations presented in the “5G PPP Phase 1 Security Landscape” document [74], the security monitoring by design paradigm was recommended. As a result, one of the VNFs in the MEC has been designated and designed to monitor user traffic and to provide rapid response to the detected threats. This solution is called Integrated Security Framework (ISF) and it closely cooperates with the SDN network used for connecting radio/light users via the radio access network (RAN) to the Internet. The main functionality of the ISF is related to detection of suspicious activities performed by or directed to 5G users, for example, scanning activity, Denial of Service (DoS) threats and traffic eavesdropping by the rouge device placed by the attacker within the 5G system range. When the hostile activity is detected with a reasonable probability, immediate actions are being performed. For this purpose, special flows are installed in the SDN switch which block malicious traffic and in effect ensures protection of the 5G users. Initial results of simulation proved that scanning activity can be greatly reduced using such an approach [28].

Figure 4-47 presents a diagram of main parts of the ISF. The main part of the security monitoring and management VNF is a virtual machine, which is responsible for security monitoring and is equipped with three network interfaces:

- Interface no. 1 - is connected to the network available for all 5G system RAN users,

- Interface no. 2 - is connected to the SDN management network, and allows access to the SDN controller,
- Interface no. 3 - is connected to the dedicated Switched Port Analyzer port in Open vSwitch, managed by the SDN application.

The main components of the ISF, running on the dedicated virtual machines, include:

- Attacks detection module,
- SDN-based security monitoring and management application,
- Web-based security dashboard.

More details concerning ISF are provided in the document "Threats Analysis and Integrated Security Framework for IoRL Use Cases" [29].

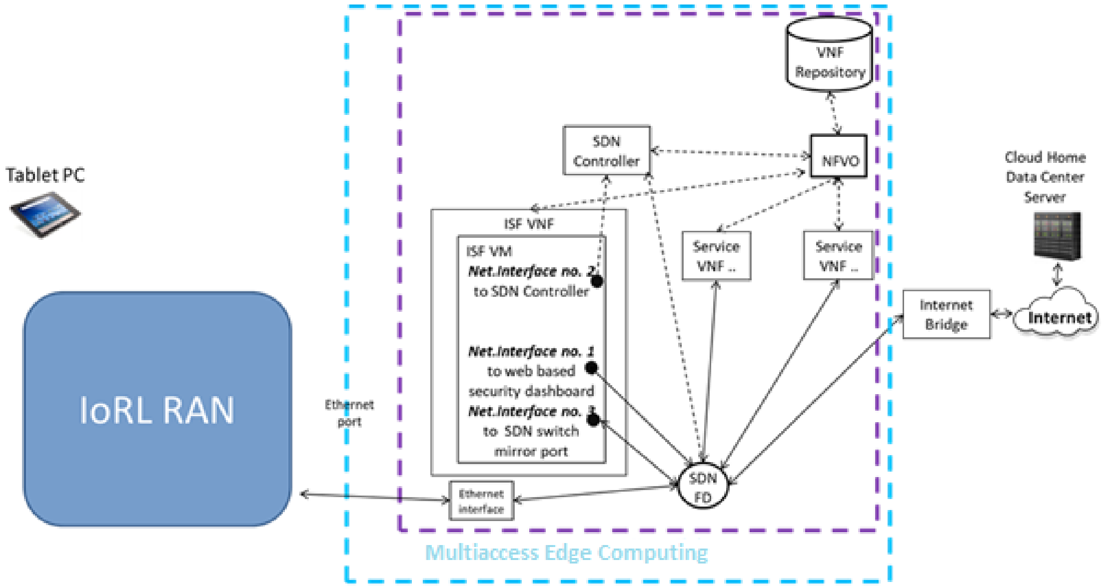


Figure 4-47 Integrated security framework in MEC

4.4.5 Multiple Video streaming VNF

Quality of video contents is increasing to meet demand of the consumers. Even though traditional TV broadcasting is not as popular as it used to be, home residents still prefer TVs to enjoy high quality contents on large screens (Table 3). However, home networks may not be suitable for delivering video in high quality and existing TV sets may not be able to perform advanced features such as picture in picture (PiP) video. To obtain such benefits 5G MEC can be used to provide high bit rate communications and scale and integrate multiple TV streams for the home use-case.

One of the main performance indicators of the home use-case is the delay and the video quality. In order to meet these requirements, a web-based TV application is developed for Linux based 4K UHD TVs. Using this application, TV users are able to display streaming video contents transmitted by the VLC server. Integration of the TV is handled by the VLC receiver, which is connected to the TV via Ethernet port as shown in Figure 4-48.

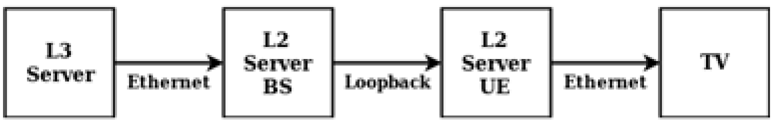


Figure 4-48 TV interface in video streaming system

In order to display more than one content simultaneously, a native application (Figure 4-49) is developed for Android based 4K UHD TVs. It is possible to display two videos (such as PiP) by listening at two different Internet ports. With the help of this use-case, TV users have the ability to watch high quality video content transmitted over the 5G network. The requirement for capacity become very demanding if a bouquet of video streams must be transmitted to a property.

The 5G android-based native TV application gets IP address of the TV automatically. The application listens on two ports to display both contents simultaneously (Figure 4-50). If the streams are available on the two ports, the TV will display the contents simultaneously. This functionality can either exist on the TV set or in the MEC.

Figure 4-49 Android-based native TV application

Figure 4-50 Application displays both contents simultaneously.

Table 3 Video Formats, Codecs, frame rates and bitrates

Resolution	Compression	Frame Rate(fps)	Network Bandwidth (Mb/s)
UHD 8k (8192x4320)	H.265/HEVC	120	280
UHD 4K (3840 x 2160)	H.265 HEVC	60	26.8
UHD 4K (3840 x 2160)	H.265 HEVC	50	22.3
UHD 4K (3840 x 2160)	H.264	60	36.2
UHD 4K (3840 x 2160)	H.264	50	30.1
Full HD (1920 x 1080)	H.265 HEVC	60	6.7
Full HD (1920 x 1080)	H.264	60	9

4.4.6 Load balancing VNF

To improve data speed and reliability, hybrid wireless networks combine different RATs such as 4G LTE, Wi-Fi, mmWave, etc. 5G allows combining radio access technologies (RATs) using coexisting multicomponent carriers for example to take advantage of the vast VLC and mmWave spectrum with the ubiquitous coverage of Wi-Fi networks. In this respect, efficient network data traffic steering across the three coexisting radio access networks is required using software-defined virtualization. The proposed load balancer sits between the home-user devices and the back-end servers on the MEC, receiving and then distributing incoming requests to any available server capable of fulfilling them. As is often the case where either a network overloads or it provides inadequate service quality to the home-user, the load balancer automatically switches between RATs to transfer the data via a more suitable path, i.e., accessing the network with less traffic load or better coverage for specific users.

Combining SDN with NFV technologies facilitates breaking the vertical integration between the network control plane and its data plane, which bypasses the inflexibility of most existing load balancing solutions that traditionally use fixed software with dedicated hardware equipment for forwarding the home-user (or client) requests to different servers, that is expensive, lacks flexibility and is easy to become a single point failure [30].

During the configuration process of a 5G hybrid access network system with co-existing VLC, mmWave and Wi-Fi networks, individual home-user positioning, its priority (weight) and its minimum Quality-of-Service (QoS) parameters are used to formulate an Access Point Assignment (APA) problem for establishing true-traffic steering automation by taking these as closed-form optimization constraints [31]. The APA problem can be resolved using convex-optimization analysis to derive a low-complexity solution by means of final formulas that can indicate, in real-time, which AP should be assigned to each home-user positioning/priority/QoS for maximizing the overall system throughput. The contribution of such a solution is that (i) it considers a three-dimensional RAT system, instead of a conventionally considered two-dimensional RAT system structure, and (ii) it bypasses the sub-gradient searching processes issued by conventional dual-Lagrangian optimisation and Dinckelbach-type algorithms to resolve the 3D-RAT APA problem in low (linear) complexity (which enables the solution to operate in real-time).

4.4.7 Video optimisation VNF

In various video-based applications for indoor use cases, video optimisation VNFs at the edge help increasing the processing power of demanding videos and ensure QoS and Quality of Experience (QoE) for the end users. Moreover, given the high automation and scalability requirements in indoor scenarios, the solution needs to enable real-time video streaming at large scale for video applications in an autonomous way. For instance, a video optimiser VNF is able to provide an autonomous control loop for automatic monitoring of metadata of video flows and network conditions to adapt the video flows in response to the dynamic network conditions in order to avoid any degraded perceived quality by the end users even in adverse network conditions e.g., congested link. It enables self-optimisation of video delivery in adverse network conditions with zero human intervention based on cognitive control loop to maintain the QoE in 5G and beyond networks for the end users in a highly stressed situation.

Advanced traffic filtering with high scalability is enabled and applied to H.265 encoded video to identify and selectively drop least important video packets from a video application stream in congested conditions, which enables run-time bandwidth-saving video optimization without notably compromising the QoE in such bandwidth-constrained scenarios. Moreover, kernel-space video processing is explored to achieve further performance gains. The video optimizer can be dynamically deployed as a VNF in the MEC to achieve agility and flexibility in this service. More technical details of this solution can be found in [38] and [39].

4.4.8 Indoor fronthaul and backhaul options

To guarantee the QoS of end-to-end (E2E) communications for indoor use cases, all the network infrastructure segments along the E2E communication path should be controlled properly to meet the overall QoS requirements. The network segments may include RAN, edge (MEC), transport network, and core network. In this white paper, as shown in Figure 4-51, the fronthaul refers to the network infrastructure part between RAN and edge, and the backhaul refers to the part between edge and core network across transport network. Essentially, the non-RAN segments and links are all covered in this section. For QoS warranty, network slicing has become a cornerstone technology for 5G and beyond networks and thus will be emphasised as a recommended solution. A set of network slicing technologies are available for exploration in this context, and the following sections present those technologies applied to fronthaul and backhaul communications.

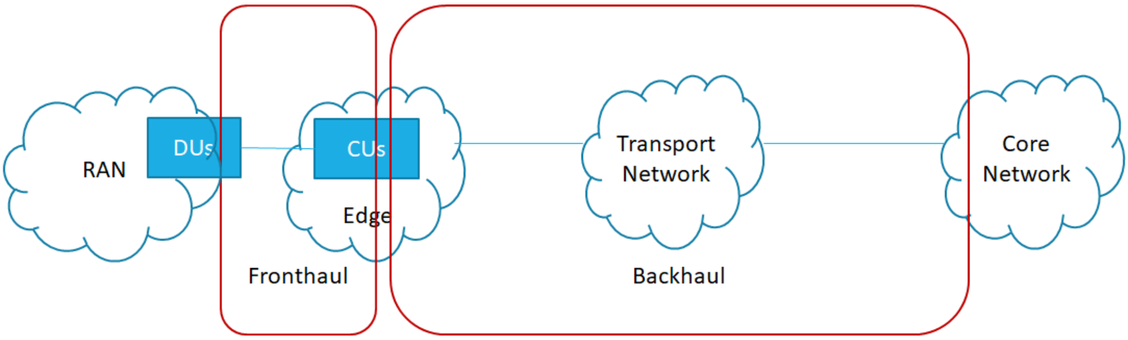


Figure 4-51 Positioning of fronthaul and backhaul in E2E network

Figure 4-52 illustrates the system overview of network slicing based on hardware data plane programmability. This Hardware Approach employs programmable Network Interface Cards (NICs) to connect the hardware directly into the Virtual Machine (VM) deployed in the edge (MEC VNF), based on the Single Root I/O Virtualization (SR-IOV) technology. Then, in order to achieve slicing-friendly capabilities into the 5G infrastructure, the NIC should provide the following. For multi-tenancy, technologies such as VLAN tagging and VXLAN/GRE (Generic Routing Encapsulation) should be applied to provide the capability to allow tenants to define networks in software and perform such off-loading into hardware. Secondly, the NIC should provide the exposition of the different lanes/queues directly to the VMs. This approach allows every VM to have a dedicated set of queues/lanes available to be used in an exclusive use and the scheduling of these lanes is an enabler of the slicing-friendly infrastructure.

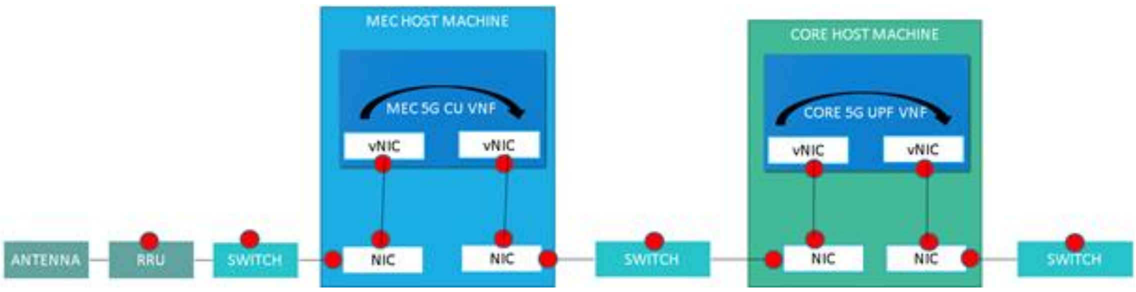


Figure 4-52 Hardware-based data plane network slicing

In this approach, the Infrastructure Provider only has the control capabilities exposed by the hardware. It means that in order to allow a slicing-friendly infrastructure in this "Hardware Approach", the programmability of the scheduler is required in order to enforce the slice QoS control. Programmable NICs such as NetFPGA and Netcope architectures allow these capabilities. It is noted that packets in this approach still need to be processed by the Linux kernel of the Guest VM and thus this is where kernel-bypass approaches can be employed in the Guest VM as a complement to achieve efficiency at high rates. In case of considering a deployment where the programmability of the Data Plane is centralised in the SDN controller, then an OpenFlow agent is required to perform the programmability of the hardware rules of the scheduler implemented in the NIC. More technical details of this solution can be found in [39].

As an alternative solution for data plane network slicing, the Hybrid Approach is the combination of both software and hardware forwarding devices in order to separate the required roles to achieve a slicing-friendly infrastructure between the software and hardware components. The system is shown in Figure 4-53, which illustrates how the traffic coming from the hardware NIC is now received in the Open Virtual Switch (OVS) in the host machine. It would require the Linux kernel to deal with the packets and thus would suffer from scalability issues. In order to overcome this problem, the Hardware Approach is integrated with OVS. In this architecture, OVS is the responsible element to forward packets to the VMs and thus introduces a control point where policies can be applied.

In terms of role separation between software and hardware, it is recommended to minimise the use of the software-based packet processing, by off-loading as much as possible workload into the hardware capabilities. Compared with the Hardware Approach, this Hybrid Approach would yield lower performance whereas it provides higher cost-efficiency and more flexibility in the Control Plane since it allows having double control points layers for the Infrastructure Provider and Network Operator. The Infrastructure Provider's control points layer is composed by two control points: one flexible yet slow software control point and a limited yet fast hardware control point. The Network Operator's control points layer, however, only has one control points layer for the tenant in the kernel space of the VM.

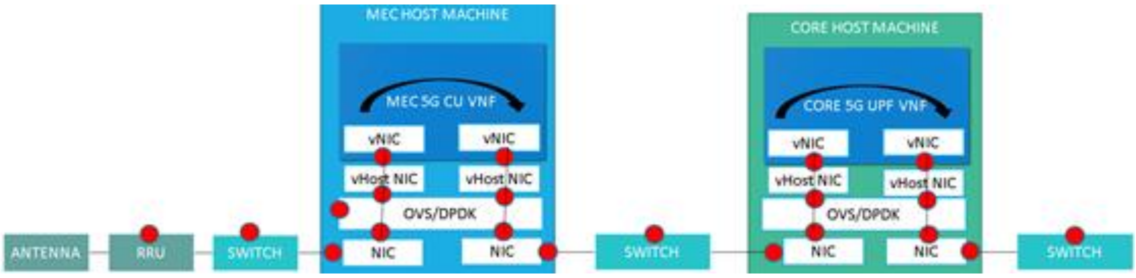


Figure 4-53 Hybrid data plane network slicing

In addition to leveraging data plane programmability to ensure the QoS for user traffic, network slicing needs the deployment of a set of specific network functions together with the resources for those network functions to achieve the services required by the target use case. This is typically achieved by the network slice management and orchestration (MANO) system in a 5G network, both at the network slice provisioning phase and at run time on demand. Those network functions need to be placed at the proper points of the network and linked in an order to perform the processing logic for the services. Service Function Chaining (SFC) or Network Service Chaining can provide such an ordered and connected sequence of network functions in order to create end-to-end composed network services in the required logical way. There are source projects that provide generic SFC reference implementations such as OpenStack and OpenDayLight, largely based on the Open vSwitch (OVS) platform. To enable built-in 5G multi-tenant network support in SFC, OVS can to be extended, e.g., using the approach provided in [40].

4.5 Existing indoor localisation solutions

Positioning is one of the core technologies of location-based services (LBS), Internet of Everything (IoE), Artificial Intelligence (AI) and future applications of super intelligence (robots

+ humans). According to the application scenarios, positioning technologies can be classified into two categories: outdoor positioning and indoor positioning. For the outdoor positioning, the mainstream global navigation satellite systems (GNSS) have been widely used in large-scale commercial applications and can well satisfy most of the positioning requirements. However, due to the signal occlusion and attenuation of satellite signals in indoor environment, such technologies cannot be well adapted to resolve the indoor positioning. To meet the diversified and widespread LBS demands in indoor environment, different technologies have been proposed and developed to tackle the indoor positioning issues, such as Wi-Fi, Bluetooth, RFID, UWB, VLP, ZigBee, etc. In this section, we will give a brief introduction to the state-of-the-art indoor positioning technologies.

Wi-Fi Positioning: Wi-Fi is a WLAN technology based on the IEEE 802.11 series communication protocol. Wi-Fi based indoor positioning methods could utilize the channel attenuation model to retrieve the distances respect to each wireless Access Point (AP) and estimate the User Equipment (UE) location via triangulation technology (ranging method). However, the positioning accuracy is significantly affected by the severe multi-path, shadowing and fading phenomenon. Fingerprint positioning (scene analysis) is an alternative and widely used method. They focus on efficiently matching the real-time measurements with the nearest pre-recorded fingerprint (scene feature) to estimate the UE location.

Bluetooth Positioning: Bluetooth is a short-term radio frequency signal based on the IEEE 802.15.1 protocol of WPAN (wireless personal area network). Bluetooth devices have low power consumption, small size, and Bluetooth technology has been widely integrated in mobile devices, including smart phones, which is easy to promote and use. The iBeacon system promoted by Apple is based on ranging method. It can achieve a positioning accuracy of 2~3 m. The drawback of Bluetooth positioning system is that each antenna has a very small coverage (about 10 m) and high installation costs.

RFID Positioning: RFID (radio-frequency identification) is a kind of technology which uses radio waves to wirelessly transmit the identity (e.g. serial number) and other characteristics for mobility tracking of objects or people. As it offers a limited range of less than a meter, RFID is not suitable for area-wide positioning, but rather for a selective object identification. It is cost-effective, ease of maintenance and provides both identification and location. This makes localization via RFID particularly suitable for tracking solutions in industrial environments (e.g. asset management).

UWB Positioning: Ultra-wideband (UWB) is a radio technology that can use a very low energy level for short range, high-bandwidth communications over a large portion of the radio spectrum. It is a carrier-free communication technology, which transmits data by sending ultra-narrow pulses of nanosecond or below. UWB positioning technology is based on sensing the electronic tags which can produce the ultra-wideband signals to measure distance and angle, and than realize location estimation. The typical application is the Ubisense system developed by Cambridge University, which could achieve a positioning accuracy of few centimetres. Although UWB positioning technology can obtain very high positioning accuracy, the expensive infrastructure cost and installation fee largely restrict its application.

ZigBee Positioning: ZigBee is a low power and shortrange wireless communication technology between RFID and Bluetooth. ZigBee based positioning technology has the advantages of low power consumption, low cost and the signal transmission is free of the effects of range of visibility. It is widely used in industrial data acquisition, smart home, medical care and environmental monitoring and other fields. ZigBee positioning includes ranging and ranging free method. The positioning accuracy of ranging free method is very low and could not adapt to indoor positioning tasks.

Ultrasonic Positioning: Ultrasonic is a kind of sound wave with a frequency higher than 20,000Hz. It has the advantages of good directivity and strong penetrability, thus could be well adapt to complex indoor environments. Ultrasonic positioning utilizes the round-trip time of the signal to calculate the ranging information, like the radar. Active Bat and Cricket are two well-known Ultrasonic positioning systems. Their architectures are simplified and could achieve a relative high positioning accuracy. However, a major characteristic of sound waves is that the transmission speed is greatly affected by the air density and humidity. Therefore, the accuracy of this positioning method is greatly affected by climate fluctuating.

Computer vision Positioning: Target recognition and location are the mainstream research topics in the field of computer vision. The indoor positioning system based on computer vision technology obtains environment information through visual sensors, and then determine the location of the target point. It includes camera calibration, image feature extraction, matching, pose estimation and other technologies. Google's VPS (visual positioning service) is one of the most famous computer vision-based positioning system. It combines the computer vision and machine learning technology and provide a positioning accuracy of centimetre. Although computer vision-based positioning could achieve high accuracy, but it usually has a very high algorithm complexity and huge computation burden. In addition, the visual signal is easily disturbed, especially in the dynamic environment.

Magnetic Positioning: Magnetic positioning technology considers the magnetic field distribution as fingerprint and achieves positioning by matching the significant magnetic field characteristics, as with Wi-Fi fingerprint positioning method. However, the indoor magnetic geld signal is easily changed by humans, and it is difficult to construct an accurate magnetic field fingerprint database in practical applications.

Visible Light-based Positioning: Benefits from the advancement of solid-state lighting and the application thereof to Visible Light Communications (VLC), Visible Light Positioning (VLP) has been targeted as a very attractive implement for indoor positioning. The positioning reference signal of each AP is modulated and transmitted through VLC link for the UE to take measurements. VLP technologies are commonly classified into 2 categories: ranging method and scene analysis, like the Wi-Fi positioning. Bytelight and Ubeacon are the two outperformed systems. Combining numbers of inherent advantages, such as low infrastructure cost, adequate coverage, free of electromagnetic interference and the potential centimetre accuracy, VLP is gaining more and more attention nowadays.

Others: There are other indoor positioning technologies such as among others Infrared positioning, INS positioning, QR code positioning, and laser positioning that will not be discussed further.

Figure 4-54 gives a brief description of the state-of-the-art indoor positioning technologies in terms of positioning performance and system complexity. Indeed, due to the inherent defects of each technology and complex indoor environment, a system with single positioning technology usually cannot satisfy the positioning requirements in different application scenarios.

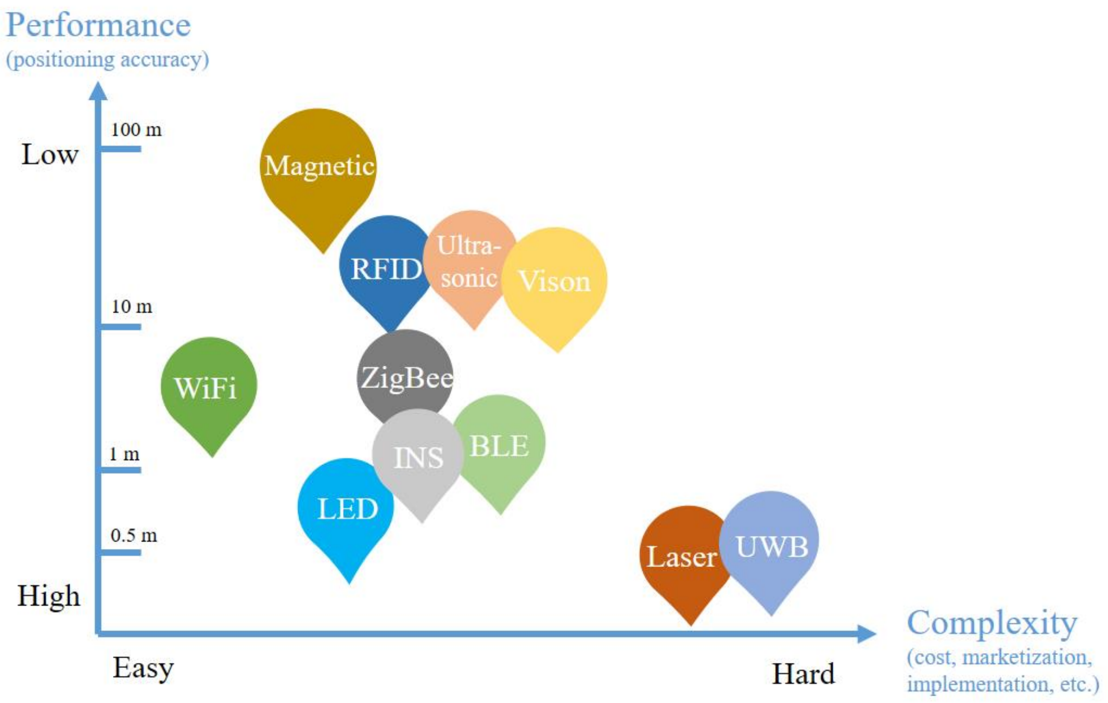


Figure 4-54 Comparison of different indoor positioning technologies

5 KPI achievements indoors

This section provides details of the expected and achieved key performance indicators measured by projects in indoors scenarios. We to recall here the 5G PPP level KPIs as reported in [75].

The coverage KPI for the indoor is measured by the Error Vector Magnitude (EVM) table for individual UE at individual location with mmWave: maximum transmission distance with a typical Rx power -15 dBm and dynamic range UL: [-30, 0] dBm DL: [-60, 0] dBm and VLC: maximum transmission distance with a typical Rx power -15 dBm and dynamic range UL: [-30, 0] dBm DL: [-60, 0] dBm. The indoor coverage will is increased by combining VLC and mmWave. The indoor position accuracy is the maximum positioning error in 3D coordinate system for mmWave and VLC. The user data rate KPI means the throughput between a client and a server based on the RAN service running on top of SDN platform with CPU optimisation. Network tools are used to accurately measure the volume of a user flow. The CPU load of the server hosting the RAN components is progressively increased to measure its influence over the quality of the connectivity service.

5.1 Throughput, EVM received power and reliability in different locations

The performance of 60 GHz mmWave, 40 GHz mmWave and VLC modules were measured in [61]. The KPIs that have been obtained are throughput, EVM and received power. The BER could be measured by using similar setup and test procedure. The performance tests of a hybrid Visible Light Communications (VLC) and 40 GHz mmWave 5G compliant system is being conducted in 4m x 6m RRLH Area 1 (see Figure 5-55) on the upper ground floor of the Integer House lab at the Building Research Establishment [26].

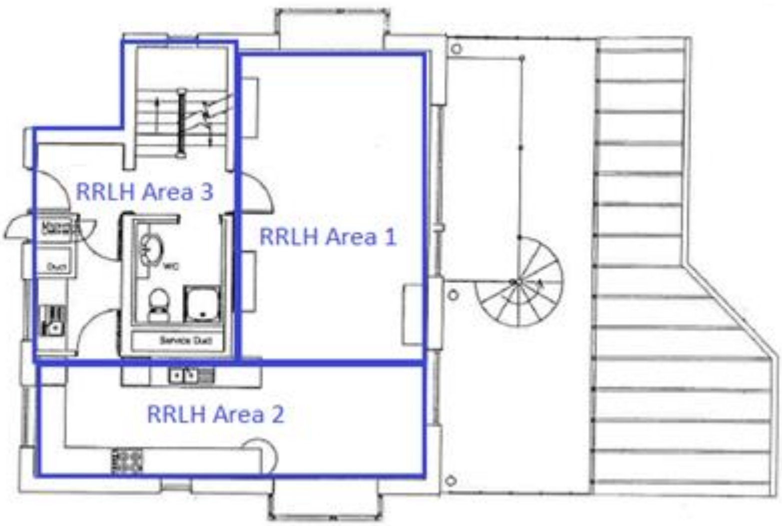


Figure 5-55 Initial plan for upper ground floor integer house

5.1.1 KPIs of 60 GHz mmWave and 40 GHz mmWave Modules

Both 60 GHz and 40 GHz measurements were performed using a Universal Software Radio Peripheral (USRP)-based testbed system. The 60 GHz and the 40 GHz measurement systems adopt a similar setup for the testbed system with different configurations. Currently, four measurement campaigns have been conducted. The key configurations for each measurement are listed in the table below.

Table 4 Key configurations for the 60 GHz and 40 GHz mmWave measurement

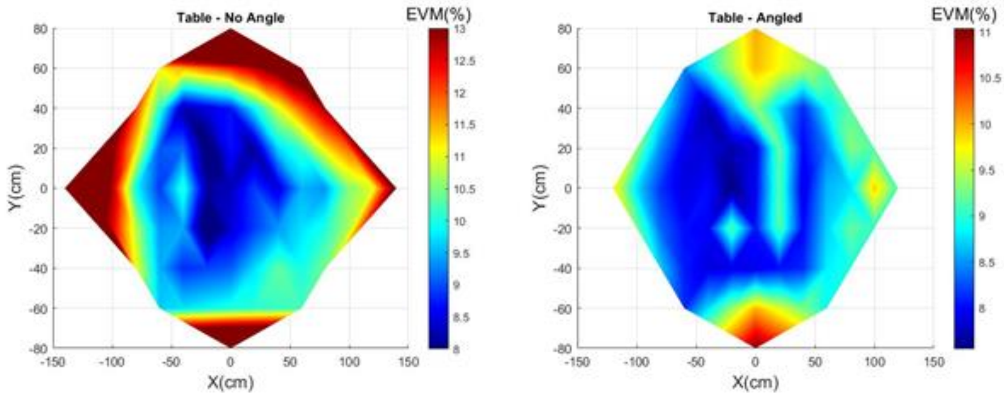
Operating frequency	Antenna type	Bandwidth	mmWave Tx Input Power	IF signal frequency	LO frequency	TX LO Input Power	RX LO Input Power
60 GHz	Horn	100 MHz	-16.65 dBm	3.5 Ghz	14 GHz	-	-
60 GHz	None	100 MHz	-16.65 dBm	3.5 Ghz	14 GHz	-	-
40 GHz	Horn	100 MHz	-27 dBm	3.5 Ghz	14 GHz	-13 dBm	-
40 GHz	Compact	100 MHz	-3.43 dBm	5.8 Ghz	15 GHz	7 dBm	4 dBm

Because the throughput is mainly based on modulation and coding schemes, if the EVM is good enough for the modulations, it is measured with a) 16QAM, 616/1024, b) 64QAM, 719/1024; c) 64QAM, 873/1024 and for all cases, the EVM is 6.5% which is the best result for 60GHz mmWave. The results are 150Mbps, 260Mbps and 310Mbps respectively.

For 60GHz mmWave, two different types of antennas, namely: “with horn antenna” and “without horn antenna”, are compared. In “with horn antenna” scenario, the best EVM of the distance cases at 1m, 3m and 7m are 13.83%, 8.85% and 6.51% separately. The best EVM of the cases that the TX and RX angles are in the range from 0º to 30º is between 6% to 9%. With those EVM, the 64QAM modulation can be adopted. However, for “without horn antenna” scenario, the best EVMs are heavily reduced even with shorter distances. At 0.5m, 1m and 2m, the EVMs are only 13.73%, 13.80% and 14.98%. Moreover, the EVM of the TX and RX angles within 30° is from 12% to 15%. The EVM can barely meet the 16QAM requirement.

For 40GHz mmWave, in “horn antenna” scenario, the best EVM is 3.97% at 3m and within the 30° angle, the EVMs can keep around 5.5%. In “compact antenna” scenario, the EVM can keep 8% at distance from 1m to 7m with different TX power gains. Within 30°, the best EVM is around 9%. The RX power of 40GHz module with compact antenna has been measured with TX IF signal power -3.43dBm. The RX power values from 1m to 7m are 1.91dBm, 0.21dBm, -5.32dBm, -6.26dBm, -5.75dBm, -3.75dBm, -10.25dBm. Note that with sufficient signal processing power using FPGA based user terminals, bandwidths can be increased from 100MHz to 400MHz to quadruple the above measurement results.

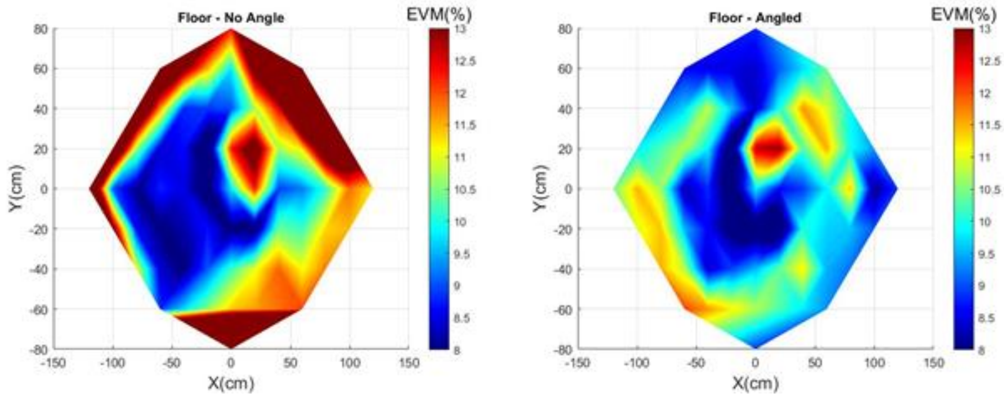
During the BRE measurement campaign, Figure 5-56 shows sample results of coverage for one mmWave TXs EVM Test at height above ground 0.7m (1.3m from Tx antenna) without/with Rx Antenna angled towards Tx antenna, and Tx antenna pointing vertically down. In most areas of the coverage region the EVM = < 8% making it suited for 64-QAM transmission (for 4-QAM this is 12% and for 16-QAM this is 10%). The propagation in the x direction (1.2m) is greater than in the y direction (0.8m) due to the physical construction of the printed circuit board (PCB) horn antenna where the horn slant is only applied in x direction and not in the y direction. Note that the antenna is polarised in one direction so that transmit and receive antennas have to be oriented in the same direction so their polarisations are aligned with each other, otherwise reception is poor.



(a) Without angling Rx toward Tx antenna (b) With angling Rx toward Tx antenna

Figure 5-56 One mmWave TXs, receiver at 0.7m above ground EVM Test

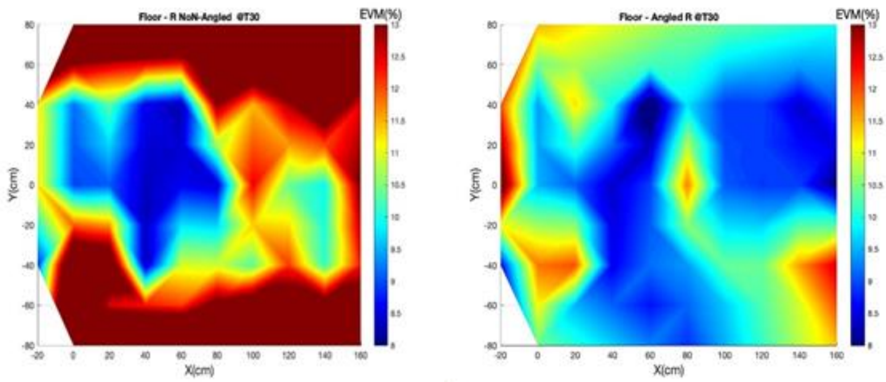
Figure 5-57 shows sample results of coverage for one mmWave TXs EVM test at height above ground 0m (2.1m from Tx antenna) without/with Rx Antenna angled towards Tx antenna, and Tx antenna pointing vertically down. In a lot of areas of the coverage region the EVM = < 8% making it suited for 64-QAM transmission.



Without angling Rx toward Tx antenna (b) With angling Rx toward Tx antenna

Figure 5-57 One mmWave TXs, receiver at 0m above ground EVM Test

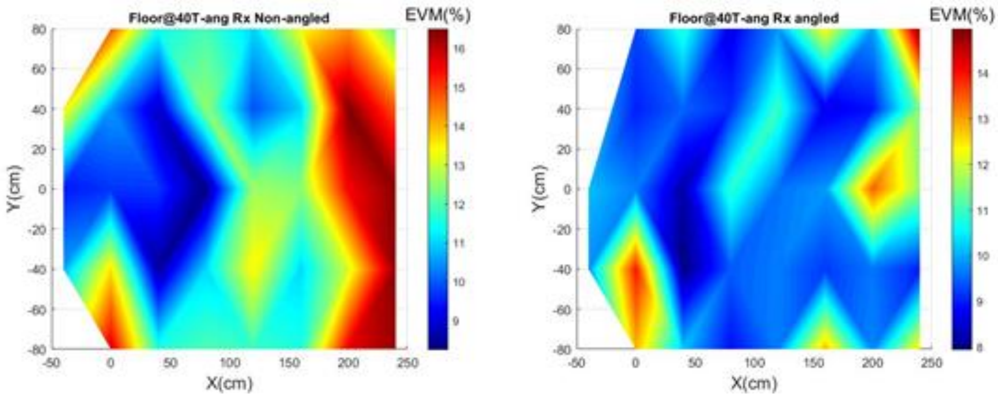
Angling the transmit antenna along the room in x direction by 30 degrees and the receive antenna towards the transmit antenna produced a coverage area of at least x=1.6m by y=1.6m, as shown in Figure 5-58 (b), whereas without directing the receiver this is restricted to x=0.8m by y=1.2m, as shown in Figure 5-58 (a).



(a) Without angling Rx toward Tx antenna (b) With angling Rx toward Tx antenna

Figure 5-58 One mmWave TXs angled at 30°, receiver at 0m above ground EVM test

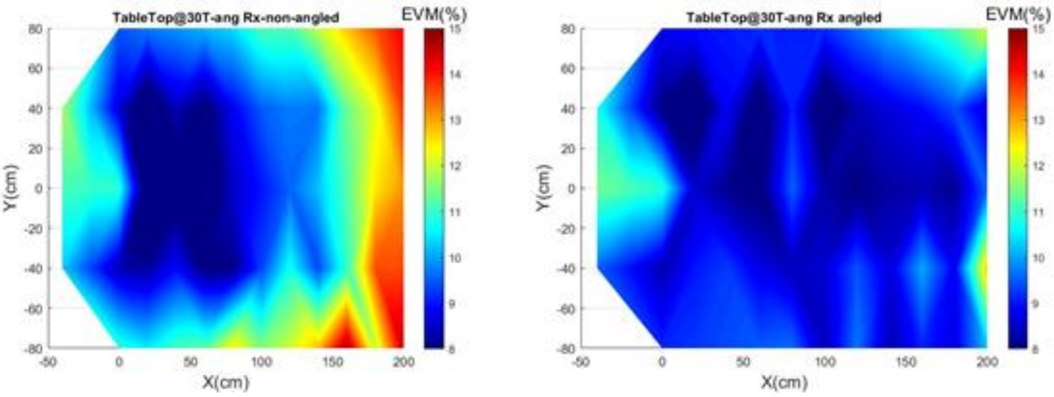
Measurements at 0m above ground with angling of the transmit antenna along the room in x direction by 40 degrees is shown in Figure 5-59. This shows that the performance of the mmWave system does improve with Tx angling at 40 degrees.



Without angling Rx toward Tx antenna (b) With angling Rx toward Tx antenna

Figure 5-59 One mmWave TXs angled at 40°, receiver at 0m above ground EVM test

Measurements at 0.7m above ground is shown in Figure 5-60. This shows that the performance of the mmWave system does improve with Rx angling towards the Tx antenna and at location nearer to the Tx antenna.



(a) Without angling Rx toward Tx antenna (b) With angling Rx toward Tx antenna

Figure 5-60 One mmWave TXs angled at 30°, receiver at 0.7m above ground EVM test

5.1.2 Electric and magnetic field measurement of 40GHz mmWave modules

Figure 5-61 demonstrates simulated prediction, which includes addition of 41 radio transmitting devices to the picture, generally found in smart homes: Z-Wave devices operating at 868 MHz, Zigbee, WI-FI and Bluetooth devices operating at 2.4 GHz and 5 GHz bands, Mobile Station operating at 1.8 GHz, positioned 90 meters away.

Peak power of 140 µV/m was produced by devices operating at lower simulated height of 1.2 m above floor level, not the mmWave antennas. This justifies why this peak is not observed anywhere on this height. Furthermore, in comparison with Figure 5-62, highest power is not recorded near the mmWave antennas, but around some of the smart devices, such as the WI-FI router, the smart thermostat and the smart fridge.

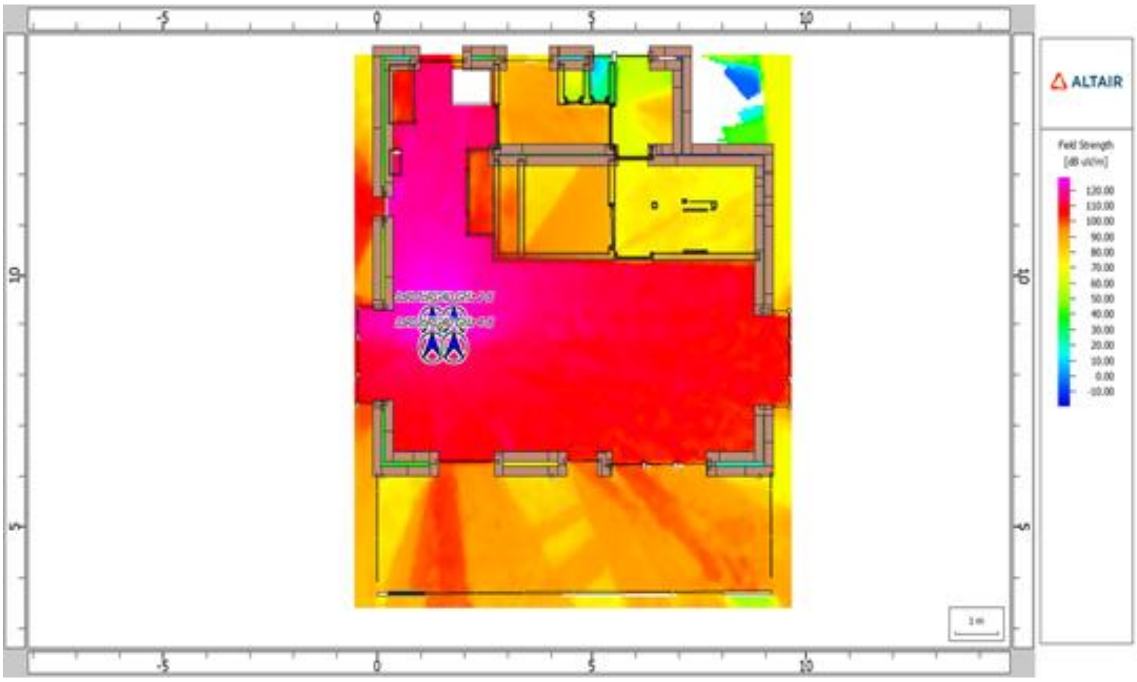


Figure 5-61 Simulation of EM radiation in integer house upper ground floor

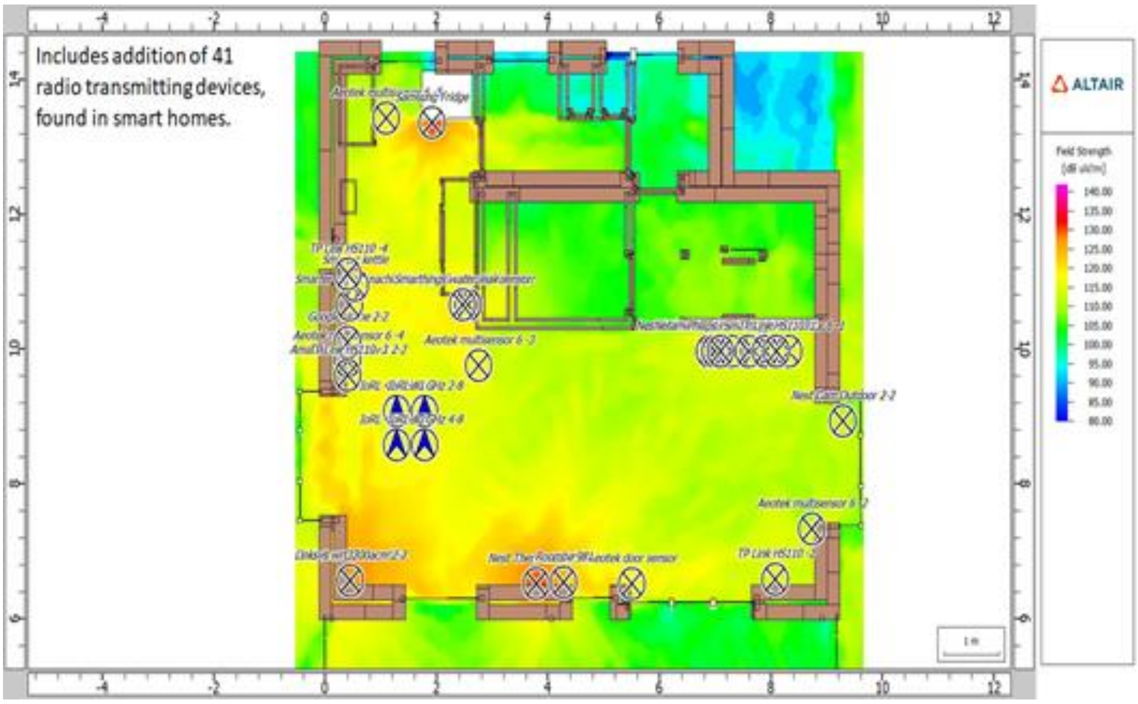


Figure 5-62 Measurement of EM radiation in integer house upper Ground floor – addition of multiple sources of radiation

5.1.3 Performance measurements of VLC module

The VLC module performance measurement was conducted with the same testbed with different waveform and configurations. Its operating frequency was 15MHz and the bandwidth is 10MHz. Two types of RX modules have been tested, the Tsinghua RX and Oledcomm RX [61].

With the best EVM 5%, the throughput of Tsinghua RX can be 1.59Mbps, 19.06Mbps and 31.44Mbps with modulation and coding schemes a) QPSK, 120/1024, b) 16 QAM, 340/1024 and c) 64QAM, 772/1024.

The best EVM of Oledcomm RX is 8.85% and with it, only the signal with schemes a) QPSK, 120/1024, b) 16 QAM, 340/1024 can be decoded and the throughput can only reach 1.59Mbps and 19.06Mbps respectively.

For Tsinghua RX, the EVM at 30cm, 60cm, 90cm and 120cm are 5.51%, 9.26%, 12.55% and 16.72%. With the LED lamps at 0º and the RX angles within 45º, the EVM can be 6.72%. But, because the maximum of LED lamps field of view is 30º, the EVM could be larger than 23%, when the angle of the LED lamps is larger than 30º.

The RX power is measured with Oledcomm RX. With -11.18dBm input power for VLC TX, the RX power are -24.56dBm, -32.99 dBm, -36.66 dBm, -44.28 dBm, -41.59 dBm and -49.65 dBm at 10cm, 20cm, 30cm, 40cm, 50cm and 100cm respectively.

Figure 5-63 shows sample results of coverage for 4 VLC LED TXs EVM Test at 2m distance with illumination LEDs off and Rx PD angle vertically up. The best performing RLH is A which provide a coverage area of radius 0.3m.

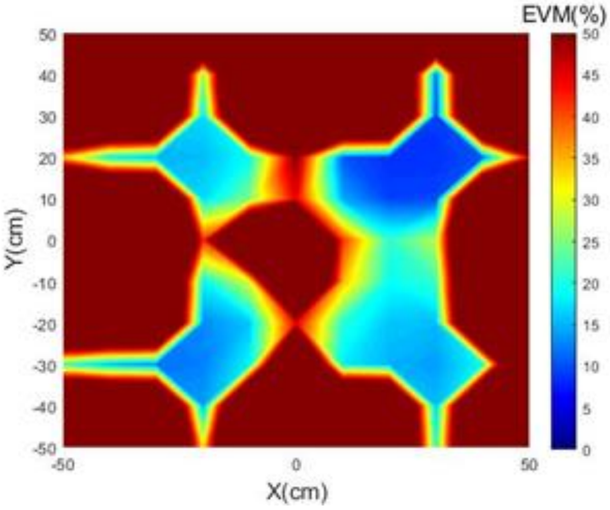


Figure 5-63 4 VLC LED TXs EVM test Rx at ground level pointing vertically up LED A and illumination LEDs off – top Right, B – bottom right, C – bottom left, D – top left

Figure 5-64 shows sample results at BRE of coverage for 4 VLC LED TXs EVM Test at 2m distance with illumination LEDs off and Rx PD angled towards the communication LED. The best performing RLH is A which provides a coverage area of radius 0.5m.

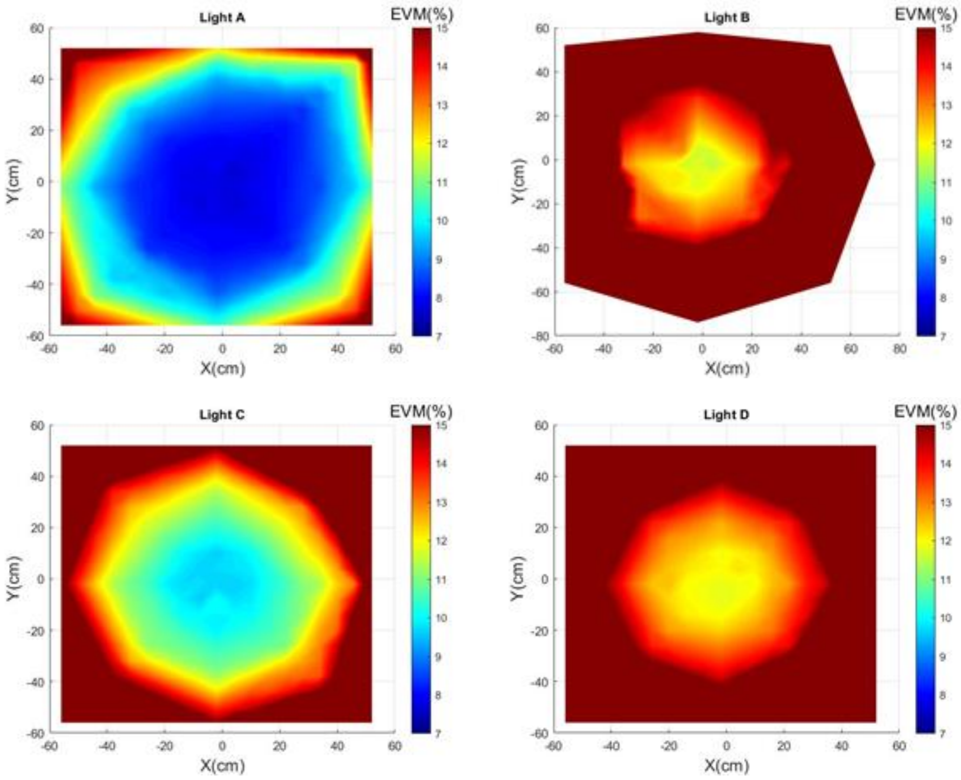


Figure 5-64 4 VLC LED TXs EVM test Rx at ground level pointing towards communication LED and illumination LEDs off

5.2 Round trip latency with mmWave uplink with 5G acknowledge

The aim of the experiment is to measure the round-trip latency of the mmWave uplink communication with 5G acknowledge. A time counter software is running on the testbed server for the time stamp generation and data processing. A BS L2 software and a UE L1L2 software communicate with DRAN and USRP through *10G* Ethernet cable separately. The UE L1L2 software generates the uplink data and use USRP to generate *3.5GHz* 5G signal for the mmWave TX. The DRAN and RRLH deliver the received the mmWave RX signal back to the system. To make the TX and RX work with *40GHz* mmWave signal, a local oscillator generator is used to provide a *14GHz* signal. A *10MHz* reference signal is supplied by DRAN to both the local oscillator generator and the USRP. The system implementation and equipment are shown in Figure 5-65. Other key configurations are listed in Table 5.

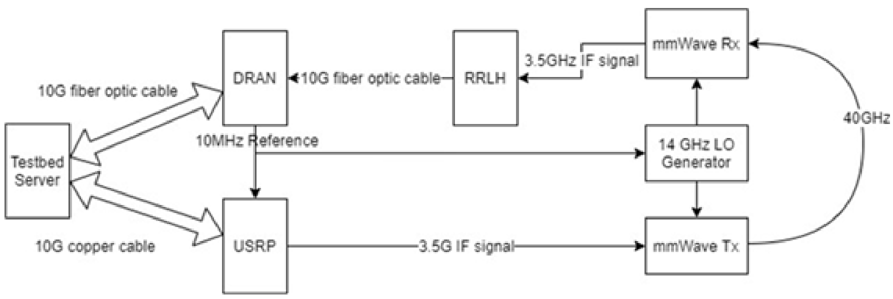


Figure 5-65 Testbed system setup for mmWave uplink measurement

Table 5 Key configurations for mmWave uplink measurement

Parameters	Value
Room Size	10x10x3.5m^2
Tx and Rx Height	1.5m
Operating Frequency	40GHz
Bandwidth	100MHz
mmW Tx Module Input Power	-27dBm
mmW Tx Module Output Power	18dBm
mmW Rx Module output Power	-7dBm
LO Output Power	-13dBm

The measurement procedure follows the steps:

- A time counter software will generate a TX timestamp and send it to the UE L1L2 software by UDP packet.
- The UE L1L2 software will encode the received data and map the data to the 5G waveform and transmit to USRP. The signal will be sent out by USRP and the mmWave TX module.
- After received signal by the mmWave RX module, DRAN and RRLH will decode it and forward to the BS L2. After that, the BS L2 can forward the received packet to the time counter software by UDP.
- Once the time counter software received packet, it will record the RX time and store the RX and TX timestamp into a file.

5.3 Round Trip Latency without mmWave uplink using ping-pong

The aim of the experiment is to measure the round-trip latency with mmWave downlink and Wi-Fi uplink. A time counter software is running on the testbed server to generate data packets with timestamp. It sends the packets to the BS L2 and receive the packets coming from the UE L1L2 software through Wi-Fi. The BS L2 software and the UE L1L2 software communicate with DRAN and USRP through *10G* Ethernet cable separately. The DRAN generates *3.5GHz* 5G radio signal for the mmWave TX. The USRP delivers the received mmWave RX signal back to the server. To make the TX and RX work with *40GHz* mmWave signal, a local oscillator generator is used to provide a *14GHz* signal. A *10MHz* reference signal is supplied by DRAN to the local oscillator generator and the USRP. The system implementation and equipment are shown in the following Figure 5-66 while the key configuration parameters are the same as the configurations in section 5.2.

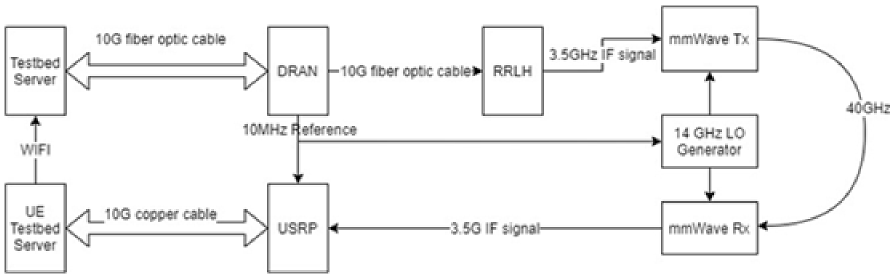


Figure 5-66 Testbed system setup for mmWave downlink and Wi-Fi measurement

The measurement procedure follows the steps below:

- A time counter software generates a TX timestamp and sends it to the BS L2 software by UDP packet.
- The BS L2 forwards the received packet to DRAN. DRAN converts it to the 5G signal, forwards it to the RRLH and is transmitted by the mmWave TX module.
- Once the mmWave RX module captures the signal, it is delivered to the UE L1L2 software by the USRP.
- After processing the received signal, the UE L1L2 software forwards the data to the time counter software data by UDP through Wi-Fi. The time counter software records the RX time and stores the RX and TX timestamp into a file.

5.4 Location accuracy against a prescribed grid

The aim of the experiment is to measure the location accuracy of the VLC and mmWave location algorithms in different parts of a room.

First the VLC and mmWave RRLH locations need to be recorded on the Location Database VNF. Then the raw Received Signal Strength (RSS) data from the User Equipment (UE) and the Time Difference of Arrival (TDoA) data from the Remote Radio Light Head (RRLH) Controller need to be recorded on the Location Database VNF. Then the Anchor and raw RSS and TDoA data need to be processed on the Location Server VNF and stored on the UE data on the Location Database VNF.

The mmWave antenna and LED x, y, z coordinates first need to be established and entered onto the location database in order to measure the location of the UE. As the location of the VLC LED and mmWave uplink antenna are in different locations on the RRLH, two separate sets of x, y, z coordinates are needed to the centre point of the circular area location of the VLC LED and to the centre point of the square area location of the uplink mmWave antenna.

5.4.1 5G-VLC positioning algorithm in laboratory environment

As shown in Figure 5-67, in the laboratory environment, there are four commercial LEDs, which are installed on the sliding ceiling track to broadcast the 5G positioning data. The coordinates of LEDs can be adjusted easily and freely. The initial coordinates of the four LEDs are set to LED A (-29 cm, -26 cm, 212.4 cm), LED B (-28.5 cm, 27.5 cm, 213.4 cm), LED C (23.5 cm, 27.5 cm, 212.4 cm) and LED D (24 cm, -26 cm, 213.4 cm). A Silicon avalanche photodetector (Hamamatsu APD C5331-12) with an optical lens is used as the VLC receiver. The receiver is placed on a plastic mold; the height of the mold is 27.2cm. The parameters of the LED and the receiver are summarized in Table 4 in section 5.1.1.

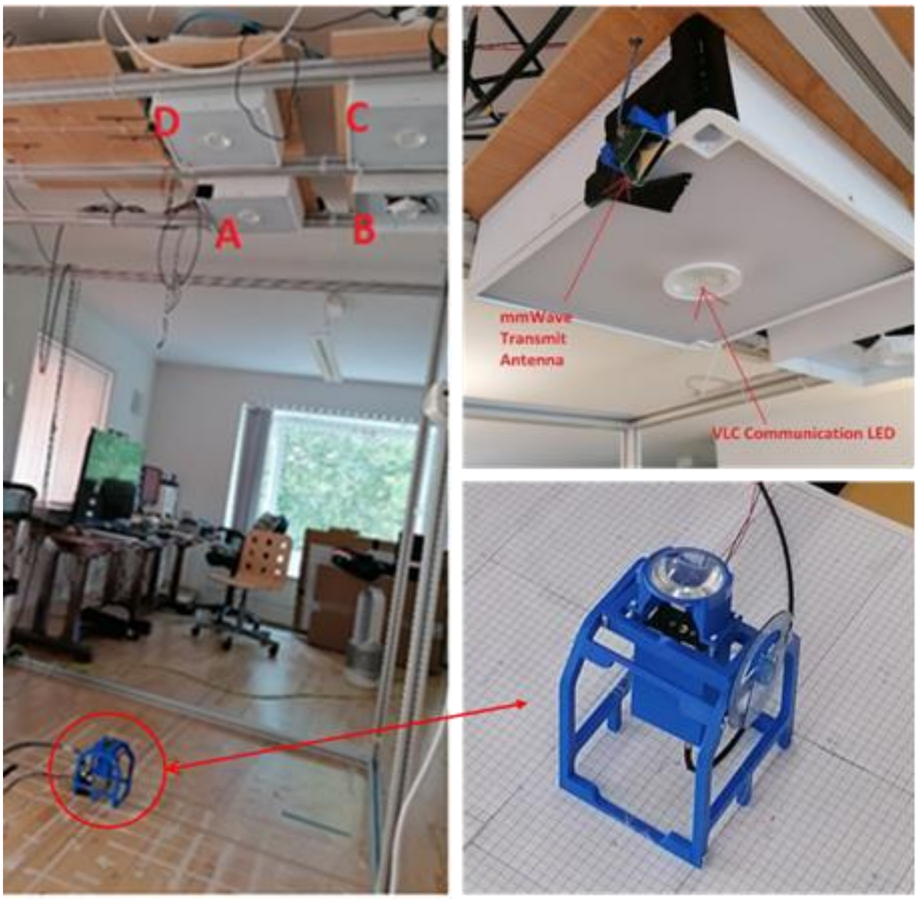


Figure 5-67 LEDs and APD receiver with lens

Under the above experimental environment, 30 (5*6) uniform distributed test points were selected over the 40cm x 50cm positioning area. The distribution of test points and coordinates of four LEDs are plotted in Figure 5-68. Each test point is measured 50 times thus there are 1500 (5*6*50) test points in total.

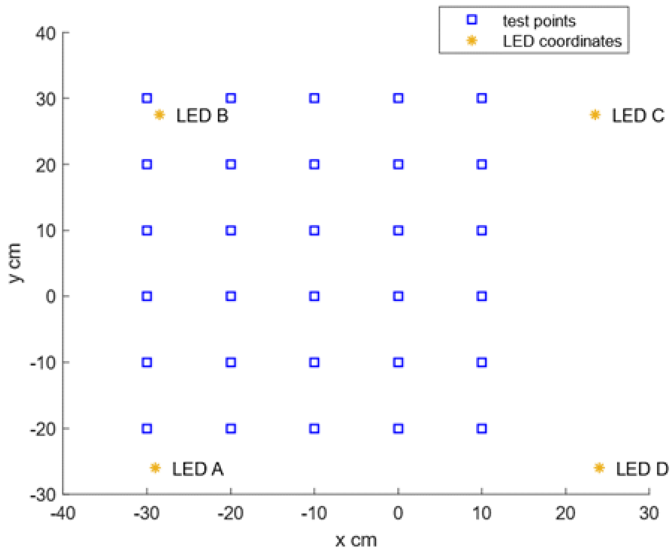


Figure 5-68 The distribution of the 30 test points and the coordinates of the four LEDs

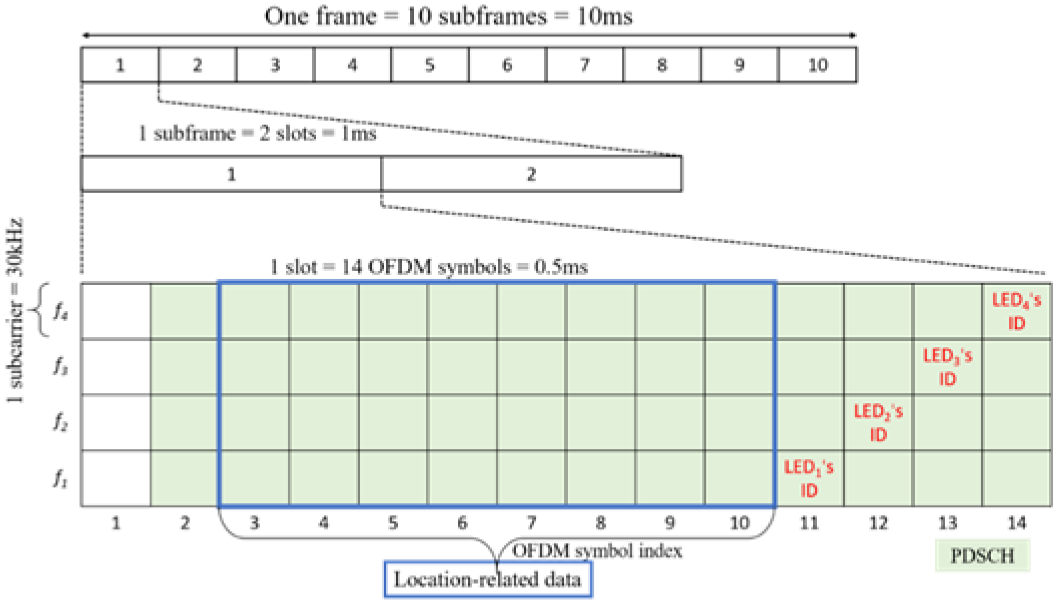


Figure 5-69 Definition of geographic data and location-related data in the 5G NR frame

The geographic data and the location-related data are integrated in the 5G NR frame, which is illustrated in Figure 5-69. Each frame consists of 10 subframes, each subframe has two slots and each slot has 14 OFDM symbols. In the frequency domain, the subcarrier spacing is 30 kHz. They are allocated in the Physical Downlink Shared Channel (PDSCH) slots. In each slot, the 3rd to 10th OFDM symbols are used to transmit the location-related data such as the multimedia contents. The last four OFDM symbols transmit four geographic data, where only one particular subcarrier frequency f is used to carry the respective geographic data. In experiments, in each OFDM symbol, the 1st, 3rd, 5th and 7th subcarriers were selected to carry the positioning data of LED A, B, C and D respectively. The detailed information is shown in Table 6.

Table 6 The detail information of corresponding positioning data

VLC TX	LED A	LED B	LED C	LED D
Subcarrier index	1	3	5	7
Frequency (kHz)	60	120	180	240

5.4.2 5G-VLC positioning results and analysis

The positioning performance is evaluated by the positioning error defined in equation as follows:

$$PositioningError = \sqrt{(x - x_e)^2 + (y - y_e)^2 + (z - z_e)^2}$$

where (x, y, z) and (x_e, y_e, z_e) are the coordinates of test points and estimated points respectively.

The experimental results are detailed in Figure 5-70. We plotted the distribution of positioning errors in this figure. The red sign represents the estimated points and the blue sign represents the test points, respectively. We selected 30 test points in total, 25 valid points and 5 invalid points. Among these 25 valid test points, the minimum positioning error is 0.55 cm, the maximum positioning error is 11.94 cm, and the mean error is 5.28 cm.

Besides that, the cumulative distribution function (CDF) curves of the 25 positioning results is plotted in Figure 5-71. It can be found that the current experimental testbed can reach a positioning accuracy of 10 cm at the confidence of 81.48 %.

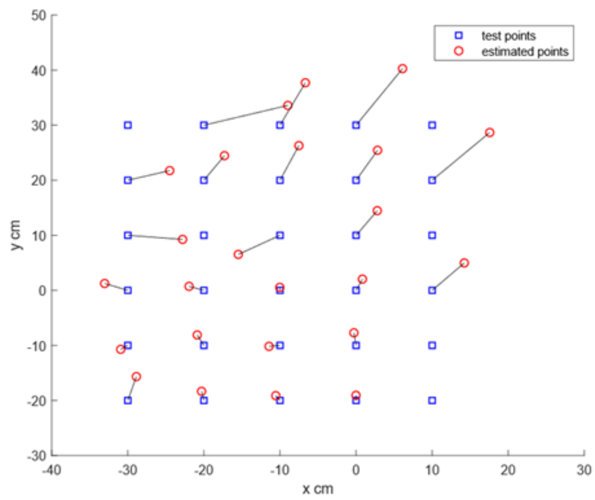


Figure 5-70 Distribution of test points and estimated points

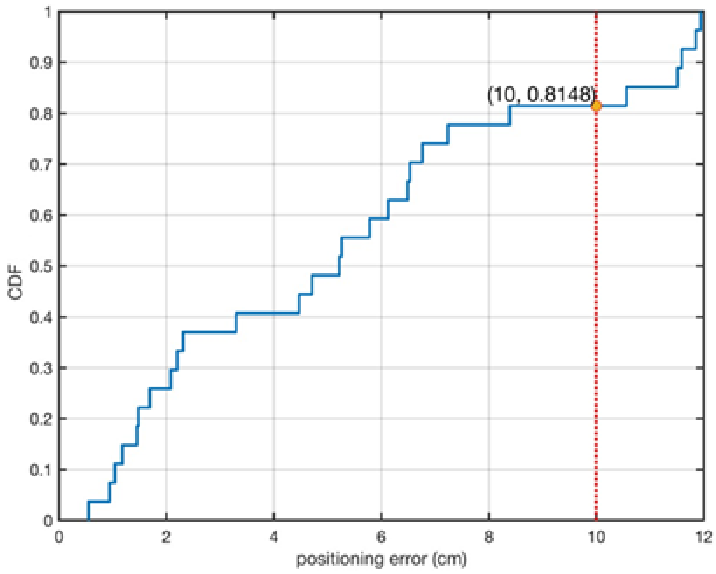


Figure 5-71 Cumulative distribution function (CDF) of positioning error

6 Outlook to beyond 5G and 6G

This section provides a description of possible new directions for indoor 5G networks.

Future requirements exceed 5G expectations

The Industry 4.0 revolution is being accelerated with 5G, bringing the digital transformation of manufacturing through novel cyber physical systems and IoT services for the indoor environments. Overcoming the boundaries between the real factory and the cyber computational space will enable Internet-based diagnostics, maintenance, operation, and direct machine communications in a cost-effective, reliable, flexible and efficient way. 5G technology includes several novel features, such as new frequency bands, advanced spectrum (e.g., mmWave and optical spectra) usage and management, and the integration of licensed and unlicensed bands. Nevertheless, the fast growth of data-centric and automated systems may exceed the capabilities of 5G wireless systems, as these will not have the capacity to deliver a completely automated and intelligent network that provides everything as a service and a completely immersive experience. 5G will not be able to fulfil the demands of future emerging intelligent and automation systems expected in 10 years, representing a bottleneck for future needs. The highly advanced industrial environments will present significant challenges for 5G specifications, spanning congestion, interference, security and safety concerns, high power consumption, restricted propagation and poor location accuracy within the radio and core backbone communication networks for the massive IoT use cases, especially inside buildings.

As such, certain industrial services envisioned for Industry 4.0, and supported by devices such as enhanced virtual and augmented reality devices, need communication capabilities that go beyond 5G (B5G) in order to be adequately supported in ultra-dense connectivity settings and comply with critical industrial requirements, requiring in some cases a minimum of 10Gbps data rate within 100µs air interface latency, reliability higher than 99.999% and location accuracy of down to 1mm. Furthermore, positioning accuracy can only achieve 0.5 meters based on the latest 5G specifications and there is a proposal motivation to make the supply chains more efficient through the identification and location of material using massive IoT technology and the collaborative control of robots, AGVs, drones that are coordinated and controlled through a distributed network. Moreover, there is clear lack of integration with new spectra, e.g., Optical Wireless Communication (OWC) and Terahertz (THz). However, such technologies face big challenges to support a massive number of users. Due to the high-power consumption and high hardware cost in the THz/OWC band, the number of radio frequency chains is usually limited, being much smaller than the number of antennas. In such cases, the number of users that can be served within one resource block is now larger than that of radio frequency chains. Hence, the integration of non-orthogonal multiple access (NOMA) in THz/OWC communications seems a promising path to break this limitation and greatly increase the number of users. In addition, the highly directional feature of mmWave makes the users' channels highly correlated, which is ideal for the application of NOMA. Benefiting from these unique advantages, the combination of THz/OWC communications and NOMA shows great potential to support the ultra-high bandwidth and massive connectivity required for B5G and 6G.

6G and even B5G deployments for industrial networks will be increasingly denser, heterogeneous and dynamic, posing stricter performance requirements with respect to 5G. Therefore, artificial intelligence will play a more prominent role in the network, going beyond classification and prediction tasks. The large volume of data generated by future connected devices for Industry 4.0 of the indoor environment will put a strain on communication technologies, which will not be able to guarantee the required quality of service. It is therefore fundamental to discriminate the value of information to maximize the utility for the end users with limited network resources. In this context, artificial intelligence strategies can evaluate the degree of correlation in observations, or extract features from input vectors and predict the a-posteriori probability of a sequence given its entire history. Complex 6G systems will require a fully-user-centric network architecture. In this way, user terminals will be able to make autonomous network decisions based on the outcomes of previous operations, without communication overhead to and from centralized controllers. Moreover, the use of artificial intelligence is considered to enhance the latency and reliability of NOMA and to anticipate the high dynamic environment and autonomously arrange transportable base stations or device-to-device (D2D) clusters in the optimum location at all times.

Therefore, the vision of B5G and 6G for the indoor industrial network is one where future industrial tasks, services, assets and devices will hugely depend on wireless connectivity, and for such rely both on far greater connectivity KPIs unlocked through novel spectra combinations and on the autonomous management of the underlying network resources by applying AI at multiple decision layers.

Reconfigurable intelligent surfaces and THz communication

Targeting ultra-reliable and scalable beyond 5G connectivity of extremely high data rates in the 100 Gbps regime at almost ‘zero-latency’, the potential of frequencies between 110-170GHz (D-band) can be explored, taking advantage of breakthrough novel technology concepts, namely, the development of broadband and spectrally highly efficient RF-front-ends in the D-band, the employment of meta-surfaces to cope with obstructed connectivity scenarios and the design of Machine Learning-based access protocols, resource and network management techniques. In order to realize this beyond 5G vision, a *novel system model* needs to be devised, including channel modelling, waveforms, beam-forming and multiple-access schemes, tailored to the particularities of the D-band regime, along with *a novel Communication Theory framework* and a *novel (ML-based) network optimization approach*.

Sustaining a flexible and ubiquitously available 100 Gbps network for backhaul and access in systems beyond 5G will require, apart from the exploitation of higher frequency bands, the adoption of novel hardware technologies and advanced materials and the rethinking of Shannon-based Communication Theory framework and traditional design principles and architectures. In this way, the conventional system concept of a 5G network as a universal resource (physical and/or virtual) manager will be transformed into the system concept of a fully adaptive (to environmental characteristics, volatility and user requirements), *power-efficient distributed computer and highly reliable connectivity provider.*

Bringing to fruition the notion of Artificial Intelligence-aided wireless beyond 5G networks entails the challenges of devising a flexible and powerful ML-based wireless network optimization framework, introducing novel propagation and channel modelling principles and a revolutionary communication theory approach and developing – in a modular fashion - cutting-edge technology components. These include beam-forming antenna arrays, meta-surface-based intelligent materials, RF-front-ends, baseband processing, medium access control protocols, ML-based resources and network management, as well as devising a suitable performance evaluation framework defined by the appropriate critical use cases and relevant performance metrics.

It is believed that in systems beyond 5G, and in particular in the mostly demanding and challenging indoor scenarios, the road to 6G will be catalysed by the following three pillars:

- **Pillar I: *D-band* for 100 Gbit/s reliable wireless connectivity, by means of advanced, power-efficient transceiver design,** in order to substantially improve radio spectrum usage by introducing novel strategies for coverage/service extension, supporting of novel use cases, and exploiting today’s unexplored spectrum.
- **Pillar II: *Communications beyond the Shannon paradigm*, by means of Reconfigurable Intelligent Surfaces for NLOS/obstructed LOS connectivity**, in order

to guarantee connectivity reliability, by making the environment itself reconfigurable. It will thus become possible to make the most out of the ultra-high bandwidth resources made available by the D-band and, at the same time, overcome impairments associated with propagation characteristics, usage scenario topology, energy, and complexity limitations.

- **Pillar III: *Artificial Intelligence* based wireless system concept**, **by means of ML approaches** to optimize the architecture, the signal and data processing, the wireless channel and propagation models and all network management functions, in order to transform 6G into intelligent platforms integrating connectivity and computing, thus opening new service models to telecom/ISP providers.

These three pillars represent the main building blocks of the 6G network architecture, which are jointly and optimally combined to successfully address all relevant major Key Performance indicators, such as throughput, latency, coverage, reliability, energy efficiency and complexity reduction.

Beyond 5G and 6G concepts

The vision for a B5G-enabled industrial network is one where every part of the production environment is fluid, except for the walls and ceilings. Industrial machines, devices, and vehicles will be made mobile by 5G or B5G and made intelligent by edge and cloud-based analytics, enabling factory owners to change their production lines according to demand in a short period of time. Every piece of equipment in these new plants can be wireless, and mapped as a digital twin with high resolution 3D Simultaneous Localization and Mapping (SLAM). AI enabled Non-Public Network (NPN) slicing for industrial networks will liberate factories from their fixed production lines. MEC will organise retrofitted connectivity and enable analytical applications like predictive maintenance even for old machines.

Mobile robot use cases exhibit very high requirements on latency, communication service availability, and determinism. This application can involve simultaneous transmission of non-real time data, real-time high resolution streaming data and mission critical, real-time control data. Enhanced coverage in indoor (from basement to roof), outdoor (plant/factory wide) and indoor/outdoor environments is needed due to mobility of the robots.

AI-driven multi-agent deep reinforcement learning (DRL) will perform resource allocation over and beyond massive machine-type communications with new spectrum links including THz and optical wireless communications to enhance the performance with regard to capacity, reliability and latency for future industrial networks. Cross-layer DRL driven resource allocation can support the massive connections over device-to-device (D2D) assisted highly dynamic cell-free network enabled by Sub-6 GHz/mmWave/THz/OWC and high-resolution 3D SLAM of up to 1 mm location accuracy and 1° orientation accuracy, four major innovation are in focus:

- Enhanced new spectrum links: OWC and THz
- AI-driven D2D cell free network architecture for highly dynamic and ultra-dense connectivity
- AI-based end-to-end directional network slicing with guaranteed QoS over highly dynamic networks
- AI-driven data fusion for 3D indoor position mapping through heterogeneous location methods enabling 1 mm location position accuracy and 1° orientation accuracy.

Resource allocation over high dynamic ultra-dense D2D cell free networks with new spectrum links including THz and OWC can support up to 100 devices per m^3 network density, up to 99.999% reliability and up to 0.1 ms air interface latency for the future industrial networks.

Orientation accuracy relates to the 3GPP study on Ranging-based Services. TR 22.855 states "±2° horizontal direction accuracy at 0.1 to 3 meter separation and AoA coverage of (-60°) to (+60°); ±2° Elevation direction accuracy at 0.1 to 3 meter separation and AoA coverage of (-45°) to (+45°)" for the smart control user case.

Location and analytics KPIs

With the evolution of 5G, we are witnessing the growth of localization and related analytics as first-class citizen in the cellular world, while the longer-term vision of cellular networks targets the realisation of pervasive mobile virtual services. Therefore, the research area of localization and location-based analytics will go far beyond the seven 3GPP positioning service levels defined in Rel. 16 and 17 for 5G, which aim at accuracy levels from a few meters to a few centimetres. Building on the theoretical foundation for both active and device-free localization, novel localization mechanisms will target the physical limits in terms of accuracy, with latencies down to a few milliseconds for the most demanding scenarios, and will support the progressive integration of new localization technologies, e.g., based on novel radio interfaces.

In this context, the main breakthrough expected in B5G evolution is the availability of large bands beyond 100 GHz (D-band, 110 GHz to 170 GHz...) and massive use of multiple antenna systems. The increase in the frequency will require multiple antenna systems able to exploit the multi-ray propagation, for larger throughput but also for precise localization. Wideband signals offer better time resolution and robustness to multipath thus improving the performance of observed time difference of arrival (OTDOA) and uplink time difference of arrival (UL-TDOA) schemes, as well as paving the way to new positioning methods such as multipath-assisted localization exploiting specular multipath components to obtain additional position information from radio signals.

In addition, the localization mechanisms currently discussed within 5G standardization are two stage techniques (single value estimation followed by the localization algorithm). Recent one-stage techniques can overcome the limitations of single value metrics and obtain position estimates directly from the received waveforms, without requiring intermediate signal metrics [51], [52], [53]. This direction of investigation is in line with 3GPP, where it has been recently proposed to digitize and record waveform of the received signal at UE side/gNB side or any other network entity and report received signal waveform to the location server or gNB. For example, soft information in the form of likelihood functions can be used for localization [54]. Soft information based localization improves the localization performance by exploiting range or angle information likelihoods, together with environmental information, such as contextual data including digital map, dynamic model, and user profiles.

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Abbreviations and acronyms

3GPP	3rd Generation Project Partnership
5G PPP	5G Public Private Partnership
5G-ACIA	5G Alliance for Connected Industries and Automation
ACK	Acknowledge
ACM	Association for Computing Machinery
AGV	Automated Guided Vehicle
AMF	Access and Mobility management Function
AMR	Autonomous Mobile Robot
APA	Access Point Assignment
API	Applications Programming Interface
APN	Access Point Name
AR	Augmented Reality
ATSSS	Access Traffic Steering, Switching and Splitting
BBU	Base Band Unit
BER	Bit Error Rate
BLER	Block Error Rate
BRE	Buildings Research Establishment
CAG	Closed Access Groups
CDF	Cumulative distribution Function
cMTC	critical Machine Type Communications
COTS	Commercial of the Shelve
CPRI	Common Public Radio Interface
C-RAN	Cloud-RAN
CRC	Cyclic Redundancy Check
CSS	Cascading Style Sheets
CU	Centralised Unit
DAS	Distributed Antenna System
DASH	Dynamic Adaptive Streaming over HTTP
DCI	Downlink Control Information
DOI	Digital Object Identifier
DRAN	Distributed RAN
DRL	Deep Reinforcement Learning
D-RoF	Digital Radio-over-Fibre
DSL	Digital Subscriber Line
DU	Distributed Unit
eMBB	enhanced Mobile Broadband
EPC	Evolved Packet Core
E-SMLC	Evolved Serving Mobile Location Centre
EU	European Union
EVM	Error Vector Magnitude
FAPI	Femto Application Platform Interface
FCC	Federal Communication Commission
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FH	Fronthaul
FMA	Follow ME Application

FMS	Follow-Me Service
FPGA	Field Programmable Gate Array
FTM	Fine Timing Measurement
FWA	Fixed Wireless Access
gNB	gNodeB - 5G base station
GNSS	Global Navigation Satellite System
GSMA	GSM Association
GUI	Graphical User Interface
H2020	Horizon 2020, the framework research programme of the EU ending in 2020
HAN	Home Access Node
HEVC	High Efficiency Video Coding
HgNB	Home GNB
HIPG	Home IP Gateway
HLS	High-Layer Split
HMD	Head-Mounted Display
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IFIP	International Federation for Information Processing
IHIPG	Intelligent Home IP Gateway
IIoT	Industrial IoT
IoT	Internet of Things
IOV	I/O Virtualization
ISF	Integrated Security Framework
ISP	Internet Service Provider
ITU	International Telecommunication Union
IWF	Inter-working Function
KPI	Key Performance Indicator
LAA	License Assisted Access
LAN	Local Area Network
LBS	Location-based Service
LED	Light Emitting Diode
LLS	Low-Layer Split
LMF	Location Management Function
LOS	Line of Sight
LPP	LTE Positioning Protocol
LSC	Location Service Client
LTE	Long Term Evolution
MAC	Medium Access Control
MANO	Management and Orchestration
MBMS	Multimedia Broadcast Multicast Services
MEC	Multi-access Edge Computing
MIMO	Multiple-input / Multiple-output
MME	Mobility Management Entity
mMTC	massive Machine Type Communications
MNO	Mobile Network Operator
MORAN	Multi-Operator Radio Access Network
MPEG	Moving Picture Experts Group
MSS	Multiple-Source Streaming

N3IWF	Non 3GPP Interworking Function
NACK	Non-acknowledge
NFV	Network Function Virtualisation
NFVI	NFV Infrastructure
NIC	Network Interface Card
NLOS	Non-Line of Sight
NOMA	Non-Orthogonal Multiple Access
NPN	Non-Public Network
NR	New Radio
NRPP	New Radio Positioning Protocol
NSA	Non-Standalone
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OTDOA	Observed Time Difference of Arrival
OVS	Open Virtual Switch
OWC	Optical Wireless Communication
PBCH	Physical Broadcast Channel
PDCCH	Physical Downlink Control Channel
PDN	Packet Data Network
PDSCH	Physical Downlink Shared Channel
PDU	Protocol Data Unit
PLC	Power-line Communication
PLMN	Public Land Mobile Network
PNF	Physical Network Function
PNI-NPN	Public network integrated NPN
POF	Plastic Optical Fibre
PPDR	Public Protection and Disaster Relief
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RAT	Radio Access Technology
REGEX	Regular Expression
RFID	Radio-frequency Identification
RIC	RAN Intelligence Controller
RIS	Reconfigurable Intelligent Surface
RLC	Radio Link Control
RLH	Radio Light Head
RRH	Remote Radio Head
RRLH	Remote Radio Light Head
RRM	Radio Resource Management
RSS	Receive Signal Strength
RTT	Round Trip Time
SAR	Specific Absorption Rate
SAS	Spectrum Access System
SAWAP	Small Area Wireless Access Point
SCF	Small Cell Forum
SDL	Supplemental Downlink
SDN	Software-defined Networking

SFC	Service Function Chaining
SIM	Subscriber Identity Module
SLAM	Simultaneous Localization and Mapping
SNPN	Standalone NPN
S-NSSAI	Single-Network Slice Selection Assistance Information
SOHO	Small Office Home Office
SR-IOV	Single Root I/O Virtualization
TBS	Terrestrial Beacon System
TCO	Total Cost of Ownership
TCP	Transport Control Protocol
TDM	Time Division Multiplex
TDOA	Time Difference of Arrival
TNGF	Trusted Non-3GPP Gateway Function
TSN	Time Sensitive Network
TTFF	Time to First Fix
TV	Television
UDP	User Datagram Protocol
UE	User Equipment
UGV	Unmanned Ground Vehicle
UHD	Ultra-High-Definition
UMTS	Universal Mobile Telecommunications System
UPF	User Plane Function
URL	Uniform Resource Locator
URLCC	Ultra-Reliable Low-Latency Communications
USRP	Universal Software Radio Peripheral
UTRAN	UMTS Terrestrial Radio Access Network
UWB	Ultra-Wide Band
VGW	Virtual Gateway
VLAN	Virtual Local Area Network
VLC	Visible Light Communication
VLP	Visible Light Positioning
VLR-DAS	Very-low Radiation Distributed Antenna System
VNF	Virtual Network Function
VPS	Visual Positioning Service
VR	Virtual Reality
VXLAN	Virtual Extensible LAN
WAT	Wireless Access Technology
WLAN	Wireless LAN
WPAN	Wireless Personal Area Network

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Annex A User Terminals & Consumer Products

User terminals and indoor consumer products that act as user terminals are more varied by nature as well as their connectivity and communication demand, in comparison to outdoor use cases. Such user terminals in a home environment encompass:

- home entertainment devices (high-definition TV sets, radio and streaming, game consoles, standard smart phones, personal computers, etc.);
- smart and connected white goods and home automation devices;
- monitoring and security accessories.

In an industrial environment such user terminals would include robots, high resolution imaging devices, etc. In a medical environment, they would include various sensors, some of which would require only low, or very low bandwidth, whilst others high or very high bandwidth, and also specialist imaging equipment, some of which generating extremely high-resolution images and requiring very high bandwidth connectivity. In some special transport use cases, like underground parking, user devices might even include connected cars downloading software updates while parked, for example.

Due to the physical size of some user terminals (or specialised equipment acting as a user terminal) some of them are fixed. In essence this means that providing a wired connectivity to those is also an option. Nevertheless, we witness a strong domination of mobile devices in general, and a preference in case of consumer products to use wireless connectivity, not being bound to a wired connection.

A.1 4K Televisions

The size of video content is increasing due to the developments in high-resolution and video quality. This causes a necessity of higher speed and bandwidth requirements in video streaming. In 4k TV scenario, the solutions presented in [61] were integrated with the smart 4K TVs.

For the Integration a web-based Linux TV application was developed for Linux based smart 4K TVs. An android based TV application was developed for android based smart 4k TVs. The main feature difference between these two applications is the multi streaming ability which was supported in android based TV application. Multi streaming ability provides to the display two incoming video streams simultaneously on the screen. The basic diagrams of these two applications are shown in the figures below.

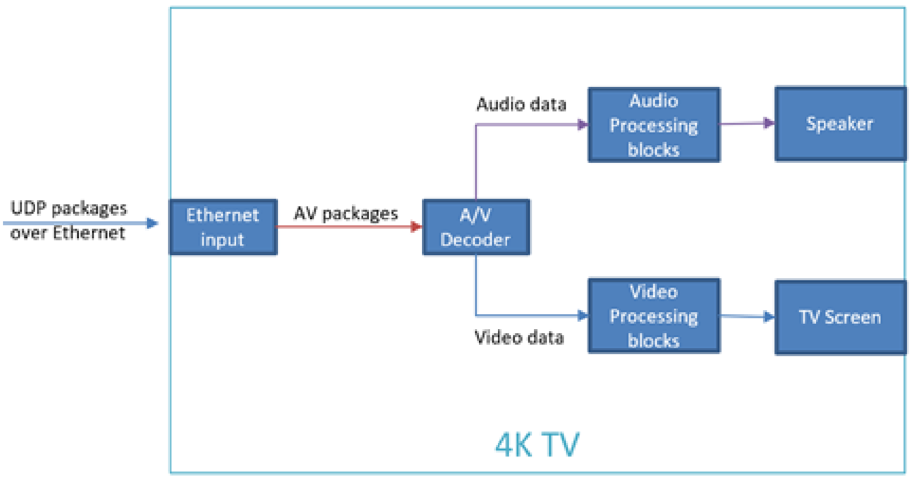

Figure 6-72 Basic diagram of Linux based 4K TV application

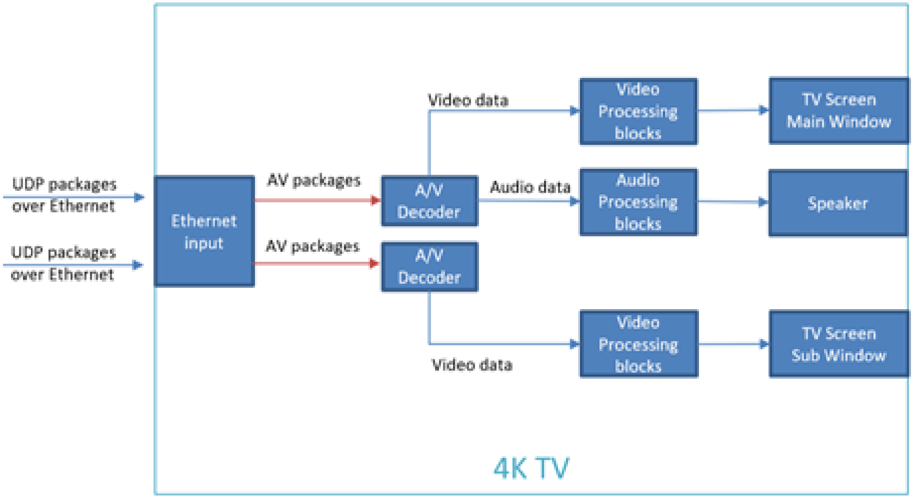

Figure 6-73 Basic diagram of Android based 4K TV application

A.2 5G Test User Terminal

The design of 5G test user terminal is similar to the RAN design but clearly with much less computer processing power and with diagnostics software, which was essential to record 5G received signal's performance measurements, namely: QAM constellation, mean and probability distribution of Error Vector Magnitude (EVM), EVM evolution with time, Block Error Rate (BLER) and Throughput for Physical Downlink Shared Channel (PDSCH), Physical Broadcast Channel (PBCH) and Physical Downlink Control Channel (PDCCH). 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 National Instruments 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 Gbps Ethernet port.

L1 UE processor is mainly responsible for cell search (SS/PBCH), blind detection for downlink control channel (PDCCH), decoding data channel (PDSCH), uplink data channel generation (PUSCH) and uplink acknowledge/Non-acknowledge (ACK/NACK) generation. The L1 UE signal process chain works in the following procedures, as show in the figure below:

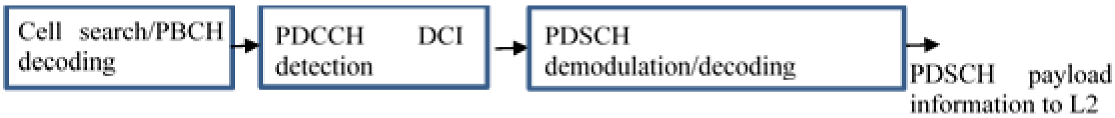

Figure 6-74 L1 UE Downlink procedure

The test procedure is composed of the following steps:

- Once the cell search module detects the frame boundary, the PBCH demodulation module starts to do the channel estimation for broadcast channel and obtain the information from the payload.
- With the information from PBCH, UE can obtain the PDCCH CORESET and search space information. Then, UE conducts blind PDCCH DCI candidate detection and the information for PDSCH could be obtained.
- With the information from PDCCH, the UE processor can start to demodulate PDSCH data from scheduled RBs. The key procedures are FFT/phase compensation, channel

estimation, equalization, de-mapper, de-scrambling, rate matching, low-density parity-check decoding, code block concatenation and CRC check.

L2/L3 UE processor is mainly used to unpack and deliver the data between L1 and user terminals. To synchronize between the processor threads of L1 and L2/L3, a trigger flag is set by L1 processor to notify the data is ready. Then the L2/L3 processor retrieves the data and unpack it based on the control information. After getting the unpacked user data, the L2/L3 processor forwards it as soon as possible by the UDP packets to the TV dongle. The IP address and UDP port of TV dongle is predefined.

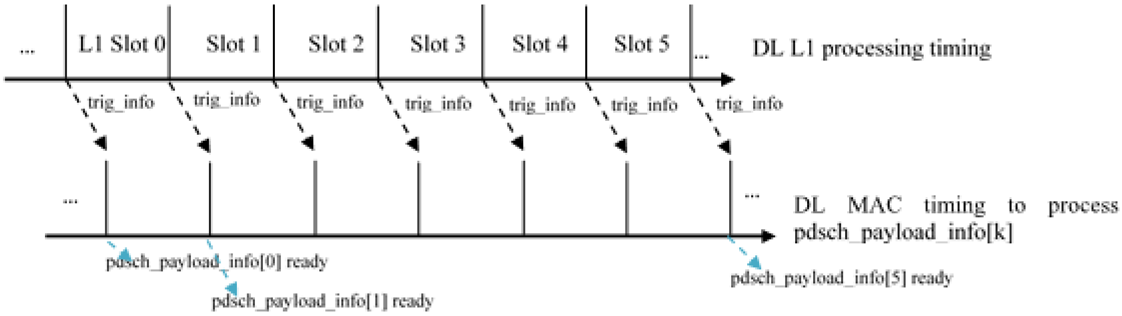

Figure 6-75 L1/L2 Interface DL Data Processing Procedure