Beyond 5G Multi-Tenant Private Networks Integrating Cellular, Wi-Fi, and LiFi, Powered by Artificial Intelligence and Intent Based Policy

5G-CLARITY Deliverable D3.1

State-of-the-Art Review and Initial Design of the Integrated 5GNR/Wi-Fi/LiFi Network Frameworks on Coexistence, Multi-Connectivity, Resource Management and Positioning

Contractual Date of Delivery:	**August 31, 2020**
Actual Date of Delivery:	**August 31, 2020**
Editor(s):	**Antonio Garcia (ACC), Tezcan Cogalan (UEDIN)**
Author(s):	**Ardimas Purwita (UEDIN)**
	Daniel Camps Mur, Hamzeh Khalili (I2CAT)
	Vladica Sark , Jesús Gutiérrez (IHP)
	Ibrahim Hemadeh, Jani-Pekka Kainulainen, Charles Turyagyenda (IDCC)
	Hilary Frank (UNIVBRIS), Rui Bian (PLF)
	Mir Ghoraishi (GIGASYS)
Work Package:	**WP3**
Target Dissemination Level:	**Public**

This document has been produced in the course of 5G-CLARITY Project. The research leading to these results received funding from the European Commission H2020 Programme under grant agreement No. H2020-871428. All information in this document is provided "as is", there is no guarantee that the information is fit for any particular purpose. The user thereof uses the information at its own risk and liability. For the avoidance of all doubts, the European Commission has no liability in respect of this document, which is merely representing the authors view.

Revision History

Revision	Date	Editor /Commentator	Description of Edits
0.1	10.02.2020	Antonio Garcia (ACC)	ToC and contributors
0.2	18.02.2020	Tezcan Cogalan (UEDIN)	Subsection structure proposal for Sections 5 and 7.
0.3	18.02.2020	Tezcan Cogalan (UEDIN)	Design subsections are removed, and an overall design subsection is added to Section 6
0.4	19.02.2020	Vladica Sark (IHP)	Added ToC for Section 6 – Positioning
0.5	21.02.2020	Antonio Garcia (ACC)	Added ToC for Section 3 and updated title multilist
0.6	24.02.2020	Charles Turyagyenda (IDCC)	Added ToC for Section 4 – multi-connectivity.
0.7	16.03.2020	Ibrahim Hemadeh (IDCC)	Some modifications made to Section 4 - Multi-connectivity: Restructuring + Content
0.8	25.03.2020	Tezcan Cogalan (UEDIN) Ibrahim Hemadeh (IDCC) Vladica Sark (IHP) Daniel Camps (I2CAT) Rui Bian (PLF) Antonio Garcia (ACC)	Tezcan Cogalan (UEDIN): Section 5 Updates; Ibrahim Hemadeh (IDCC): Some modifications made to Section 4 - Multi-connectivity: Improved Structure; Vladica Sark (IHP): Section 6 – Positioning; Daniel Camps (I2CAT): Section 3 – Wi-Fi; Antonio Garcia (ACC): Section 3 – LTE/5GNR
0.9	31.03.2020	Antonio Garcia (ACC)	First integrated Draft
0.91	20.04.2020	Ibrahim Hemadeh (IDCC) Daniel Camps (I2CAT) Rui Bian (PLF) Tezcan Cogalan (UEDIN) Jesus Gutierrez Teran (IHP) Antonio Garcia (ACC)	Second integrated Draft
0.92	04.05.2020	Ibrahim Hemadeh (IDCC) Daniel Camps (I2CAT) Rui Bian (PLF) Tezcan Cogalan (UEDIN) Antonio Garcia (ACC)	Further Section 3 and 4 updates. Added Acronym list
0.93	14.05.2020	Tezcan Cogalan (UEDIN) Ardimas Purwita (UEDIN) Daniel Camps (I2CAT) Antonio Garcia (ACC) Ibrahim Hemadeh (IDCC) Jani-Pekka Kainulainen (IDCC) Hilary Frank (UNIVBRIS)	Updated section 5. Added Section 3 requirements. Added FCC 6GHz unlicensed spectrum ruling information. LiFi-specific positioning requirements are added. Some of the acronym-related issues are resolved. ToC table is updated – new section numberings. Updated Section 3: Added figures 33 and 34. Added more details to Section 3.3. Section 3.2 MC requirements are placed in table Further Section 3.1 updates (3.1.1, 3.1.2 and 3.1.3). Added Section 3.1.1. Section 3.3 content has been moved to section 6.
0.94	17.06.2020	Tezcan Cogalan (UEDIN) Antonio Garcia (ACC)	Resolved referencing issue for the figures. Resolved bibliography related issues.
0.95	18.06.2020	Tezcan Cogalan (UEDIN) Antonio Garcia (ACC)	Full draft for official internal review
0.96	18.06.2020	Jesús Gutiérrez (IHP)	Revision of the full draft
0.97	19.06.2020	Tezcan Cogalan (UEDIN)	UEDIN's review comments/modifications are merged with IHP's full draft revision.
0.97	22.06.2020	Mir Ghoraishi (GIGASYS)	Overall revision of the full draft
0.98	26.06.2020	Tezcan Cogalan (UEDIN)	Reference related issues are resolved.
0.98	07.07.2020	Mir Ghoraishi (GIGASYS)	Review of the Section 6
0.99	07.07.2020	Antonio Garcia (ACC)	Merging/Resolution of external reviews
1.0	24.07.2020	Antonio Garcia (ACC) Teezcan Cogalan (UEDIN) Mir Ghoraishi (GIGASYS) Jesus Terran (IHP)	Final version for upload to EU Portal

Table of Contents

List of Figures

List of Tables

1 Introduction

This deliverable, D3.1, is a report on the first activities in 5G-CLARITY WP3 "Control and User Plane" which is titled as "State-of-the-art review and initial design of the integrated 5GNR/Wi-Fi/LiFi (5GNR: 5G New Radio) network frameworks on coexistence, multi-connectivity, resource management and positioning". According to the Description of Work (DoW), D3.1 intends to introduce the state-of-the-art technologies on integrated network coexistence, multi-connectivity, resource management and positioning. It also describes the initial design of the integrated 5GNR/Wi-Fi/LiFi network frameworks that provides, i) coexistence and cooperation between private and public networks operating in licensed as well as unlicensed bands; ii) multi-connectivity to different Wireless Access Technologies (WATs); iii) enhancements on aggregated system area capacity through intelligent resource management; and iv) cm-accuracy on indoor positioning.

1.1 WP3 overview

5G-CLARITY WP3 aims to develop the user and control plane framework that enables coexistence of the heterogeneous 5GNR/Wi-Fi/LiFi network. The relation of WP3 with other 5G-CLARITY Work Packages is depicted in Figure 1.1. WP3 focuses on the design and development of a multi-connectivity framework, including interfaces, signalling, scheduling and Radio Resource Management (RRM) that integrates 5GNR, Wi-Fi and LiFi, while providing added value services like coexistence between public and private networks, and indoor positioning with high accuracy. The output of WP3 is directly fed to WP5 "Integration, Experimentation, Proof-of-Concept and Demonstration", and works closely related to the activities of WP4 "Management Plane" looking at the management plane aspects to deliver management, control and user plane designed aligned to the use cases, requirements and architecture defined in WP2 "Scenario Description, Architecture and Requirements".

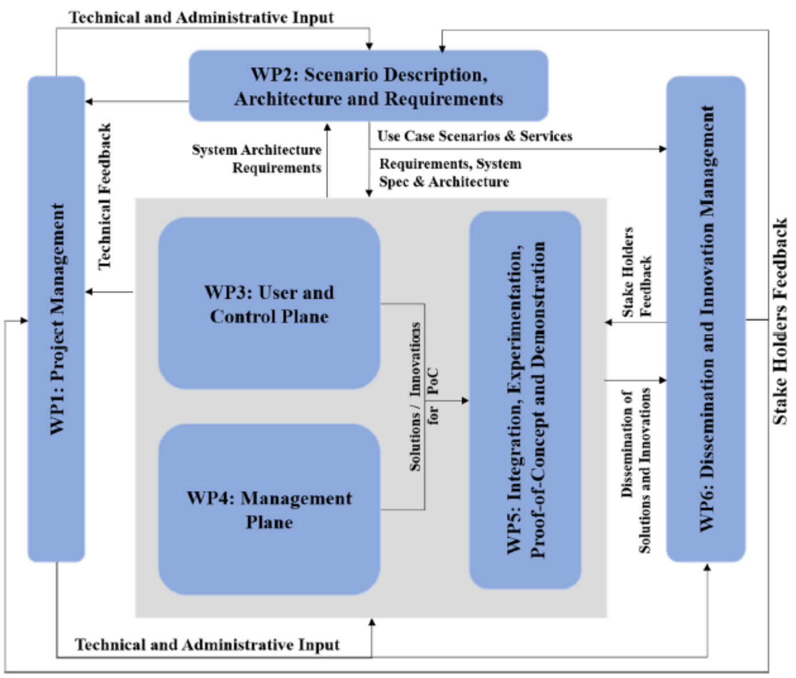


Figure 1.1: 5G-CLARITY work package structure

The main objectives of WP3, mapped from the DoW are as follows:

- O3.1. Design and evaluate a user and control plane framework of an indoor private 5GNR/Wi-Fi/LiFi network that coexists with public networks operating in licensed bands and with technologies operating in unlicensed bands.

- O3.2. Design and evaluate a multi-connectivity framework that integrates 5GNR/Wi-Fi/LiFi user and control plane to achieve:
    - a minimum User Equipment (UE) application layer data rate of 1 Gbps.
    - a maximum air interface latency (round trip) of 1 ms.
    - a minimum air interface reliability of 99.9999%.
    - a maximum handover time between WATs of 5 ms.
- O3.3. Design and verify a user and control plane framework of the indoor private 5GNR/Wi-Fi/LiFi network that provides a minimum aggregate system area capacity of 500 Mbps/m^2 through smart Radio Resource Management (RRM) algorithms and SDN platform.
- O3.4. Design and evaluate a user and control plane framework of the private 5GNR/Wi-Fi/LiFi heterogeneous network that achieves indoor localization capability of:
    - a maximum of 1 cm accuracy.
    - a minimum of 99% submeter accuracy.

WP3 is articulated by means of four main tasks as follows:

- **Task 3.1**: "Spectrum sharing framework between the private 5GNR/Wi-Fi/LiFi network and other private/public networks." The aim of this task is to design a user and control plane framework of the integrated private 5GNR/Wi-Fi/LiFi network with functionalities so that:

    i) the integrated private 5GNR/Wi-Fi/LiFi network can coexist and cooperate with public networks

    ii) the integrated private 5GNR/Wi-Fi/LiFi network can operate in licensed and unlicensed bands.

  The specific work carried out in this task will include:

    a. Design and develop a single control plane framework that can be used by any type of WAT;

    b. Develop (or improve the existing) signalling interfaces between different WATs such as 5GNR/Wi-Fi/LiFi.

- **Task 3.2**: "Mobility and multi-connectivity protocols, SDN controllers, and network element agents for evolved eMBB and URLLC services." The scope of this task is to design and develop a RAN architecture that supports integration of the latest generation of Wi-Fi (802.11ax) and LiFi (802.11bb) technologies with the future (>R16) 5G architectures. The designed RAN architecture will allow aggregation of 5G, Wi-Fi and LiFi air interfaces which in turn provide multi-connection to different WATs and enhances the communication service, i.e. throughput, latency, reliability. The designed RAN architecture will also enable employment of smart resource allocation algorithms through SDN controllers that schedule uplink and downlink traffic to the most favourable channels.

  This functionality allows reliable transmission and reduced air interface latency. The specific work carried out in this task will include:

    a. Develop a multi-connectivity framework to aggregate 5G, Wi-Fi and LiFi air interfaces

    b. Development of an SDN controller that schedules data traffic to different/combined WATs

    c. Evaluation of the multi-connectivity framework performance on achievable data rate, reliability and latency.

- **Task 3.3**: "Integrated 5GNR/Wi-Fi/LiFi scheduling and radio resource management." This task will investigate the network architecture and RRM algorithms required to enhance aggregated system area capacity. Besides KPIs considered for a single user in T3.2, the area spectral efficiency performance of the integrated 5GNR/Wi-Fi/LiFi network is expected to provide insights on achievable user/device connection density.

The work carried out in T3.3 will include:

a. Investigation of number of Wi-Fi/LiFi Access Points (APs) that are needed to enhance network coverage as well as area spectral efficiency

b. Development of UE-AP association algorithms for the multi-connectivity framework

c. Development of an SDN intelligence interface selection that conducts vertical/horizontal handover and load balancing algorithms in hybrid RF/LiFi networks

d. Development of learning-based radio and computing resource management algorithms that make use of the SDN controller provided in T3.2

e. Simulation-based aggregate system area capacity performance evaluation of the indoor private 5GNR/Wi-Fi/LiFi network

- **Task 3.4**: "Enhanced indoor positioning through HetWAT and related data/control plane developments." The scope of this task is to demonstrate the indoor positioning accuracy of the integrated 5GNR/Wi-Fi/LiFi network. Improving the positioning accuracy has already been considered as a study item by 3GPP for RF based technologies. In this task, LiFi and mmWave will be used to further enhance the indoor localization capabilities of 5GNR/Wi-Fi networks. The work carried out in this task will include:

a. Development of indoor positioning algorithms that intelligently combine different WATs

b. Development of a LiFi AP for joint broadband data transmission and localization

c. Demonstration of indoor positioning accuracy and synchronization precision of the developed localization algorithms

d. Demonstration of sub-meter accuracy availability

1.2 Objective and scope of this document

D3.1 takes input from 5G-CLARITY D2.1 [1], provides output to WP2 (T2.2), WP3, WP4, WP5 and WP6, and marks the acceptance criteria to reach the project's milestone M3.1: "Initial design of integrated 5GNR/Wi-Fi/LiFi framework on coexistence, multi-connectivity, resource management and positioning prepared".

D3.1 introduces the state-of-the-art technologies on integrated network coexistence, multi-connectivity, resource management and positioning, and describes the initial design of the integrated 5GNR/Wi-Fi/LiFi network frameworks that provide:

- coexistence and cooperation between private and public networks operating in licensed as well as unlicensed bands
- multi-connectivity to different WATs
- enhancements on aggregated system area capacity through resource management
- cm-accuracy on indoor positioning

As can be seen from the description of the D3.1 and the structure of the main tasks contained in WP3, the current deliverable will analyse the state-of-the-art technologies associated to each of the four main tasks of WP3, establish the advancements that each main tasks will bring forward and propose the initial design choices available to each area and then propose the overall and integrated design of the control and user plane framework providing a joint and consistent view of it. This overall design will have to be done in parallel and in close collaboration with the activities in WP4 on management plane (majority of the project partners participate in both WPs) so that both WP3 and WP4 initial designs and preliminary architecture decisions can feed into the overall architecture of the 5G-CLARITY system in WP2.

1.3 Document structure

The rest of this document is structured as follows:

- Chapter 2: Integrated Network Coexistence. This chapter includes state of the art review, requirements and design choices related to this section.
- Chapter 3: Multi-Connectivity. This chapter includes state of the art review, requirements and design choices related to this section.
- Chapter 4: Resource Management. This chapter includes state of the art review, requirements and design choices related to this section.
- Chapter 5: Positioning. This chapter includes state of the art review, requirements and design choices related to this section.
- Chapter 6: Control/User Plane Integrated Design and Architecture. This chapter includes overall integrated design choices within a consistent architecture proposal hosting the control and user plane frameworks aligned with WP4 management plane framework counterpart.
- Chapter 7: Conclusions

2 Integrated Network Coexistence

2.1 State-of-the-art

Current LTE network deployments and, most particularly, the upcoming 5G ones, are undergoing key architectural changes based on new paradigms such as core network and radio access disaggregation, extreme densification, virtualisation and edge computing. The addition of the 5GNR radio interface, which is capable of delivering higher performance compared to the previous radio interfaces (GSM, UMTS, LTE) and capable of operating in newly allocated higher frequency bands (> 6GHz), is opening the usage to new spectrum resources to compensate, to a certain extent, the amount of spectrum needed to overcome the data capacity increase. However, leveraging and integrating legacy cellular radio interfaces and 5GNR with further additional technologies such as the traditional ones operating in unlicensed spectrum (Wi-Fi) and newer ones operating on visible light wavelengths (LiFi) are key to enable the aggregation of further spectrum.

2.1.1 Spectrum access regulatory types and bands

2.1.1.1 Regulatory types

Historically, access to localized spectrum licenses were issued for fixed PtP, temporary broadcast events, etc., but never for access to normal mobile service to end users and enterprises. Recently regulatory bodies have started to enable localized mobile licenses, which are suitable for covering enterprise sites or wide areas such as cities as discussed in Section 2.1.2.

In [2], a study on spectrum assignment within the context of the European Union, the categorisation of spectrum access types, including newer approaches such as Licensed Shared Access (LSA) and Dynamic Spectrum Access (DSA) were defined as indicated in Figure 2.1.

The majority of the spectrum bands defined in 3GPP (see Section 2.1.1.2) belong traditionally to Exclusive Individual Licenses normally assigned to MNOs as part of auctions or beauty contests in the different national jurisdictions. However, bands such as 3GPP LTE B46 (5150-5925 MHz) are License Exempt and can be used as part of licensed-assisted operation using Frame Structure Type 3 (see Section 2.1.5.2.1).

Since the categorisation above was made within European scope, other innovative shared access approaches such as the one discussed in section 2.1.7.3 were not included in the categorisation. In US the Citizens Broadband Radio Service (CBRS) shared access approach can be considered an enhanced approach combining spectrum access categories 1, 5 and 6 from Figure 2.1.

Type of spectrum access	Details and examples	General authorisation ^	Individual right of use ^	Collective use	Exclusive use	Users must notify or get licence	Regulator controls usage	Fees #	Charges ∞
1. Licence exempt	Open access for certified devices E.g. low power Wi-Fi, SRDs, mobile user equipment , VSAT users	★★★★★		✓	✖	✖	✖	✖	✖
2. Light licencing (nominal)	As above but licence or notification required. E.g. Some PMSE usage; radio amateurs; High power outdoor Wi-Fi	★★★★	★	✓	✖	✓	✖	✓ or ✖	✖
3. Light licensing (restrictive)	As above but includes individual frequency co-ordination and restrictions on number of users E.g. some SAP services; UK 1800 MHz DECT guard band	★★★	★★	✓	✓ or ✖	✓	✓	✓ or ✖	✓ or ✖
4. Private commons	The exclusive licensee gives access to its spectrum under specified conditions.	★★★	★★	✓	✖	✖	✖	✓	✓
5. Dynamic Spectrum Access (DSA)	Incumbent grants automated short term access for third party using database or sensing. E.g. TV white space	★★	★★★	✓	✖	✓ or ✖	✓ or ✖	✓ or ✖	✓ or ✖
6. Licensed shared access (LSA)	Access granted to a third party by an incumbent user, typically a government body.	★	★★★★	✓	✖	✓	✖	✓	✓
7. Exclusive individual licensing	Exclusive rights to specific portion of spectrum for individual user. E.g. mobile licences		★★★★★		✓	✓	✓	✓	✓

Figure 2.1: Definitions of different spectrum access types

Notes:
^ Star system indicates the characteristics of the licencing type. e.g. four stars for general authorisation and one star for individual rights of use indicates that Light licensing (nominal) is most similar to the general authorisation approach.
 # Payments designed to recover administrative costs
∞ Payments designed to distinguish between competing operators and increase spectrum efficiency e.g. payments made at spectrum auctions

2.1.1.2 Spectrum Bands Availability

2.1.1.2.1 4G

The latest list of operating E-UTRA (LTE) frequency bands can be found as defined in Table 5.5-1 of [3],. From [4] the most awarded LTE FDD spectrum frequency bands are 1800 MHz, 2.6 GHz, 800 MHz, 2100 MHz and 700 MHz. A full list is shown in Figure 2.2.

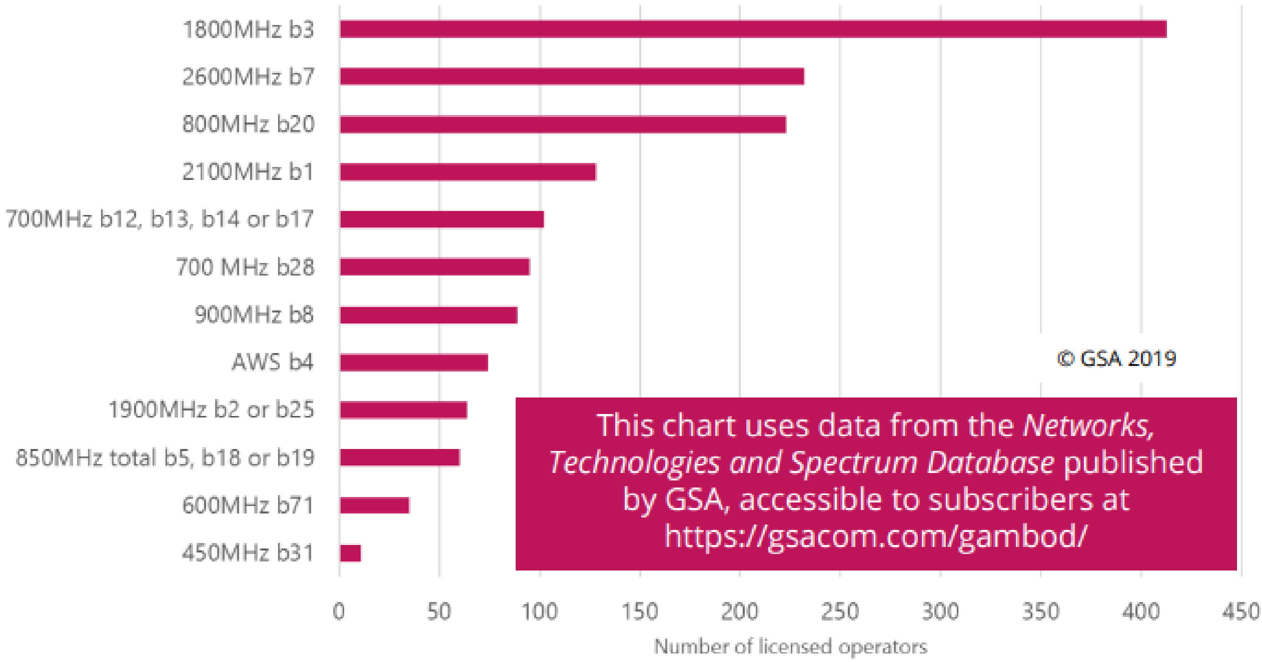


Figure 2.2: GSA Most licensed FDD LTE spectrum bands

These common FDD bands could become likely candidates for 5GNR DSA (see Section 2.1.4.1) to support migration strategies between LTE and 5GNR in low bands. From [5] a total of 147 LTE TDD networks were commercially launched in 73 countries by November 2018. Most of these TDD networks are using 1.9GHz, 2.3 GHz (B40), 2.6 GHz (B38/B41), 3.5 GHz (B42) and 3.7 GHz (B43). LTE TDD bands such as the ones with big spectrum bandwidths, i.e. B41, B42 or B43, will be likely to support some migration strategies between LTE and 5GNR enabled with 3GPP dynamic spectrum sharing approaches.

2.1.1.2.2 5GNR

The frequency bands for 5GNR are being separated into two different frequency ranges. The Frequency Range 1 (FR1) includes sub-6GHz frequency bands, some of which are bands traditionally used by previous standards such as LTE (Section 2.1.1.2.1), with an extension to cover potential new spectrum offerings from 410 MHz to 7125 MHz. The Frequency Range 2 (FR2) includes frequency bands from 24.25 GHz to 52.6 GHz. Bands in this mmWave range have shorter range but higher available bandwidth than bands in the FR1. The latest list of operating 5GNR FR1 and FR2 frequency bands are defined in Table 5.2-1 and Table 5.2-2 of [6]. According to [7], by the end of March 2020, 381 operators in 123 countries had announced investments in 5G. From those, a total of 70 operators in 40 countries had launched 5G services. In [5], the Global TD-LTE

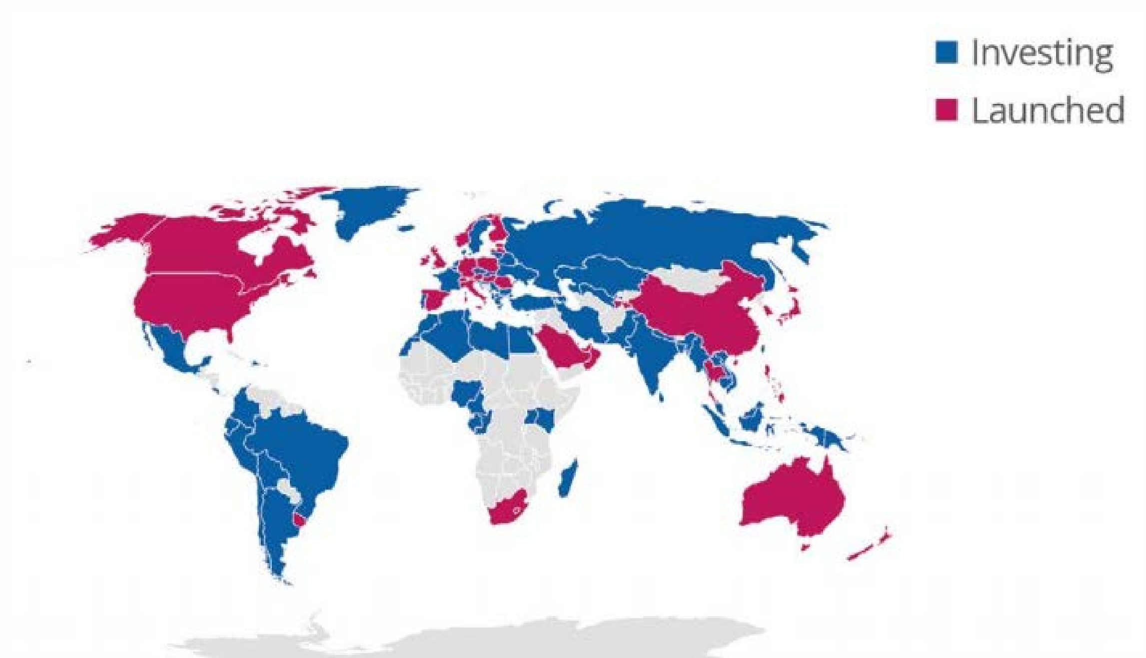


Figure 2.3: GSA Map of global operator investments in 5G (March 2020)

Interest group (GTI) reported that, by April 8, 2019, 13 operators had announced the launch of 5G mobile of Fixed Wireless Access (FWA) services, most of which would be using 3.5 GHz (n77/n78) and 2.6 GHz (n41) TDD spectrum.

In [8], the Global mobile Supplier´s Association (GSA) reported that C-Band spectrum (n77/n78 3300-4200 MHz) had been licensing to 64 operators for 5G. The lower end of this spectrum, initially allocated for former WiMAX and re-used for LTE as B42 (3400-3600 MHz) and B43 (3600-3800 MHz), is being also auctioned/refarmed for 5G use in many countries. C-Band spectrum within the sub-6GHz range has emerged as leading 5GNR pioneer band since it provides more spectrum availability than traditional mobile bands below 2.6 GHz while, at the same time, offering better propagation conditions than mmWave bands.

Out of the proposed low, mid and high 5GNR bands, within the scope of NPN and 5G-CLARITY, the following bands could be considered from the point of view of coexistence:

- Low Bands: small spectrum quantity (<20 MHz per license) but good propagation characteristics for macrocell deployments
- Mid Band (C-band): high spectrum quantity (100 MHz or more per license) with worse propagation characteristics than the low bands
- High Bands (mmWave): very high spectrum quantity (hundreds of MHz per license) with very bad propagation characteristics

According to the above description, low bands will have better indoor propagation for enterprise networks, but not enough bandwidth for data throughputs required in some NPN use cases and will therefore not make them ideal for NPN deployments. High bands can be very suitable for NPN, but their propagation characteristics will make them unlikely to be deployed with macrocells. Mid band (C-band) is probably the band that will most likely be used both outdoors for macrocell deployments and indoors for NPN deployments and will therefore require a more careful consideration on the coexistence and sharing issues between 2 different administrative domains. Therefore, the C-band should be the focus for 5G-CLARITY.

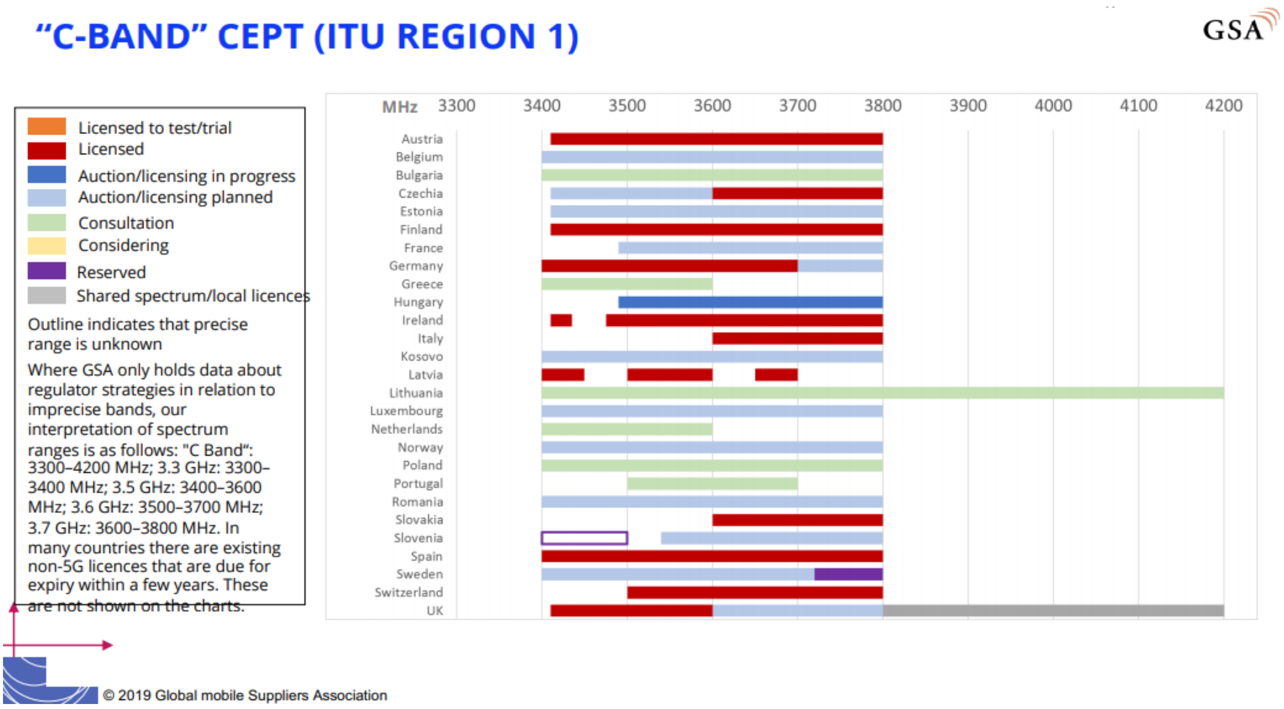


Figure 2.4: GSA status of C-Band in ITU Region 1 (CEPT)

As can be seen in Figure 2.4, the regulatory status in EU shows a strong focus for C-Band definition in n78 (the 5GNR block of former LTE B42 and B43) and to a lesser extend n77, indicating that the most likely spectrum that the ecosystem will support for initial 5GNR Small Cell platforms and NPNs in Europe will be n78. In terms of UE devices from [8], 35 5G devices have been announced explicitly supporting band n78 (11 CPE, 14 phones, 6 modules and 2 hotspots and 2 USB modems), while 21 5G devices have been announced explicitly supporting band n77 (8 CPE, 6 modules, 5 phones, 2 others).

Therefore 5G-CLARITY targets n78 as 5GNR spectrum to support the pilots described in [1] and the study/evaluation of coexistence issues and spectrum management from the mobile band angle.

2.1.1.2.3 Wi-Fi

Wi-Fi technology is standardized by the IEEE 802.11 group and has evolved into a family of physical layer technologies under a common MAC layer based on Carrier Sense Multiple Access-Collision Avoidance (CSMA-CA). IEEE 802.11 technologies operate on the ISM bands at 2.4 GHz, 5 GHz and the V-Band (60 GHz).

For the purpose of 5G-CLARITY we classify Wi-Fi technologies as the technologies that operate below 6 GHz (Sub-6) and those operating in the 60 GHz band (mmWave). Sub-6 Wi-Fi technologies will be considered in the private venue to deliver wireless access to 5G-CLARITY terminals, whereas Sub-6 and mmWave technologies will be considered mostly for positioning services.

Sub-6 Wi-Fi include the IEEE 802.11n, the IEEE 802.11ac and the IEEE 802.11ax technologies, which are also known commercially as Wi-Fi 4, Wi-Fi 5 and Wi-Fi 6, respectively. Table 2-1 provides a comparison of the physical layer of these three technologies, where the following evolutionary trends can be appreciated:

- Sub-6 IEEE 802.11 technologies were designed to operate in the 2.4 GHz and the 5 GHz bands, where the 2.4 GHz band has 60 MHz of effective bandwidth organized in 13 chunks of 20 MHz overlapping channels, and the 5 GHz band has 25 non-overlapping channels with 20 MHz carrier bandwidth. The 5 GHz band is therefore much more attractive to provide capacity as required in the private venues considered in 5G-CLARITY, although comes with specific challenges related to the radar coexistence in the UNII-2 band (Figure 2.5). Both IEEE 802.11n and IEEE 802.11ax can operate in the 2.4 GHz and 5 GHz bands, but IEEE 802.11ac only supports the 5 GHz band.

- A path to increase capacity used in the successive IEEE 802.11 Sub-6 technologies has been to increase carrier bandwidth by means of channel bonding techniques. Hence, IEEE 802.11n supports operation using the standard 20 MHz channel bandwidth or bonding 2 channels into a 40 MHz channel. IEEE 802.11ac and IEEE 802.11ax support bonding 4 chunks of 20 MHz channels into a single 80 MHz channel, bonding 8 chunks of 20 MHz channels into a single 160 MHz channel, or pairing two non-contiguous 80 MHz channels into a single 160 MHz channel. Notice though that the 80 and 160 MHz channel configurations are only possible in the 5 GHz band, as depicted in Figure 2.5. Channel bonding has also an impact on the channel access mechanisms used in IEEE 802.11. In particular, channel bonding does not imply using a single carrier spanning the whole channel bandwidth, but rather requires aggregating multiple single channel PHYs under a common MAC, where carrier sensing is performed independently in the underlying channels. Hence, while enhancing the capacity of a single AP, channel bonding poses challenges when different APs overlap with each other.
- MIMO has been instrumental in increasing the single link and system capacity of IEEE 802.11 technologies. IEEE 802.11n was the first technology to support single user MIMO (SU-MIMO) with up to 4 spatial streams, although this feature was rarely available in practice since terminals typically can only afford two separate antennas. To mitigate the antenna asymmetry between APs and terminals, IEEE 802.11ac introduced support for MU-MIMO in downlink and up to 8 spatial streams, which required 8 antennas in the AP to group transmissions towards up to 8 single antenna terminals. IEEE 802.11ax added MU-MIMO support in the uplink.
- A third avenue to enhance capacity has been a progressive increase in the maximum MCS supported by each technology, with IEEE 802.11n supporting up to 64 QAM, IEEE 802.11ac up to 256 QAM, and IEEE 802.11ax up to 1024 QAM. Obviously higher MCS requires a higher SNR and, therefore, the practical impact of such technologies as 1024 QAM in IEEE 802.11ac/ax is still uncertain.
- The combination of the previous enhancements results in maximum peak rate PHY capacities of 600 Mbps in IEEE 802.11n with 40 MHz and 4 spatial streams, 6.9 Gbps with 160 MHz and 8 spatial streams in IEEE 802.11ax and 9.6 Gbps with 160 MHz and 8 spatial streams in IEEE 802.11ax.
- Finally, it is worth highlighting that, in addition to an increase in the maximum MCS, a major novelty delivered in IEEE 802.11ax is the support for OFDMA, whereby the AP can schedule transmission towards multiple users into a single packet. Instead, previous Wi-Fi technologies occupy the full channel bandwidth for a single user in each packet transmission.

Table 2-1: Sub-6 Wi-Fi technologies

Feature	802.11n	802.11ac	802.11ax
Band	2.4 GHz, 5 GHz	5 GHz	2.4 GHz, 5 GHz
Channel BW	20, 40 MHz	20, 40, 80, 80+80, 160 MHz	20, 40, 80, 80+80, 160 MHz
MIMO	SU-MIMO	MU-MIMO DL	MU-MIMO DL+UL
Max PHY Rate	600 Mbps (40 MHz, 4 SS)	6.9 Gbps (160 MHz, 8 SS)	9.6 Gbps (160 MHz, 8 SS)
Max MCS	64 QAM	256 QAM	1024 QAM
Max Spatial Streams (SS)	4	8	8
Modulation	OFDM	OFDM	OFDMA

Besides improvements on the PHY layer, IEEE 802.11ax also provides several MAC and system level enhancements with respect to IEEE 802.11n and IEEE 802.11ac. The interested reader is referred to [9] for a detailed overview.

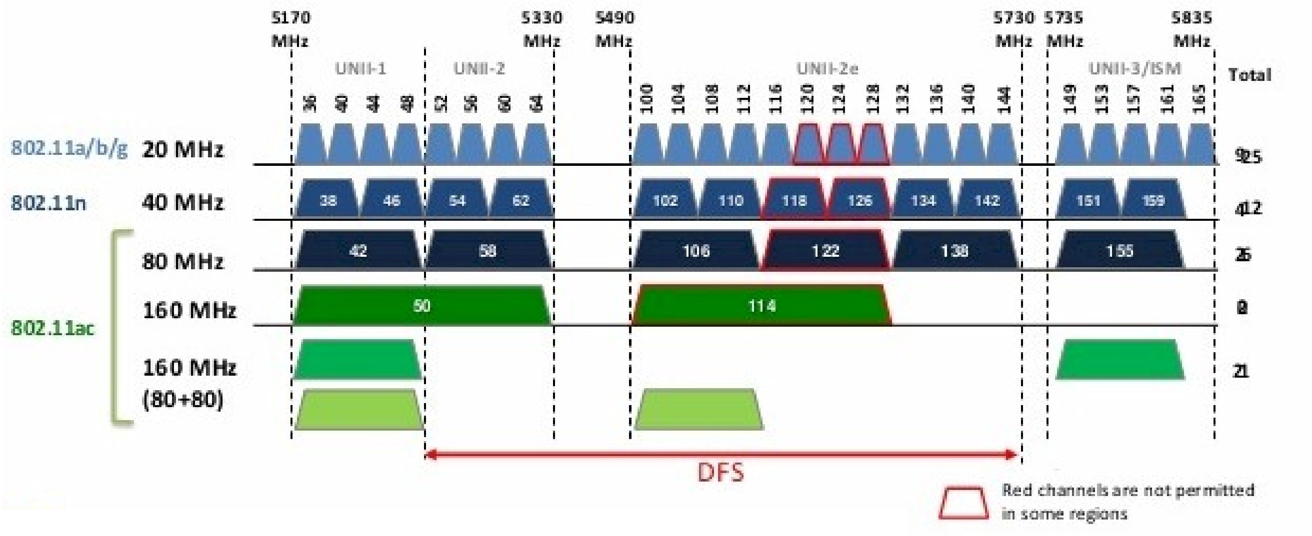


Figure 2.5: IEEE 802.11 channels in the 5 GHz band

While the IEEE 802.11n, IEEE 802.11ac and IEEE 802.11ax technologies constitute the basic Sub-6 Wi-Fi technologies that will be considered in 5G-CLARITY to provide wireless access to the private venue users, it is worth mentioning that the IEEE 802.11 group is standardizing a new technology named IEEE 802.11be. This technology will extend the use of Wi-Fi into the 6 GHz band, which was under consideration for ISM use by the FCC in the US [10]. On the April 23rd, 2020 FCC announced the adoption of rules that make 1200 MHz of spectrum in the 6 GHz band (5.925–7.125 GHz) available for unlicensed use in the US [11]. The FCC is authorizing two types of unlicensed operations in the 6 GHz band as shown in Figure 2.6 and Figure 2.7. First, they authorize unlicensed standard-power APs in the U-NII-5 and U-NII-7 bands through use of an Automated Frequency Coordination (AFC) system. This will permit operations at the same power levels already permitted in the 5 GHz U-NII-1 and U-NII-3 bands (5.150-5.250 GHz and 5.725-5.850 GHz bands, respectively), enabling synergistic use of both the 5 GHz and 6 GHz bands for promoting unlicensed broadband deployment while, at the same time, protecting incumbents users (6 GHz is comprised of allocations for Fixed Services, Mobile Services and FSS) across four sub-bands. Second, they open the entire 6 GHz band for unlicensed indoor low power APs. Client devices communicate using power levels that depend on the type of AP—either the standard-power or the indoor low-power AP—to which they are connected. The AFC System Framework (and the database) proposed by FCC is similar to the TV Whitespace and CBRS systems (for details on CBRS Shared Access see Section 2.1.7.3).

Device Class	Operating Bands	Maximum EIRP	Maximum EIRP Power Spectral Density
Standard-Power Access Point (AFC Controlled)	U-NII-5 (5.925-6.425 GHz) U-NII-7 (6.525-6.875 GHz)	36 dBm	23 dBm/MHz
Client Connected to Standard-Power Access Point		30 dBm	17 dBm/MHz
Low-Power Access Point (indoor only)	U-NII-5 (5.925-6.425 GHz) U-NII-6 (6.425-6.525 GHz) U-NII-7 (6.525-6.875 GHz) U-NII-8 (6.875-7.125 GHz)	30 dBm	5 dBm/MHz
Client Connected to Low-Power Access Point		24 dBm	-1 dBm/MHz

Figure 2.6: FCC expanded unlicensed use of the 6 GHz band

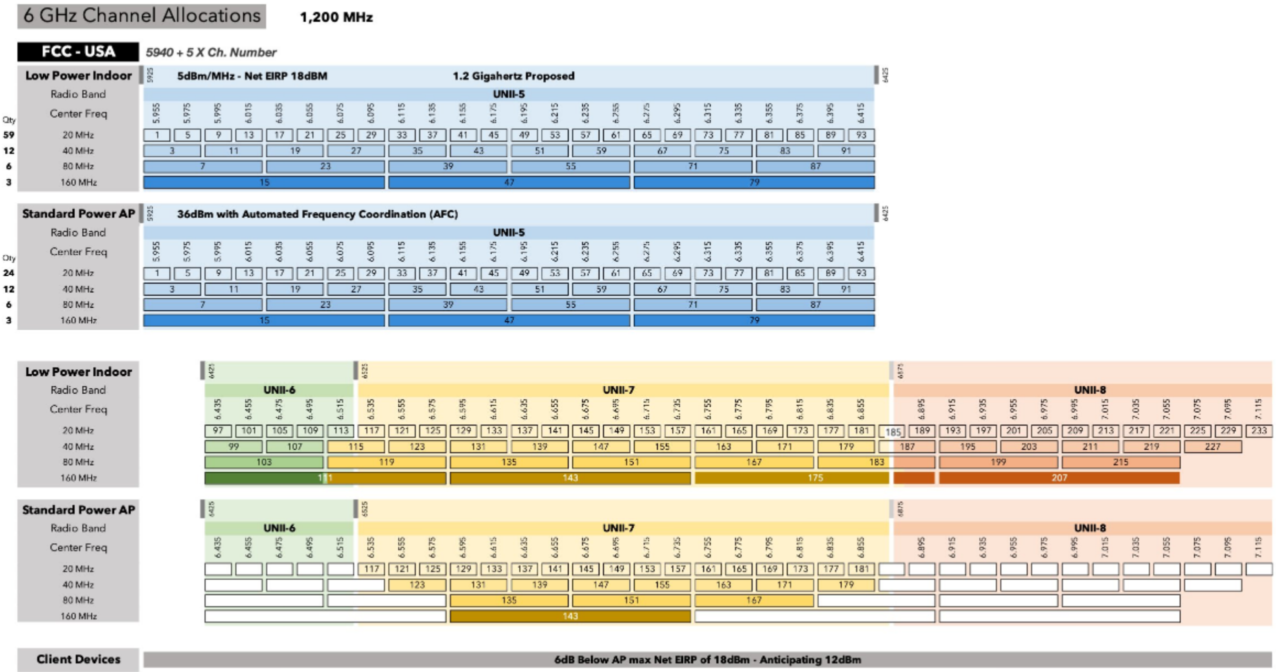


Figure 2.7: 6 GHz channel allocations for Wi-Fi

Given the still very early phase in the standardization process, the unlikely availability of IEEE 802.11be hardware modules during the execution of 5G-CLARITY and the uncertainty around the availability of the 6 GHz band in Europe, IEEE 802.11be will not be considered as a target technology for 5G-CLARITY project. This decision may be reviewed in the course of the project if the standardization and regulatory process advances fast enough.

The limited availability of crowded Sub-6 GHz spectrum and the massive bandwidth of unused spectrum at mmWave frequencies (which leads to the achievement of both very high throughput and low latency connectivity) has raised the interest of using mmWave bands for Wi-Fi when applied to 5G wireless systems [12], [13]. In contrast, a global unlicensed band exists at 57-64 GHz, being largely uncongested compared to that of Sub-6 public bands currently used for Wi-Fi.

The 60 GHz Wi-Fi, also known as Wireless Gigabit (WiGig) networks, are standardized with the IEEE 802.11ad standard. The IEEE 802.11ad standard was finished by the end of 2012. The communication distance at these frequencies is limited due to the high propagation loss. Additionally, obstructions like walls and doors substantially limit or completely prevent signal propagation. Rather than emitting signals in all directions, the communication is directed only in the direction towards the precise location of the other end of the link. This, together with the large available bandwidth at these frequencies, enables data transmission at gigabit speeds.

The 60 GHz band is divided in six channels, spaced at 2.16 GHz and providing 1.76 GHz of bandwidth each. The unlicensed spectrum at 60 GHz varies from country to country. This makes some of the these channels not available in some countries. The unlicensed spectrum and the channels in different countries are given in Figure 2.8.

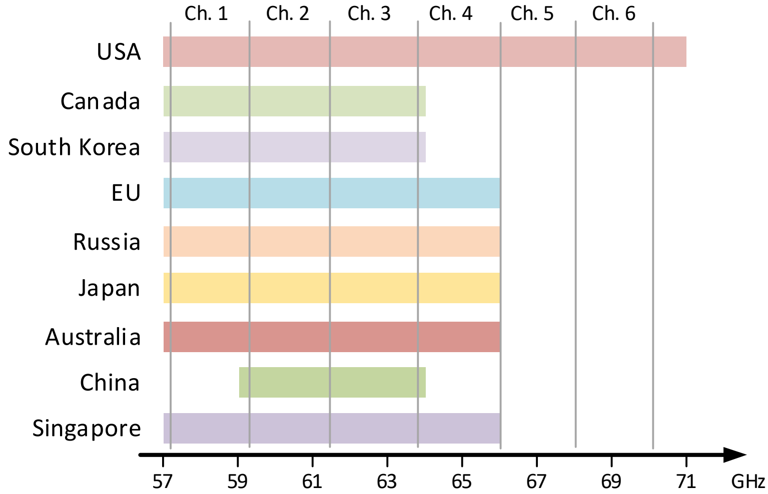


Figure 2.8: 60 GHz unlicensed bands in different countries and its channel allocations

IEEE 802.11ad defines both single carrier (SC) and orthogonal frequency division multiplexing (OFDM) modulations. The maximal theoretical data rate for is 4.620 Gbps for SC and 6.756 Gbps for OFDM modulation. The data is encoded using Low-Density Parity Check (LDPC) codes. The SC modulation coding schemes are mainly intended to be used in low power portable devices. The OFDM on the other hand, is used for achieving highest data transmission. Due to the high attenuation, high gain antennas are preferred in this band. Usually, phased antenna arrays are used in order to enable beam forming and beam steering. No MIMO support is envisioned in IEEE 802.11ad.

The upcoming IEEE 802.11ay is an enhancement of the current IEEE 802.11ad. It should allow up to 4 MIMO streams allowing bandwidths of 20-40 Gbps at maximal distances of up to 300-500 meters. It is likely that channel bonding and MU-MIMO will be also supported.

2.1.1.2.4 LiFi

The RF spectrum is only one part of the entire electromagnetic spectrum as shown in Figure 2.9. In LiFi, the optical spectrum, including both visible light (VL) and infra-red (IR), is used to carry information. Such a spectrum resource is plenty. The VL spectrum alone, which approximately crosses 400 THz to 790 THz, is more than 1000 times wider than the entire RF spectrum. Moreover, both VL spectrum and IR spectrum are unlicensed. In IEEE 802.11bb task group, where a LiFi standard could be released as early as 2021, the targeted band is in 380 nm to 5000 nm for both uplink and downlink operations [14].

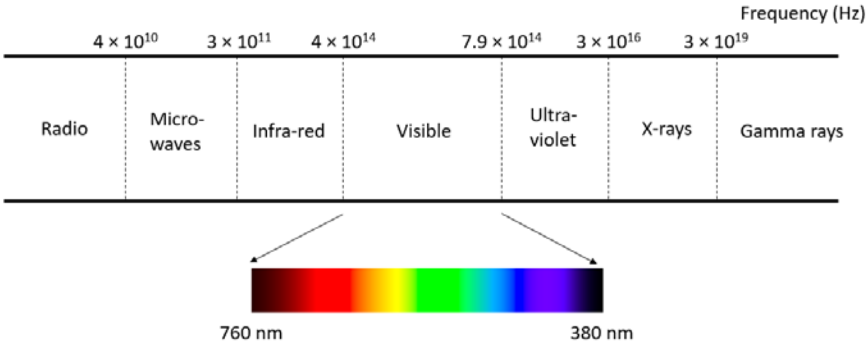


Figure 2.9: The electromagnetic spectrum

2.1.2 Mobile spectrum to enable Private Networks

Recently regulatory bodies have started to enable localized mobile licenses, which are suitable for covering enterprise sites or wide areas such as cities or campus. There are various models and practical examples as indicated in [15] and shown in Figure 2.10:

- Dedicated local licenses for specific areas or sites. Germany is releasing 3.7-3.8 GHz frequencies for private 5G networks at industrial sites.
- National spectrum allocations sub-leased by MNOs to enterprises operating in specific areas. This occurs in markets such as Finland and Australia.
- Spectrum-sharing models using "dynamic access" and a database-driven system for allocations such as the innovative US CBRS model [16].
- Secondary licensing of national MNO bands for private use where they are not being used by the main licensee. The UK has recently adopted this model.
- Indoor-only permissions for using bands that avoid long-range interference with incumbent users. The UK is adopting this model for 26 GHz.
- Release of previous "guard bands" for unlicensed or "lightly-licensed" use, such as some 1.8 GHz spectrum in the Netherlands.

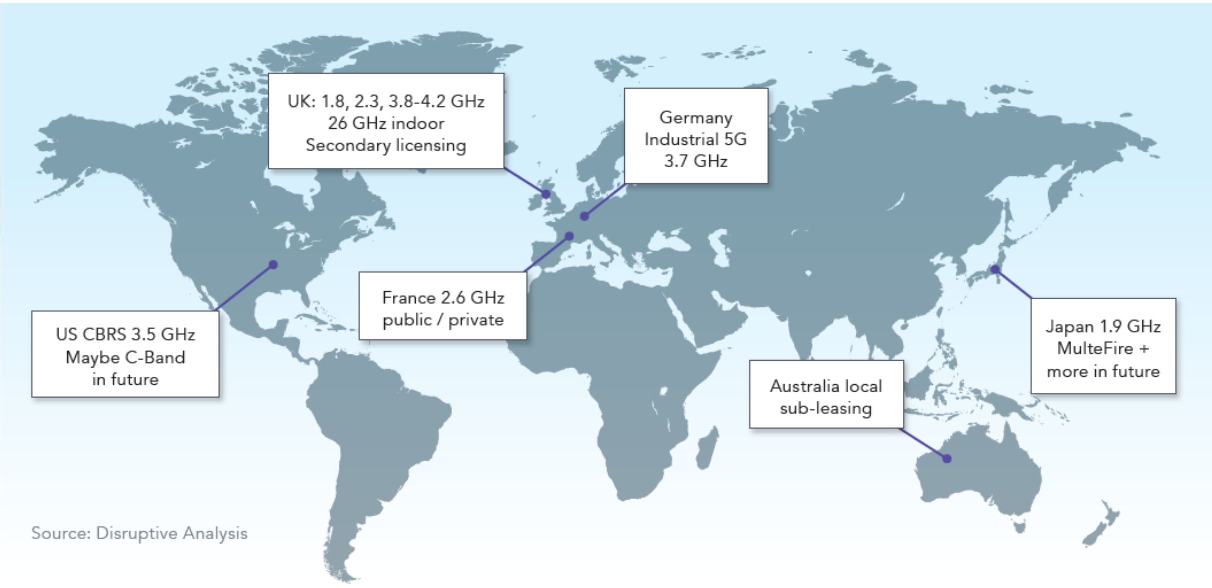


Figure 2.10: Regulators adopting localised mobile spectrum allocations

2.1.3 Network coexistence

2.1.3.1 4G

2.1.3.1.1 Internetwork coexistence

In [17], CEPT ECC discusses the interference that can occur when more than one TDD network operates in the same geographic area and in the same band if the networks are uncoordinated, i.e. if some equipment is transmitting while other equipment is receiving in the same time-slots. As shown in Figure 2.11, the BS-UE interference (yellow arrows) happens in all cases and is handled as part of the standards whereas UE-UE and BS-BS interference (orange arrows) happens in the case of unsynchronised TDD networks.

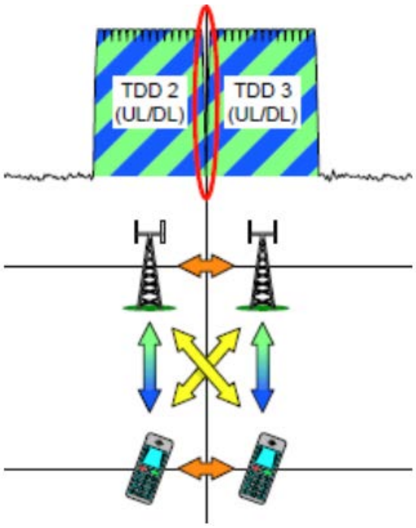


Figure 2.11: Adjacent network interference scenarios for unsynchronised TDD

In that case, guard band and/or additional filtering and/or other techniques often can be used in order to reduce interference. However, in the case of TDD-TDD coexistence, another way to avoid all BS-BS and UE-UE interference without using guard band and specific filtering is to synchronise BSs so that they roughly transmit and receive in the same time slots. More precisely, synchronised operation means that no simultaneous uplink and downlink occur between any pairs of cells which may interfere with each other in the same band. The word "synchronisation" is often used in several other contexts (e.g. frequency synchronisation for FDD networks, BS-UE synchronisation, etc.), and this CEPT ECC Report focuses on phase/time synchronisation for interference-mitigation purposes, which involves different techniques. Since synchronised operation reduces UE-UE and eNB-eNB interference compared to unsynchronised operation, different regulatory constraints (such as block edge masks) may apply to those two different situations. In [18], there are examples of different block edge masks for **synchronised TDD** and **unsynchronised TDD** operations. In the commercial LTE TDD 3.5 GHz deployment in Japan, the regulator enforced synchronised TDD in the licensing conditions (phase synchronisation and same TDD DL/UL ratio 2) for all four operators with awarded spectrum in order to avoid wasting spectrum by using guard bands.

Along the same lines as CEPT, in [5] GTI discusses the coexistence issues that multiple TDD networks might have if uncoordinated in the same geographical area. It is suggested that the best way to avoid interference is to synchronize neighbouring BSs to make them transmit and receive at the same time. There are three mechanisms which have been mostly standardized by 3GPP, including synchronization by Global Positioning System (GPS)/Global Navigation Satellite System (GNSS), synchronization over the backhaul network and over-the-air synchronization. Synchronization is not only needed for the cells operating in the same frequency, but also for the cells operating in the same band if the guard band is not sufficient. This way to avoid interference is not only suitable for multiple LTE TDD networks but also suitable for multiple 5G networks, which have the same interference as LTE TDD networks.

Regarding **TDD to FDD network coexistence**, according to CEPT, for avoiding BS to BS interference, two 5 MHz guard bands need to be reserved between TDD and FDD adjacent spectrum blocks with costly filters and careful site deployment. However, it is recommended that mixed TDD and FDD band plans are avoided to exclude difficult interference scenarios and inefficient spectrum use.

2.1.3.1.2 Intra-network coexistence

Within the group of typical Radio Resource Management (RRM) functions (e.g. Radio Bearer Control, Radio Admission Control, Dynamic Resource Allocation/Packet Scheduling, Connected Mobility & Control, Load Balancing, etc.) the most important one with regards to intra-network coexistence within the scope of Hetnet and single frequency layer operation is Inter-Cell Interference Coordination (ICIC) as described in [19], which is briefly described in this section.

ICIC has the task to manage radio resources such that inter-cell interference is kept under control particularly for the cases of cell edge UEs. ICIC mechanism includes a frequency domain component and time domain component. The frequency domain ICIC manages radio resource, notably the radio resource blocks, such that multiple cells coordinate use of frequency domain resources. For the time domain ICIC introduced in Release 10 (eICIC), subframe utilization across different cells are coordinated in time through backhaul signalling or OAM configuration of so called Almost Blank Subframe (ABS) patterns. The ABSs in an aggressor cell are used to protect resources in subframes in the victim cell receiving strong inter-cell interference. ABSs are subframes with reduced transmit power (including no transmission) on some physical channels and/or reduced activity. The eNB ensures backwards compatibility towards UEs by transmitting necessary control channels and physical signals as well as System Information. Patterns based on ABSs are signalled to the UE to restrict the UE measurement to specific subframes, called measurement resource restrictions. There are different patterns depending on the type of measured cell (serving or neighbour cell) and measurement type. Extending the coverage of a cell by means of connecting a UE to cell that is weaker than the strongest detected cell is referred to as cell range extension (CRE). With time domain ICIC, a CRE UE may continue to be served by a victim cell (i.e., the weaker cell) even while under strong interference from aggressor cells (i.e., the stronger cell). A UE under strong interference from aggressor cells may need to mitigate interference from the aggressor cells on some physical channels and signals in order to receive data from serving cell or to detect the weak cells or to perform measurements on the weak cells. In Release 11 further enhanced ICIC (feICIC) enabled interference handling by the UE through inter-cell interference cancellation for control signals, enabling even further CRE. The main enhancement in 3GPP Release 11 was to provide the UE with Cell specific Reference Symbol (CRS) assistance information of the aggressor cells in order to aid the UE to mitigate this interference. To define proper CRS-based measurements and improve demodulation for time domain ICIC with large bias (e.g. 9 dB), it was necessary to define signalling support indicating which neighbour cells have ABS configured.

2.1.3.2 5G

2.1.3.2.1 Inter-network coexistence

In [20], CEPT ECC sought to support Administrations in setting up the synchronisation frameworks at national level for the introduction of 5GNR in the 3400-3800 MHz band in a multi-operator environment leveraging on the synchronised, unsynchronised and semi-synchronised modes. That Report extended the contents in previous ECC Report 216 [17] and in ECC Report 281 [21] as discussed in Section 2.1.3.1 to account for the following new aspects:

- 5GNR new frame structures bring new compatibility and performance aspects to be considered in the case of synchronised operation between 5GNR and LTE-TDD, which make it desirable to also consider unsynchronised operation.
- The adoption of Active Antenna System (AAS) technology to Mobile/Fixed Communications Network (MFCN) base stations brings new challenges for unsynchronised operation (in terms of cost-effectiveness and spectrum efficiency of the Least Restrictive Technical Condition's implementation), which makes it desirable to consider synchronised operation.
- Semi-synchronised operation is a new mode of operation that was not studied previously.

Different interference scenarios may occur when two TDD networks are deployed in blocks within the same band (including the co-channel interference and the adjacent channel interference). Cross link interference (CLI) will occur when simultaneous transmissions in uplink (UL) and downlink (DL) take place in different TDD networks (i.e. one BS (or MS) belonging to one network transmits while another BS (or MS) belonging to the other network receives (this is called "simultaneous UL/DL transmissions" throughout the CEPT Report). Simultaneous UL/DL transmissions do not take place in synchronised operation, but only in unsynchronised and semi-synchronised operations.

Figure 2.12 illustrates the interference scenarios for simultaneous UL/DL transmissions: the green arrows represent the desired links, while the potential interference is represented by the yellow arrows. BS-MS interference happens in all cases (FDD and TDD, whether synchronised or not) and is handled as part of the standards. MS-MS and BS-BS interference in unsynchronised and semi-synchronised TDD networks are within are discussed in [18].

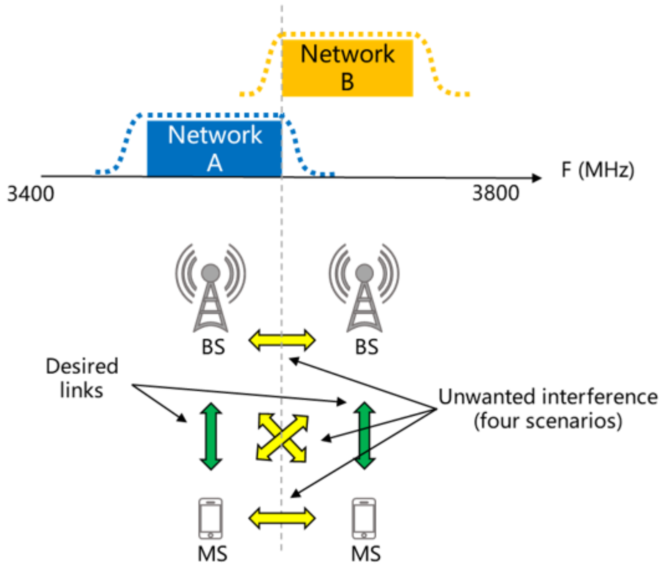


Figure 2.12: Interference scenarios in case of simultaneous UL/DL transmissions in MFCN TDD networks

Synchronised operation

In order to deploy synchronised TDD mobile networks in a multi-operator scenario, operators need to reach agreement on:

- A common phase-clock reference (e.g. UTC - Coordinated Universal Time) and accuracy / performance constraint that depend on the underlying technology (see Figure 2.13).
- Permanent monitoring of the agreed clock source. When losing the primary reference time clock (PRTC) equipment may continue operation for a period of time ("holdover period") that has to be agreed and which depends on the quality of the local oscillator in the BS and on the wireless network accuracy requirement. If the PRTC is lost for a duration longer than the holdover period, the system shall no longer be considered in synchronised operation and may start interfering other channels, and therefore proper action shall be taken (e.g. the BS shall be shut down until the PRTC is recovered).
- A frame structure (including TDD DL/UL ratio and frame length) in order to avoid simultaneous UL/DL transmissions (guard periods may be different). The assessments in the ECC Report provide information on the implications associated with some specific but representative frame structures in terms of throughput performance, spectrum efficiency and latency.

The synchronisation requirements for the different TDD technologies, including 5GNR are depicted in Figure 2.13.

Technology	Parameter	
	Frequency accuracy relatively to the reference oscillator	Phase accuracy relatively to the reference clock
GSM, UMTS, WCDMA, LTE-FDD	50 ppb	N/A
LTE-TDD	50 ppb	±1.5 µs (for cell radius ≤ 3 km)
	50 ppb	±5 µs (for cell radius > 3 km)
5G-NR	50 ppb	±1.5 µs

Figure 2.13: Frequency and phase synchronisation requirements for different MFCN technologies [20]

In [20], the baseline and transition region out of block power limits for synchronised operation of MFCN BSs are defined. ECC baseline accounts for the fact that BS-BS and MS-MS interference scenarios do not take place in case of synchronised operation. ECC baseline regulatory limit does not introduce additional constraints compared to the spectrum emission mask as defined by the standards.

The purpose of synchronised operation is to prevent BS-BS and MS-MS interference scenarios. Synchronised operation avoids performance degradation due to such interference without requiring additional mitigation techniques such as additional filtering, inter-operator guard bands or geographical separation between BSs.

Unsynchronised operation

The unsynchronised operation refers to the general case where neither time synchronisation between operators' MFCNs nor inter-operator frame alignment is implemented. ECC has defined the restricted baseline out of block power limit for unsynchronised and semi-synchronised operation of MFCN BSs.

Semi-synchronised operation

The semi-synchronised operation corresponds to the case where part of the frame is consistent with synchronised operation, while the remaining portion of the frame is consistent with unsynchronised operation. This requires the adoption of a frame structure for all TDD networks involved, including slots where the UL/DL direction is not specified, as well as synchronising the beginning of the frame across all networks. Semi-synchronised operation is therefore a mode of operation similar to synchronised operation, with the exception that the frame structure alignment is relaxed to allow some controlled degree of flexibility at the expense of some additional interference that can be controlled to some extent.

In [20], CEPT assesses the impat of a several 5GNR frame structures on spectrum efficiency, UL/DL throughput and latency. The analysis takes into account "LTE compatible" 5GNR frame structures, suitable for the cross-technology synchronised operation between a 5GNR and LTE-TDD networks. With reference to the synchronised operation of 5GNR BSs and LTE-TDD BSs, every LTE-TDD frame configuration has at least one compatible 5GNR equivalent configuration. The 5GNR TDD pattern should be based on the following sequence of DL, UL and special slots: "DDDSUUDDDD". Two example variants may be considered:

- Variant 1 (Figure 2.14): non-zero frame start offset between LTE-TDD and 5GNR, e.g. "DDDDDDDSUU".
- Variant 2 (Figure 2.15): LTE-TDD and 5GNR have an aligned frame start, e.g. "DDDSUUDDDD";

These variants, with 30 kHz subcarrier spacing (SCS) can be aligned to LTE-TDD "DSUDD" frame structure with 15 kHz SCS (LTE-TDD frame configuration #2). There should also be a compatible structure for the symbols within the LTE-TDD "S" sub-frame.

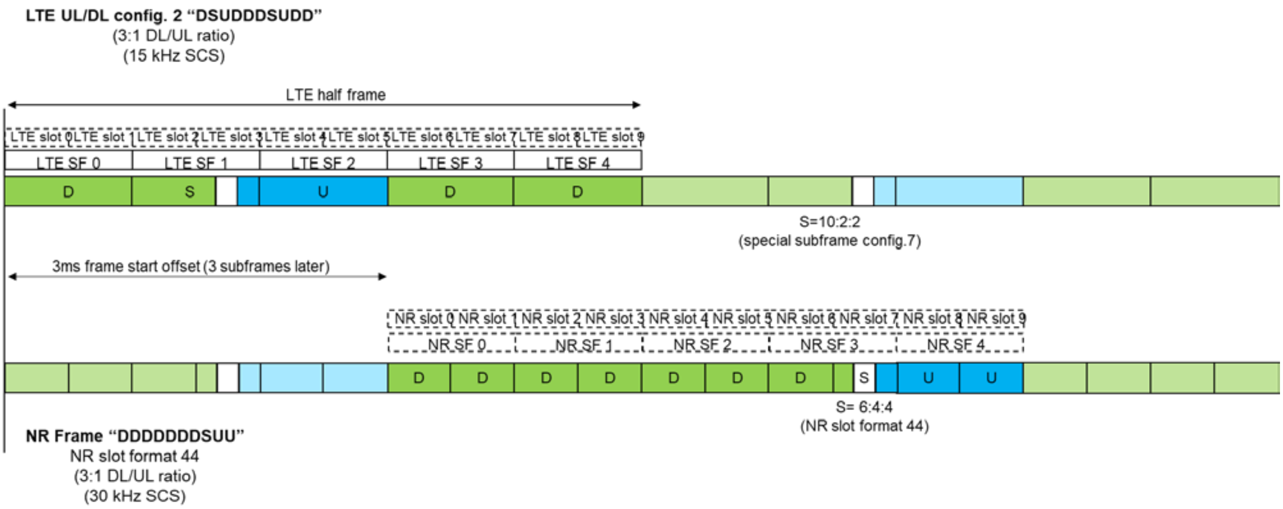


Figure 2.14: Variant 1 - Synchronised operation of 5GNR ("DDDDDDDSUU" frame) and LTE-TDD ("DSUDD" frame)

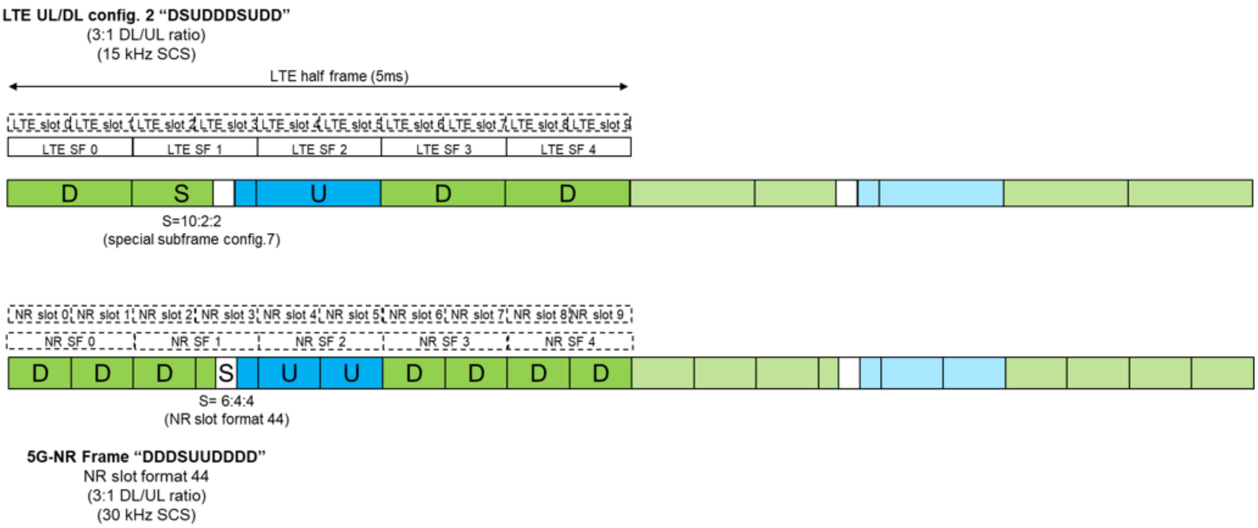


Figure 2.15: Variant 2 - Synchronised operation of 5GNR ("DDDSUUDDDD" frame) and LTE-TDD ("DSUDD" frame)

2.1.3.2.2 Inter-network coexistence – Remote Interference Management (RIM) and Cross Link Interference (CLI)

The 5GNR core RF requirements in 3GPP Release 15 were derived with the assumption of synchronised operation between two TDD systems. This follows the same approach adopted during LTE-TDD requirements specification. In 3GPP TSG RAN1, in case of synchronised operation of multiple TDD networks on adjacent channels, no coexistence issue due to adjacent channel interference among TDD networks was considered. The tools that RAN1 sought to mitigate BS-BS and MS-MS interference were sufficient guard bands, sufficient geographical separation, sufficient physical isolation (such as outdoor to indoor propagation isolation), or applicable transmission power. When LTE-TDD is present and used in the same band as 5GNR then, depending on the scenario such as large cell vs. small cell deployments or on the geographical separation, sufficient physical isolation, restrictions on the transmission directions may be necessary between the LTE-TDD and 5GNR carriers to avoid the use of fixed guard bands. Likewise, similar restrictions on the transmission directions of 5GNR Macro BSs would be necessary between neighbour 5GNR networks in adjacent frequencies, although the constraints in terms of DL and UL patterns might be different than for coexistence with LTE-TDD. In [22], RAN4 investigated the adjacent channel coexistence effects arising when CLI or, more generically dynamic TDD, is operated in an aggressor network (see Figure 2.16). This would also effectively be a case of unsynchronized operation.

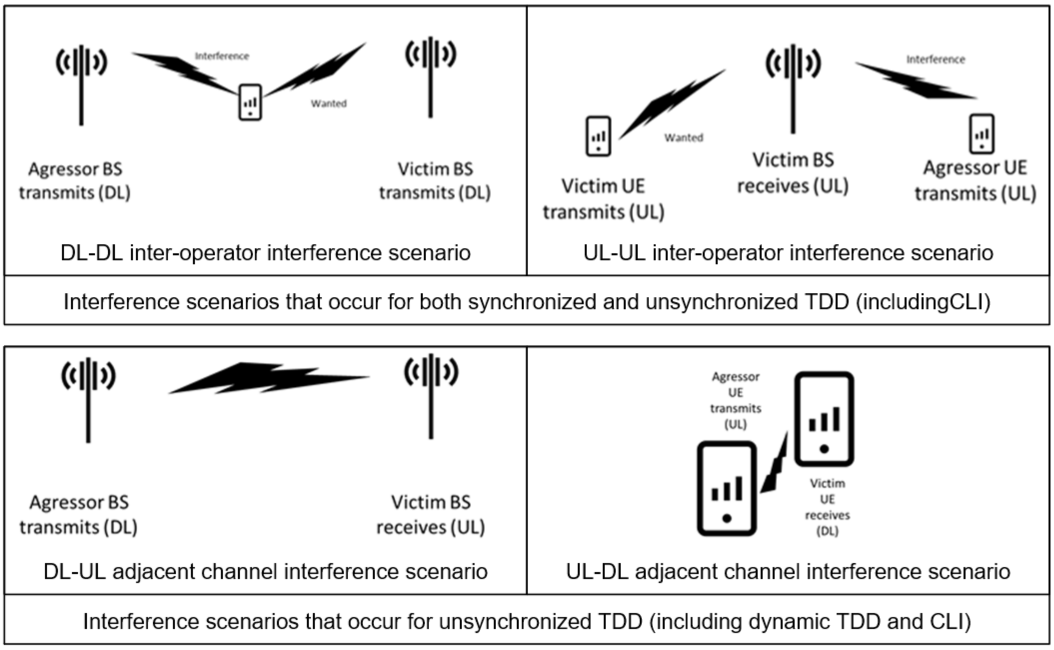


Figure 2.16: Dynamic TDD adjacent interference scenarios [22]

The recommendations of the study for 5GNR FR1 and FR2 (See Section 2.1.1.2.2 for definition of FR1 and FR2) were as follows:

- FR1
  - Macro-to-Macro scenario: performance degradation was observed from the BS-to-BS interference for macro-macro scenario, which suggests that dynamic TDD should not be operated in such scenarios.
  - Indoor scenarios (Indoor-to-Macro and Indoor-to-Indoor): Performance degradations were not observed from operating dynamic TDD between an indoor network and a macro network and vice versa if there is enough isolation between them. No significant impact from operating dynamic TDD for the indoor scenario was observed as long as the BS and UE powers are similar and the operators co-ordinate so that base station positions are offset. If higher BS power is assumed, some throughput degradation in the indoor scenario was observed due to BS to BS interference. The observations imply that dynamic TDD can be used in indoors as long as care is taken.
- FR2
  - Macro-to-Macro scenario: Some performance degradation was observed from the BS-to-BS interference for macro-macro scenario. The differences in the simulation results imply that operating dynamic TDD in this scenario without impact to neighbour network may be deployment dependent and requires at least careful planning and collaboration between operators to avoid performance impact.
  - Indoor scenarios (Indoor-to-Macro and Indoor-to-Indoor): Performance degradations were not observed from operating dynamic TDD between an indoor network and a macro network if there is enough isolation between them. Results suggested that to avoid degradation, careful layout and parameterization are necessary for indoor to indoor scenario. Overall, the observations imply that dynamic TDD can be used indoors if care is taken.

- Micro-to-Micro scenario: in this case, the differences in the simulation results imply that to avoid BS to BS interference, operators may need to consider the proximity of micro BS in the same area. Overall, the observations imply that dynamic TDD can be used in certain micro deployments if care is taken.

In [23] 3GPP specifies Remote Interference (RIM) and Cross-Link Interference Management (CLI) as discussed below.

Remote Interference Management – RIM

The atmospheric ducting phenomenon, caused by lower densities at higher altitudes in the Earth's atmosphere, causes a reduced refractive index, causing the signals to bend back towards the Earth. A signal trapped in the atmospheric duct can reach distances far greater than normal. In TDD networks with the same UL/DL slot configuration, and in the absence of atmospheric ducting, a guard period is used to avoid the interference between UL and DL transmissions in different cells. However, when the atmospheric ducting phenomenon happens, radio signals can travel a relatively long distance, and the propagation delay exceeds the guard period. Consequently, the DL signals of an aggressor cell can interfere with the UL signals of a victim cell that is far away from the aggressor. Such interference is termed as remote interference. The further the aggressor to the victim is, the more UL symbols of the victim will be impacted. To mitigate remote interference, the network enables RIM frameworks for coordination between victim and aggressor gNBs. The coordination communication in RIM frameworks can be wireless or backhaul-based. The backhaul-based RIM framework uses a combination of wireless and backhaul communication, while in the wireless framework, the communication is purely wireless. In both frameworks, all gNBs in a victim set simultaneously transmit an identical RIM reference signal carrying the victim set ID over the air. In both frameworks, upon realizing that the atmospheric ducting has disappeared, the victim gNBs stop transmitting the RIM reference signal.

Cross-Link Interference Management – CLI

UL transmission in one cell may interfere with DL reception in another cell, when different TDD DL/UL patterns are used between neighbouring cells. This is referred as CLI. This is in practice what happens for the internetwork coexistence for unsynchronised/semi-synchronised operation as described in Section 2.1.3.2.1. To mitigate the CLI, the network signalling enables the involved gNBs to exchange and coordinate their intended TDD DL-UL configurations over Xn and F1 interfaces as described in [24] and [25]. Based on the information exchanged, a receiving gNB can adjust its transmission pattern to avoid (causing) the CLI. Moreover, to support flexible resource adaptation for TDD cells, the victim UEs can be configured to perform CLI measurements.

2.1.3.3 Wi-Fi

Coexistence between overlapping Wi-Fi networks administered by different entities is a well-known problem referred to as Overlapping Basic Service Sets (OBSS) problem in the industry, where a BSS is the technical term used to refer to a Wi-Fi network composed of a single AP and a set of associated terminals. OBSS APs share the same spectrum and compete to access the channel using the CSMA-CA mechanism defined in Wi-Fi, however performance is degraded in these environments due to the hidden node and exposed node problems. The hidden node problem arises when terminals use too high Carrier Sense Threshold (CST) and cannot hear each other transmissions, for example between terminals associated to OBSSs. The exposed node problem happens when a terminal senses an ongoing transmission from another BSS and defers from transmitting, while the terminal’s transmission could have been received successfully by its own AP due to channel capture effect [26]; thus, in the exposed node problem the terminal uses too low CST. Both hidden and exposed node problems degrade overall system capacity in OBSS scenarios. In addition, the OBSS problems worsen as successive IEEE 802.11 technologies use higher carrier bandwidths by means of channel bonding, since less bandwidth in the ISM bands becomes available to the overlapping networks.

Several mechanisms have been proposed to mitigate the OBSS problems. For example, the BSS colour and Dynamic Sensitivity Control (DSC) mechanisms were proposed in IEEE 802.11ax to increase the overall area capacity in an OBSS situations. The BSS colour mechanism addresses the exposed node problem by having terminals and AP from the same BSS include a distinctive bit pattern in the PHY header of their transmissions. Thus, when sensing a transmission with a different BSS colour, terminals choose to ignore the Network Allocation Vector (NAV) included in the frame or retry the channel access immediately. The authors in [27] show that the BSS colour mechanism results in an increase of area capacity from 60 $Mbps/km^2$ to almost 80 $Mbps/km^2$ in a dense outdoor Wi-Fi deployment. The DSC mechanism attempts to address both the exposed and hidden node problem by varying the CST level used in each station within the BSS in a distributed manner. In particular, terminals within the BSS set their individual CST based on the power of the beacon they receive from the AP. The authors in [28] report a 20% throughput increase in a dense IEEE 802.11n deployment in an apartment building when using DSC and channel selection.

Using channel bonding can also result in additional coexistence problems when OBSSs are using different channel bonding configurations. For example, when IEEE 802.11ac bonds several channels one channel is selected as the primary channel while the others are considered secondary channels. Hence, when performing channel access the full carrier sense mechanism is only implemented in the primary channel, whereas a shorter carrier sense is performed in the secondary channel. The reason for this modified channel access mechanism is that bonded channels could become starved in an OBSS if a full access channel is performed in each of the component channels. Despite the optimized carrier sense mechanism defined in IEEE 802.11ac the authors in [29] demonstrate experimentally how a BSS network operating with an 80 MHz channel can be impacted in very severe ways by an overlapping BSS using only 20 or 40 MHz channels. If the primary channel of both OBSS networks coincides, the overall system throughput is split fairly among the BSSs according to their channel bandwidth. However, if the 20 MHz network operates not on the primary but on the secondary channel of the 80 MHz BSS, then the 80 MHz BSS starves. It is therefore critical in OBSS scenarios to coordinate the channel configuration of the different networks in order to achieve a fair system performance.

Finally, some studies proposed a solution for addressing the OBSS problem adding an SDN enabled coordination layer that can control OBSS APs. For example, in [30] the authors propose the Coordination framework for Open APs (COAP), which is an SDN interface that allows an Internet Service Provider (ISP) to control and configure remotely APs deployed in an apartment building that can interfere with each other. CoAP allows the ISP to observe the channel utilization of the various APs, throttle transmissions on some of them if need, as well as configuring channel and power of each AP. Centralized mechanisms have a great potential to mitigate OBSS problems but are difficult to deploy in practice if ISPs do not cooperate.

2.1.3.4 LiFi

In the ongoing IEEE 802.11bb task group, the amendment would specify changes to the IEEE 802.11 MAC on the overlapping basic service set (OBSS) detection and coexistence.

In comparison to the coexistence issues in RF-based techniques, the situation in LiFi-LiFi coexistence would be rather different. Since light travels in straight lines and does not propagate through opaque objects and walls, optical wireless signals can be confined within a desired space. This feature eliminates concerns over the intercepting and eavesdropping of the transmission, resulting in secure data links and networks. In addition, this feature can be exploited to eliminate interference between neighbouring cells. This is also the reason why LiFi-LiFi coexistence issues can easily be dealt with by arranging the geometry setup of multiple LiFi APs.

In addition to using separate geometry setup between multiple LiFi APs, there are other solutions to solve issues caused by multi LiFi coexistence. As noted, the usable spectrum is plenty for LiFi. Thus, the coexistence of multiple LiFi links, without having a degradation in throughput due to the interference, is possible with the use of optical filters. With this feature, the LiFi-XC system, which is a commercial product of PureLiFi, can deliver full duplex operation and have both uplink and downlink work simultaneously without interfering each other [31]. In addition to the use of optical filters, the use of low-pass or band-pass filters can also be utilised to minimise the effects from LiFi coexistence when different signal bandwidths are used.

For the coexistence of LiFi systems, which use the same or similar wavelength band and signal bandwidth, the co-channel interference can be dealt with by signal processing procedures. Multiple input multiple output (MIMO) techniques, which significantly improve the spectral efficiency, have been well developed in RF communication. MIMO techniques have also been studied and applied to optical wireless communication. Comparing to single input single output (SISO) system, MIMO system uses more than one transmitter and receiver. Excluding technique such as wavelength division multiplexing (WDM) which uses different wavelength for different channels, the light medium has the same characteristics in all channels within a MIMO system. Thus, co-channel interference will exist. However, a great effort of research has been taken on approaches dealing with such interference [32]. Such interference cancellation techniques can be applied in the LiFi-to-LiFi coexistence scenario to solve the potential issues.

2.1.4 4G-5G integration coexistence

2.1.4.1 4G-5G dynamic spectrum sharing

With regards to LTE TDD and 5G coexistence, as suggested in [5], the interference between TD-LTE and 5GNRcan be easily mitigated by a synchronized operation with aligned sub-frame configurations. For LTE TDD, DL/UL ratio 2 is the most widely used frame structure since it maps well on the internet browsing use case. This is a 3:1 DL/UL ratio with 5 ms DL/UL switching period. For 5GNR the frame structure 8:2 DL/UL ratio with 5 ms DL/UL switching period can be adopted for NR to synchronize with LTE TDD. Additionally, the slot format configuration in NR is very flexible, which can match all the configurations of special subframes in LTE. The only modification is to adjust the starting point of the frame as in Figure 2.17.

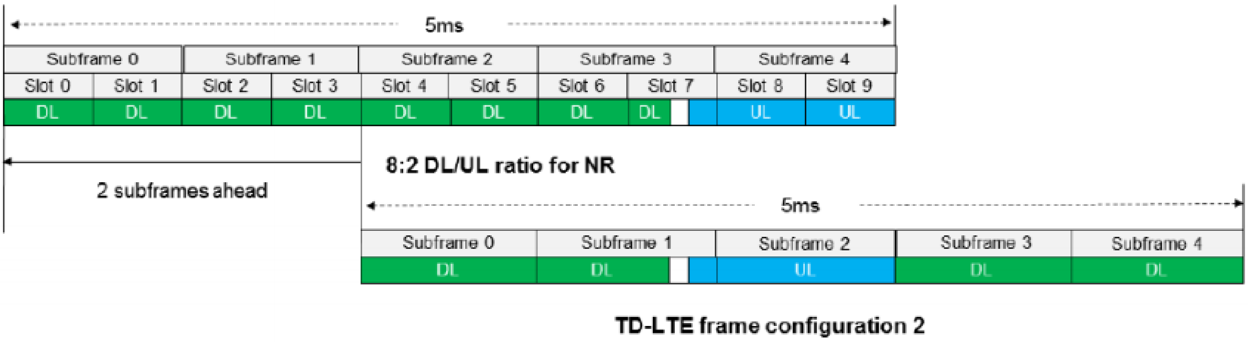


Figure 2.17: LTE TDD and 5GNRframe alignment

3GPP Release 16 with Dynamic Shared Spectrum (DSS) is also bringing additional support to enable a smooth migration from LTE to 5GNR by enabling the sharing of the same carrier to operators wanting to re-farm their spectrum step by step. 3GPP Release 16 increases the number of rate matching patterns in 5GNR to enable spectrum sharing when CA is used for LTE as described in 3GPP 38.213, 38.214 and 38.211.

2.1.4.2 4G-5G in-device coexistence

In-Device Coexistence (IDC) solution, as described in [19], is extended to address EN-DC operation. Only FDM solution, where the list of NR carriers suffering from IDC problems is signalled in IDC indication, is supported in the Release 16 version of the specifications. The requirement on RRM/RLM/CSI measurements in different phases of IDC interference defined in TS 36.300 is [33] and TS 38.101 apply.

2.1.5 Cellular and unlicensed (Wi-Fi) integration coexistence

As indicated in [34], most of the recent focus in the use of unlicensed spectrum (LAA, LTE-U, LWA or LWIP) for delivery of LTE services has been taken by License Assisted Access (LAA) approaches, with developments of LTE-U and LWA based ecosystems stalled. In [35], 37 operators are investing in LAA (8 with deployed/launched networks), 12 operators are investing in LTE-U (3 with deployed/launched networks) and 3 operators investing in LWA (1 with launched network). The state of the market does not seem to be favouring the LWA approach and beside state of the art discussion on LWA described in Section 3.1.1.3.1 the recommendation for 5G-CLARITY is not to support it, particularly within the scope of the 5GNR focus.

2.1.5.1 4G and Wi-Fi Core integration coexistence

2.1.5.1.1 LTE WLAN aggregation (LWA)

From [34], definition LWA (LTE WLAN Aggregation) is a 3GPP Release 13 standardised technology that aggregates carriers at the Radio Packet Data Convergence Protocol (PDCP) layer and uses the dual connectivity (DC) feature from 3GPP Release 12. LWA supports downlink aggregation. While in 3GPP Release 14, eLWA added uplink support. For a more detailed description of LWA see Section 3.1.1.3.1.

2.1.5.1.2 LTE WAN integration with IPSec tunnel (LWIP)

From [34] definition LWIP (LTE WAN Integration with IPSec Tunnel) is a 3GPP Release 13 feature similar to LWA but performs aggregation and switching at the IP layer. It has been designed not to require changes to existing WLAN infrastructure and can support uplink data transmission as well as downlink. For a more detailed description of LWIP see Section 3.1.1.3.2.

2.1.5.2 4G and Wi-Fi RAN level integration coexistence

2.1.5.2.1 LTE Licenced-Assisted Access (LTE-LAA) via Listen-Before-Talk (LBT)

In 3GPP TR36.889 [36], the coexistence between LAA and Wi-Fi in unlicensed spectrum using Listen-Before-Talk (LBT) is studied and the grounds for the specification of LAA via LBT is laid. It showed that when an appropriate channel access scheme was used, it was feasible for LAA to achieve fair coexistence with Wi-Fi, and for LAA to coexist with itself based on the evaluated scenarios. The channel access framework included a category 4 LBT scheme including random back-off and variable contention windows at least for the downlink data transmissions. It was recommended that the key parameters of the LBT scheme such as contention windows and defer periods should be configurable within limits to enable fair coexistence with other technologies operating in unlicensed spectrum. It was also recommended that LAA supported uplink LBT at the UE. In [19] LAA/eLAA are described. LAA was first introduced in Release 13 with support for licensed LTE band in downlink carrier aggregated with a carrier in unlicensed 5 GHz spectrum. eLAA in Release 14 added uplink support. In LAA, the configured set of serving cells for a UE therefore always includes at least one SCell operating in the unlicensed spectrum according to Frame structure Type 3, also called LAA SCell. LAA eNB and UE apply LBT before performing a transmission on LAA SCell. When LBT is applied, the transmitter listens to/senses the channel to determine whether the channel is free or busy. If the channel is determined to be free, the transmitter may perform the transmission; otherwise, it does not perform the transmission. The combined time of transmissions compliant with the channel access procedure by an eNB should not exceed 50 ms in any contiguous 1 second period on an LAA SCell. Fair coexistence in the unlicensed channel is provided by a region-specific LBT capability to ensure that channels are clear before transmission. LBT is mandatory in the EU and Japan. In [37] LBT is standardized and provides the basis for harmonization to the EU essential requirements of Directive 2014/53/EU for the EU market [38] which in Article 3.2 states “Radio equipment shall be so constructed that it both effectively uses and supports the efficient use of radio spectrum in order to avoid harmful interference”. [37] specifies the technical characteristics and methods of measurements for 5 GHz Wireless Access Systems (WAS) including Radio Local Area Network (RLAN) equipment and also describes spectrum access requirements to facilitate spectrum sharing with other equipment as per [38].

In [38] LBT, or Adaptivity (Channel Access Mechanism) as defined there, is an automatic mechanism by which a device limits its transmissions and gains access to an Operating Channel. Adaptivity is not intended to be used as an alternative to DFS to detect radar transmissions, but to detect transmissions from other RLAN devices operating in the band. Two types of adaptive equipment are defined: Frame Based Equipment and Load Based Equipment. The Clear Channel Assessment procedures and conditions of operations for these 2 types of devices, including the energy threshold levels and channel occupancy time conditions for both

Initiating and Responding device are defined in the ETSI Harmonised Standard. A very simplified diagram of the operation, as presented in [39], is shown in Figure 2.18.

Since the focus in 5G-CLARITY is 5GNR and any LTE equipment that will be used will not support LTE-LAA radios, the coexistence aspects of LTE-LAA will not derive any requirements/design decisions for the project.

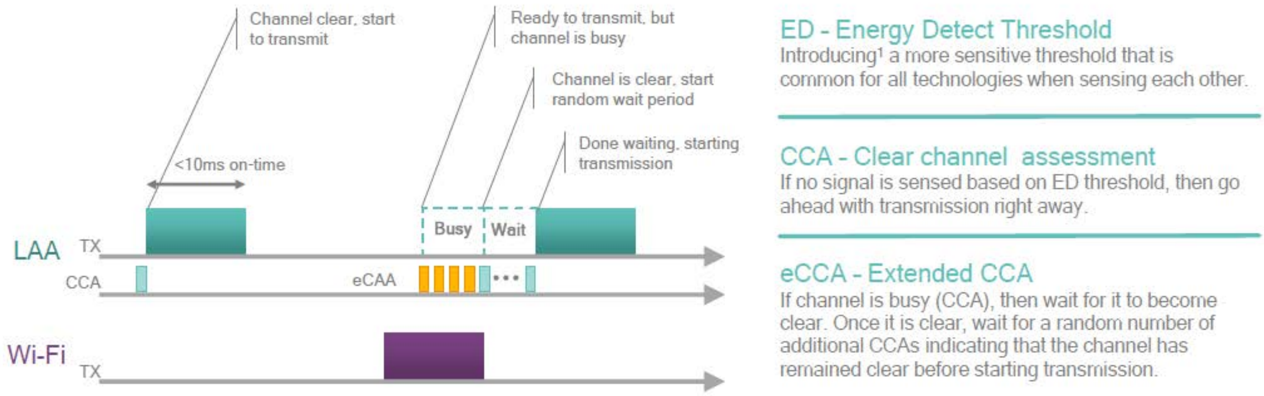


Figure 2.18: Qualcomm LBT in unlicensed 5 GHz as defined in ETSI EN 301 893

2.1.5.2.2 Interference avoidance for in-device coexistence

As discussed in [19], to allow users to access various networks and services ubiquitously, an increasing number of UEs are equipped with multiple radio transceivers. For example, a UE may be equipped with LTE, Wi-Fi, and Bluetooth transceivers, and GNSS receivers. Due to the extreme proximity of multiple radio transceivers within the same UE operating on adjacent frequencies or sub-harmonic frequencies, the interference power coming from a transmitter of the collocated radio may be much higher than the actual received power level of the desired signal for a receiver. This situation causes IDC interference and is referred to as IDC problems. The challenge lies in avoiding or minimizing IDC interference between those collocated radio transceivers, as current state-of-the-art filter technology might not provide enough rejection for certain scenarios. IDC problem can happen when the UE (intends to) uses WLAN on the overlapped carrier/band or adjacent carrier/band to the unlicensed carrier used for LAA operation, e.g. when related UE hardware components, such as antennas, are shared between LAA and WLAN operations. If there is a risk of IDC problem which cannot be avoided (e.g. by level of regulation), the IDC functionality for a UE should be configured by the eNB when the UE is configured for LAA operation. When a UE experiences IDC problems that it cannot solve by itself and a network intervention is required, it sends an IDC indication via dedicated Radio Resource Control (RRC) signalling to report the IDC problems to the eNB. The UE may rely on existing LTE measurements and/or UE internal coordination to assess the interference and the details are left up to UE implementation. A UE that supports IDC functionality indicates related capabilities to the network, and the network can then configure by dedicated signalling whether the UE is allowed to send an IDC indication.

When notified of IDC problems through an IDC indication from the UE, the eNB can choose to apply a Frequency Division Multiplexing (FDM) solution or a Time Division Multiplexing (TDM) solution:

- The basic concept of an FDM solution is to move the LTE signal away from the ISM band by e.g., performing inter-frequency handover within E-UTRAN, removing SCells from the set of serving cells or de-activation of affected SCells, or in case of uplink CA operations, allocate uplink PRB resources on CC(s) whose inter-modulation distortion and harmonics does not fall into the frequency range of the victim system receiver.
- The basic concept of a TDM solution is to ensure that transmission of a radio signal does not coincide with reception of another radio signal. LTE DRX mechanism is used to provide TDM patterns (i.e. periods during which the LTE UE may be scheduled or is not scheduled) to resolve the IDC issues. DRX based TDM solution should be used in a predictable way, i.e. the eNB should ensure a

predictable pattern of unscheduled periods by means of e.g. DRX mechanism or de-activation of affected SCells.

To assist the eNB in selecting an appropriate solution, all necessary/available assistance information for both FDM and TDM solutions is sent together in the IDC indication to the eNB. The IDC assistance information contains the list of E-UTRA carriers suffering from IDC problems, the direction of the interference and depending on the scenario it also contains TDM patterns or parameters to enable appropriate DRX configuration for TDM solutions on the serving E-UTRA carrier. Furthermore, the IDC indication can also be configured to include uplink CA related assistance information containing the victim system as well as the list of supported uplink CA combinations suffering from IDC problems. Furthermore, the IDC indication can also be configured to indicate that the cause of IDC problems is hardware sharing between LAA and WLAN operation, in which case the UE may omit the TDM assistance information. The IDC indication is also used to update the IDC assistance information, including for the cases when the UE no longer suffers from IDC problems.

In 5G-CLARITY no 4G and Wi-Fi RAN level integration will be implemented in the pilots and therefore no coexistence mechanisms will be enabled for this case.

2.1.5.3 5G and Wi-Fi integration coexistence

The 3GPP TR38.889 [40] presents the results of a study on the operation of NR in Sub-7 GHz unlicensed spectrum (NR-U). This report documents the modifications which are needed in 5GNR protocol stack to allow 5GNR to operate in unlicensed spectrum as a secondary cell through carrier aggregation, as a PSCell through DC, and as a primary cell in stand-alone (SA) deployment. This study concluded that it was feasible to modify NR to operate in unlicensed spectrum in CA with a licensed band NR carrier(s), DC with LTE or NR in a licensed band, SA with DL and UL in unlicensed band, and SA with DL in unlicensed band and UL in licensed band. The study also showed that in 5 GHz, when the appropriate channel access schemes are used, it is feasible for NR-U to achieve fair coexistence with Wi-Fi, and for NR-U to coexist with itself, under conditions described in the study. The report also concluded that, if NR-U had similar adjacent channel leakage as LAA, then NR-U and Wi-Fi could coexist in adjacent channels. If NR-U had similar leakage and selectivity requirements as LAA, the LAA study could be used to conclude that NR-U will cause less adjacent channel interference to a Wi-Fi system compared to another Wi-Fi system. With regards to 6 GHz operation and due to its greenfield nature, the study performed coexistence evaluations using technology neutral assumptions (e.g. channel access mechanism with equal Clear Channel Assessment-Energy-Detection threshold). Given the assumptions used in the report evaluations, results showed that Wi-Fi and NR-U performance is improved when a common Clear Channel Assessment-Energy Detection (CCA-ED) threshold is used between Wi-Fi and NR-U compared to when different CCA-ED thresholds are used between Wi-Fi and NR-U. For standalone use of unlincensed spectrum see also section 2.1.6.3.

In 5G-CLARITY no 5GNR and Wi-Fi RAN level integration will be implemented in the pilots and therefore no coexistence mechanisms will be enabled for this case.

2.1.6 Cellular on unlicensed coexistence

2.1.6.1 MulteFire

MulteFire [41] is a technology that enables wireless networks based on 3GPP standard technology (LTE) operating SA in unlicensed or shared spectrum, such as 5 GHz. Albeit it is tightly aligned to 3GPP Release 13 and Release 14 standards enabling LAA/eLAA, it removes the requirement for licensed spectrum as spectrum anchor of these features. It implements LBT to efficiently coexist with other spectrum users in the same band, such as Wi-Fi or LAA/eLAA itself. MulteFire allows anyone to deploy and operate their own private network, targeting areas such as Industrial IoT or enterprises. MulteFire can also be configured as a Neutral Host Network (NHN), e.g. for an enterprise or venues, to serve users from multiple operators. The Release 1.1 specification, completed in December 2018 [41], brought general enhancements to previous Release 1.0, new optimizations especially for IoT, such as support for NB-IoT and eMTC in unlicensed spectrum, support for new bands such as 1.9 GHz focusing on Japan and lower bands 800/900 MHz. The MulteFire technology tries to leverage both on the advantages of LTE and Wi-Fi technology in the unlicensed spectrum and plans to provide a clear path towards 3GPP NR-U.

2.1.6.2 LTE-U

As indicated in [34], the LTE-U ecosystem has largely stalled to the point where only twelve operators had announced investments in LTE-U networks with three limited scale networks launched in three countries while nine operators were known to have invested in the technology in trials or pilots in seven countries.

LTE-U is a 3GPP pre-Release 13 technology whose standard was led by LTE-U Forum. It is like LAA in the sense it uses Carrier Aggregation techniques that do not require core network intervention and where the spectrum management is fully done in the context of the eNB. Unlike LAA, which uses LBT, LTU-U uses a combination of Dynamic Channel Selection and adaptive duty cycle Carrier Sensing Adaptive Transmission (CSAT) to determine when the 5 GHz unlicensed Wi-Fi spectrum is in use to maintain fair coexistence. LTE-U can easily migrate towards LAA/eLAA, which will probably be a “natural” consequence of the state of the market for LTE-U.

As described in [42], in hyper-dense deployment of Wi-Fi and LTE-U small cells, there is a possibility that no clean channel can be found. In such cases, LTE-U can share the channel with neighbouring Wi-Fi or another LTE-U system by using Carrier Sense Adaptive Transmission (CSAT) algorithm. Typical co-channel coexistence techniques in unlicensed bands such as LBT regulations and CSMA used by Wi-Fi are based on the concept of contention-based access. In these techniques, transmitters are expected to sense the medium and make sure is clean before transmission. The goal of these algorithms then is to provide coexistence across different technologies in a TDM fashion. LTE Advanced in unlicensed spectrum uses a third mechanism (CSAT) that is in-line with the same concept of TDM coexistence based on medium sensing. In CSAT, the small cell senses the medium for longer (than LBT and CSMA) duration (around 10s of msec to 200msec) and according to the observed medium activities, the algorithm gates off LTE transmission proportionally. CSAT defines a time cycle where the small cell transmits in a fraction of the cycle and gates off in the remaining duration as shown in Figure 2.19. The duty cycle of transmission versus gating off is dictated by the sensed medium activity of other technologies. CSAT in spirit is similar to CSMA except that it has longer latency, an impact that is mitigated by avoiding channels where Wi-Fi APs use for discovery signals and QoS traffic (i.e. primary channels). CSAT ensures fair and efficient channel sharing, with the impact of a LTE-U node to its neighbouring Wi-Fi APs no worse than a neighbouring Wi-Fi AP. The LTE-U, which is on the secondary cell, is periodically activated and de-activated using LTE MAC Control Elements. The procedures and timeline are carefully chosen to ensure compatibility with Rel. 10/11 UE behaviour. During the LTE-U off period, the channel is clean to neighbouring Wi-Fi which can resume normal Wi-Fi transmissions. The small cell will measure Wi-Fi medium utilization during the LTE-U off period, and adaptively adjust On/Off duty cycle accordingly. The TDM cycle can be set to a few hundreds of milliseconds, which can effectively accommodate the activation/de-activation procedures while controlling the data transmission delay.

Due to the lack of real market traction for LTE-U and also due to the fact that no LTE-U equipment will be used in the context of 5G-CLARITY, there will be no requirements/design dependencies derived for the project.

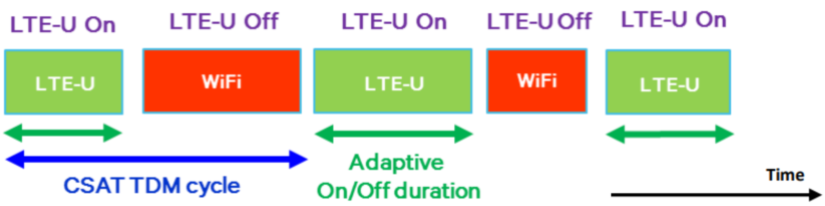


Figure 2.19: CSAT enabling LTE-U and Wi-Fi sharing the same channel

2.1.6.3 NR-U

3GPP Release 16 enables 5GNR operation in unlicensed spectrum in the 5 GHz and 6 GHz unlicensed bands [40]. It supports licensed-assisted operation similar to LAA (the anchor carrier in licensed spectrum is used to establish the connection which then can be carrier aggregated with the unlicensed carrier resources) and a standalone operation, similar to LTE-U where no licensed spectrum is necessary. Operation in unlicensed spectrum is dependent on several key principles including ultra-lean transmission and use of the flexible NR frame structure which were already included in 3GPP Release 15. Channel access mechanisms based on LBT are enhanced in 3GPP Release 16. 5GNR reuses the same LBT mechanism as defined for Wi-Fi and LTE in unlicensed spectrum (see Section 2.1.5.2.1). For further information on coexistence see Section 2.1.3.2.

In 5G-CLARITY no NR-U will be implemented in the pilots and therefore no coexistence mechanisms will be enabled for this case.

2.1.7 Shared access spectrum

As discussed in [43] regulators in a number of countries have authorized automated and even dynamic frequency coordination databases to manage real-time assignments in shared bands and to protect incumbent operations (including military and public safety systems) from harmful interference. While spectrum database coordination is nothing new, it has in recent years evolved from manual, to automated, to dynamic – adding automation and propagation modelling to static licensing data. This evolution has generally progressed from the manual, database-informed coordination of fixed links and satellite earth stations; to database-assisted coordination of PtP links on a semi-automated basis (e.g., in the 70/80/90 GHz bands); to the fully-automated frequency coordination of unlicensed sharing of vacant TV channels (TV White Space); to, most recently, the dynamic coordination of a three-tier hierarchy of sharing by Spectrum Access System databases across the 3550-3700 MHz band with U.S. Navy radar (the CBRS).

2.1.7.1 Static sharing

On 25 July 2019, Ofcom published a Statement, “Enabling wireless innovation through local licensing” [44]. In this statement, two new licence schemes were set out with a twofold objective. First, making it easier for a wider range of users in the UK to access radio spectrum on a shared basis. Secondly, the improvement of wireless connectivity in enterprise sites as well as underserved areas. These two schemes are:

- Shared access licence [45], which gives access to four spectrum bands which support mobile technology.
- Local access licence [46], 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

2.1.7.1.1 Shared access license

The Shared Access licence enables new stakeholders, such as small businesses and community groups, to foster innovation and enable new use cases. As shown in Figure 2.20 (from [45]), this type of license could be useful for all sorts of different businesses and industries.

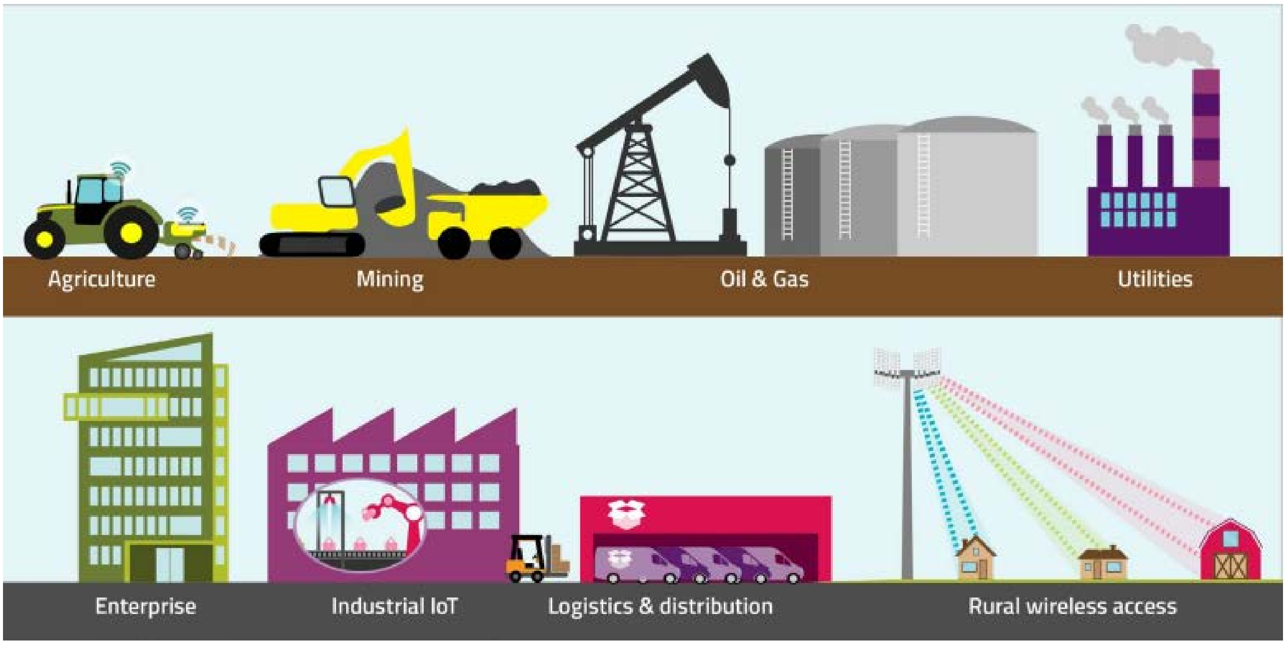


Figure 2.20: Possible users of UK Shared Access License

The Shared Access licenses available are:

- **1781.7-1785 MHz paired with 1876.7-1880 MHz** (referred as "the 1800 MHz shared spectrum"): This is part of the wider 1800 MHz mobile band (initially established as although this particular portion has not been licensed for national mobile services) and is supported by commercially-available mobile base stations and equipment, including most mobile handsets. There is a total of 2 x 3.3 MHz available in the band. With this limited bandwidth this would be most suitable for voice or low data rate services.
- **2390-2400 MHz** (referred as "the 2300 MHz shared spectrum"): This is part of the 2300 MHz mobile band and sits just above the 2350-2390 MHz band, which is used for mobile in the UK. It is supported by commercially available mobile base stations and equipment and is included in some of the latest smartphones. There is 10 MHz available in this band.
- **3.8-4.2 GHz**: This band sits just above the 3.6-3.8 GHz mobile band (LTE B43), and chipsets for this band which support 5G technology are currently available. There is 390 MHz of spectrum available in the band.
- **24.25-26.5 GHz** (referred as "the lower 26 GHz band"): This band is available for indoor low power licences only. This is part of one of the pioneer mmWave 5G bands in Europe and has 2.25 GHz of spectrum available in total.

The potential (non-exhaustive) uses of the shared bands are suggested in Figure 2.21 from [45].

Uses	1800 MHz shared spectrum	2300 MHz shared spectrum	3.8-4.2 GHz	Lower 26 GHz band
Private network	✓ (narrowband)	✓	✓	✓ (indoor)
Mobile coverage (rural)	✓	certain locations[3]	✗	✗
Mobile coverage (indoor)	✓	✓	✗	✓
Fixed wireless access[4]	✗	✗	✓	✓[5]

[3] Due to coexistence with other users, the availability of medium power licences in the 2300 MHz shared spectrum will be limited initially.
[4] Fixed wireless access (FWA) networks provide an alternative solution to traditional fixed broadband services. These networks use a wireless link for the final connection to a home or business, avoiding the installation of a line into the building.
[5] FWA is available through existing fixed links authorisation. However, we are not encouraging people to apply for new licences in the band. See paragraph 5.29 of our Statement for more information.

Figure 2.21: Potential uses for the UK Shared Access bands

Ofcom plans to enable DSS for these licenses in the future whereby equipment would communicate directly to a central database to access the spectrum.

The technical conditions of the **low power Shared Access licenses** are:

- License given on a first come first served basis
- Transmission needs to start within 6 months and you need to continue to remain operational
- Switching off equipment from time to time for maintenance is permitted, but the purpose of the license is that if a user is not going to use the spectrum in an area, then the license can go to another that will. This avoids spectrum hoarding
- Frequency might be changed from time to time for interference management or spectrum planning
- Authorisation given for an area of 50 m centred around coordinate provided by user, where the low power shared license can be used by any number of base-stations that can be moved if needed. Larger areas can be covered with application of licenses for multiple areas
- Fixed, mobile and nomadic terminals connected with a base station (even outside of the licensed area) are also authorised, and in the case of 1800 and 2300, the mobile and nomadic terminals are license exempt
- Users can apply for indoor areas or indoor and outdoor areas. Initially 2300 MHz will be only indoor
- Outdoor base station can be deployed at a maximum height of 10 m above ground

The license imposes certain band emission (Equivalent Isotropic Radiated Power or EIRP) limits to be respected. No synchronisation is required for any band except for the 2300 MHz for base stations outdoors, where coexistence with Telefónica adjacent band in 2350-2390 MHz requires frame synchronisation at frame boundaries and the use of the same TDD UL/DL configuration 2 (this aligns to CEPT recommendations for synchronised TDD deployments as discussed in Section 2.1.3. In the future synchronisation might be mandated in 3.8-4.2 GHz in case of interference between adjacent users.

The technical conditions of the **medium power Shared Access licenses** are:

- Authorisation for single base stations and any connected terminal stations. Additionally, mobile terminal stations in the 1800 MHz and 2300 MHz shared spectrum are license exempt
- The medium power licence is available for the 1800 MHz and the 3.8-4.2 GHz band, but it's not available for the lower 26 GHz band
- This licence could be suitable for users who need a longer transmission range from their base station, but don't expect to need to change the locations of BSs once they're deployed. This could suit providers of FWA services in rural areas, along with industrial or enterprise users with sites spread over a larger area, such as ports, agriculture or forestry
- Users will not be permitted to deploy wide area networks in the 3.8-4.2 GHz band; this includes national or regional mobile networks
- Different areas in UK are categorised as rural for which these medium power Share Access licenses can be applied
- Urban areas applications can only be considered on an ad-hoc basis

Channel size	Price per channel
2 x 3.3 MHz	£80
10 MHz	£80
20 MHz	£160
30 MHz	£240
40 MHz	£320
50 MHz	£400
60 MHz	£480
80 MHz	£640
100 MHz	£800

Figure 2.22: Ofcom yearly Shared Access license fees per bandwidth

The Shared Access license yearly fees paid per area (Low Power) or BS (Medium Power) are indefinite and are shown in Figure 2.22. The fees are cost-based which means they are calculated to make sure Ofcom recovers the costs of administering the license. Users can transfer their rights to access spectrum (and their obligations to pay the associated fees and comply with licence conditions) to another party by trading them.

2.1.7.1.2 Local Access License

A Local Access licence is a mechanism that enables the shared use of spectrum which is already licensed on a national basis to MNOs, in locations where a particular frequency is not being used, and for cases where the normal spectrum trading framework for current licensed mobile spectrum is not applicable or practical. Given the nature and extent of the existing use of licensed mobile spectrum, Ofcom anticipates that spectrum is only likely to be available for sharing in remote areas to support, for example, private networks or wireless broadband services. There may also be other specific locations that are not served by the existing mobile networks, for example underground mining operations, where mobile technology to support a private network could be used without impacting MNOs' current deployments or future plans.

The **Local Access** licence conditions:

- is available for any frequency band covered by the Mobile Trading Regulations

- will be time limited (the default period is three years, but other durations are available)
- is for a single location or area
- is not restricted to the same technology as the incumbent licensee
- can be transferred on a total outright or total concurrent basis to another party
- requires licensees to notify any customers of the time limits on the authorisation
- will include Ofcom's standard terms on access, inspection, and other standard terms
- will incur a cost-based one-off fee of £950 per licence

The current frequencies covered by the Mobile Trading Regulations are:

- 791-821 MHz paired with 832-862 MHz ("800 MHz band")
- 880-915 MHz and 925-960 MHz ("900 MHz band")
- 1452-1492 MHz ("1400 MHz band")
- 1710-1781.7 MHz and 1805-1876.7 MHz ("1800 MHz band")
- 1900-1920 MHz ("1900 MHz band")
- 1920-1980 MHz and 2110-2170 MHz ("2100 MHz band")
- 2350-2390 MHz ("2300 MHz band")
- 2500-2690 MHz ("2600 MHz band")
- 3410-3600 MHz ("3.4 GHz band")

To minimise the risks of interference the Local Access license, the licensee must liaise and co-operate with other holders of licenses in the same frequency band(s). This may require adjusting transmission power and other technical parameters of transmission in such a way that harmful interference is not caused by one network deployment to that of another licensee within the band. Where a licensee is deploying a mobile service, they need to follow the appropriate in block and out of block power limits. The licence could also include, when deploying TDD systems outdoors or in a shared indoor location, the requirement to synchronise with other users in the band or use a restrictive transmission mask. In such cases these provisions will likely mirror those in the incumbent licensee's authorisation.

2.1.7.2 Semi-static sharing – LSA

The European LSA is a database-assisted model that facilitates two-tier sharing between primary (incumbent) and secondary licensees. In this regulatory model analysed in [47] and outlined initially at the 2.3-2.4 GHz band [48], the regulator plays a direct role in managing the database of information by which primary and secondary licensees share the band. This LSA framework is contingent on the agreement of both the incumbent and of the MFCN operator to the conditions of use of the spectrum.

The LSA framework assumes that the regulator creates and operates a Licensed Shared Access Repository database. This database provides information on the terms of sharing and the incumbent locations, operating parameters and other data needed by each LSA licensee. Each LSA licensee operates a proprietary LSA Controller within its own network, interfacing with the Repository. The LSA Controller, which is internal to the carrier's network, must check in periodically and report the status of its use, allowing the regulator Repository to verify non-interference and ongoing compliance with the sharing agreement. Figure 2.23

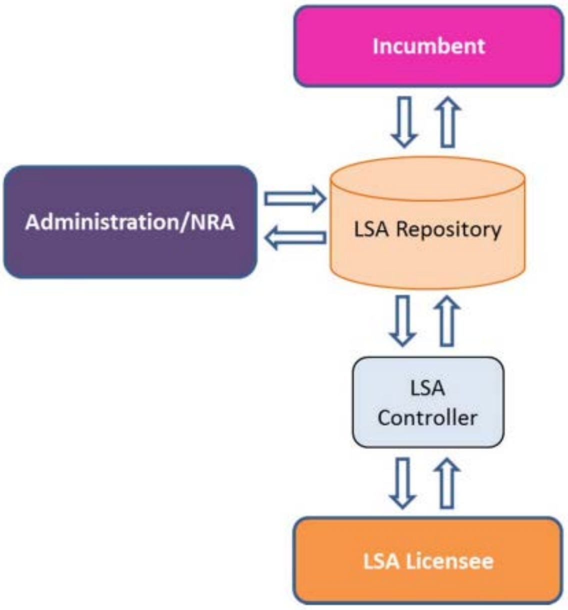


Figure 2.23: Example LSA functional blocks and interactions

depicts an example of implementation of LSA with repository and controller.

2.1.7.3 Dynamic sharing – Citizens Broadband Radio Service (CBRS)

In April 2015 [16] and later modified in May 2016 [49], the FCC established the regulatory grounds for the CBRS, involving the shared commercial use of the 3.5 GHz (3550-3700 MHz, defined in 3GPP as B48 as indicated in Section 2.1.1.2.1) with incumbent military radars and fixed satellite stations. The CBRS specifications and certification framework were defined together between the Wireless Innovation Forum [50] and the CBRS Alliance [51].

The Dynamic Spectrum Sharing (DSS) rules were defined in order to make additional spectrum available for flexible wireless broadband use while ensuring interference protection and uninterrupted use by the incumbent users. The main components of the CBRS system as depicted in Figure 2.24 are:

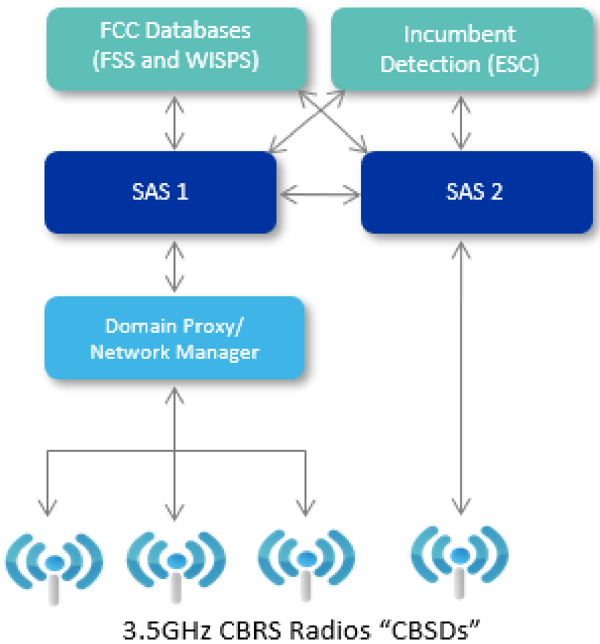


Figure 2.24: CBRS Overall Architecture

- **Spectrum Access System**: it centrally coordinates the access to the shared spectrum, modelling the RF environment, enforcing the priorities/policies and ensuring fair access to spectrum. Different Spectrum Access System (SAS) administrations have been authorised by FCC to operate (Federated Wireless, Google, Commscope, Sony, Amdocs) and inter-SAS protocols are defined for coordination between these different SAS administrations managing different sets of Citizens Broadband Radio Service Devices (CBSD). The SAS maintains a map of CBSD and incumbent devices and uses a sensor network (the Environmental Sensing Capability – ESC) deployed around the country to monitor the band. Using an internal propagation model, the SAS can predict potential interference between CBSDs and any incumbent systems. When a CBSD requests access to a range of frequencies from the SAS, based on the location of the CBSD, its class, and its antenna characteristics, the SAS grants access to one or more CBRS frequencies at a certain power. The SAS can instruct the CBSDs to reduce their output power (or shut off entirely) to reduce interference with other CBSDs and incumbent systems when they need channel access.
- **Environmental Sensing Capability**: network of dedicated sensors (potentially leveraging on capabilities of deployed devices) that detect incumbent activity and informs the SAS so that channels being used by lower priority tier can be cleared.
- **Domain Proxy**: CBSD aggregation and proxy function for managing large networks or localised clusters which can be integrated into EMS/NMS or managing a deployment or cluster in a standalone mode.
- **CBRS Device**: radio nodes operating in the CBRS band which report their location and radio capabilities to the SAS. This report allows these nodes to get spectrum for transmission, according to the granted radio parameters (bandwidth, carrier frequency, maximum Tx power, etc.) allowed by the SAS.

In CBRS, a novel three-tier sharing paradigm coordinates spectrum access among the incumbent military radars, satellite ground stations and temporarily protected FWA legacy stations and new commercial users.

The three tiers sharing the 150 MHz of CBRS spectrum as shown in Figure 2.25 are:

- **Protected Incumbents**: this tier is protected from interference from PAL and GAA users. They are primarily radars and FSS (coastal areas mainly) and temporarily the Wireless ISPs in 3650-3700 MHz.
- **Priority Access License (PAL):** this tier is protected from interference from GAA users. Up to 70 MHz can be available per county to be awarded via auction during 2020. In principle a maximum of 40 MHz can be given to a given licensee.
- **General Authorised Access (GAA):** this tier can use any portion of spectrum not assigned to Protected Incumbents or PALs in an area. A minimum of 80 MHz will be reserved for this tier per county, although up to the full 150 MHz can be made available by the SAS if no Protected Incumbents or PAL users are present.

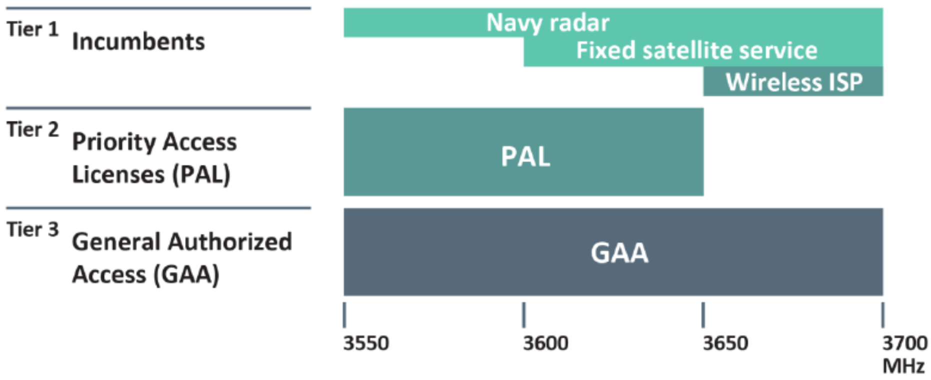


Figure 2.25: Three-tier coordination in CBRS

As described in [43] the CBRS framework enables the use of sensing network inputs to enable real time awareness of naval radars and allows dynamic interference protection managed by the SAS as shown in Figure 2.26.

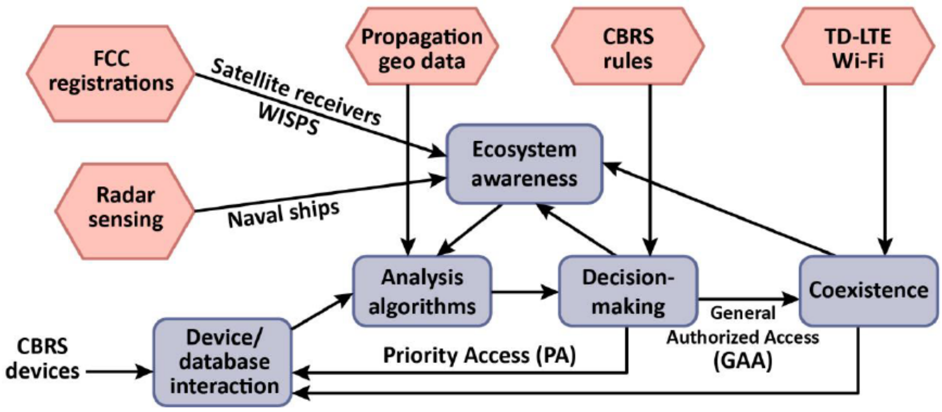


Figure 2.26: Admission control system architecture CBRS

As described in [43] each SAS has a "map" of all deployments on the seven PAL channels and can facilitate opportunistic GAA use of vacant PAL spectrum in discrete geographic areas on a "use-it-or-share-it" basis. In the CBRS band, licenses (PALs) ensure interference protection for deployed nodes but confer no right to exclude opportunistic users (GAA) when and where the spectrum is not in use. Because the SAS has awareness of the transmit power, bandwidth and other characteristics of each device authorized to operate in a local area, it can make assignments to GAA users that optimize performance and minimize mutual interference.

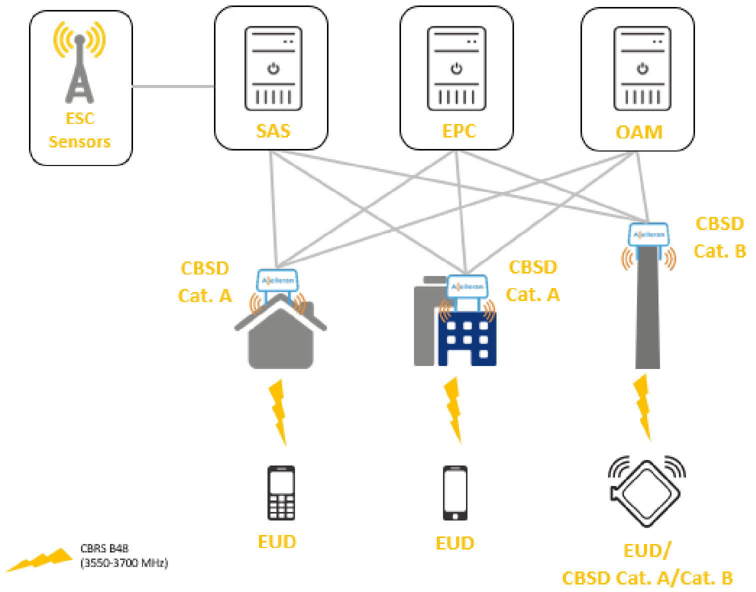


Figure 2.27: Accelleran Local Area BS class OnGo/CBRS E1012 small cell deployment

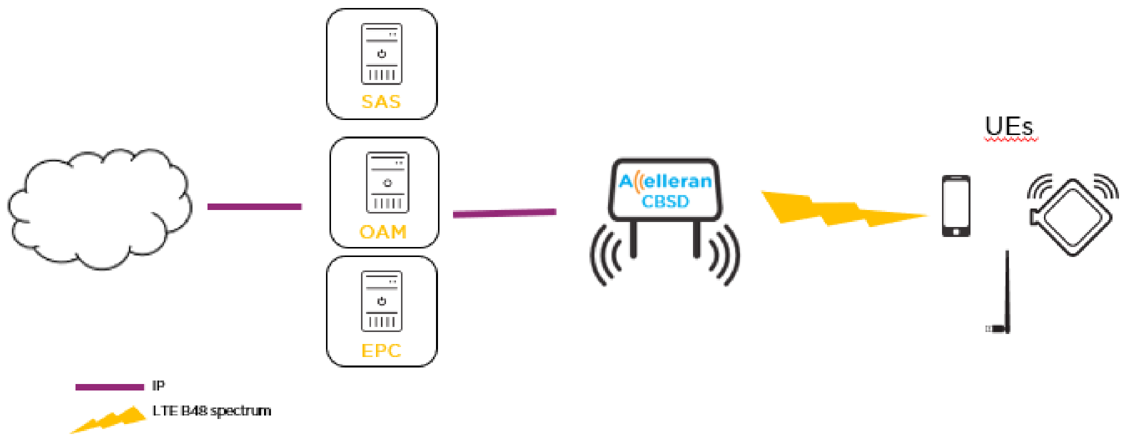


Figure 2.28: Overall CBRS architecture in LTE system (using Accelleran small cell as example)

Albeit CBRS can be technology neutral, its applicability is mainly done in the context of 3GPP based technologies, namely LTE TDD. Figure 2.27 and Figure 2.28 show the overall CBRS architecture within an LTE system and the example deployment of Accelleran E1012 CBRS small cell. The CBRS Alliance Release 1 standard, published in February 2018, described the extensions required to 3GPP standards to enable LTE operation in the US 3.5 GHz CBRS band. It encompassed radio, networks service and coexistence specification. The network services standard defines NHN and private networks operation. The CBRS Alliance Release 2 standard, published in April 2019, added MSO and fixed wireless use cases, non-SIM access mode (non-EPS-AKA) and UE profiles. The standard included new LTE network identifiers for private or NHN networks, referred to as a shared HNI, which are administered by the CBRS Alliance in conjunction to ATIS IOC [52] oversight. SAS operation is extended to facilitate coexistence between GAA devices.

The CBRS Alliance Release 3 standard, recently published in February 2020, included for the first time support for 5GNR. In [53] and [54] CBRS specifications define the 5GNREN-DC Use Case based on NSA mode for Private and NHNs initially as derived from 3GPP Release 15. In [55] CBRS defines the coexistence between and among multiple LTE and NR networks where Coexistence between CBSDs belonging to the CBRS Alliance Coexistence Group is coordinated by one or multiple Coexistence Managers (CxMs). The specification includes GAA coexistence requirements for CBSDs including cell phase synchronization, TDD Configuration for LTE-TDD and NR-TDD CBSDs amongst others. The current version of the document focuses on Band 48 [11] LTE-TDD using Frame Structure 2 (FS2) and limited support for n48 NR-TDD deployment. Additionally all NR TDD CBSDs in a CBRSA CxG shall support two uplink downlink configurations that corresponds to two mandatory LTE TDD configurations as in Figure 2.29. All CBSDs (LTE TDD or NR TDD) in a “TDD configuration connected set” need to use the same or equivalent TDD configurations.

UL:DL ratio	Slot Number																			
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
4:5	D	D	D	F	U	U	U	U	D	D	D	D	D	F	U	U	U	U	D	D
2:7	D	D	D	F	U	U	D	D	D	D	D	D	D	F	U	U	D	D	D	D

Equivalent to LTE TDD configuration 2

Equivalent to LTE TDD configuration 1

NR-TDD Subframe ‘F’ Symbol Pattern for the CBRSA CxG
(equivalent to LTE-TDD special subframe configuration 7)

NR Slot	3, 13													
NR Symbol	0	1	2	3	4	5	6	7	8	9	10	11	12	13
UL-DL pattern	D	D	D	D	D	D	G	G	G	G	U	U	U	U

Figure 2.29: Mandatory NR-TDD TDD UL/DL Configurations for the CBRSA CxG

CBRS Alliance Release 4 is expected to be finalised in December 2020. Amongst some of the work and study items expected to be added are the following:

- PAL Coexistence: TDD configuration coordination amongst PAL deployments in the same geographic area, PAL to PAL / GAA to GAA coexistence impact, PAL to GAA TDD coordination
- Enhanced NR TDD Configurations: NR mixed numerology deployments, aligned NR/NR and NR/LTE frame configurations
- NR Standalone Public Networks
- NR Standalone Non-Public Networks
- Inter-CxM support enabling consistent assignments of TDD configurations between CSAS/CxMs and the sharing of grouping information to enable the creation of single TDD configuration connected sets
- UE profiles for 5GNRSA Public Network operation and Non-Public Network operation
- 5GNRDSS and EN-DC (EUTRA or NR CA, EUTRA-NR DC, DSS, NR SA)

Besides the addition of 150 MHz spectrum, the flexible and innovative CBRS 3-tier licensing framework lowers the barrier to spectrum and promotes investment for new entrants offering cost-effective LTE solutions for both indoor and outdoor applications and opening up new use cases, many of which fall along the lines of private LTE and neutral hosts deployments. It is estimated that up to now only 1% of enterprise networks are using licensed spectrum in the US, mostly DAS systems, but with CBRS, the private LTE penetration in enterprise will increase dramatically.

It is worth to note that on 23rd April 2020 FCC announced the adoption of rules that make 1200 MHz of spectrum in the 6 GHz band (5.925-7.125 GHz) available for unlicensed use in the US [11]. The FCC are authorizing two types of unlicensed operations in the 6 GHz band (see Section 2.1.1.2.3). One of them, authorizing unlicensed standard-power access points in the U-NII-5 and U-NII-7 bands is being done via the use of an AFC system. This will permit operations at the same power levels already permitted in the 5 GHz U-NII-1 and U-NII-3 bands (5.150-5.250 GHz and 5.725-5.850 GHz bands, respectively), while at the same time protecting incumbents' users (6GHz is comprised of allocations for Fixed Services, Mobile Services and

FSS). The AFC System Framework and Database proposed by FCC is similar to the CBRS system. Some CBRS SAS administrators such as Federated Wireless have already announced they will apply their CBRS learnings and technology for the 6GHz band [56]. For 5G-CLARITY this will not be relevant beside the fact that it indicates that dynamic spectrum sharing mechanisms similar to CBRS will become more common in the industry.

2.2 Spectrum Sharing framework requirements

Access to scarce spectrum and efficient use of that scarce resource by enabling inter-network coexistance is key to maximize the overall system capacity and minimize interference between network nodes. Additionally, the incorporation of unlicensed spectrum in its own right within the 5GNR standards and the advent of new innovative spectrum sharing regulatory frameworks to enable universal access to spectrum for private networks, make the selection of appropriate requirements in 5G-CLARITY spectrum sharing framework important for the deployment in the pilots. The following are the 5G-CLARITY requirements associated to this spectrum sharing framework.

Table 2-2: Spectrum Sharing framework requirements

Requirement ID	Description
SSF-R1	5GNR shall support phase-synchronised TDD operation to ease the inter-network coexistence with public networks with adjacent 5GNR spectrum assignments
SSF -R2	5GNR shall support compatible DL/UL formats to ease the inter-network coexistence with public networks with adjacent 5GNR spectrum assignments
SSF -R3	5GNR shall support phase-synchronised TDD operation to ease the inter-network coexistence with public networks with adjacent LTE spectrum assignments
SSF -R4	5GNR shall support compatible DL/UL formats to ease the inter-network coexistence with public network of adjacent LTE spectrum assignments
SSF -R5	5GNR shall support flexible configuration of 5GNR/LTE spectrum assignments via CBRS-like framework, to coordinate spectrum use and allow flexible mapping to different licensing regimes
SSF -R6	5GNR shall support the use of a cluster grouping for co-channel deployment of the 5GNR/LTE NPN network for efficient use of spectrum resources provided by a CBRS-like SAS
SSF -R7	5GNR shall support the use of typical intra-network techniques to minimize interference and maximize coexistence within a co-channel deployment of the 5GNR/LTE NPN network
SSF -R8	5GNR shall support the use of FR1 N78 spectrum band for 5GNR-based network connectivity in NPN scenarios
SSF -R9	5GNR may support the use of FR1 N77 spectrum band for 5GNR-based network connectivity in NPN scenarios
SSF-R10	Wi-Fi Access Points shall support 5 GHz band operation
SSF-R11	Wi-Fi Access Points shall support channel bonding of 40MHz, 80MHz and 160 MHZ channels
SSF-R12	Wi-Fi Access Points shall be able to report the occupied airtime in their operating channel
SSF-R13	Wi-Fi Access Points shall be able to report the number of stations connected at a given time
SSF-R14	Wi-Fi Access Points shall provide a NETCONF-based interface to configure their operating channel, bonding configuration and transmission power by an external spectrum manager

3 Multi-Connectivity

This section provides an overview of state-of-the-art 3GPP multi-radio connectivity and non-3GPP access to 5G Core Network (5GC). The section also provides requirements for 5G-CLARITY multi-connectivity framework. Figure 3.1 illustrates the main cases of DC and multi-connectivity for 3GPP and Non-3GPP Access. When UE is connected with 3GPP capable radio, it may either use dual connectivity, multi-radio dual connectivity or LTE WLAN interworking function to connect data network via 3GPP RAN. Alternatively, UE / GW may connect to 5GC either via Non-3GPP interworking function (N3IWF), Trusted Network Gateway function (TNGF) or by connecting directly to AT3S function in the User Plane Function (UPF). The connection to N3IWF may either be trusted by the network operator or untrusted.

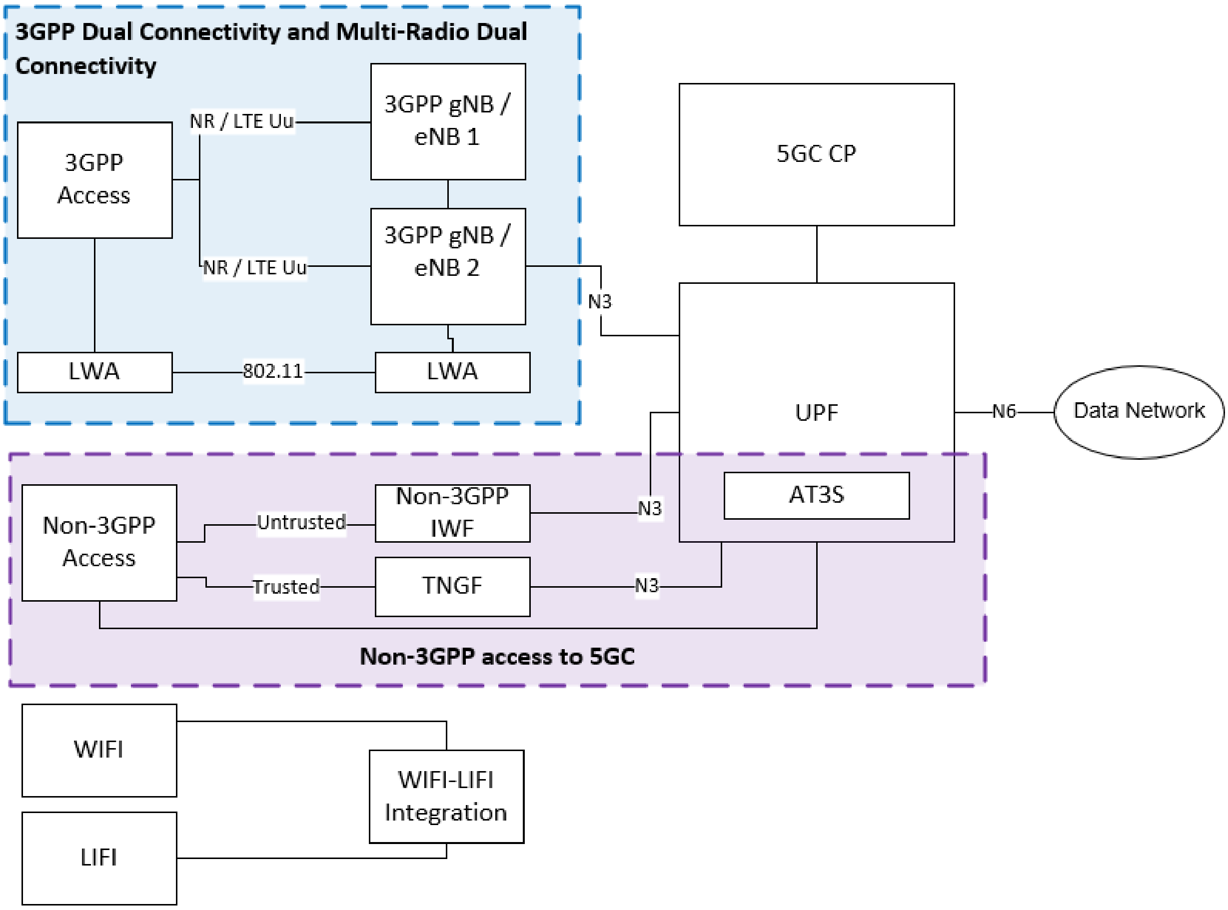


Figure 3.1: Overview of 3GPP Multi-Radio Dual Connectivity and Non-3GPP access to 5GC multi-connectivity

3.1 State-of-the-art

3.1.1 3GPP Dual Connectivity and Multi-Radio Dual Connectivity

This section describes DC and multi-radio dual connectivity as well as multi-radio connectivity with LTE-WLAN aggregation function. The concept of DC was first introduced in Release 12 as a solution to improve the per-user throughput. DC enables UEs to access radio resources supplied by two distinct schedulers in two separate radio nodes. In Release 13, the concept of RAN-level spectrum interworking was introduced by aggregating the capabilities of LTE and WLAN in the downlink, and then for the uplink in Release 14. Subsequently, the concept of DC was extended to Multi-Radio Dual Connectivity (MR-DC) in Release 15 and to support integrated access backhaul in Release 16. Figure 3.2 illustrates standardization path from Release 12 to Release 15.

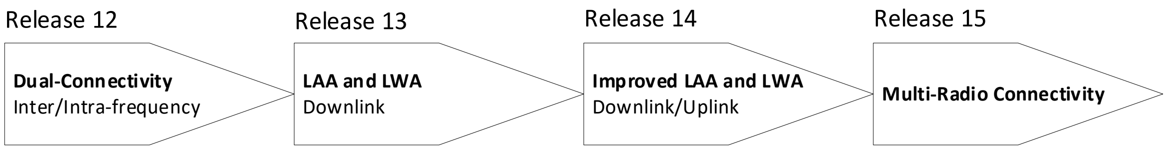


Figure 3.2: Standardization of DC in various 3GPP specification releases.

3.1.1.1 Dual Connectivity (DC)

DC improves per-user throughput by utilising radio resources from separate eNBs [57]. In this case eNBs/gNBs participating in DC for a specific UE either act as a master eNB (MN) or as a secondary eNB (SN). The Master Cell Group (MCG) is defined as the group of the serving cells associated with the MN, while the Secondary Cell Group (SCG) is defined as the group of the serving cells associated with the SN. In DC, a UE is connected to one MN and at least one SN, which are connected via a non-ideal backhaul over the X2 interface. There are two scenarios assumed for DC in Release 12: In the first scenario, macro and small cells operate on the same frequency carrier (intra-frequency), while in the second scenario they operate on different carrier frequencies (inter-frequency).

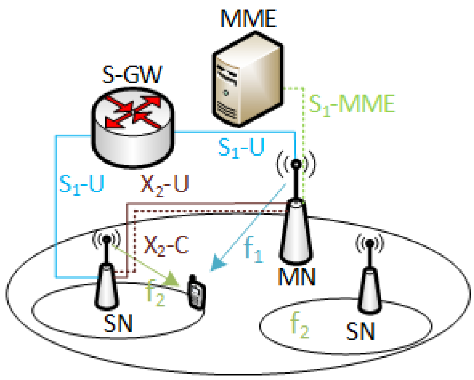


Figure 3.3: DC deployment scenario

The concept of DC deployment is shown in Figure 3.3. It is assumed that there will be a single S1-MME connection per UE. In the data-plane, different S1 bearers can be transmitted through the MN and the SN, or a single bearer can be splitted between MN and the SN. In the latter case, a single PDCP layer is placed in the MN, while the Radio Link Control (RLC) and MAC layers are present both in the MN and in the SN.

3.1.1.2 Multi-Radio Dual Connectivity (MR-DC)

MR-DC introduced in Release 15 is a generalization of the intra-E-UTRA dual connectivity described in [23], where a multiple Rx/Tx capable UE may be configured to utilise resources provided by two different nodes connected via non-ideal backhaul, one providing NR access and the other one providing either E-UTRA or NR access. One node act as the MN and the other as the SN. The MN and SN are connected via a network interface and at least the MN is connected to the core network [58].

Figure 3.4 illustrates control plane options for MR-DC. The inter-eNB CP signalling for dual connectivity is performed via the X2-C. The signalling towards MME is performed by S1-C. There is only one S1-C connection per DC UE for the Master Node (MN) and the MME. Every eNB handles UEs separately. This means the eNB gives the PCell to some UEs while providing Secondary Cell(s) for Secondary Cell Group to others. Each eNB involved in DC for a certain UE controls its radio resources and is primarily responsible for allocating radio resources of its cells. Separate synchronization between MN and Secondary Node (SN) is performed by the X2 interface. Figure 3.4 presents C-plane connectivity options of eNBs in DC deployment scenario for a given UE.

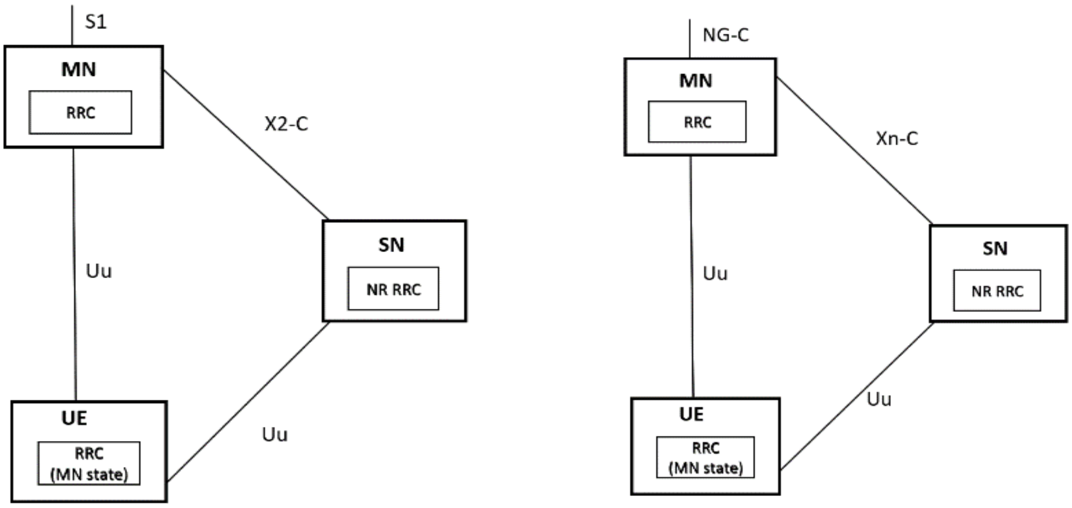


Figure 3.4: Control plane architecture for EN-DC (left) and MR-DC with 5GC (right).

In MR-DC, the UE has a single RRC state, which is anchored on the MN RRC and a single C-plane link to the Core Network. Figure 3.5 shows the C-plane architecture for MR-DC. All radio nodes have its RRC entity, eNB for E-UTRA and gNB for NR. This generates RRC PDUs for transmission to the UE.

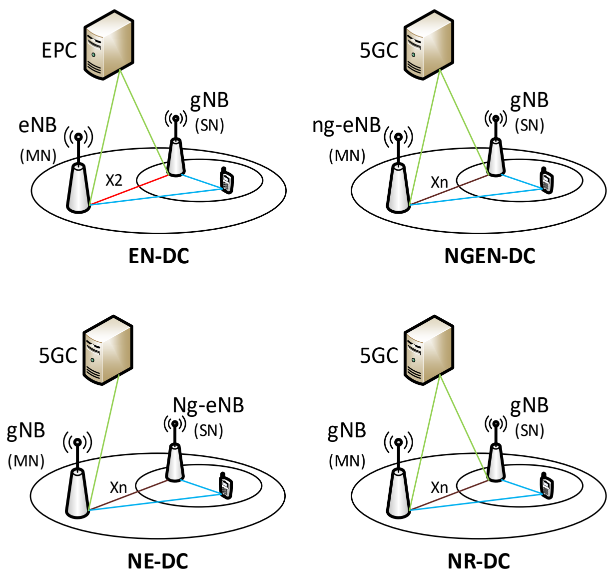


Figure 3.5: MR-DC four modes.

As illustrated in Figure 3.5, MR-DC includes four architecture modes:

1. **E-UTRA-NR Dual Connectivity (EN-DC):** a UE is connected to one eNB that acts as a MN and one gNB that acts as a SN with an Evolved Packet Core (EPC).
2. **NG-RAN E-UTRA-NR Dual Connectivity (NGEN-DC):** a UE is connected to one ng-eNB that acts as a MN and one gNB that acts as a SN with a 5GC. The ng-eNB is connected to the 5GC and the gNB is connected to the ng-eNB via the Xn interface.
3. **NR-E-UTRA Dual Connectivity (NE-DC):** a UE is connected to one gNB that acts as a MN and one ng-eNB that acts as a SN. The master gNB is connected to the 5GC via the NG interface and to the secondary gNB via the Xn interface. The secondary gNB might also be connected to the 5GC via the NG-U interface.
4. **NR-NR Dual Connectivity (NR-DC):** a UE is connected to one gNB that acts as a MN and another gNB that acts as a SN. In addition, NR-DC can also be used when a UE is connected to two gNB-DUs, one serving

the MCG and the other serving the SCG, connected to the same gNB-CU, acting both as a MN and as a SN.

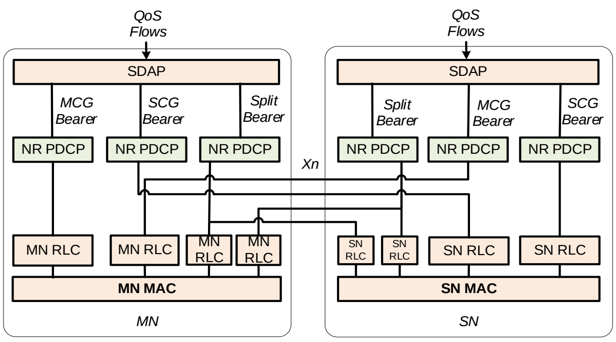
In multi-RAT DC with 5GC, new PDCP is utilized for all bearer types. In NGEN-DC, E-UTRA RLC/MAC is utilized in the MN while 5GNR RLC/MAC is employed in the SN. In NE-DC, 5GNR RLC/MAC is used in the MN while E-UTRA RLC/MAC is used in the SN. Figure 3.6 illustrates different bearer termination options for DC and MR-DC.

Two different architectures are prescribed for DC in the user plane.

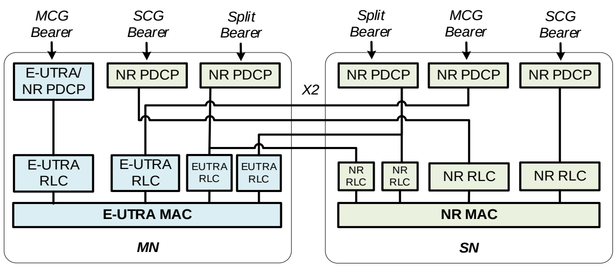
- The S1-U terminates in the MN and the user plane data is transferred from MN to SN via the X2-U interface.
- The S1-U terminates in the SN.   presents user plane connectivity options of eNBs in DC deployment scenario for a given UE.

Different bearer options can be configured with different user plane architectures:

- For MCG bearers, the S1-U connection for the corresponding bearer(s) to the S-GW is terminated in the MN. For transmission of user plane data for such type of bearers via the Uu interface, the SN is not involved.
- For split bearers, the S1-U link to the S-GW is terminates in the MN. PDCP data is transferred between the MN and the SN via X2-U. The SN and MN are involved in transmitting data of this bearer type over the Uu.
- The SN is directly linked to the S-GW through the S1-U interface for SCG bearers. The MN is not involved in the transmission of UP data for such type of bearers over the Uu interface.



Network side protocol termination options for MCG, SCG and split bearers in MR-DC with 5GC (NGEN-DC, NE-DC and NR-DC).



Network side protocol termination options for MCG, SCG and split bearers in MR-DC with EPC (EN-DC).

Figure 3.6: Protocol termination options at the network

3.1.1.3 LTE-WLAN aggregation

LTE WLAN aggregation at the RAN level is a topic that was thoroughly addressed in 3GPP Release 13 and Release 14. The intent of this functionality is to provide an integration solution that is similar in design and performance to the multi-connectivity architectures between a master and a secondary eNBs that were presented in the previous section.

A key aspect in the design of integration architectures between WLAN and 3GPP, which is not present in the 3GPP multi-connectivity solutions, is the impact of requiring upgrades in an existent base of deployed WLAN APs such as those that exist in a campus deployment. To address this important requirement 3GPP came up with two separate solutions: i) 3GPP LTE WLAN Aggregation (LWA), targeting greenfield deployments where Wi-Fi APs could embed new functions specified by 3GPP, and ii) 3GPP WLAN Radio Level Integration with IPSEC Tunnel (LWIP) targeting scenarios with legacy APs that could not be modified. In this section we introduce and compare in detail these two 3GPP LTE WLAN integration technologies.

3.1.1.3.1 3GPP LTE WLAN aggregation (LWA)

Figure 3.7 describes the LWA architecture proposed by 3GPP in Release 13. Traffic flows within an EPC bearer until the eNB, where it can be split between the E-UTRAN and the WLAN access networks at the PDCP layer of the eNB. An interface between the eNB and the Wi-Fi AP where the UE is anchored is defined called Xw, with Xw-U and Xw-C, being the traditional user and control plane interfaces based on GTP. A logical function known as Wireless Termination (WT) is embedded in the AP that binds Xw bearers into Ethernet MAC addresses. On the UE side, a reordering function is defined at the PDCP that puts together packets coming from the WLAN and the E-UTRAN accesses. Release 13 defined LWA only in the downlink, and Release 14 added support for the uplink.

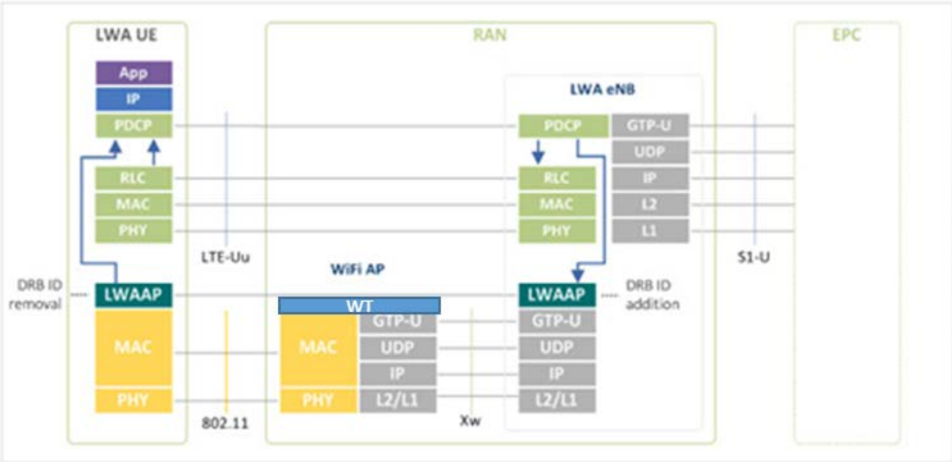


Figure 3.7: LTE Wi-Fi Aggregation (LWA) from [59]

In the data-plane, LWA allows to transmit the PDCP PDUs belonging to LWA bearer either through LTE, through WLAN, or both simultaneously (split bearer), where in the latter case the ratio of packets going through each access can be configured. PDCP PDUs sent via WLAN are encapsulated in LWA Adaptation Protocol (LWAAP), which carries the bearer ID (needed for merging back to LTE PDUs in UE), given that each PDU includes a Xw-U sequence number. Only RLC Acknowledged mode is allowed, so eNB knows about PDPC packets lost over WLAN interface.

In the control plane, procedures are defined to allow the activation/deactivation of LWA bearers by the eNB. The eNB specified WLAN mobility set, identified by the SSID, identifies the set of APs the UE can connect to. WLAN mobility (within the WLAN mobility set) is controlled by UE. To manage the connectivity the UE must support WLAN measurement reports that are delivered to the eNB through RRC. This reporting for WLAN is like the one used in 3GPP, where the UE reports events based on signal thresholds with neighbouring WLAN APs.

Regarding security, it is worth noting that PDCP packets transmitted over WLAN are encrypted. However, LWA also defined WLAN level encryption as mandatory. When connecting to the WLAN network the UE must complete the Extensible Authentication Protocol-Authentication and Key Agreement (EAP-AKA) with the EPC.

Several works in the state of the art have identified the performance achievable by LWA networks. In [60], the authors investigate algorithms to decide what mode a given user should use, i.e. LTE/Wi-Fi only or split mode, and to control the ratio between WLAN and LTE packets in split mode. Using a network simulator based on ns3, the authors show that LWA can significantly outperform other path aggregation mechanisms working at higher layers such as Multipath TCP (MPTCP), providing up to 75% better fairness among UEs associated to the same eNB. For a summary of the LWA deployment level in the market see Section 2.1.5.

3.1.1.3.2 3GPP WLAN Radio Level Integration with IPSEC Tunnel (LWIP)

In Release 13, 3GPP also defined 3GPP WLAN Radio Level Integration with IPSEC Tunnel to address scenarios where the WT functionality could not be added to existent legacy APs. Figure 3.8 depicts the architecture used in LWIP, where the main difference with respect to LWA is that an IPSEC tunnel is setup between the UE and IPSEC gateway (LWIP-SeGW) connected to the eNB.

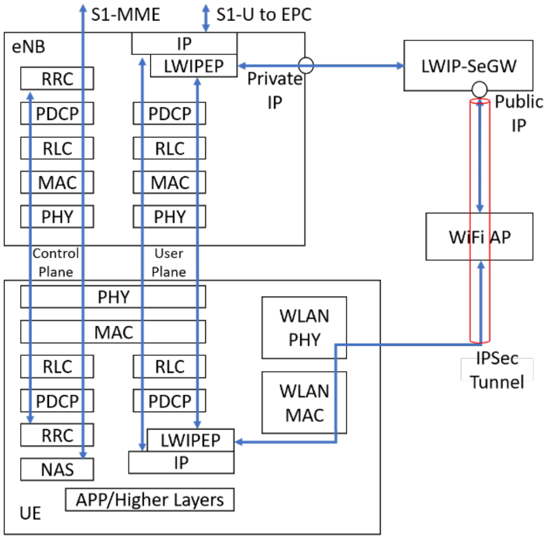


Figure 3.8: LWIP architecture from [61]

In LWIP a single IPSEC tunnel per UE is used for UL and DL data. Multiple bearers can be transmitted over the same IPSEC tunnel. For this purpose, user plane IP packets are encapsulated within a GRE before being transmitted through the E-UTRAN stack (PDCP) or the WLAN network (IPSEC tunnel). The GRE header carries the bearer ID, but no reordering is possible. Therefore, in LWIP a bearer cannot be split between LTE and WLAN, which is a major disadvantage as compared with LWA because LWIP is unable to aggregate the performance of the two access networks for a given UE. However, aggregation is still possible if performed within the UE above the IP layer.

The LWIP control plane is like the LWA one with the activation of the LWIP bearers decided by the eNB, and the WLAN mobility set and measurements being also like LWA.

Regarding security, in addition to the WLAN association and EAP-AKA, authentication also present in LWA, in LWIP the UE establishes IPSEC tunnel with LWIP-SeGW, where the IPSEC keys are derived by the UE and the eNB using the KeNB key installed in the eNB by the MME.

Several works in the state-of-the-art have investigated the performance of LWIP. The authors in [61] develop a custom application acting on top of the LWIP to enable the aggregation of the WLAN and 3GPP access for a given IP flow. For this purpose, the authors needed to implement reordering in the eNB and the UE using low level programming. The paper presents the performance benefits of their solution that allows to split packets between radio access networks specifying a ratio like in the LWA case. The authors in [62] enhance the 3GPP standard LWIP defining a collocated LWIP architecture that enables flow aggregation like in LWA. Several experiments are performed comparing splitting and switching strategies between E-UTRAN and WLAN concluding that split bearer performs equivalently to switched bearer for UDP flows and switched bearer outperforms split bearer in the case of TCP flows.

3.1.2 Non-3GPP access to 5GC

The 5GC network supports both untrusted non-3GPP access networks and trusted non-3GPP access networks (TNANs). An untrusted non-3GPP access network is connected to 5GC Network via N3IWF, whereas a trusted non-3GPP access network may be connected to the 5GC Network via TNGF. Figure 3.9 and Figure 3.10 shows Non-roaming architecture for 5G core network with untrusted non-3GPP access and trusted non-3GPP access. Both the N3IWF and the TNGF interface with the 5GC network control plane and user plane functions via the N2 and N3 interfaces, respectively.

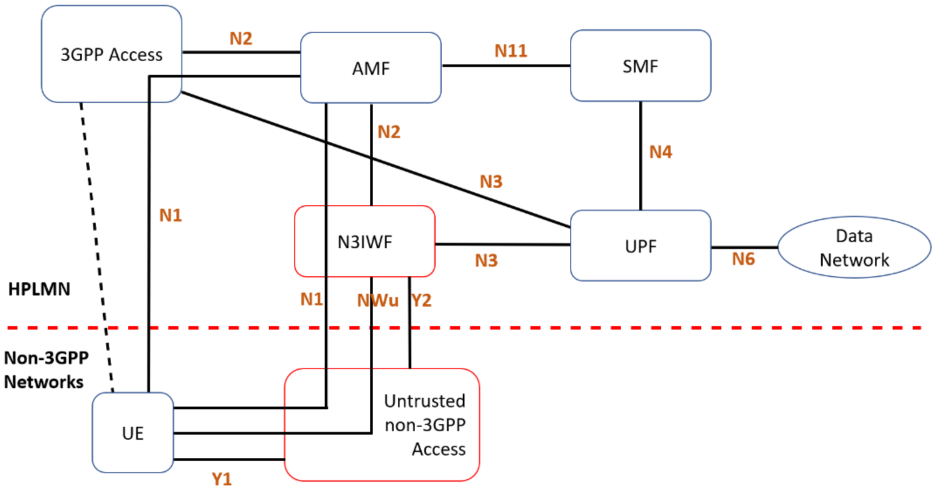


Figure 3.9: Non-roaming architecture for 5G Core Network with untrusted non-3GPP access

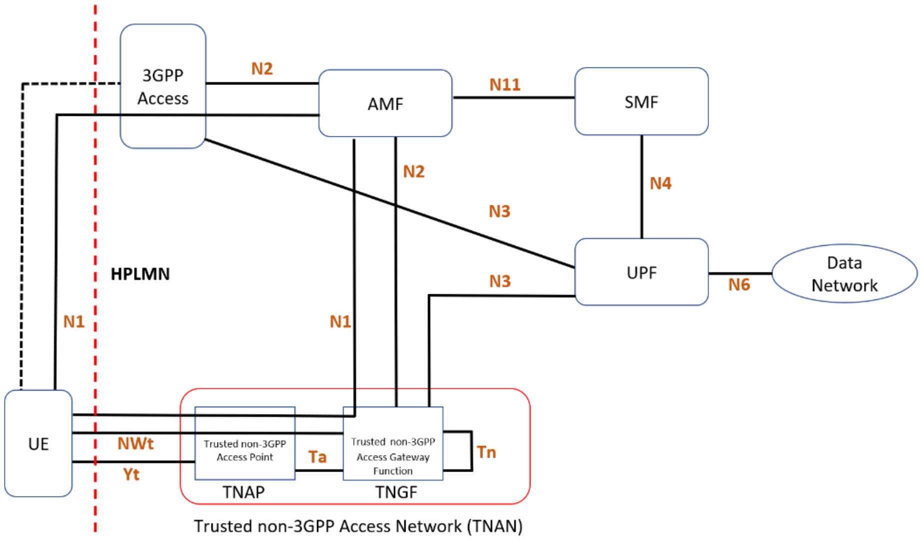


Figure 3.10: Non-roaming architecture for 5G Core Network with trusted non-3GPP access

3.1.2.1 Trusted and untrusted access via TNGF/N3IWF

Access networks in 5G is considered either as trusted or untrusted. The 3GPP study did not specify how trust is established between the WLAN access and the 5G operator. Generally, WLAN access deployed by the same operator would enjoy trust. But the 3GPP trusted model enables a WLAN access deployed by either a third party or a different mobile operator who is trusted by the 5G mobile operator.

One of the key differences between trusted and untrusted access is the security framework on connection establishment. To setup communication between the 5GC and the UE for an untrusted non-3GPP access network, the UE creates a secure link to the 5GC through a N3IWF as described in 3GPP TS 24.501 [63]. The UE continues with the creation of an IPsec Security Association with the chosen N3IWF by initiating an (Internet Key Exchange) IKEv2 Security Association procedure as described in RFC 7296 [64]. The registration ensures the encryption of all subsequent IKE messages by using the IKE Security Association.

An important difference between the N3IWF and the ePDG of previous release, is the proximity of N3IWF to the gNB and use of the N2 and N3 interfaces against ePDG's proximity to core network element. Hence, towards the 5GC, N3IWF would appear like any other 5GNR gNB. The location of an N3IWF is not defined by

3GPP. As the N3IWF needs to terminate flows from UEs operating on third party networks, positioning the N3IWF close to the 5GNR gNB becomes a good option. The location of the N3IWF also enable the performance of gateway functions towards UE in roaming scenarios when moving between different PLMN from the 3GPP access as described in [65].

From [65] devices that are unable to support 5GC NAS signalling over WLAN access are known as "Non-5G-Capable over WLAN" or Non-5G-Capable over WLAN (N5CW) devices. The specifications for such devices have been defined earlier in TS 23.501. However, through a trusted WLAN that supports a trusted Interworking Function (TWIF), N5CW devices may access 5GC in a PLMN. [65] provides a detailed description of how a N5CW device attaches to 5G Core Network and transmit data through PDU session. Non-5G-Capable over WLAN device can link to a trusted WLAN access network and instantaneously attach to a 5GC. When this is done, a single EAP – based authentication protocol is performed for linking the N5CW device to the trusted WLAN access network and attaching the N5CW device to the 5GC.

When a UE is linked through a NG-RAN and through a standalone non-3GPP access, multiple N1 instances will occur for the UE. There will be one N1 instance over NG-RAN and one N1 instance over non-3GPP access. A UE concurrently linked to the same 5GC of a PLMN over a 3GPP access and a non-3GPP access will be provided by a single Access and Mobility Management Function (AMF) in this 5GC. The modifications for the procedure of releasing the N2 signalling link and the N3 UP connection for a N5CW device linked to 5GC through trusted WLAN access are described in [65].

The procedure for UE's registration to 5GC through an untrusted non-3GPP access is specified in 3GPP TS 23.502. From [65], it utilizes a vendor-specific Extensible Authentication Protocol procedure known as "EAP-5G". The "EAP-5G" technique is deployed between the UE and the N3IWF and is used only for encapsulating Non Access Stratum (NAS) messages (not for authentication). Specification of the authentication method are detailed in 3GPP TS 33.501.

From [63] the UE supports NAS signalling with the 5GC via the N1 interface as described by 3GPP TS 24.501 This implies that the UE can request registration to a given single Network Slice Selection Assistance Information (S-NSSAI) without the non-3GPP access knowledge of the S-NSSAI. The N2 and N3 interfaces are used to link standalone non-3GPP accesses to 5GC CP and UP functions as specified in 3GPP TS 23.501. The AMF uses N2 procedures to create the access resources at the N3IWF for a PDU Session. This is triggered by the UE signalling to the AMF using NAS procedure. The procedure for UE's registration to 5GC through a trusted non 3GPP Access Network is specified in 3GPP TS 23.502. The process is like the untrusted non-3GPP access, but the trusted N3AN connects to the 5GC through TNGF.

The UE connects to a TNAN and attaches to 5GC via the TNAN, by using the EAP-based procedure specified in 3GPP TS 23.502, which is similar to the 5GC network attachment procedure over untrusted non-3GPP access. The connection between the UE and the TNAN can be any data link (L2) that enables EAP encapsulation. From [64] TNAN is comprised of two type of NFs. The first is the Trusted Non-3GPP AP, which terminates the UE's over-the-air access connection described in IEEE Std. 802.11. The second is TNGF, which shows the N2/N3 interfaces and enables the UE to connect to the 5GC. Details of the registration procedure, deregistration procedure and 5GC initiated selective deactivation of User Plane connection of a PDU session associated with a Trusted non-3GPP Access are all described in 3GPP TS 33.501.

When the UE chooses to use trusted non-3GPP access to link to a 5GC in a PLMN:

- the UE initially chooses a PLMN, and next
- the UE choose a non-3GPP access network (a TNAN) that enables trusted connectivity to the chosen PLMN. The N3AN selection is affected by the PLMN selection.

A UE that accesses the 5GC over a standalone non-3GPP access shall, after UE attachment, support NAS signalling with 5GC CP functions using the N1 interface. The NAS messages are regularly swapped between the UE and the AMF. The UE can also be authenticated by reuse of the existing UE security context in AMF.

From [66] when a UE is linked to a 3GPP access of a PLMN, if the UE chooses a TNGF and the TNGF is located in a PLMN separate from the PLMN of the 3GPP access, such as in a different VPLMN or in the HPLMN, the UE is served differently by the two PLMNs. The UE is attached with two separate AMFs. PDU Sessions over the 3GPP access are served by V-SMFs different from the V-SMF serving the PDU Sessions over the non-3GPP access.

The N3IWF and TNGF are defined in release 15 and 16 respectively with similar Control and User Plane functionalities. A key distinction between the N3IWF and TNGF occurs when the CN notifies a UE of trust with WiFi access. In this case for NAS protocol, the NULL encryption is deployed and between the UE and TNGF, user plane IPsec Security Association is established. 5G-CLARITY intends to integrate non-3GPP and 3GPP access technologies using enhanced AT3S in its design for use case demonstrations. These technologies are 5GNR (3GPP access), WiFi and LiFi (non-3GPP access) networks.

The integration to the 5GC via the N3IWF or TNGF, will depend on whether the non-3GPP access network is considered untrusted or trusted. Sections 6.2.1.1 and 6.2.3.2 discusses the 5G-CLARITY design in greater details.

3.1.2.2 Wireline access network

3.1.2.2.1 Connection to the 5GC via the Wireline Access Gateway Function (W-AGF)

Wireline Access Gateway Function (W-AGF) is a gateway offering Control Plane and User Plane connectivity from the wireline access networks to the 5GC. W-AGF is deemed as trusted because the access and the 5GC networks are both owned by the same network operator. Hence, W-AGF is Authenticated via the AMF by establishing mutually authenticated Transport Layer Security (TLS) with the core.

W-AGF functionalities have been defined in Wireline 5G Broadband Access network and Wireline 5G Cable Access Network. These definitions have been specified in WT- 456 and WT- 457 for broadband access and Cablelabs WR-TR-5WWC-ARCH for cable access, respectively. It defined W-5GAN connection to the 5G core network through W-AGF. The 5GC Control Plane and User Plane functions interface with the W-AGF through the N2 and N3 reference points. W-AGF supports both 5G Residential Gateway and Fixed Network Residential Gateway.

3.1.2.2.2 5G Residential Gateway (5G-RG)

5G Residential Gateway supports N1 signalling with 5GC by connecting to the AMF via the N1 interface. 5G-RG and FN-RG are based on the specification defined in [67] and [68] which require that W-5GAN be linked to the 5GC through the W-AGF. The N2 and N3 reference points are the link to 5GC Control Plane and User Plane functions. The specification also shows that 5G-RG supports simultaneous connection to 5GC of a PLMN through a 3GPP access and a W-5GAN access while being served by a single AMF. 5G-RG maintains the NAS signalling with the AMF through the W-5GAN after all the PDU sessions through the W-5GAN access has been released or handed over to the 3GPP access.

A 5G-RG has the capability of connecting to 5GC, while playing the role of UE towards the core network. The 5G-RG can serve as either a 5G-BRG or 5G-CRG. From [68] a UE linked to a 5G-RG or FN-RG can access the 5G core network through the N3IWF or through the TNGF. In such scenario the combination of 5G-RG/FN-RG, W-AGF and UPF serving the 5G-RG or FN-RG acts as Untrusted Non-3GPP Access Network or as a Trusted Non-3GPP Access Network [67] as shown in Figure 3.9 and Figure 3.10. 5G multi-operator core network (5G MOCN) is supported for 5G-RG connected through NG RAN as described in [68].

Figure 3.11 shows non-roaming architecture for 5GC using 5G-RG with a 5G wireline access network and NG RAN. It illustrates 5G-RG support for the N1 reference point.

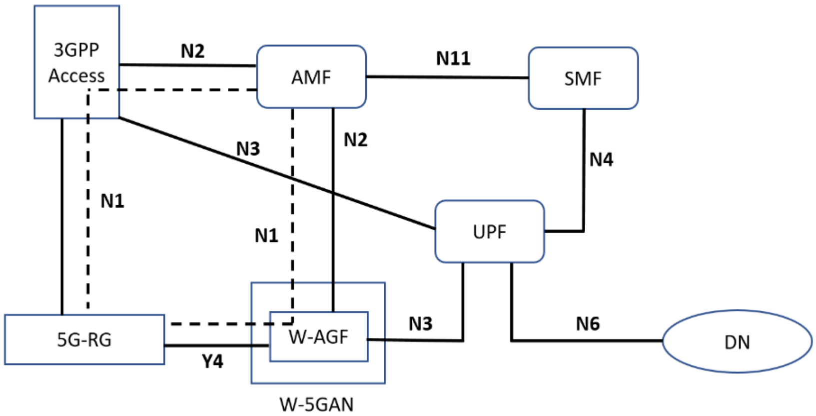


Figure 3.11: Non-roaming architecture for 5GC using 5G-RG

3.1.2.2.3 Fixed Network Residential Gateway (FN-RG)

FN-RG and 5G RG are very similar in operation except FN-RG does not support the 3GPP N1 signalling and is not 5G capable. W-AGF acts on behalf of FN-RG, where the FN-RG connects to the 5GC via wireline 5G access network (W-5GAN). According to [67], W-AGF enables FN-RG connectivity to 5G core network by supporting 5G functionality on behalf of FN-RG. Example of such functionalities where W-AGF acts on behalf of FN-RG towards 5GC connectivity are NAS registration and session management functionality. From [67] W-AGF is specified as "Access Gateway Function (AGF) in WT-456 for supporting 5G-RG and FN-RG and as Fixed Mobile Interworking Function (FMIF) for supporting FN-RG only in the case of presence of Broadband Network Gateway (BNG) in WT-457". It described W-AGF as a Network Function in W-5GAN which enables connectivity between the 5GC and 5G-RG/FN-RG.

As discussed in Section 3.1.1 devices that do not support 5GC NAS signalling over WLAN access are known as non-5G-capable over WLAN devices, or N5CW. Therefore, to support 5GC access from N5CW devices, a trusted WLAN access network must enable the functionality. It is this role that W-AGF plays in providing connectivity between 5GC and FN-RG.

Figure 3.12 shows how the W-AGF interfaces the 5GC control plane and user plane functions through N2 and N3 interfaces on behalf of the FN-RG. It also demonstrates that FN-RG does not support the 3GPP N1 reference point but depends on W-AGF.

From [67] the W-AGF performs the following key functions:

- Acting as endpoint of N1 towards AMF.
- Maintains Connection Management (CM) and Registration management (RM) states and other associated information received from 5GC such as support of UE Route Selection Policy (URSP). From [69] the routing selection priorities for the UE as supplied by the 5GC are specified by 3GPP as UE URSP. The policy rules are contained within the Policy Charging Function (PCF) and are initially transferred to the UE during network registration or Packet Data Unit (PDU) session establishment. The UE uses these policies to help determine which cellular or non-3GPP access to prefer when multiple options are available. The URSP can be instrumental in mobile data offload to Wi-Fi.
- Linking Y5 towards FN-RG and N1/N2 interfaces towards 5GC as well as mapping between a Y5 user plane connection and a PDU session user plane tunnel on N3.

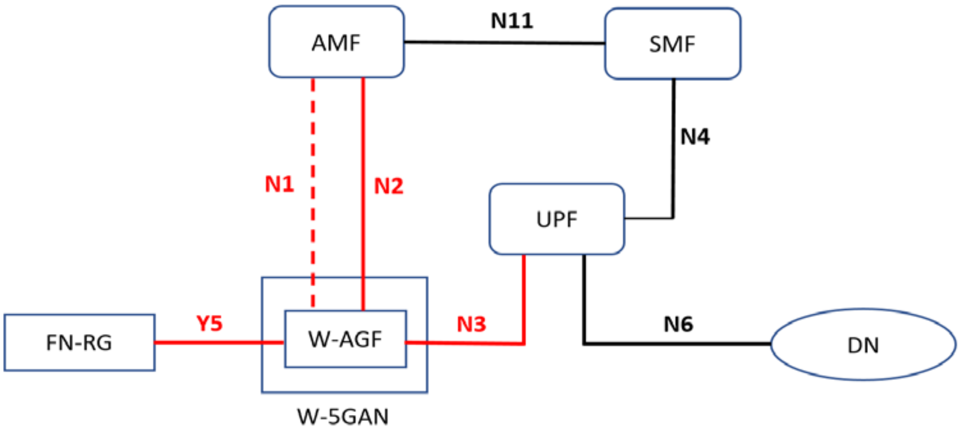


Figure 3.12: Non- roaming architecture for 5GC for FN-RG with W-5GAN and NG RAN

3.1.2.3 Access traffic steering, switching and splitting function

Purpose of the AT3S framework is to support Access Traffic Steering, Switching and Splitting (ATSSS or AT3S) between 3GPP and non-3GPP accesses. 3GPP System Architecture specifies the following aspects of the AT3S:

- Establishment of Multi-Access PDU (MA-PDU) sessions.
- Steering modes that can be applied in a MA-PDU session for deciding how traffic should be steered between the 3GPP and non-3GPP accesses.
- Performance measurements to support AT3S operation.
- AT3S architecture support for IP and Ethernet traffic.
- AT3S solution impacts the 3GPP charging framework, e.g. to enable the network operator to differentiate charging for data traffic that is switched and/or split between 3GPP and non-3GPP accesses.
- Support of two steering functions: A high-layer steering function, based on the MPTCP protocol, and a low-layer steering function based on the AT3S function (ATSSS-LL).
- QoS resources allocation on MA-PDU establishment.
- 5GC Network Policy framework to define the AT3S rules.
- MA-PDU sessions establishment when UE moves from EPC to 5GC.

Figure 3.13 illustrates the AT3S architecture in a 5G network where UEs supporting AT3S functionality support one or more of the steering functionalities specified, e.g. MPTCP functionality and/or AT3S-LL. Each steering functionality in the UE enables traffic steering, switching and splitting across 3GPP access and non-3GPP access, in accordance with the AT3S rules provided by the network. On the network side, the UPF may support MPTCP Proxy functionality, which communicates with the MPTCP functionality in the UE by using the MPTCP protocol. The UPF may support AT3S-LL functionality, which is similar to the AT3S-LL functionality defined for the UE.

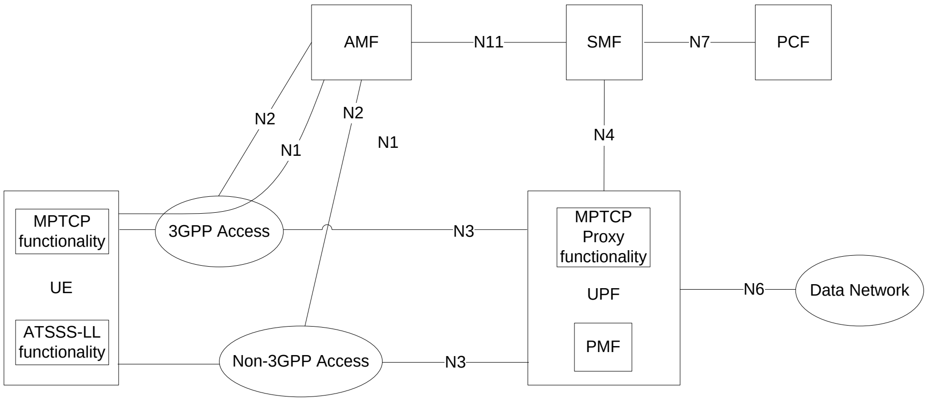


Figure 3.13: Non-roaming and Roaming with Local Breakout architecture for AT3S support

Access Traffic Steering is the procedure that selects an access network for a new data flow and transfers the traffic of this data flow over the selected access network. Access traffic steering is applicable between 3GPP and non-3GPP accesses. Currently, five steering modes are described in [70] namely active-standby, smallest delay, load-balancing, redundant and priority-based. When the load-balancing steering mode is selected, a weight information element is used to indicate the proportion of the traffic to be forwarded to 3GPP and non-3GPP access networks. When either the active-standby or priority-based is selected, a priority information element is used to indicate at which condition the traffic should be forwarded to 3GPP and non-3GPP access networks. The low priority network (or standby network) is used if the active network is unavailable or congested. The former is the condition for the active-standby mode and the latter is the condition for the priority-based steering mode. Whereas, when redundant mode is selected, both access networks are used to transmit the same data flows [71]. It is important to note that the noted steering modes can also be used for traffic switching and splitting. The reason of calling them as “steering” mode is for reason of simplicity according to [70].

Access Traffic Switching is the procedure that moves all traffic of an ongoing data flow from one access network to another access network in a way that maintains the continuity of the data flow. Access traffic switching is applicable between 3GPP and non-3GPP accesses.

Access Traffic Splitting is the procedure that splits the traffic of a data flow across multiple access networks. When traffic splitting is applied to a data flow, some traffic of the data flow is transferred via one access and some other traffic of the same data flow is transferred via another access. Access traffic splitting is applicable between 3GPP and non-3GPP accesses.

Multi-Access PDU Session: is a PDU session whose traffic can be sent over 3GPP access, or over non-3GPP access, or over both accesses.It is important to note that AT3S mechanisms can be used for simultaneous connectivity over 3GPP and non-3GPP accesses. Having a simultaneous connectivity over only 3GPP access is not handled by AT3S and it is provided by MR-DC as described in Section 3.1.1.2.

The overall AT3S execution procedure is depicted in Figure 3.14 and can be summarized as follows:

1) PCF (PC-AT3SF) defines AT3S policy based on information from UDR (UDR-AT3SF) and UE (UE-AT3SF) and sends AT3S policy to SMF (CP-AT3SF).
2) AT3S policy is configured at the UE (UE-AT3SF) and SMF (CP-AT3SF).
3) CP-AT3SF in SMF determines to perform AT3S operation, generates AT3S rules based on PC-AT3SF policy and pushes AT3S rules to UPF via N4 interface (for downlink traffic) and UE via N1 interface (for uplink traffic). The AT3S rules are based on UE capability for steering and supporting functionality (MPTCP and/or ATSSS-LL), hence, the rules are flow based for each UE.
4) UPF (UPc-AT3SF) executes the AT3S rule. When downlink data arrives, the UPF (UPc-AT3SF) determines the appropriate access path(s) based on the AT3S rule.

5) UPF (UPu-AT3SF) sends the downlink data to the UE via the selected access path(s).
6) UE (UE-AT3SF) performs path performance measurement for each access path and reports to SMF via SM-NAS signalling. UE-AT3SF also derives AT3S rules for uplink direction.
7) Based on performance measurement results, SMF (CP-AT3SF) updates the AT3S rules and configures updated rules to UE and UPF.

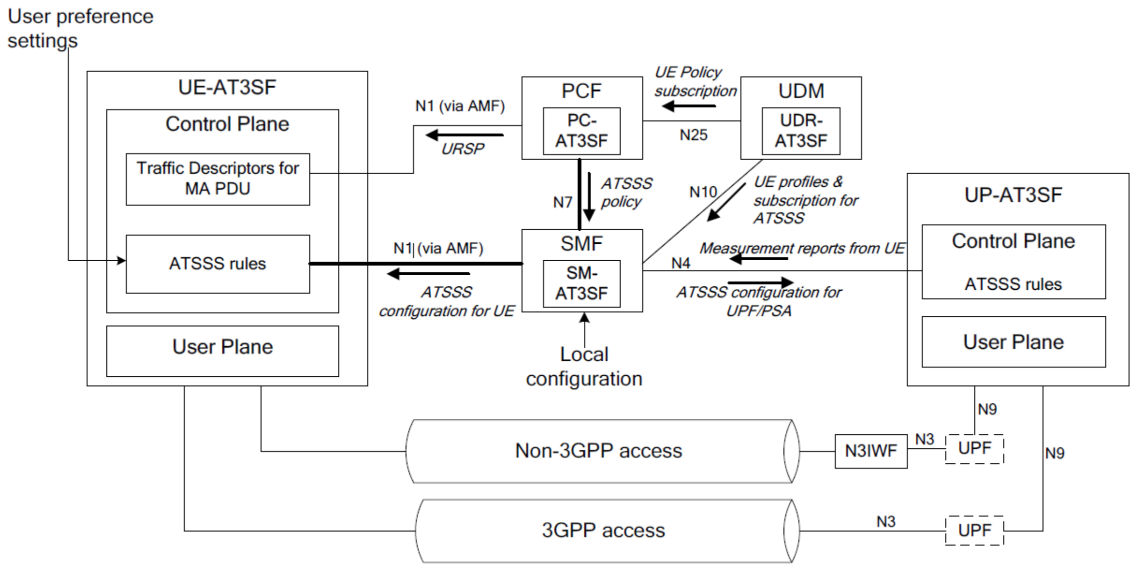


Figure 3.14: AT3S execution and interaction between AT3SFs [70]

AT3S may use multi-path TCP proxy to select and steer traffic flows. MPTCP is a set of extensions to regular TCP [72] to provide a MPTCP service [73], which enables a transport connection to operate across multiple paths simultaneously [74]. The AT3S system need to be able to communicate servers that supports MPTCP as well as traditional TCP servers. In order to support TCP servers, the MPTCP capable devices may need to fall back to traditional TCP. In order to support the use of MPTCP session between an MPTCP host and a TCP host, or to help to aggregate MPTCP subflows, an MPTCP proxy may be used. Following figure illustrates MPTCP proxy architecture.

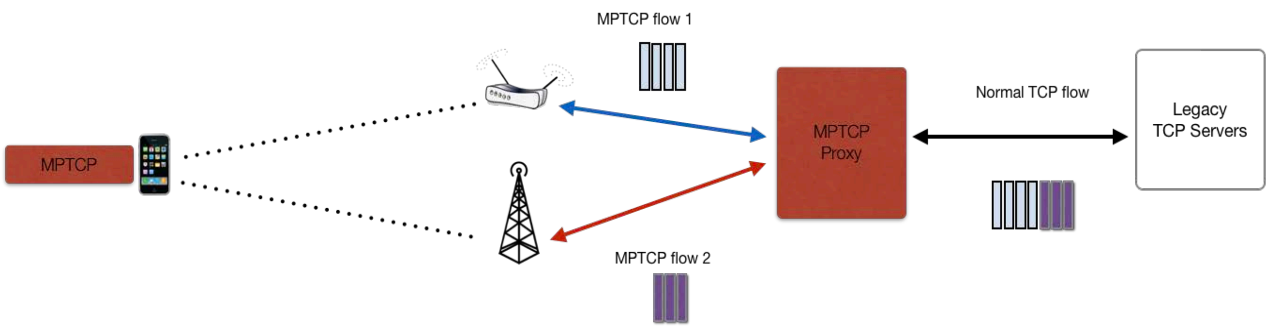


Figure 3.15: Illustration of an MPTCP proxy [70]

3.1.3 LiFi and Wi-Fi Integration

Since optical radiation does not interfere with other electromagnetic waves, LiFi enables safe and reliable data transmissions where RF communication exists [75]. The hybrid LiFi and Wi-Fi network (HLWNet) is a recently proposed and promising approach to indoor wireless communication which integrates the LiFi and Wi-Fi techniques. The HLWNet was first mentioned in [76] in order to combine the high-speed downlink data transmission of LiFi and the ubiquitous coverage of Wi-Fi for uplink as well as downlink transmissions. Research efforts have been made towards the framework which includes the network structure, cell deployment, multiple access schemes, modulation techniques, illumination requirements and backhauling. The challenges, including user behaviour modelling, interference management, handover and load balancing, are being studied by researchers where a detailed survey of these works can be found in [77]. Most of these research efforts focus on theoretical analysis and/or simulations without an experiment or a prototype design.

A very first implementation of HLWNet is presented in [78]. Two HWLNet models are proposed namely hybrid and aggregated. In the hybrid model, a Visible Light Communication (VLC) network is used to complement Wi-Fi network for downlink transmission by offloading data from Wi-Fi network whereas Wi-Fi network is used for both downlink and uplink transmissions. In the aggregated model, both bidirectional Wi-Fi and VLC links are aggregated to improve the achievable throughput in both downlink and uplink directions. The Linux Ethernet bond driver in adaptive load balancing mode is used to aggregate the data link of Wi-Fi and VLC networks.

In [79], HWLNet named Light-Radio WLAN (LiRa) that uses Wi-Fi for downlink and uplink communications whereas VLC for downlink only is proposed. The main purpose of LiRa is to minimize impact of VLC control frames (ACK) on legacy Wi-Fi traffic by prioritizing VLC APs on Wi-Fi channel. Although its performance is demonstrated via over-the-air experiments, LiRa requires modifications on Wi-Fi driver and protocol as well as harms legacy Wi-Fi devices in uplink transmission due to prioritizing VLC APs for uplink transmission. In [80], in order to integrate VLC and Wi-Fi networks, an additional sub-layer named link convergence (LC) is defined in between IP and data link layers. The purpose of defining such a sub-layer is to mitigate any modification on Wi-Fi MAC driver or protocols, hence can be implemented to any commercial Wi-Fi network interface card. A single AP which is capable of Wi-Fi and VLC technologies is considered. Due to the considered AP structure, a user can only use VLC link of the connected Wi-Fi AP. The functions described for the LC layer at the AP side are (i) periodic beacon generation; (ii) local ARP table that maps single IP address to Wi-Fi and VLC MAC addresses; (iii) VLC link maintenance table; (iv) selective ARQ to retransmit the lost packets; and (v) downlink handover between VLC and Wi-Fi. At the user side, the functions described for the LC layer are (i) sending control information, link strength, etc… on VLC link access request to the AP; (ii) periodic beacon feedback transmission; (iii) selective ARQ; and (iv) reordering the received packets from the VLC MAC layer before forwarding them to the IP layer. It is important to note that a single AP is capable of Wi-Fi and VLC technologies.

A software-defined networking (SDN)-enabled switch connects both LiFi and Wi-Fi APs and extracts key performance indicator (KPI) information from them. This information is sent to the SDN controller which makes decisions on the flow routes of each incoming data packet. In [75], an SDN-enabled testbed platform with a HWLNet deployment is considered. Horizontal (LiFi to LiFi) and vertical (LiFi to Wi-Fi or Wi-Fi to LiFi) handover decisions are managed by the SDN controller. A high-definition video transmission for a mobile user is considered to demonstrate user service disruption within the HWLNet deployment. It is shown that, the current SDN controller can effectively manage horizontal and vertical handover events where the user experiences around 5s of service disruption during the vertical handover event from LiFi to Wi-Fi. However, it is noted that such a service disruption is not noticeable as the video transmission typically employs a buffer storage that can handle the transmission jitter.

In [75], a real-world HWLNet deployment in a school is also demonstrated. Different from the SDN-enabled testbed platform, the purpose of this deployment is to show how LiFi can complement Wi-Fi networks by offloading data from Wi-Fi network in order to increase its user quality of service experience (QoS). The considered network deployment consists of 8 LiFi APs inside a classroom and 2 Wi-Fi APs that are used to serve seven classroom and deployed in the corridor of the school. It can be expected that a large number of users request service from the two Wi-Fi APs. The capability of each LiFi AP is noted as maximum 8 users with a maximum aggregate data rate of 43 Mbps. Twenty-two laptops (a laptop for each student) are connected to LiFi APs inside a classroom and each of the two neighboring classrooms with the same student population was served by Wi-Fi only. It is shown that the data rate of neighboring Wi-Fi only classrooms increased significantly by offloading data traffic onto LiFi network. A proper HWLNet deployment by adopting the SDN-based dynamic load-balancing to the real-world use case is noted as a future work.

Different from the noted HWLNet implementation studies, MPTCP [81] is used to integrate the HWLNet links including Wi-Fi uplink and downlink as well as VLC downlink and IR uplink in [82]. Employing MPTCP in the HWLNet deployment enables pairing Wi-Fi and VLC links flexibly. In other words, Wi-Fi and VLC APs/networks can be deployed independently, and their link capacities can be utilized simultaneously. The data frames are separated at the network layer and different IP headers are added to the frames transmitted through different links. During VLC uplink transmission, a Contention Access Period (CAP) signalling frame is generated in order to provide user location information and size of time slot when there is a change in the conditions such as beacon identity change or counter time out. Similar to the noted SDN-enabled HWLNet deployment, a central coordinator is considered to store user access/link information and manage all transmission links. Two LiFi APs and one Wi-Fi AP are considered in the experiment platform. Also, a user location based simple handover mechanism is employed in the demonstration. It is shown that employing MPTCP in a HWLNet mitigates service disruption and improves achievable data rates for mobile users by effectively managing Wi-Fi and LiFi links – either use both of them if there is enough signal quality for both networks or use one of them during a handover event.

3.2 High level requirements for 5G-CLARITY multi-connectivity framework

The 5G-CLARITY multi-connectivity framework aims for integrating a wide range of technologies, particularly 5GNR, 4G LTE, IEEE Wi-Fi and IEEE LiFi. The conceptualised framework is required to enable traffic steering, switching and splitting functionalities among the accessible technologies in order to boost the achievable data-rate, reduce latency and to improve link reliability. Table 3-1 specifies the 5G-CLARITY requirements associated with this multi-connectivity framework.

Table 3-1: Multi-connectivity framework requirements

MC Requirements	Description
MC-R1	The 5G-CLARITY multi-connectivity framework shall concurrently support the control plane functionality or protocol stacks for the following access technologies: 5GNR, 4G LTE, Wi-Fi and Li-Fi.
MC-R2	The 5G-CLARITY multi-connectivity framework shall concurrently support the user plane functionality or protocol stacks for the following access technologies: 5GNR, 4G LTE, Wi-Fi and Li-Fi.
MC-R3	The 5G-CLARITY multi-connectivity framework shall decouple 5GNR, LTE, Wi-Fi and Li-Fi access network control software from the underlying hardware through virtualization.
MC-R4	The 5G-CLARITY multi-connectivity framework shall support software defined per UE traffic steering and shaping operations such as: scheduling, packet filtering, segmentation, duplication, concatenation, etc.
MC-R5	The 5G-CLARITY multi-connectivity framework shall support the offloading of user plane traffic from one access technology to other access technologies. No single access is considered as primary
MC-R6	The 5G-CLARITY multi-connectivity framework shall support split bearers between traffic flows, e.g. LiFi in downlink and NR or Wi-Fi in uplink, etc.

MC-R7	The 5G-CLARITY multi-connectivity framework shall provide a multi-access context service platform that extracts access specific information/metrics from the following access technologies: 5GNR, LTE, Wi-Fi and Li-Fi; for instance, radio network information and location information.
MC-R8	The 5G-CLARITY multi-connectivity framework shall provide APIs to expose the multi-access context to several applications, e.g. user applications, network applications, 3rd-party applications, etc.
MC-R9	The 5G-CLARITY multi-connectivity framework shall aggregate the following access technologies: 5GNR, LTE, Wi-Fi and Li-Fi.

4 Resource Management

The support for different service types and utilizing various access networks in 5G systems requires an enhanced resource management framework. For 5G systems, the term resource can represent a portion of the channel bandwidth as it is in 4G systems and/or an access technology such as 5GNR, Wi-Fi or LiFi. Therefore, using all the available resources efficiently and satisfying different service requirements such as data rate, latency, reliability, etc., have great importance for network/infrastructure operators. This section firstly provides an overview of the state-of-the-art resource management related components including access technology-specific resource structures and multi-user access schemes, network deployment types, user-cell association and scheduling approaches. This is followed by a list of requirements that is going to be fulfilled by 5G-CLARITY resource management framework solution.

4.1 State-of-the-art

4.1.1 Physical resource structure and multi-user access

4.1.1.1 4G/5G

In Europe, Frequency Division Duplexing (FDD) is used as the duplexing method for 4G/LTE. An FDD frame has 10 ms duration and consists of subframes and slots. Each subframe has 1 ms interval, which is also termed as Transmission Time Interval (TTI) and consists of two equally sized slots with 0.5 ms, as shown in Figure 4.1. In each slot, there are 6 (extended cyclic prefix) or 7 (normal cyclic prefix) OFDM symbols based on the used cyclic prefix type. In each OFDM symbol, the subcarriers are located with 15 kHz spacing. During one slot, 12 consecutive subcarriers (180 kHz) correspond a Resource Block (RB). The number of RBs, N_{RB}, spans between 6 and 100 depending on the transmission bandwidth, as given in Table 4-1.

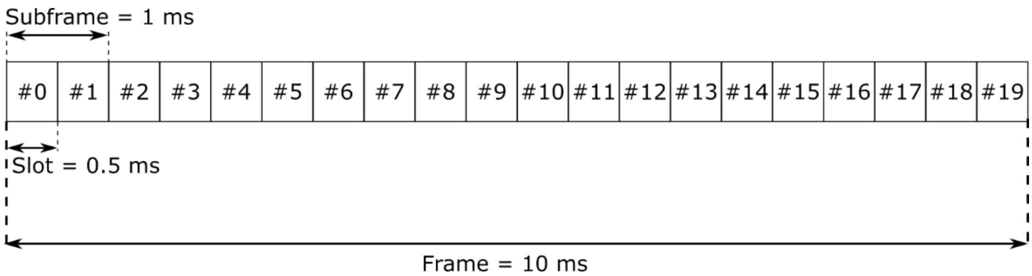


Figure 4.1: LTE frame structure

Table 4-1: Number of RBs for different channel bandwidths

Bandwidth [MHz]	1.4	3	5	10	15	20
N_{RB}	6	15	25	50	75	100

In LTE systems, the modulation order to be used on a RB is represented by a Modulation and Coding Scheme (MCS) index, and it is chosen by the Adaptive Modulation and Coding (AMC) functions. Adaptive downlink power allocation to the available RBs is not supported in LTE. This implies that the power amplifier is always transmitting at full power and the downlink-rate adaptation is controlled by adjusting the MCS indexes using AMC functions [83]. The AMC functions use channel quality indicator (CQI) reports to decide on the MCS indexes. In LTE, CQI reporting and MCS index assignments are based on a set of defined structures. Due to extensive signaling overhead, CQI reporting with per RB granularity and using different MCS indexes across scheduled RBs for a user are not supported [19]. Thus, subband and wideband based CQI reporting modes and single MCS assignment to all RBs allocated to a user are currently used in LTE systems.

Based on LTE specification [84], CQI reports can be sent periodically or aperiodically. In the periodic reporting, UE reports its CQI based on a fixed period. In the aperiodic reporting, UE reports its CQI based on a request from the eNB. Moreover, the CQI reporting is classified into modes as wideband (Mode 1-0), UE-selected subband (Mode 2-0) and higher layer configured subband (Mode 3-0). In wideband CQI reporting Mode 1-0, the UE reports a single CQI for the whole bandwidth. However, in periodic CQI feedback in Mode 2-0 and aperiodic Mode 3-0, the UE reports a CQI for a portion of the bandwidth. The difference between Mode 2-0 and Mode 3-0 is how the reported subband is chosen. In Mode 2-0, the UE selects the best M subbands and reports the averaged CQI value of the selected M bands. However, in Mode 3-0, the eNB decides which subband will be reported by the UE.

In LTE, orthogonal frequency division multiple access (OFDMA), which allows multiple users to access the frequency resources at the same time, is used as the multiple access technique. In LTE, the smallest unit that can be assigned to users is the RB. The way to assign the available RBs is called resource allocation (RA) and it is also based on a defined structure. In LTE, RA is divided in three different types, Type 0, Type 1 and Type 2 [84].

In Type 0, contiguous RBs are grouped and RB groups (RBGs) are allocated to users based on a bitmap. The granularity of the allocation in Type 0 is a RBG where the number of RBGs is 19 for 15 MHz and 25 for 20 MHz.

In Type 1, RBs are grouped as in Type 0. However, in Type 1, an additional grouping is also used to group RBGs. In LTE specification [84], the grouped RBGs are termed 'subset' and number of subsets are defined as 4 for 15 MHz and 20 MHz channel bandwidths. Same as in Type 0, the bitmap approach is used to indicate which resources are allocated to users. However, in Type 1, the bitmap indicates a selected subset and allocated RBs in this subset. Accordingly, the granularity of the allocation is a RB in Type 1.

In Type 2, the allocation does not rely on a bitmap. A resource indication value (RIV) is used to indicate the start position and length of the RA. Based on the indicated RIV information, Type 2 supports contiguous RB allocation whereas non-contiguous RB allocation can be supported by using virtualised resource blocks (VRBs).

Whereas in 5G, OFDM numerology such as subcarrier spacing, symbol length as well as TTI are scalable in order to support operation in (i) different bands such as sub-6 GHz and mmWave bands; and (ii) different service requirements such as enhanced Mobile BroadBand (eMBB), Ultra-Reliable Low Latency Communications (URLLC) and massive Machine Type Communications (mMTC). As in LTE, a frame has a duration of 10 ms and consists of 10 subframes with a duration of 1 ms. However, the slot duration as well as bandwidth of a RB (as in LTE, 12 consecutive subcarriers correspond to a RB) in 5G are dependent on the OFDM numerology μ [85]. Table 4-2 shows numerology dependant subcarrier spacing, RB bandwidth, number of slots per subframe and slot duration. For all considered OFDM numerologies, the number of OFDM symbols per slot is 14. As it can be seen from Table 4-2, μ=0 represents the RB used in LTE.

Table 4-2: Numerology dependant resource structure

μ	Subcarrier spacing ($2^{\mu}.15$)	RB bandwidth	Number of slots per frame	Number of slots per subframe	Slot duration (TTI)
0	15 kHz	180 kHz	10	1	1 ms
1	30 kHz	360 kHz	20	2	0.5 ms
2	60 kHz	720 kHz	40	4	0.25 ms
3	120 kHz	1440 kHz	80	8	0.125 ms
4	240 kHz	2880 kHz	160	16	0.0625 ms

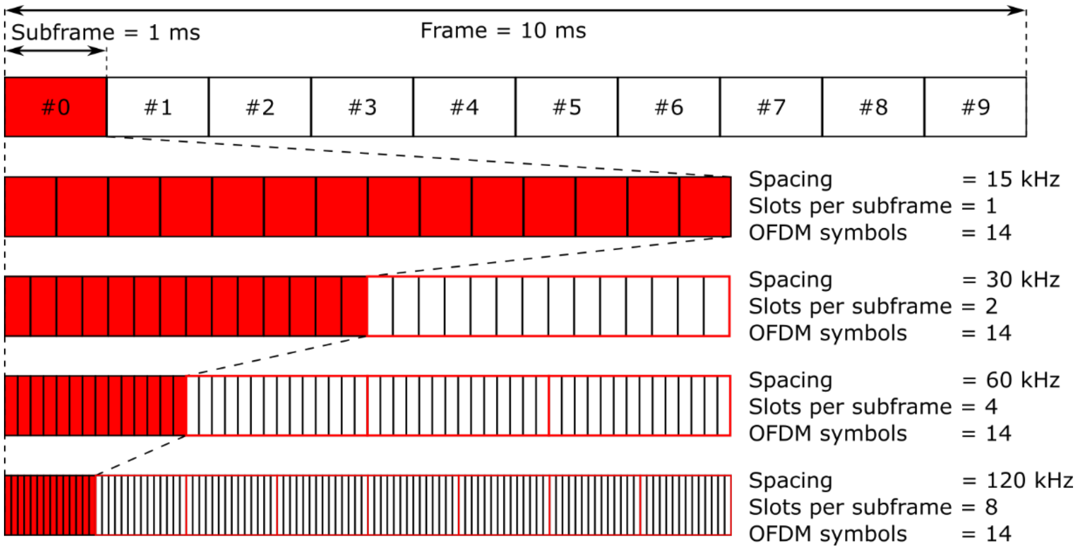


Figure 4.2: 5G frame structure

Different from LTE, a slot format is described in 5G. In time division duplex (TDD) LTE, downlink and uplink traffic is allocated based on a subframe which means that all the symbols within a subframe/slot either used for downlink or uplink traffic. However, in 5G NR, each symbol within a slot can be allocated to different traffic directions or can be left unallocated. Such a symbol allocation within a slot is named as slot format in 5G in order to make the 5GNRsystem flexible to operate on TDD and FDD [86].

Another new concept in 5GNRcompared to LTE is bandwidth part (BWP) which consists of a contiguous set of RBs. As 5GNRoperates on up to 100 MHz in sub-6 GHz (termed as FR 1) and up to 400 MHz in mmWave (termed as FR 2) with bands, not every UE has the capability to operate on such high bandwidths. Using BWP enables UE to operate on the given BWP instead of the whole carrier bandwidth. Therefore, BWP is used to subdivide the operating bandwidth and allow it to be used for different purposes such as energy efficiency or spectrum efficiency. Based on 3GPP specifications, a UE can be configured up to 4 BWPs in downlink as well as uplink directions but can only be active on one of them at a time. These configured 4 BWPs can have different subcarrier spacing and number of RBs and they are identified with their starting RB. The switching of BWPs during transmission can be initiated by using DCI, inactivity timer or the MAC entity through random access procedure [87].

As in LTE, wideband or subband CQI reports can be sent periodically or aperiodically in 5G. Different from LTE, the subband granularity in 5G depends on configured BWPs. The size of a subband to perform measurements can be 4, 8, 16 or 32 depending on the size of the BWP and its associated number of RBs [88]. Therefore, in 5G, additional reporting configurations are used such as starting RB and number of RBs. Moreover, in 5G, three different tables are considered for CQI reporting and its MCS index determination according to different values for the BLock Error Rate (BLER) criteria.

5G also uses OFDMA as the multiple access technique. As noted, three different RA types are considered in LTE. A similar approach is also considered in 5G. Two of the three considered RA types in LTE are used with some modifications in 5G. In RA Type 0 in 5G, a similar approach to RA Type 0 in LTE is considered. Consecutive RBs are grouped as RBGs and allocated to users based on a bitmap. Different from LTE, the size of a bitmap as well as RBG depend on the size of the BWP and considered configuration in 5G [88]. RA Type 1 in 5G is similar to RA Type 2 in LTE. Instead of a bitmap, a RIV is used to indicate starting RB and number of consecutive RBs within the considered BWP. For time domain scheduling, 5G also has similar mechanisms to LTE but with more flexibility and granularity.

4.1.1.2 Wi-Fi

As in cellular networks, Wi-Fi networks continue its evolution under IEEE 802.11 standardization groups. The differences from one Wi-Fi standard to another are either in physical layer such as utilizing wider channel bandwidths, employing more antennas, using faster modulation and coding schemes or in medium access layer such as using different multi-user access mechanism. For most of the recent Wi-Fi standards such as 802.11a/g/n/ac, OFDM is used as the waveform with the same subcarrier spacing of 312.5 kHz. The difference in the OFDM numerology for these standards is the number of subcarriers used for data transmission. For instance, 48 subcarriers are used for data transmission in 802.11a and 802.11g whereas 52 subcarriers are used in 802.11n and 802.11ac. Other differences from 802.11n to 802.11ac are the supported channel bandwidths and modulation orders. In 802.11n, a maximum of 40 MHz channel bandwidth, as a chunk of 20 MHz bandwidths, can be utilized with a maximum modulation order of 64-QAM and a maximum spatial stream of four for a single user. However, in 802.11ac, up to 160 MHz, again as a chunk of 20 MHz channels, can be utilized with a maximum modulation order of 256-QAM and up to eight spatial streams for multiple users [89].

One of the aims of Wi-Fi standards is to have backward compatibility at the PHY and MAC layers. In the noted Wi-Fi standards, distributed coordination function (DCF) which employs carrier-sense multiple access with collision avoidance (CSMA/CA) with random backoff timers is used as the multi-access mechanism. The basic idea of CSMA/CA is to allow data transmission without causing an interference. In other words, a token is used among users that are connected to the same AP or are in close proximity to use the same channel bandwidth on different APs.

The data transmission in CSMA/CA works as follows. Firstly, a device sends a short signal called request to send (RTS) to verify that the intended channel bandwidth(s) to be used is free for transmission. The RTS signal also informs the receivers on the source, destination and duration of the intended transmission. If the received RTS is for the intended destination and the intended channel bandwidth(s) to be used is free for transmission, the destination device sends another short signal called clear to send (CTS) to confirm that the medium is free for transmission for the source device. The CTS signal also informs the nearby devices that the intended channel bandwidth(s) will not be free for the duration of the intended transmission. Therefore, the nearby devices set their network allocation vectors (NAVs) to prevent any sensing or transmission initializations during the informed transmission period. Lastly, the source device transmits its data and the destination device sends an acknowledgment signal if the transmission was successful. In case of the intended channel bandwidth(s) are not free for transmission, the source device prevents itself to instantiate any transmission during a backoff time which is a random amount of time. This process is done for each chunk of 20 MHz channel bandwidths in case of utilizing 80 MHz or 160 MHz of channel bandwidths in 802.11ac [89].

In Wi-Fi standards, DCF can be considered as the main coordination function. In addition to DCF, another coordination function named point coordination function is also described. In point coordination function, contention-free and contention periods are defined, and APs are responsible to coordinate these periods by sending beacon frames at regular intervals. During the contention period, DCF is used and during the contention-free period, AP allows stations to send a packet, one at a time. Based on the described multi-access mechanisms DCF and point coordination function, it can be seen that the scheduling in W-iFi networks is in time domain. In other words, the whole channel bandwidth of 20 MHz (or bonded chunks of 20 MHz up to 160 MHz) is used for high bandwidth demanding applications such as video transmission or very low bandwidth demanding applications such as e-mail or text transmission, regardless of the application traffic type. Although enhanced distributed channel access (EDCA) is used to improve QoS of Wi-Fi networks, it assigns different priority levels to different traffic classes and reduces waiting time for high priority traffic types. Therefore, CSMA/CA based DCF for multi-user access does not efficiently use the available channel bandwidth which becomes a major problem in dense network deployments due to interference [90].

In a recent Wi-Fi standard named 802.11ax (also known as WiFi 6) the inefficient use of channel bandwidth is mitigated by employing OFDMA as the multi-user access mechanism. In other words, 802.11ax makes Wi-Fi radio access like 4G/5G networks. However, 802.11ax uses OFDMA on top of DCF. Therefore, OFDMA in 802.11ax is not time-based as in 4G/5G, it is frame-based [90]. In 802.11ax OFDMA, adjacent subcarriers (tone) are grouped together and formed a resource unit (RU). Different from 4G/5G where a group of adjacent 12 subcarriers form a RB in 4G/5G networks, there are several definitions on the number of adjacent tones to be grouped to form a RU in 802.11ax, from 26-tone to up to 996-tone as shown in Table 4-3 [90].

Another major change in 802.11ax compared to other Wi-Fi standards is the subcarrier spacing, in other words symbol duration. As noted, 802.11a/g/n/ac use 312.5 kHz subcarrier spacing, which is equivalent to a symbol duration of 3.2 µs. Whereas in 802.11ax, the subcarrier spacing is equal to 78.125 kHz and the symbol duration is 12.8 µs. In other words, number of subcarriers per 20 MHz channel is quadrupled from 64 to 256.

In Table 4-4, the three most recent Wi-Fi standards namely 802.11n/ac/ax are compared in order to summarize the differences in PHY and MAC layers.

Table 4-3: IEEE 802.11ax OFDMA RU structure

Number of subcarriers per RU	Number of RUs per channel bandwidth			
	20 MHz	40 MHz	80 MHz	160 MHz (80+80)
26-tone	9	18	37	74
52-tone	4 + 1x26-tone	8 + 2x26-tone	16 + 5x26-tone	32 + 10x26-tone
106-tone	2 + 1x26-tone	4 + 2x26-tone	8 + 5x26-tone	16 + 10x26-tone
242-tone	1	2	4 + 1x26-tone	8 + 2x26-tone
484-tone	NA	1	2 + 1x26-tone	4 + 2x26-tone
996-tone	NA	NA	1	2

Table 4-4: Comparison of IEEE 802.11n/ac/ax features

Feature	802.11n	802.11ac	802.11ax
Operating band	2.4/5 GHz	5 GHz	2.4/5/6 GHz
Supported bandwidth	20/40 MHz	20/40/80/160 MHz	20/40/80/160 MHz
Waveform	OFDM	OFDM	OFDM
Symbol duration	3.2 µs	3.2 µs	12.8 µs
Subcarrier spacing	312.5 kHz	312.5 kHz	78.125 kHz
Maximum modulation order	64-QAM	256-QAM	1024-QAM
Channel access mechanism	DCF - CSMA/CA	DCF – CSMA/CA	DCF - OFDMA

4.1.1.3 LiFi

Currently, there are commercial LiFi products which are based on either 802.11 or ITU-T G.vlc. The IEEE 802.11bb Task Group on Light Communications is focused on introducing necessary changes to the base IEEE 802.11 standards to enable communications in the light medium. A LiFi standard could be released as early as 2021, according to the IEEE 802.11bb. The new Light Communication PHY will be discussed and specified within this task group. The commercial success of LiFi would require the participant in the development of IEEE 802.11bb, which ensures that LiFi can be integrated seamlessly across the ecosystem, from chipset developers, to infrastructure providers and more.

LiFi-XC, which is a commercial product of PureLiFi, supports fully networked, cellular communications, on full-duplex links with 43 Mbps throughput on downlink and uplink. LiFi-XC uses an OFDM PHY, designed based on IEEE 802.11. The system architecture of LiFi-XC is shown in Figure 4.3. Multi-user access and roaming between APs are supported.

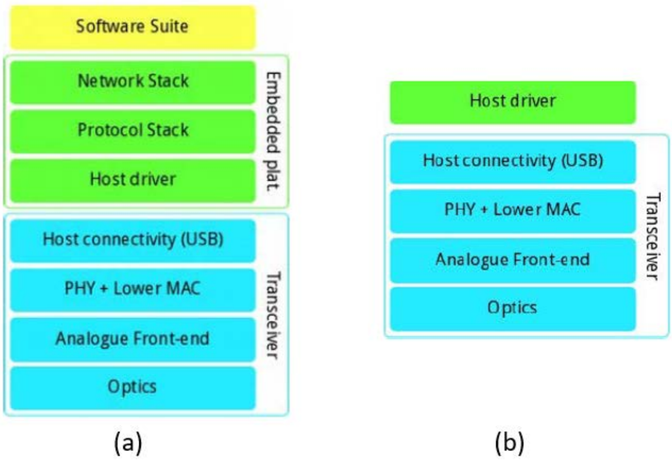


Figure 4.3: LiFi-XC system architecture (a) AP, (b) STA

4.1.1.3.1 IEEE 802.11 OFDM PHY

According to OFDM PHY described in [91], the system provides a WLAN with data payload communication capabilities of up to 54 Mbps. The system uses 52 subcarriers that are modulated using binary or quadrature phase shift keying (BPSK or QPSK) or using 16- or 64-quadrature amplitude modulation (16-QAM or 64-QAM). Forward error correction coding is used with a coding rate of 1/2, 2/3 or 3/4. Major parameter of the OFDM PHY are shown in Table 4-5 [91].

Table 4-5: Major parameters of the IEEE 802.11 OFDM PHY

Information data rate	**6, 9, 12, 18, 24, 36, 48 and 54 Mbps (20 MHz channel spacing)**
Modulation	**BPSK OFDM, QPSK OFDM, 16-QAM OFDM, 64-QAM OFDM**
Error correcting code	**K=7 (64 states) convolutional code**
Coding rate	**1/2, 2/3, 3/4**
Number of subcarriers	**52**
OFDM symbol duration	**4.0 us**
Occupied bandwidth	**16.6 MHz**

The standard format for the Physical layer protocol data unit (PPDU) is shown in Figure 4.4. The PHY Preamble field is used for synchronization. It consists of 10 short symbols and 2 long symbols. The PHY Preamble is followed by the SIGNAL field and DATA. The SIGNAL field contains information such as the type of modulation and the coding rate as used in the rest of the packet, and the length of the data to be transmitted. The DATA field includes the PHY service data unit (PSDU) with additional SERVICE field, tail and pad parts.

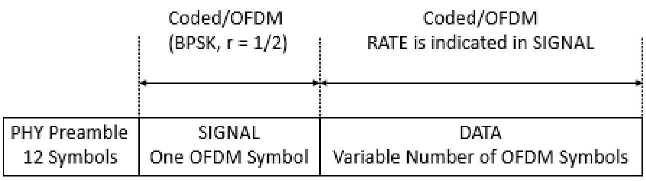


Figure 4.4: PPDU format

4.1.1.3.2 LiFi-XC PHY

For the LiFi-XC system, the PHY is implemented based on IEEE 802.11 OFDM PHY with modifications which suit for LiFi applications. The architecture of the transceiver follows standard OFDM system design and the block diagrams for both transmitter (Tx) and receiver (Rx) are shown in Figure 4.5.

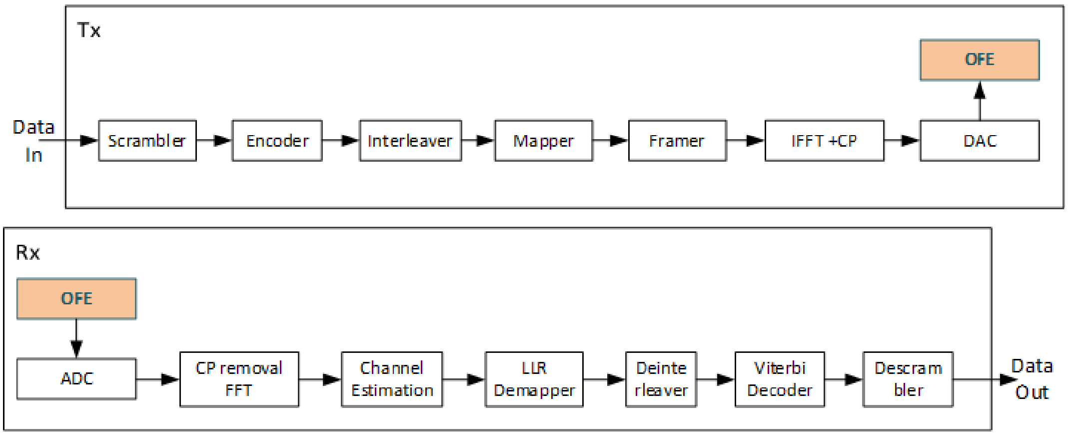


Figure 4.5: Block diagram of baseband Tx and Rx architectures

4.1.1.3.3 LiFi-XC MAC

The LiFi-XC MAC is implemented based on the point coordination function defined in IEEE 802.11. Modifications have been made for the requirements of LiFi applications. The modified point coordination function protocol offers high protocol efficiency and multi-user support [31].

4.1.2 Heterogeneous network deployment

In planning cell sites, there are three common models based on [92], namely Monte Carlo multi-cell model, stochastic geometry model, and single-cell linear model. The single-cell linear model is accurate only if there is always a dominant interfering BS. However, most contributions in the 5G-CLARITY do not assume the existence of a dominant interfering BS at every cell. Therefore, 5G-CLARITY will focus on the two former models.

The Monte Carlo multi-cell model is a cell specific configuration. An example is a hexagonal cell layout, which is typically used in the conventional cellular networks. Reference scenarios of 5G, Wi-Fi (IEEE 802.11ax), and LiFi (IEEE 802.11bb) can be found in [93, 94, 95], respectively. These task groups provide various baseline scenarios for simulation works. The reference scenarios include indoor scenarios (such as residential rooms, offices, or hospitals), urban macro, or outdoor small cells. In these scenarios, the BSs are arranged in varied configurations, e.g., grid, two-stripe, or random configurations. An actual network deployment data set for cellular networks is published by Ofcom in 2013 and can be found in [96].

The commonly used stochastic geometry model is Poisson point process (PPP), see [97] and references therein. The main advantage of PPP is its tractability. The justification of PPP being sufficiently accurate to actual deployments of macro BSs is provided in [97]. One of the main insights from [97] is that the coverage probability with the actual deployments is upper bounded by that with the square-grid deployments and lower bounded by that with the PPP deployments. Consequently, many studies assume both scenarios (the square-grid and the PPP configurations) in order to evaluate a performance of interest, e.g., in LiFi [98].

Figure 4.6 depicts examples of network deployments. Figure 4.6 (left) shows an example of Wi-Fi systems in an open office environment. This example is taken from [94]. A realization of PPP with its Voronoi tessellation is shown in Figure 4.6 (right). More examples can be found in [94, 95, 96, 97, 98].

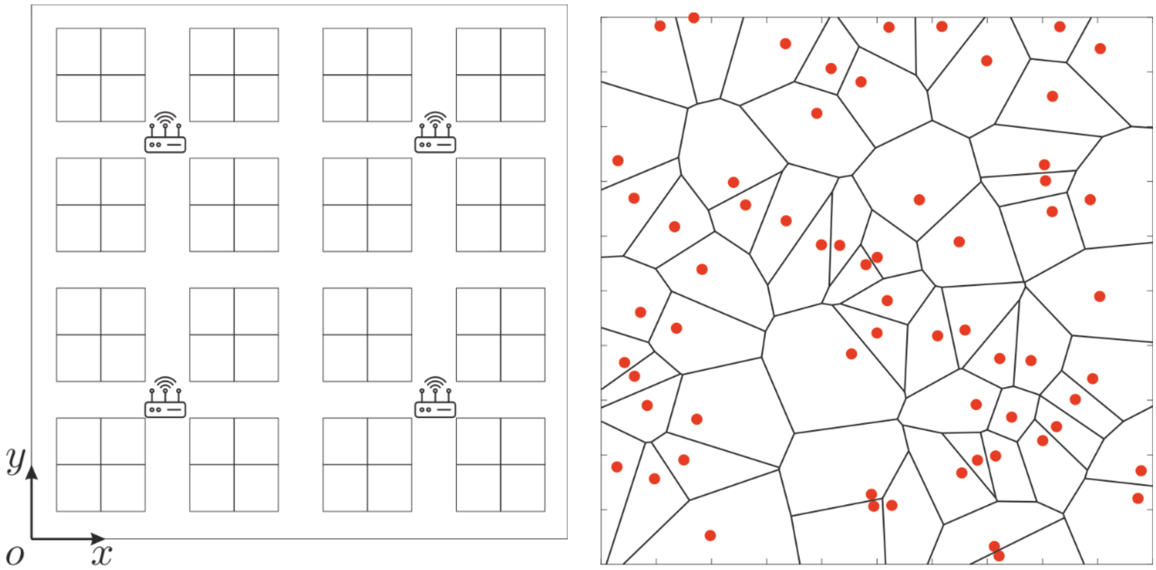


Figure 4.6: (Left) An example of a square grid deployment of Wi-Fi systems in an open office environment [94], and (Right) a realization of PPP for 4G/5G cellular systems.

The Monte Carlo multi-cell and the stochastic geometry models provide two extreme approaches in the performance evaluation of heterogeneous networks. That is, in the Monte Carlo multi-cell model, the evaluation is carried out by means of high-fidelity simulations, where many factors can be incorporated, such as blocking objects (humans) or reflecting objects (walls, ceilings, or furniture). Meanwhile, PPP provides an analytical, tractable tool, which is computationally faster than the simulations. The effect of density of BSs can be quickly evaluated by using PPP. Therefore, in 5G-CLARITY, whenever the high fidelity is required, the Monte Carlo multi-cell model will be used to evaluate the performance of the heterogeneous 5GNR/Wi-Fi/LiFi network. Otherwise, the PPP will be the 5G-CLARITY approach to investigate density of BSs and/or APs as well as users.

4.1.3 User-cell association

A common assumption for the user cell association is that a user associates to a BS/AP whose corresponding received signal strength indicator (RSSI) is the highest. Equivalently, this assumption is the same as the maximum signal-to-interference-plus-noise ratio (SINR) connectivity model [99]. Another connectivity model is the flexible cell association [100], in which a bias factor is used to set a preference of a user in connecting to one of WATs (5G, Wi-Fi, or LiFi) at any given time. However, the flexible cell association is not relevant for multi-connectivity systems.

In 5G-CLARITY, a user is assumed to be able to simultaneously use all WATs. The association model for each WAT is assumed to be based on the highest RSSI, unless otherwise stated. Therefore, the analytical framework in [100] needs to be extended in order to accommodate the multi-connectivity systems. Not many studies focus on the cell association on the multi-connectivity systems. Two related studies can be found in [101] and [102], where different criterions (e.g., SINR, bitrate, or energy efficiency) are used for the cell association algorithms. Significant improvements, such as decreasing of radio failure rates and improvement of energy efficiency and spectral efficiency, can be achieved as explained in [101] and [102].

Both [101] and [102] are only theoretical and simulation studies. To the best of authors' knowledge, there is still no study that reports experiments on cell association algorithms on the multi-connectivity systems beyond the RSSI or SINR criterion. Note that the implementation of cell association algorithms that are based on the RSSI criterion on the multi-connectivity systems is straightforward, for example, by means of implementing MPTCP in a current mobile device with multiple WAT interfaces. However, based on [9], RSSI or SINR are not the right criterion for heterogeneous networks.

In [103], an implementation of load balancing algorithms that do not only use the RSSI criterion in multi-tier networks is shown to be viable. The AP selection is determined based on information such as the number of associated clients, packet error rate, fairness index, etc. Then, a Linux utility called *hostapd_cli* is used to associate or de-associate clients from APs.

The use of SDN in [103] is in line with the vision of 5G-CLARITY, which also aims to employ the SDN paradigm in orchestrating traffics coming from multi-WAT-enabled devices. Therefore, the study in [103] will be a reference in 5G-CLARITY on the feasibility of the implementation of advanced cell association algorithms in multi-connectivity systems with commercial off-the-shelfs (COTSs).

SDN enables flexibility on the application developments including the ones for managing the cell association. The implementation of a Machine Learning technique is not an exception. For example, the study in [104] shows a testbed that employs a predictive model for a cell association algorithm in COTSs. Consequently, a 70% throughput improvement can be achieved. Based in [103] and [104], the implementation of cell association algorithms considering load balancing that is *X*-aware (such as mobility-aware [105], context-aware [106], or intelligent content-aware [107]) in multi-connectivity systems with COTSs are viable. Given this background, 5G-CLARITY aims to implement a load balancing algorithm beyond the RSSI criterion in multi-connectivity systems.

4.1.4 Resource scheduling

In the conventional cellular systems, user-RB scheduling policies are based on vendor/operator preferences and are not specified in the standards. Some very well-known resource scheduling policies namely max-min, round-robin (RR), and proportional fair (PF) and their variants have been used the conventional systems. In the max-min scheduling, the purpose is to maximize the minimum achieved rate and prioritize the user that achieves the minimum rate. In the RR scheduling, the channel conditions or QoS information of the users are not taken into account in the resource allocation process. The users access the channel in a circular order and use the whole channel during their access period. Therefore, although it is fair in the sense of the channel access period that is utilised by every user, rate performance depends on both the period of channel use and the SINR conditions of the users. However, in the PF scheduling, instantaneous and average data rate performance of the users are considered to allocate resources. Therefore, PF considers both the channel conditions and amount of the resources allocated to each user.

The noted scheduling policies can provide a good tradeoff between fairness and system throughput for data-oriented services. In 4G systems, resource scheduling for mobile data service considers different traffic/QoS classes namely guaranteed bit rate (GBR), non-GBR, maximum bit rate and aggregated rate per user. However, during the evolution of 4G systems, the term “resource” has been extended from RB to bandwidth parts and different wireless access technologies such as 5G and Wi-Fi, as described in Section 3.1. Moreover, the term “service” has also been extended from mobile data to eMBB, URLLC and mMTC in 5G systems. To effectively manage the noted diverse resources and services, “network slicing” concept is defined in 5G systems. By utilizing SDN and network function virtualization (NFV) technologies, the network slicing concept enables running several service or business models on a common physical infrastructure. Therefore, effectively scheduling/managing the available physical resources in order to achieve the required KPIs for different service types and Service Level Agreements (SLAs) for different business model has a significant importance for 5G networks.

4.1.4.1 Optimization-theory based approaches

In [108], a utility-based resource allocation algorithm is proposed to guarantee QoS requirements for real-time and non-real-time traffic types. In order to consider the performance metrics of different traffic types within the resource allocation process, a universal sigmoid function with different parameters that affect the slope and range of the curve is considered as the unified utility function. Two different resource allocation algorithms are proposed to solve the non-convex optimization problem for allocating resources to different traffic types. Whereas in [109], a utility proportional fairness resource allocation problem is proposed to fairly serve real-time and non-real-time traffic types. As a logarithmic function is used to provide fairness among different sigmoid-like utility functions, it is shown that the proposed problem is strictly concave function, hence, a convex optimization problem. Then, the considered convex optimization problem is divided into two simpler optimization problems which one of them is solved in the UE side and the other one is solved in the base station side.

The noted utility-based resource allocation studies [108, 109] consider a homogeneous network deployment such as 4G eNB as the base station. In [110], a two-tier heterogeneous network deployment is considered along with machine-type devices that require delay-sensitive, high reliable transmission and regular mobile user devices that require high data throughput. Different QoS demands, traffic load in both macro and small cells, inter-cell interference, traffic statistics and location distribution of different user types are considered within an optimization framework for bandwidth resource slicing that aims to maximize the overall network utility.

The bandwidth resource slicing in the considered heterogeneous network deployment is assumed to be centrally controlled by an SDN-enabled controller. It is shown that the considered optimization problem is a mixed-integer combinatorial problem which is difficult to solve, and a partial optimal solution is proposed by relaxing binary variables in the original problem. The proposed partial optimal solution is solved by a concave research algorithm, named alternative concave search in [110].

A similar heterogeneous network deployment with multiple RATs along with a multi-connectivity scheduler named Lagrange approximation supple radio controller is proposed in [111]. The main features of the proposed multi-connectivity scheduler are listed as (i) operates using the instantaneous network state information; (ii) balances network cost and proportional fairness of the utilities of different traffic types such as delay-tolerant, delay-sensitive and non-guaranteed; and (iii) considers practical system constraints such as RB allocation types considered in 4G as explained in 4.1.1.1.

In [112], the similar practical system constraints for RB allocation are considered for a resource partitioning and accommodation problem to enable multi-tenant multi-service RAN for homogenous 5G network. However, different from [111], flexible subcarrier spacing of 5G systems described in 4.1.1.1 is considered in the scheduling problem in [112].

Apart from the optimization theory based approaches, a more practical approach that utilizes the earliest deadline first scheduling used in Linux kernel is proposed for radio resource allocation in RAN slicing in [113]. The idea is to modify the earliest deadline first scheduling by (i) modelling buffered traffic as a task instance; (ii) replacing processing time with radio resources; and (iii) adapting radio resource requirement fluctuations. In the proposed system architecture in [113], a slice admission control and self-organizing function modules are also considered along with the per-cell basis scheduling in order to support latency as well as guaranteed bit rate requirements. The way the proposed scheduler works is explained as follows. First, at the beginning of the current TTI, the scheduler collects the number of RBs allocated to each slice in the previous TTIs. Then, calculates the total number of RBs allocated to each slice and distance to deadline from the current TTI. Then, the scheduler prioritizes the slices based on their deadline such as the slice that has the lowest deadline has the highest priority. In order to serve non-guaranteed traffic, a common slice is added at the end of the priority list of slices. The priority list is then sent to MAC scheduler and the MAC scheduler starts from the first slice in the list. The possibility of having a slice-customized scheduler is also considered within the MAC scheduler in order to ease the integration of the proposed solution.

It must be noted that all these studies considered either a homogeneous network deployment or a heterogeneous network deployment with the same type of RAT but with different coverage areas/transmission power/number of resources. For example, the considered multi-RAT in [111] is explained as having different number of physical RBs in each cell, macro or small. This is different from the multi-RAT definition given in 5G-CLARITY [1] which is named multi-WAT instead of multi-RAT due to having LiFi in addition to 5G and Wi-Fi.

In a recent study [114], an SDN-enabled heterogeneous network deployment that comprised Wi-Fi, LTE and LiFi is considered. A traffic engineering scheme is proposed to provide reliable and guaranteed services when the state of the network and/or wireless resources such as bandwidth availability and channel gain constantly changes. Contributions of this study are noted as (i) developing a queuing theory-based mathematical framework for modelling the inter-planes of the SDN-enabled network; (ii) developing routing policies to support traffic engineering scheme and load balancing on the network and medium access layers; and (iii) developing service provisioning automation mechanism that supports dynamic user-cell association and resource allocation.

4.1.4.2 Learning based approaches

As the complexity level of 5G and beyond 5G networks increases by (i) deploying heterogeneous networks that utilize different WATs as well as power/coverage levels; and (ii) introducing different traffic types that require diverse KPIs, the optimization theory based resource management problems become NP-hard problems. Although these NP-hard problems can be solved by relaxing the original problems as noted in 4.1.4.1, they need to be solved in each instance when one of the system parameters such as requested service type, user position and/or CSI is changed [115]. In order to alleviate such an unprecedented level of complexity, learning based approaches are proposed to manage resource, user-cell associations, network slices and interference in [115, 116, 117] and references therein.

For example, in [116], Machine Learning applications for resource management in the MAC layer, networking and mobility management in the network layer are discussed. Whereas, in [115], the same applications are not only discussed for learning based approaches but also for learning based approaches that utilize the mathematical models of the wireless communication networks. It is shown in [115] that the proposed model-aided learning approaches do not need a large training data sets to achieve good performance. A similar model-aided learning approach is proposed in [117] for a context-aware heterogeneous 4G/Wi-Fi/LiFi network selection. The proposed algorithm consists of three levels namely (i) utility modelling level for asymmetric downlink-uplink traffic; (ii) learning level for traffic type-location-time information; and (iii) ruling level to change load statistical distributions periodically.

In 5G-CLARITY, real-time and non-real-time RAN intelligence will be discussed within WP4 along with network management and artificial intelligence (AI) engine [118].

4.2 Resource management requirements

Resource management in 5G-CLARITY can be considered as a two-stage process. In the first stage, traffic flows for different WATs can be routed based on the service/slice type. For example, for an eMBB slice, different data packets can be routed to 5G, Wi-Fi and LiFi networks at the same time in order to aggregate throughput of all three WATs. However, for a URLLC slice, the same data packets can be routed to 5G, Wi-Fi and LiFi in order to provide diversity gain and improve link reliability in a way that if one WAT fails to deliver the package, another WAT can compensate this loss, as described in Section 3.1.2.3. In the second stage, physical resources of each WATs such as RBs for 5G and RUs for Wi-Fi/LiFi can be shared on the gNB/AP level in order to fairly serve each slice and user.

In particular, 5G-CLARITY will design a solution fulfilling the requirements described in Table 4-6:

Table 4-6: Resource management framework requirements

Resource management requirement ID	Description
RM-R1	5G-CLARITY resource management system shall control traffic flows and physical resources of 5GNR gNBs, Wi-Fi and LiFi APs.
RM-R2	5G-CLARITY shall support the use of SDN controller to manage traffic flows as well as

	physical resources of 5GNR, Wi-Fi and LiFi networks.
RM-R3	5G-CLARITY shall support enhanced user-cell/AP association algorithms that utilize 5GNR, Wi-Fi and LiFi networks efficiently and dynamically.
RM-R4	5G-CLARITY resource management system shall support serving different traffic types and QoS classes, simultaneously.
RM-R5	5G-CLARITY resource management system shall receive performance measurement results of the user devices as well as telemetry data from 5GNR, Wi-Fi and LiFi networks.
RM-R6	5G-CLARITY shall manage the 5GNR, Wi-Fi and LiFi resources in real-time.
RM-R7	5G-CLARITY shall manage the 5GNR, Wi-Fi and LiFi traffic flows in real-time and non-real-time.
RM-R8	5G-CLARITY resource management system shall support the use of utility-based scheduling algorithms.
RM-R9	5G-CLARITY resource management system shall decouple uplink and downlink traffic.
RM-R10	5G-CLARITY resource management system shall have the capability to schedule uplink and downlink traffic to different WATs.
RM-11	5G-CLARITY shall support the use of different scheduling algorithms for 5GNR gNBs, Wi-Fi and LiFi APs.
RM-12	5G-CLARITY shall support the use of machine learning algorithms for resource and mobility management of the heterogeneous 5GNR/Wi-Fi/LiFi network.

5 Positioning

The popularity and success of outdoor GNSS [119] [120], e.g. GPS, has accelerated the research and development of high precision indoor positioning systems. These indoor positioning systems would play a crucial role in many applications. These applications include augmented reality, museum tours, warehouses, factories, mobile robot navigation, hospitals, etc. It would also play a key role in the development of Industry 4.0, since automation of many tasks demand precise indoor positioning.

Multiple indoor positioning technologies are emerging today. Many rely on RF-based positioning, while many others use non radio frequency (RF)-based positioning methods. The non RF-based methods leverage, for example, inertial based positioning [121] [122] [123] [124], optical based positioning, like optical camera communication (OCC) or light detection and ranging (LIDAR), magnetic field positioning, etc. Some of these methods can be directly implemented on user equipment (UE) such as smartphones. The methods employing OCC are promising high precision positioning. Others, like magnetic field and inertial-based positioning, are lacking this precision, mainly due to the low quality of the sensors used in the UEs.

This section provides an overview of the state-of-the-art in the fields 5G-CLARITY targets as potential solutions to achieve the desired requirements and KPIs.

RF indoor positioning can be performed by measuring different parameters of the received radio signal. The simplest approach for distance and position estimation utilizes the received signal strength (RSS) of the radio signal at the receiver. As the received signal power decays with the distance, this approach is simple and straightforward. To achieve improved ranging and localization precision as well as accuracy, the so-called time of flight (ToF) methods are more suitable. In these methods, the time needed for a radio wave to travel from the transmitter to the receiver is estimated, from which the distance or the position is easily calculated. Some of these RF-based positioning algorithms are also applicable to LiFi positioning systems.

5.1 5G

5.1.1 5G positioning state-of-the-art

3GPP positioning feature has been supported since Rel-9 LTE networks; several RF-based positioning methods have been introduced, and advanced techniques are under investigation for NR in Rel-16. Recent 3GPP NR positioning study conclusions have been stated in [125]. There has been discussion of many different possible positioning solutions in the study item. Conclusions have been made that the 3GPP NR systems should support solutions of observed time difference of arrival (OTDOA), uplink time difference of arrival (U-TDOA), angle information, multi-cell round trip time (Multi-RTT), and enhanced cell-ID (E-CID) in NR Rel-16 [126].

In addition, 3GPP Rel-15 NR provides support for RAT-independent positioning techniques and Observed Time Difference Of Arrival (OTDOA) on LTE carriers. 3GPP Rel-16 further extends NR to provide native positioning support by introducing RAT-dependent positioning schemes.

RAT-dependent NR positioning schemes being considered for standardization in Rel-16 are the following:

- D-TDOA.
- U-TDOA.
- Downlink angle-of-departure (DL-AoD).
- Uplink angle-of-arrival (UL-AOA).
- Multi-RTT.
- Enhanced cell ID (E-CID).

UE-based measurement reports for positioning are:

- Downlink reference signal reference power (DL RSRP) per beam/gNB.
- Downlink reference signal time difference (DL RSTD).
- UE RX-TX time difference.

gNB-based measurement reports for positioning are:

- UL-AOA.
- Uplink reference-signal receive power (UL-RSRP).
- UL relative time of arrival (UL-RTOA).
- gNB RX-TX time difference.

NR adopts a solution similar to LTE's Positioning Protocol A (LPPa) for Broadcast Assistance Data Delivery, which provides support for A-GNSS, real-time kinematic (RTK) and OTDOA positioning methods. Precise point positioning RTK (PPP-RTK) positioning will extend LPP A-GNSS assistance data message based on compact "SSR messages" from Quasi-Zenith Satellite System (QZSS) interface specifications. UE-based RAT-dependent DL-only positioning techniques are supported, where the positioning estimation will be done at the UE-based on assistance data provided by the location server.

DL-based positioning is supported by the provision of a new reference signal called the positioning reference signal (PRS). Compared with LTE, the PRS has a more regular structure and a much larger bandwidth, which allows for a more precise correlation and ToA estimation. The UE can then report the ToA difference for PRSs received from multiple distinct base stations, and the location server can use the reports to determine the position of the UE.

UL-based positioning is based on Release 15 sounding reference signals (SRSs) with release 16 extensions. Based on the received SRSs, the base stations can measure and report (to the location server) the arrival time, the received power and the angle of arrival from which the position of the UE can be estimated. The time difference between DL reception and UL transmission can also be reported and used in RTT based positioning schemes, where the distance between a base station and a UE can be determined based on the estimated RTT. By combining several such RTT measurements of involving different base stations, the position can be determined.

On 'Positioning', 3GPP claims the achievement of 10s of CM accuracy in Rel-16, with the aim at enhancing these values (cm accuracy), promote the use of positioning for vehicle-to-everything (V2X) communications, leveraging 3D positioning (looking at vertical and horizontal), and with the goal of latency and reliability improvements [127]. Recent research [128] has shown some simulation results that prove that both UL-AOA and DL-AOD can reach meter level accuracy in indoor scenarios.

5.1.2 5G positioning requirements

5G-CLARITY will not consider 5GNRas a technology for use experimentally in extracting positioning measures, but only as a reference for the technologies we employ in this project to what 3GPP is targeting regarding positioning precision and requirements on latency. The following numbers refer to the requirements for positioning in Rel-16 and beyond have been discussed in TR 38.855. Regulatory requirements set the minimum KPI for positioning, as below:

- Horizontal positioning error <= 50m for 80% of UEs.
- Vertical positioning error < 5m for 80% of UEs.
- E2E latency and Time to First Fix (TTFF) < 30 s.

Additional targets are based on the needs from commercial use cases. In 3GPP TR 38.855 target performance for commercial use cases indoor and outdoor deployment scenarios are listed:

- Horizontal positioning error < 3m for 80% of UEs in **indoor** deployment scenarios.

- Vertical positioning error < 3m for 80% of UEs in **indoor** deployment scenarios.
- Horizontal positioning error < 10m for 80% of UEs in outdoor deployments scenarios.
- Vertical positioning error < 3m for 80% of UEs in outdoor deployment scenarios.
- End to end latency and TTFF < 1s.

In order to address the new requirements in in industry and verticals, NR in Rel-17 should meet the following performance targets [129]:

- For general commercial use cases (e.g., TS 22.261): < 1 m position accuracy
- For IIoT Use Cases (e.g., 22.804): < 0.2 m position accuracy
- Latency requirement is < 100 ms; for some IIoT use cases, latency in the order of 10 ms is desired.

5.2 Wi-Fi

5.2.1 Wi-Fi positioning state-of-the-art

Today's COTS Wi-Fi devices do not support positioning of UEs over Wi-Fi. RSSI can be used for ranging between a Wi-Fi AP and a UE in order to perform trilateration. Nevertheless, this approach suffers from huge imprecision indoors, due to multipath propagation. The high noise in the RSS sensors worsen this problem. In order to improve the Wi-Fi RSSI-based positioning precision, fingerprinting is usually used [130] [131] [132] [133]. When fingerprinting is used, the UE acquires the RSSI values from the available APs and compares them to previously created database. This database is created by extensive measurements in a given indoor environment. An average of 0.5-1 m positioning error can be achieved with this approach if a good training dataset is available [134].

For indoor use, there are proprietary solutions operating in the 2.4/5 GHz ISM bands [135], as well as UWB solutions [136]. The 2.4/5 GHz ISM band solutions are lacking accuracy due to the relatively small channel bandwidths available in these bands.

Support for ToF ranging in Wi-Fi has been incorporated in the IEEE802.11az standard [137]. Nevertheless, no COTS devices supporting the IEEE802.11az are available yet. This standard should use fine time measurement (FTM) protocol to perform range measurements between UE and multiple APs and using trilateration should estimate the position of the UE.

5.2.2 5G-CLARITY Wi-Fi positioning requirements

The Wi-Fi positioning requirements in terms of positioning precision and latency would be:

- Average horizontal positioning error in LOS scenario < 1.5 meter
- Average vertical positioning error in LOS scenarios < 3 meters
- Latency < 100 ms
- Measurement frequency >= 100 measurements per second

Table 5-1 describes the requirements the 5G-CLARITY Wi-Fi system must comply with for the use of this technology for positioning purposes.

Table 5-1: Positioning framework requirements for Wi-Fi system

Wi-Fi requirement ID	Description
WIFI-R1	ToF – based ranging and positioning

WIFI-R2	A Wi-Fi system should be able to decode the frames coming from the UEs
WIFI-R3	Angle of arrival estimation for triangulation
WIFI-R4	Ranging positioning precision of under 1 meter can be achieved at best
WIFI-R5	A minimum of four anchor nodes are needed for a two-dimensional positioning (if time-of-arrival (TOA) is used)
WIFI-R6	In a ToA based positioning scenarios the anchor nodes should be tightly synchronized
WIFI-R7	If no tight synchronization between anchor nodes is possible, Two-Way-Ranging (TWR) can be performed between the anchor nodes and the UEs. This would require more transmissions when multiple UEs require positioning, but the minimum number of anchor nodes for two-dimensional positioning would be three.

In 5G-CLARITY, a mechanism for obtaining positions from Wi-Fi nodes stemming from range (distance) measurements will be developed. Due to the lack of ToF-based solutions for Wi-Fi, two approaches are feasible. The first one involves the development of algorithms for obtaining these measurements in a simulation environment, to then estimate the position of the UE. The second one relies on the measured data from APs which, after being properly processed, can serve to obtain a better estimation of the position.

To evaluate the performance of ToF-based ranging and positioning, tests with software defined radio (SDR) equipment will be performed. The use of SDRs allow to set up the same parameters, e.g. channel bandwidth and transmit power, as in Wi-Fi.

5.3 Millimeter Wave

5.3.1 mmWave positioning state-of-the-art

mmWave frequency bands vary from country to country, spanning up to 9 GHz. A few channels each having bandwidth of 2 GHz are usually available in this band. The large bandwidth allows for an excellent ToF estimation accuracy and precision. However, it is still pending to unleash their potential advantages for accurate positioning, which are largely unknown in practice (an in scenarios including mobility).

One of the challenges of supporting positioning features in the mmWave frequency range whilst reaping its benefits, i.e. increased bandwidth to achieve better precision accuracy, is the requirement imposed to the network to maintain the connectivity with the terminal. This is obviously not feasible due to the susceptibility of mmWave links to blockage and the associated high path loss [138]. Nevertheless, small wavelength (5 mm at 60 GHz) allows deployment of large antenna arrays which can be packed in small form factor. This way, mmWave systems can achieve sufficient beamforming gain to combat the inherent high free-space path loss and to provide sufficient link budget [138] [12]. The highly directional beams and fast varying channels one can encounter in an indoor or outdoor environment represent the main bottleneck in realizing robust mmWave networks.

5GNRequipment in the mmWave bands envisions channel bandwidths of up to 800 MHz. This large bandwidth would enable a sub-centimetre precision ToF-based ranging and positioning. Additionally, having a possibility for beam steering, the AoA can be estimated, which would allow for position estimation using a single access node. Additional improvement of the position estimates can be achieved by using additional access nodes (i.e. anchor nodes).

The high accuracy positioning stemming from the use of mmWave bands will ensure benefits for indoor spaces and dense deployments, as these systems will provide greater spatial resolution that will allow operators and private networks to offer new targeted services and solutions.

The achievable data rates in these wireless systems are subject to highly directional communication links [139]. This entails additional challenges when considering mobile environments to ensure a continuous communication, e.g. need of large beam training overhead. Integration of features such as ranging and localization in wireless communications systems are becoming paramount to overcome these limitations [140]. As an example, pencil beams achieved via antenna arrays at these frequencies ensure a wide coverage area (distance), but at the expense of very high setup time due to the exhaustive searching process. Localization provides a promising solution for finding out the best mmWave beams within a small setup time [141].

The main advantage of a combined range/angle-based localization is that the whole process can be performed using a single base station. This would significantly relax the requirements for nanosecond precision synchronization in purely ToA based localization. However, the main disadvantage is that the number of frames sent for each user increases with the number of users. This is not the case with a ToA based localization where the same frames can be reused by unlimited number of users. Therefore, depending on the scenario, different approaches can be used for localization of UEs.

An approach for implementation of a two way ranging (TWR) algorithm in an SDR platform in the 60 GHz band was presented in [142]. The ranging precision and accuracy achievable with this approach were evaluated. The achieved root mean square (RMS) ranging error is better than 5 millimetres. It outperforms all similar systems that use ToF- based methods for a similar channel bandwidth.

5.3.2 Requirements of the 5G-CLARITY mmWave system

mmWave positioning requirements on the accuracy of positioning and the latency would be:

- Average horizontal positioning error in LOS scenario < 1 centimetre
- Average vertical positioning error in LOS scenarios < 10 centimetres
- Latency < 100 ms
- Measurement frequency >= 100 measurements per second

Table 5-2 describes the requirements the 5G-CLARITY mmWave system must comply with for the use of this technology for positioning purposes.

Table 5-2: Positioning framework requirements for mmWave system

mmWave requirement ID	Description
MMWAVE-R1	The mmWave solution should use a phased antenna array in order to support beams steering
MMWAVE-R2	Depending on the size of the phased antenna array, the antenna radiation direction can be used to enable a combined angle/range positioning
MMWAVE-R3	Ranging positioning precision of less than 1 centimetre should be possible in the best case
MMWAVE-R4	In positioning scenarios, horizontal positioning precision of less than 5 centimetres should be possible in scenarios with two or more anchor nodes
MMWAVE-R5	Vertical positioning precision depends strongly on the position of the anchor nodes which are placed in the horizontal plane. In the optimal case, the horizontal positioning precision should be better than 15 centimetres.
MMWAVE-R6	In a time-of-arrival (ToA) based positioning scenarios, the anchor nodes should be tightly synchronized

MMWAVE-R7	If no tight synchronization between anchor nodes is possible, a TWR ranging can be performed between the anchor nodes and the UEs. This would require more transmissions when multiple UEs require positioning.

5.4 LiFi positioning

5.4.1 State-of-the-art in LiFi positioning

5.4.1.1 LiFi-RF common approaches

In this section, several common approaches are introduced for LED-based positioning systems.

5.4.1.1.1 RSS based (trilateration, fingerprinting, proximity)

RSS-based algorithms have been well developed and used in indoor visible light positioning systems. In an indoor VLC system, the received signal power follows a channel model which includes the position of both transmitter and receiver. As the RSS values can be easily measured at the receiver, it can be used for estimating the receiver position based on the model. Several algorithms are developed and published for LED positioning systems.

1) Trilateration: In a positioning system based on trilateration, at least three LEDs with known locations are required. When the received signal intensity is measured, the distance between the receiver and each transmitter can be estimated. The location of the receiver can then be determined. In [143], four spatially distributed LEDs are modulated with different frequency starting from 12.5 kHz and doubled up to 100 kHz in each LED. Different from [144], RSS measurements are used to estimate the distance between LEDs and the receiver which is a photodiode. Then, a trilateration algorithm is used to find the location of the receiver. A 100 cm x 118.5 cm x 128.7 cm area is used for the experiments and it is shown that an average positioning error of 1.9 cm is achieved.
2) Fingerprinting: Fingerprinting-based positioning system usually contains two steps: off-line survey and on-line positioning. During the off-line survey process, information of the indoor environment, such as RSS, is collected and saved in the data base for different positions. Then during the on-line positioning process, by comparing the received information with the recorded data in the database, the location is estimated. Work in [145] has presented the RSS-based fingerprinting positioning system with experimental results. According to [145], depending on a considered scenario (e.g., free space, with obstacles or random orientation) and step size of the fingerprint map, an accuracy of 14 cm to 29 cm can be achieved.
3) Proximity: The concept of the proximity-based positioning system is that when a receiver detects signal from a transmitter with known location, the receiver is considered to be close to the transmitter. When there are multiple transmitters, by comparing the RSS values, the position of the receiver can be estimated where the transmitter with strongest signal is considered to be the closest. In addition, when two RSS values are similar, the receiver is supposed to be in the middle of those two transmitters. In this way, the rough estimation of the location can be determined. Compared with other positioning methods, this is easy to implement. However, the accuracy heavily depends on the density of the transmitter distribution.

5.4.1.1.2 AoA (triangulation, image transformation)

AoA refers to the angle between the line of sight and the normal angle of the transmitter's plane. AoA values cannot be measured directly by a photodiode (PD). There are two general approaches to obtain AoA values: i) image transformation and ii) modelling. Image transformation uses a camera to take photos and calculate the AoA based on the images. The second approach, modelling, makes use of the channel model mentioned above in the RSS based techniques, and takes the radiation angle into account. By measuring the received light intensity, the radiation angle can be obtained from the model.

Triangulation is the most widely used algorithm for positioning using AoA [146]. The position of a receiver is estimated after measuring the AoAs relative to several transmitters with known locations [147].

5.4.1.1.3 Time of Arrival/ Time Difference of Arrival (ToA/TDoA) (trilateration, multilateration)

For a LED-based positioning system using ToA, it requires very accurate time synchronisation between LEDs and receivers. Therefore, TDoA is usually used instead of ToA. Typically, at least two receivers are required to acquire the time difference between the arrived signals. However, with the use of multiple LEDs which send frequency division multiplexing signals, it is possible for single receiver to capture the signals and analyse the time difference [148]. Based on the simulation results given in [148], a minimum accuracy of 4 cm can be achieved around the centre of the room. Whereas, the positioning accuracy is reported as 53 cm around the corners of the room.

5.4.1.2 LiFi-specific approaches

In addition to the RF-based positioning approaches, there are several LiFi-specific positioning approaches proposed in the literature. These approaches can be grouped based on the geometry of the transmitter, the geometry of the receiver and type of the receiver such as photodiode or image sensor.

5.4.1.2.1 Multi-directional (angular diversity) receiver

The angle diversity receiver (ADR), which contains multi directional receiver pixels within one module, has been studied for indoor positioning systems [149]. As mentioned in previous sections, for indoor localisation systems based on RSS, multiple transmitters or receivers are required. If single receiver is used, there need to be at least three transmitters with known location to be installed in order to use the trilateration method. If single transmitter is used with multiple receivers, the receivers need to be placed with a minimum separation distance which is required to introduce RSS difference. However, this approach leads to a large receiver size. By introducing angle diversity into the receiver design, it is possible to achieve RSS difference by the incidence angle difference and the receiver can be more impacted in size. With ADR, it is reported in [149] that two-dimensional positioning is possible due to an angle-gain profile according to AOA only, and three-dimension positioning is achieved using RSS. Based on the simulation results given in [149], a three-dimension positioning accuracy of less than 6 cm can be achieved. In [150], four different experimental scenarios are considered. In three of these scenarios, static points are chosen, and experiments are carried out for a single and three LED cases in a room of size 12 m x 10 m, 12 m x 10 m and 24 m x 16 m. In one of the scenarios where the room size is 18 m x 12 m, the location of a mobile user is tracked when three LED lamps are used. For the case of three LEDs, different carrier frequencies are used for each LED. On the receiver side, an ADR with 6 PDs is used. RSS measurements of 3 of the 6 photodiodes that are pointed different orientations are used determine the receiver position. Such an ADR structure helps to reduce the required number of LED lamps for accurate positioning in other approaches such as trilateration. For all the considered experiment scenarios, the average positioning accuracy is reported as 0.4 m.

5.4.1.2.2 Multi-directional (angular diversity) transmitter

An uplink positioning system using angle diversity transmitter (ADT) in conjunction with accelerometers at the mobile station was proposed in [151]. Similar to ADR, each ADT module contains multiple LEDs with identical characteristics and are mounted on the surface of the semi-sphere. One LED is mounted at the centre of the surface while the rest are placed symmetrically along the side. The ADT is fixed on the mobile station. In the system, each LED is turned on in sequence at the start, and the optimum LED is selected which has the highest channel gain to the receiver. By doing this, the ADT minimises the dependence of the positioning accuracy on the orientation of the mobile station. Work in [151] reports the positioning system with ADT and distributed PDs by using the RSS method. It shows that using an ADT that is composed of 19 LEDs can achieve reduced localisation errors of less than 15 cm, even if the mobile station is greatly tilted. In [144], a luminaire consists of multiple LEDs is used with a bi-convex lens to provide angular diversity. The positioning performance of such a luminaire with an optic element such as lens and a simple photodiode on the receiver side is investigated without relying on signal intensity, ToF or imaging methods. The proposed positioning architecture given in [144] is not sensitive to the intensity and spatial emission pattern of individual LEDs as well as orientation of the receiver as long as the photodiode used in the receiver side has a wide field-of-view (FOV) in order to have lights within the FOV. The principle is to have some overlapping illumination regions from these LEDs and identify intersection of the illuminated areas. LEDs within the luminaire can identify themselves to the receiver and the receiver locates itself in the room. In the experimental setup, 7 LEDs are used to compose the ADT luminaire and each LED was modulated with a different frequency starting from 4 kHz to 10 kHz by 1 kHz spacing. It is shown that when 1 luminaire is used in a 5 m x 5 m x 3 m room, the positioning accuracy is within 33.5 cm and the accuracy can be improved by using more luminaires such as using 9 luminaire improves the positioning accuracy to 12.9 cm.

5.4.1.2.3 OCC

In light of the recent advancements in image sensor and camera technologies such as higher resolutions, increased frame rates, reduced form factor, OCC [146]. Nowadays, OCC can be considered as one of the main enablers of highly accurate indoor positioning systems. A detailed information on how OCC is used for indoor localization is provided in Section 5.5.

5.4.2 5G-CLARITY LiFi positioning requirements

Several approaches that are either RF-based or LED-based are described for LiFi positioning in Section 5.4.1. Within these approaches, RSS-based positioning systems can be considered as relatively easy to implement approaches. However, the cost would be: (i) scaling for trilateration as specific modulation frequencies should be used in each LED luminaire and this can be problematic for large indoor environments such as factory shop floor; (ii) time and manpower to conduct offline surveys for fingerprinting; and (iii) positioning accuracy dependency on inter-site distance and AP/LED luminaire density for proximity solutions. Moreover, random device orientation significantly affects the positioning accuracy performance of the RSS-based approaches. In order to achieve the positioning accuracy requirement of < 10 cm in 5G-CLARITY, ADT and ADR are considered as the LiFi-specific approaches that are independent from the considered environment, device orientation as well as AP/LED luminaire deployment. It is important to note that OCC is also considered as a LiFi-specific positioning system. However, different from ADT and ADR, OCC requires a camera/image sensor for signal detection which does not exist in all devices and may not be used in all devices. Therefore, LiFi-specific positioning system is based on the use of a simple non-imaging photodiode for signal detection and considered separate from OCC-based system.
Table 5-3 describes the requirements the 5G-CLARITY LiFi system must comply with for the use of this technology for positioning purposes.

Table 5-3: Positioning framework requirements for LiFi-specific approaches

LiFi-specific positioning requirement ID	Description
LSP-ADT-R1	An LED array should be comprised of multiple LEDs that are pointed to different orientations in order to cover different areas of the environment.

LSP-ADT-R2	One or more non-imaging photodiodes can be used on the receiver side.
LSP-ADT-R3	The number of LEDs in an LED array should be greater than or equal to 19[1] in order to achieve an average precision of 10 cm in positioning – in case of single non-imaging photodiode on the receiver side.
LSP-ADT-R4	The designed ADT-based LiFi-specific positioning solution should provide enough accuracy even the receiver has a random orientation independent of the number of non-imaging photodiodes used on the receiver side.
LSP-ADT-R5	In the designed ADT-based solution, each LED should be switched on in sequence and the LED that exhibits the highest channel gain should be selected. Therefore, a closed-loop communication link between the transmitter and receiver is required.
LSP-ADT-R6	The ADT-based positioning solution may utilize integrated acceleration and gyroscope sensors to improve its positioning accuracy.
LSP-ADT-R7	The designed ADT solution should be robust to accelerometer and gyroscope measurement errors.
LSP-ADT-R8	The semi-angle of the ADT LED array should be large enough to provide illumination requirements for its deployed environment, e.g., office or factory.
LSP-ADT-R9	Field-of-view (FoV) of the non-imaging photodiode should be large enough to receive light independent of its orientation - in case of using a single photodiode.
LSP-ADR-R1	A receiver array should be comprised of multiple non-imaging photodiodes that are pointed to different orientation.
LSP-ADR-R2	The designed ADR-based LiFi-specific positioning solution should not require a separation distance between the receive photodiodes. If there is a separation between the receive photodiodes, this should not degrade the positioning accuracy performance.
LSP-ADR-R3	The designed ADR-based solution will use an algorithm to derive the incidence angle gain distribution and gain difference that will be used to estimate 2-D position of the receiver.
LSP-ADR-R4	The designed ADR-based solution should be able to get information on the transmitter characteristics to obtain the expected received signal power that will be used to estimate 3-D position of the receiver.

5.5 OCC positioning

5.5.1 OCC for communications and positioning state-of-the-art

The widespread availability of CMOS cameras in smartphones, together with the penetration of LEDs in the lighting market, can be exploited to enable OCC. For example, a smartphone camera can receive on-off modulated data from light sources by exploiting the rolling shutter effect. Such system was first proposed by authors of [152]. Subsequently, systems based on the same concept have provided improved data rates [153] [154]. The IEEE 802.15.7r1 specification also set of OCC transmission techniques tailored at different use cases, e.g. from car to car communications to display to smartphone communications [155]. Unfortunately, the IEEE 802.15.7r1 efforts did not achieve enough convergence to boost the adoption of a single OCC standard in the market, hence a plurality of proprietary approaches continues to be the norm these days.

A few Visible Light Positioning (VLP) systems have been proposed, leveraging deployed LED infrastructure [156] [157] [158] [159]. Epsilon is a system that comprises LED beacons and requires integrating a specific light sensor with the smartphone [156]. Trilateration is used to determine the location of the light sensor. The distance between a LED and the receiver is computed based on RSS, which may be impaired by interference and other phenomena. LEDs transmit their own position by using BFSK, channel hopping and

1 Based on [151], an average accuracy of 10 cm is achieved when the ADT is composed of 19 LEDs and the accelerometer measurement error for the tilt angle of the receiver is equal to 5º.

intensity modulation. On the other hand, Luxapose [157] also uses LED landmarks, which broadcast their identities or coordinates by using on-off keying and exploits the rolling shutter effect of a smartphone camera to decode the transmitted data. The camera is used as an AoA sensor. Localization accuracy is ~0.1 m, and the system also provides orientation accuracy of 3º. However, the system is not able to preserve its precision when it is not located directly under the light sources. Furthermore, image processing is performed in a server: an image is captured and sent by the mobile device to the server, and the latter calculates the mobile position and returns it back to the device. This operation is slow, leading to a positioning delay of 9 seconds, offering low responsiveness precluding lively human user experience, and also requires suitable network connectivity between the smartphone and the server. Lumicast by Qualcomm is based on a similar concept but performs the position computation locally (i.e. at the smartphone itself), offering an improvement to Luxapose. While accuracy of Lumicast is comparable to that of Luxapose, and it takes 100 ms to obtain the first localization, Lumicast is only able to provide orientation in yaw, [158]. PIXEL is a recent visible light positioning (VLP) system based on light polarization modulation [159]. While this system is suitable for constrained devices, the accuracy obtained is slightly worse than the decimeter-level accuracy provided by Luxapose and Lumicast, and it takes 1.8 s to obtain the first localization. In addition, PIXEL requires using a light polarizer in both the transmitter and receiver sides. In [160], the positioning information is used in Carrefour's mobile application to help the customers on way-finding, product finding and personal couponing. LED luminaries send a unique beacon and it is detected by the image sensor of a mobile phone in [160]. Then, the mobile phone identifies the horizontal location with 10 cm accuracy and orientation with 2 degrees of accuracy. It is noted in [160] that a person or item can be positioned within 0.1 s and this position is updated as often as five times per second.

5.5.2 Requirements for the 5G-CLARITY OCC system

Current solutions in the state of the art are not considered appropriate for 5G-CLARITY because they require dedicated LED luminaires to broadcast a low data-rate OCC signal. However, 5G-CLARITY will use LEDs for high-speed data communication. Hence, in order to avoid having to deploy separate LEDs for positioning and communications, we need to design an OCC solution where the OCC signal and the LiFi signal can be multiplexed in the same transmitter.

In particular, 5G-CLARITY will design a solution fulfilling the requirements listed in Table 5-4:

Table 5-4: Positioning framework requirements for OCC system

OCC requirement ID	Description
OCC-R1	The OCC modulation will use limited BW (<20KHz) so that a single LED transmitter can multiplex in frequency OCC and LiFi signals
OCC-R2	The designed solution will be able to operate with commercial LED luminaires
OCC-R3	The OCC receivers can recover a position when being in line of sight (LoS) with one or more LED fixtures
OCC-R4	A minimum number of 4 LEDs are needed to achieve optimal accuracy The designed OCC positioning solution will experience a graceful degradation when the number of LEDs in LoS reduces, with optimal accuracy achieved when 4 LEDs are visible
OCC-R5	The provided OCC positioning solution will provide both position and orientation, with a precision of at least 10 cm in positioning and 10º in orientation, when a minimum number of LEDs is available in line of sight
OCC-R6	The designed OCC positioning solution should provide enough accuracy even when the alignment between the OCC devices and the LED fixtures is not ideal

OCC-R7	OCC receivers will decode an image locally from which a location will be derived. A position measurement should be obtained using a single image
OCC-R8	OCC receivers will be able to recover at least 10 positioning measurements per second
OCC-R9	OCC receivers will be able to inform a positioning server about the obtained measurements
OCC-R10	The designed OCC positioning system should be able to run in a smartphone or in an embedded IoT device with a CMOS camera interface

Figure 5.1 sketches the design of the 5G-CLARITY OCC positioning solution, which will comprise the following steps:

1. An OCC device being in LoS with a set of LED luminaires will take an image where the various LEDs are visible.
2. Processing the captured image, the OCC device will decode an identifier transmitted by each LED.
3. The recovered identifier will be looked up against a local database in the device, which contains the position of the recovered LED within a 3D coordinate system
4. Based on the relation between the 2D and 3D coordinates of the recovered LEDs, the device will find its position within the 3D coordinate system
5. The recovered position will be transmitted to the 5G-CLARITY positioning system

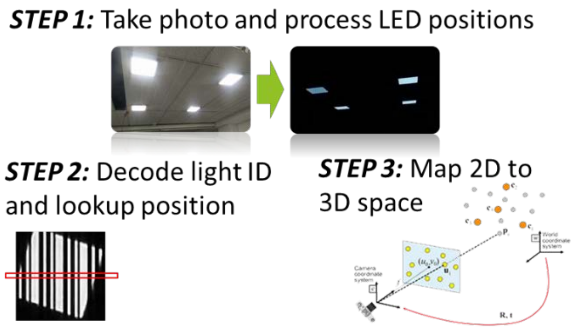


Figure 5.1: High level design of the 5G-CLARITY OCC positioning system

5.6 Hybrid indoor-positioning

The envisioned architecture of 5G networks considers a layer of small-cells that may serve densely populated regions. Cells of different WATs and various sizes (macro, micro, femto, pico, atto, etc.) are also envisioned to co-exist [161]. The use of technologies that are sensible to moving environments, such as mmWave solutions presented in Section 5.3.1, makes the combination of different WATs necessary to ensure adequate communication/positioning capabilities in the network [162].

The availability of multiple position estimates stemming from the use of different technologies can additionally improve the localization precision or functions that can leverage the localization functionality. A scenario where multiple WATs coexist will be beneficial to achieve full coverage. For localization purposes, it is important that the wireless connection established between the AP and the UE is performed under LOS conditions. Therefore, WATs which are used in LOS scenarios will be favoured for the location estimation.

The intelligent combination of position estimates stemming from technologies like Sub-6 in combination with mmWave can also improve the latency, as the beam search procedure performed by the mmWave radio can be dramatically reduced (see Section 5.3.1). Before a connection between UE and access node using mmWave is performed, a beam search procedure must be executed. This procedure is performed as exhaustive search of hierarchical search. Both approaches are time consuming and, therefore, they benefit from the availability of a position estimation using other WATs, which can additionally reduce the beam search area and, hence, reduce the time required for it. The use of multiple technologies, e.g.mmWave, at access and mobile nodes was presented in [163] where the Sub-6 band is used as a side channel to determine AoA at the side of access node [164].

5G-CLARITY would investigate the possibilities for adopting of the hybrid positioning approach and would propose methods for intelligent combining of different WATs for improving localization precision and accuracy.

6 Control and User Plane Integrated Design and Architecture

6.1 Management plane design and architecture dependencies

The 5G-CLARITY architecture leverages on O-RAN Alliance reference architecture as described in [165] and initially discussed in [166]. The O-RAN reference architecture provides a logical split between the management plane (in 5G-CLARITY is worked out in WP4) and control and user plane (5G-CLARITY WP3). As can be seen in Figure 6.1, the O-RAN Alliance defines, amongst others, the interfaces between the SMO (Service Management and Orchestration), including the non-Real Time RAN Intelligent Controller or non-RT RIC), with the SMO functions mapping to the context and scope of 5G-CLARITY WP4, and the near RT functions of the near-Real Time RAN Intelligent Controller (near-RT RIC), CU, DU and RU mapping to the context and scope of 5G-CLARITY WP3. The CU is the 3GPP Centralised Unit while the DU is the 3GPP Distributed Unit as discussed in 5G-CLARITY system architecture [166]. The RU is the Radio Unit for which 3GPP has no normative interface but with a recommendation for a Low Layer Split based on either Split 7.2 (defined in O-RAN) or Split 6 (normative in Small Cell Forum).

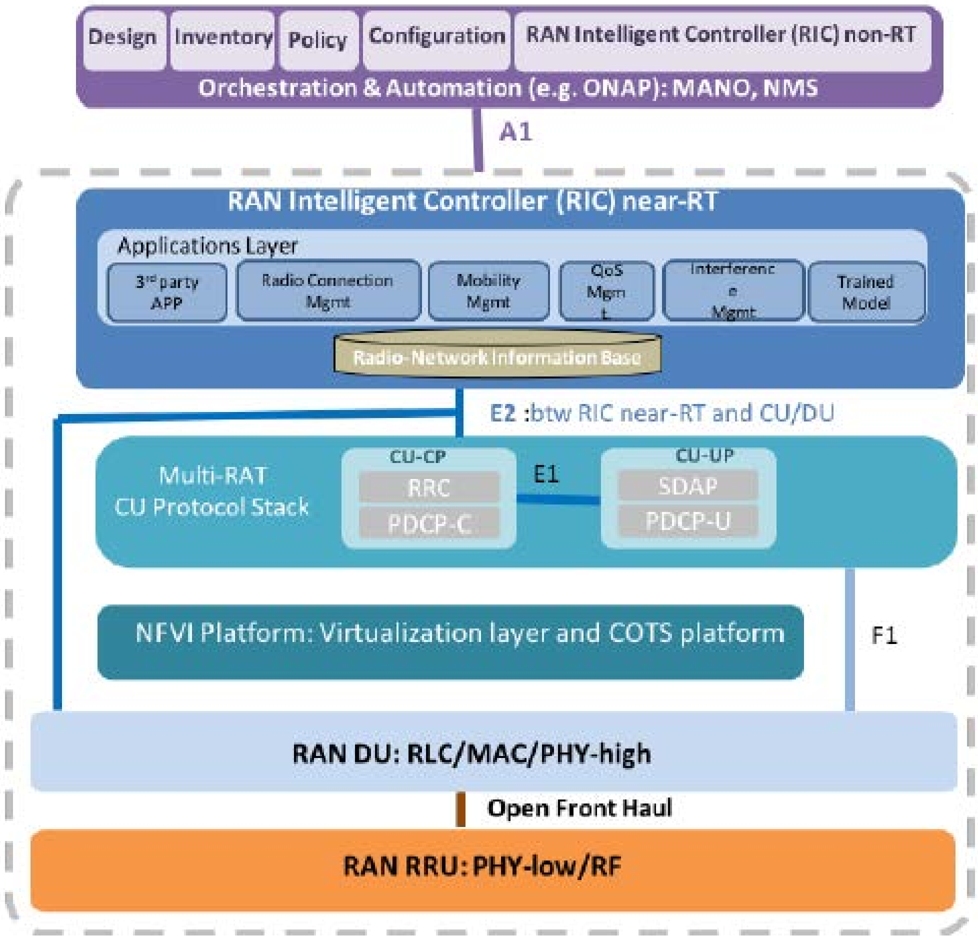


Figure 6.1: O-RAN Alliance reference architecture

In a more recent O-RAN Alliance document [167] there is more detailed description of the logical O-RAN architecture as shown in Figure 6.2.

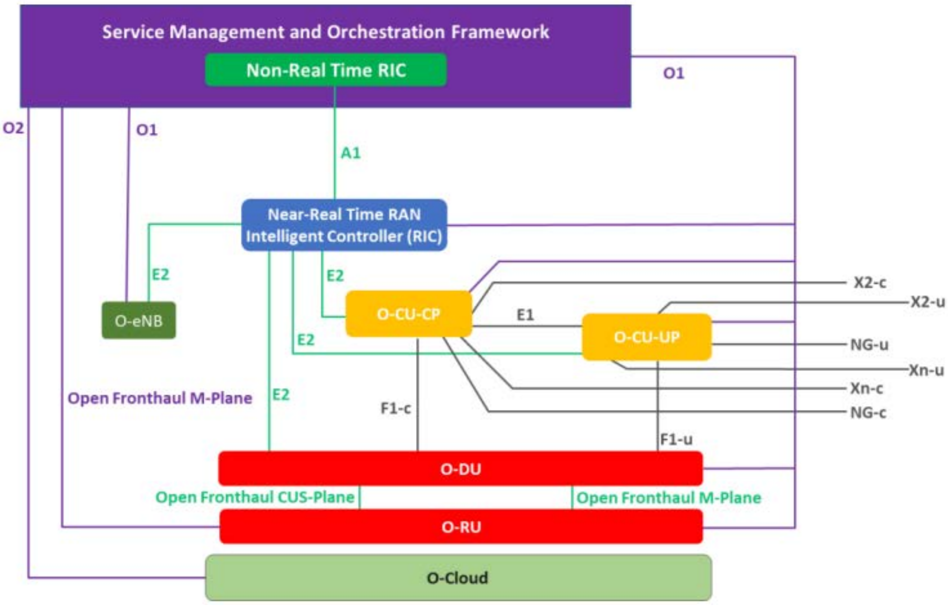


Figure 6.2: O-RAN overall logical architecture

A1 is the interface between the non-RT RIC function in SMO and the near-RT RIC function. The non-RT RIC function resides in the SMO layer that also handles deployment and configuration as well as data collection. In the SMO layer there are also functions that handle AI/ML workflow (training and update of ML models) and functions for deployment of ML models and other applications. The SMO Layer may also have access to data other than that available in the RAN network functions and this enrichment information can be used to enhance the RAN guidance and optimization functions. One purpose of the SMO layer is to optimize the RAN performance towards fulfilment of the SLAs in the RAN intent (RAN intent is defined as an expression of high-level operational or business goals to be achieved by the radio access network). The purpose of the A1 interface is to enable the non-RT RIC function to provide policy-based guidance, ML model management and enrichment information to the near-RT RIC function so that the RAN can optimize RRM under certain conditions. The A1 interface supports three types of services:

- Policy Management Service
- Enrichment Information Service
- ML Model Management Service

The near-RT RIC is a logical function that enables near real-time control and optimization of eNB/CU/DU nodes functions and resources via fine-grained data collection and actions over the E2 interface with control loops in the order of 10 ms to 1 s. The near-RT RIC hosts one or more xApps that use E2 interface to collect near real-time information (e.g. on a UE basis or a Cell basis) and provide value added services. The near-RT RIC control over the E2 nodes is steered via the policies and the enrichment data provided via A1 from the non-RT RIC.

The O1 interface is the interface between management entities in the SMO Framework and the O-RAN managed elements for operation and management. It is used to fullfill Fault, Configuration, Accounting, Performance and Security (FCAPS) management, Software management and File management.

6.2 Control and user plane internal architecture

6.2.1 Non-3GPP access to 5GC

6.2.1.1 Integration of Wi-Fi and LiFi access using a SDN enabled L2 network

As introduced in deliverable D2.2 [166], 5G-CLARITY proposes to integrate the Wi-Fi and LiFi wireless access networks within a single SDN enabled layer 2 (L2) network, which can then be integrated with the 5GC using the standardized N3IWF or TNGF gateways.

The main motivation for using a customized L2 SDN network, as compared to a standard IEEE 802.1 Ethernet segment, is to provide the 5G-CLARITY control plane with the ability to control with fine granularity the path followed by packets belonging to different 5G-CLARITY slices within the L2 segment. Notice that a standard 802.1 Ethernet segment implements per-VLAN data plane learning does not allow for this fine level of control. Another key requirement for the L2 SDN control plane is to support seamless mobility, meaning that when user devices roam through the various Wi-Fi and LiFi APs connected to the L2 SDN network, forwarding paths should be automatically updated.

Figure 6.3, extracted from deliverable D2.2, depicts the 5G-CLARITY Wi-Fi-LiFi integrated L2 SDN network that provides access to Wi-Fi and LiFi user devices and connects to a standard 802.1 Ethernet segment. The Access L2 mobility function, collocated in the Wi-Fi and LiFi access points, and the Anchor L2 mobility function, collocated in the devices connected to the 802.1 Ethernet segment enable seamless mobility for user devices.

In this section, we describe a tentative design for the integrated Wi-Fi-LiFi L2 SDN network that will be further developed and evaluated in the upcoming WP3 deliverables.

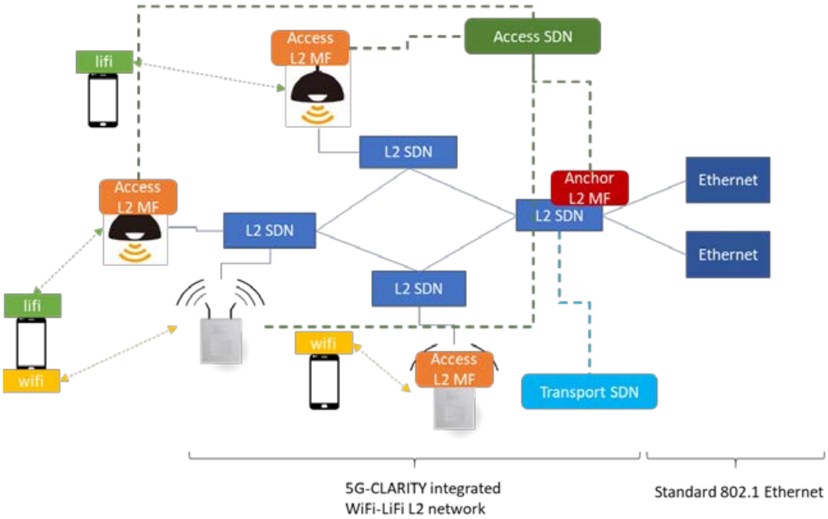


Figure 6.3: 5G-CLARITY integrated Wi-Fi/LiFi SDN L2 network

A key component of the proposed solution is an integrated wireless and wired SDN switch developed by i2CAT. This switch is depicted in Figure 6.4 and consists of a Single Board Computer (SBC) running Ubuntu Linux OS that features multiple mini-PCIe interfaces. These mini-PCIe interfaces are used to connect to Wi-Fi modems, preferably based on Qualcomm-Atheros drivers [168], and gigabit Ethernet adapters. Regarding the Wi-Fi connectivity an initial design will be pursued targeting IEEE 802.11ac support, which will be later upgraded to IEEE 802.11ax if time allows. All the forwarding intelligence of the proposed device will be implemented in software running in the Linux OS, by means of software switching based on Open vSwitch [169] and management interfaces based on Netconf [170]. The advantage of the proposed device, as compared to Wi-Fi access points and SDN switches offered by commercial vendors as separate devices, is that it offers an integrated solution that embeds only the required functionality resulting in a much more competitive offering.

The left part of Figure 6.4 depicts the SBC and the target Wi-Fi and GbE modules, while the right part depicts a hierarchical data plane that enables the forwarding of packets across the SDN network. This data-plane is an evolution of the one developed by i2CAT in the 5G-PICTURE project [171] [172]. In 5G-CLARITY this data-plane will be enhanced to support both wireless and wired backhaul connections, while only wireless backhaul was supported in 5G-PICTURE, and to enable access connectivity of the LiFi access points provided by PLF in 5G-CLARITY. The proposed data-plane consists of three software switches, based on Open vSwitch, connected in a hierarchical manner:

- The backhaul bridge (*bh_sX*) is in charge of forwarding packets based on a layer 2 path identifier carried in each packet, which can be implemented using an outer VLAN tag.
- A set of access bridges (*acc_br*), where we have one bridge per wireless service[2] that connects the virtual access interfaces in the L2 SDN box associated to that service. Notice that we can have two types of access interfaces, i.e. Wi-Fi or Ethernet, the former implemented with a virtual AP (vAP) and the latter with a VLAN interface on the access link.
- Finally, we have the integration bridge (*int_sX*) that binds the access bridges to specific paths in the backhaul, i.e. it binds ports coming from the access bridges to VLAN switched paths over the L2 fabric. Therefore, by interacting with the integration bridge the 5G-CLARITY control plane can easily control how packets from a given wireless service are forwarded within the integrated L2 SDN network.

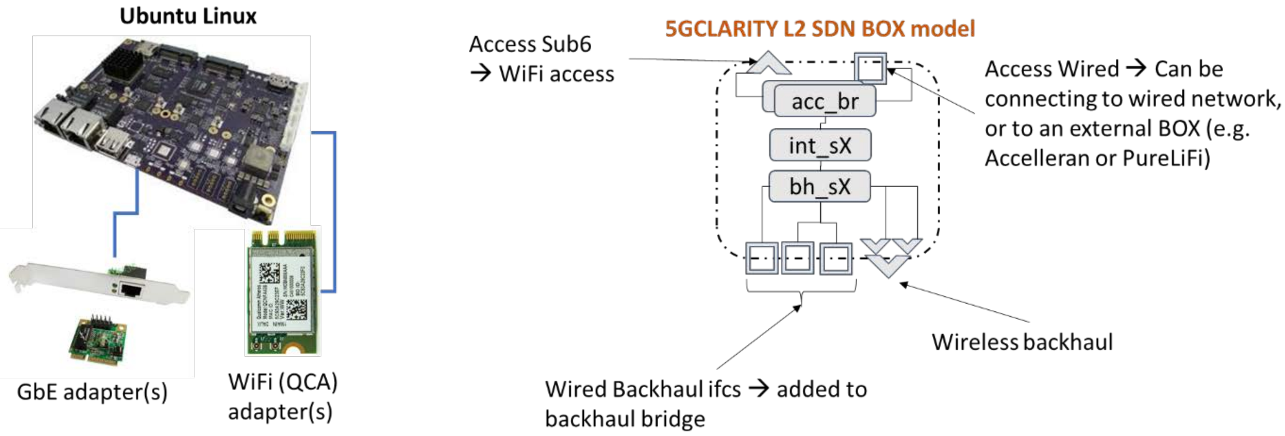


Figure 6.4: 5G-CLARITY lightweight L2 SDN wireless-wired switch

Figure 6.5 describes the proposed forwarding model with a greater level of detail. Each dash-dot box represents an integrated L2 SDN switch (c.f. Figure 6.4). We can see that some of these boxes have an integrated wireless access interface (depicted with a triangle), and a set of access or backhaul wired interfaces represented with a square. We can also see in Figure 6.5 two LiFi access points, represented with a yellow dash-dot box, that connect using Ethernet to the L2 SDN wireless-wired switch.

Figure 6.5 represents the case of having one 5G-CLARITY wireless service that radiates a given SSID over a selected subset of Wi-Fi and LiFi APs. In order to instantiate this service an access bridge representing the service is instantiated in all the L2 SDN wireless-wired switches, i.e. BOX1, BOX3, BOX4, and the LiFi access points, i.e. LIFI1 and LIFI3, where this service is present (depicted in blue). We can see the following elements that are part of this service:

- To connect LiFi access points a VLAN interface (ethX.200) is provisioned in the link “LIFI1 – BOX1” and in “LIFI3-BOX4”. Notice that if we would have other services over the same links additional

[2] Refer to Deliverable D2.2 for a definition of a 5G-CLARITY wireless service

VLANs would be provisioned.

- A VLAN 200 is provisioned to the Ethernet interface in BOX3 connecting to the 802.1 Ethernet segment, which means that all traffic coming from this Wi-Fi-LiFi service will be delivered to the Ethernet segment tagged with VLAN 200.
- Virtual Wi-Fi access points belonging to this service are instantiated in BOX3 and BOX4, connecting to the corresponding access bridge.
- Backhaul forwarding paths need to be deployed to provide connectivity between the devices where the access services are instantiated and the devices that connect to the Ethernet segment. In this regard in order to connect LIFI1 two unidirectional forwarding paths are setup identified with VLANs 20 and 21 (depicted in red), and to connect LIFI3 and the Wi-Fi service in BOX4 two additional unidirectional forwarding paths are setup identified with VLANs 30 and 31 (depicted in green). No additional path is required to connect the Wi-Fi service in BOX3 because BOX3 has an interface directly connected to the Ethernet segment. Notice that the 5G-CLARITY control plane can easily implement traffic engineering on a per-service level by managing forwarding paths or the binding between the services and the pre-provisioned forwarding paths.

The last aspect to highlight is how the Anchor L2 mobility function depicted in Figure 6.3 is implemented. In the proposed architecture this function is automatically performed by the access bridge in the root device (BOX3 in Figure 6.5), which maintains a binding between the MAC address of each user device and the L2 forwarding path, i.e. red and green paths in the figure, that is being used to carry packets from this device.

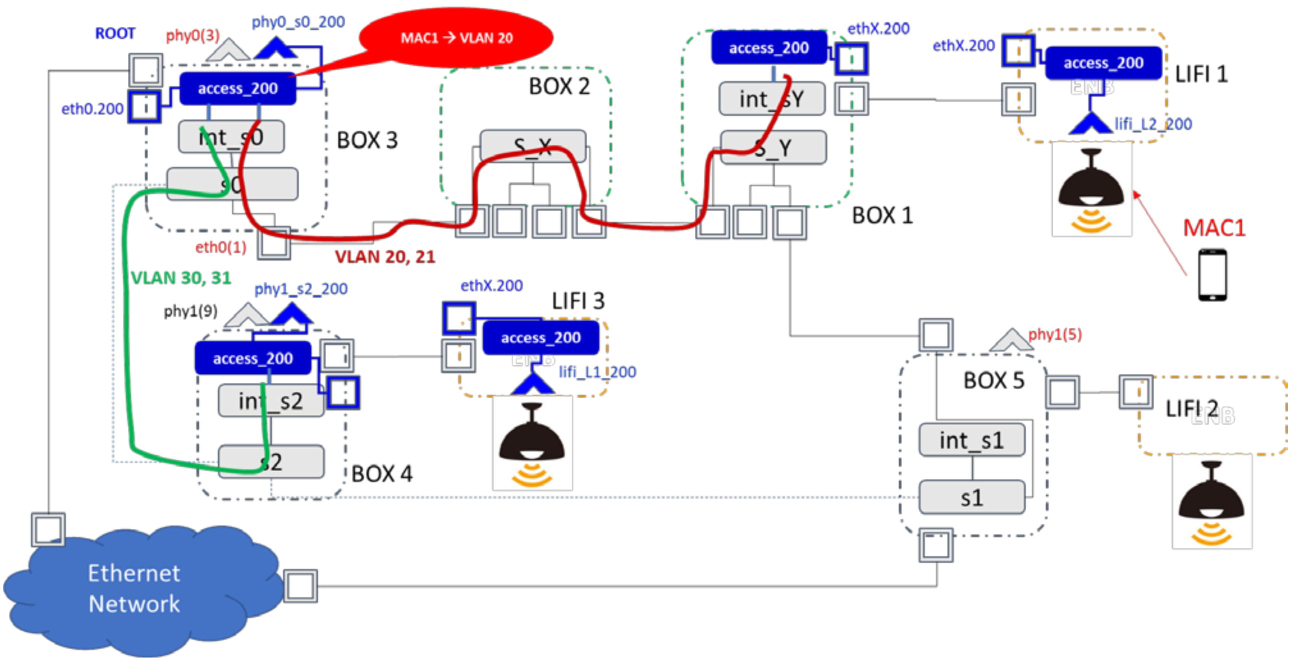


Figure 6.5: Forwarding model in 5G-CLARITY SDN L2 network

Figure 6.6 illustrates how the proposed architecture can sustain device handovers. When the device with address MAC1 moves from LIFI1 in Figure 6.5 to LIFI3 in Figure 6.6 the LiFi access point detects the new attachment and generates a Gratuitous ARP packet that has as source MAC address the address of the device that just attached to the LiFi AP (i.e. MAC1). The ARP packet reaches BOX3 through the green forwarding path (VLANs 30, 31), after which the access bridge in BOX3 updates the binding between this MAC address (MAC1) and the fabric forwarding path so that subsequent packets addressed to this MAC address are forwarded to LIFI3 instead of LIFI1. The same model can be applied to Wi-Fi handovers. The Gratuitous ARP message is generated by the Access L2 mobility function depicted in Figure 6.3.

Notice that the proposed architecture supports devices that integrate Wi-Fi and LiFi interfaces, which from the perspective of the L2 SDN network will appear indistinguishable from a separate Wi-Fi and LiFi devices. Aggregation of the two paths will be performed by the multi-connectivity framework described in Section 6.2.3. In upcoming WP3 tasks we will prototype the presented system and demonstrate how it can support mobility between Wi-Fi and LiFi access networks.

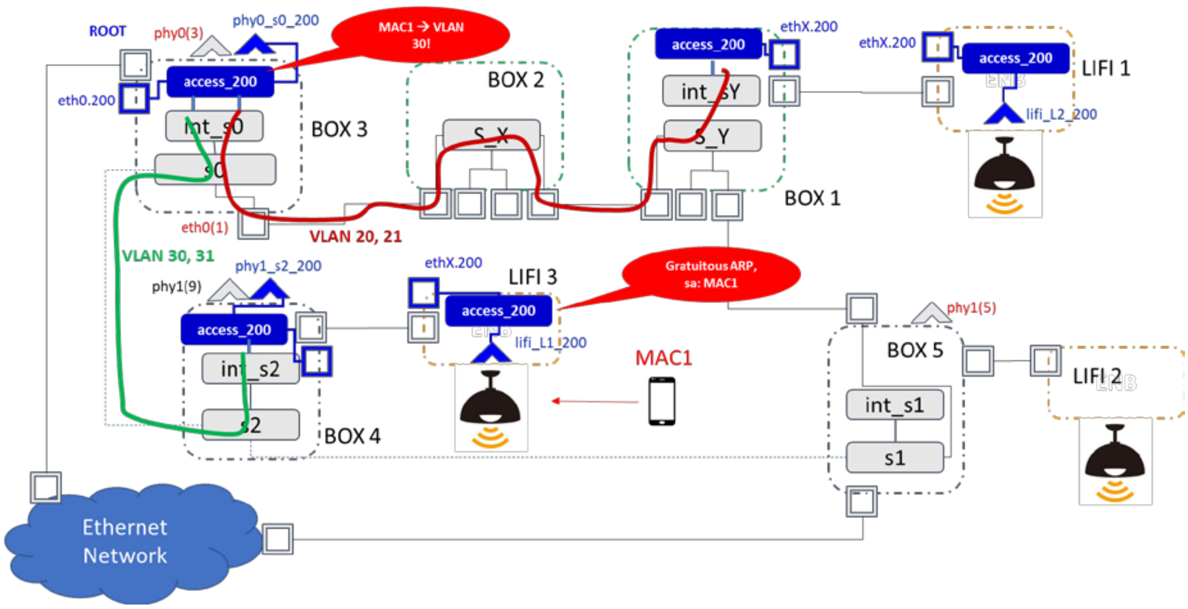


Figure 6.6: Mobility support in 5G-CLARITY SDN L2 network

6.2.1.2 Integration to 5GC via N3IWF/TNGF

As explained in Section 3.1.2, non-3GPP access network is integrated to 5GC network via N3IWF or TNGF if the non-3GPP network is considered as untrusted or trusted, respectively. In Figure 6.7, user plane for non-3GPP access via N3IWF is depicted. According to Figure 6.7, the UE sets up a generic routing encapsulation (GRE) tunnel against the N3IWF (or TNGF), which is then mapped to a per-UE and per-access network GPRS tunnelling protocol (GTP) tunnel for the N2 (control plane) and N3 (user plane) interfaces against the 5GC. As the proposed Wi-Fi-LiFi integrated L2 network ensures that the IP address of the UE remains the same, mobility within the proposed integrated non-3GPP network does not impact the GRE tunnels established between the UE and the N3IWF (or TNGF).

Control plane for non-3GPP access via N3IWF (or TNGF) also follows a similar protocol stack to the user plane. The differences are on (i) the network function interface from N3IWF to 5G core which is AMF via N2 interface; and (ii) message transmission which is NAS instead of PDU for the control plane. In order to establish secure connection between the UE and the N3IWF (or TNGF) to securely transfer the user and control plane messages, Nwu (or Nwt) interface is used.

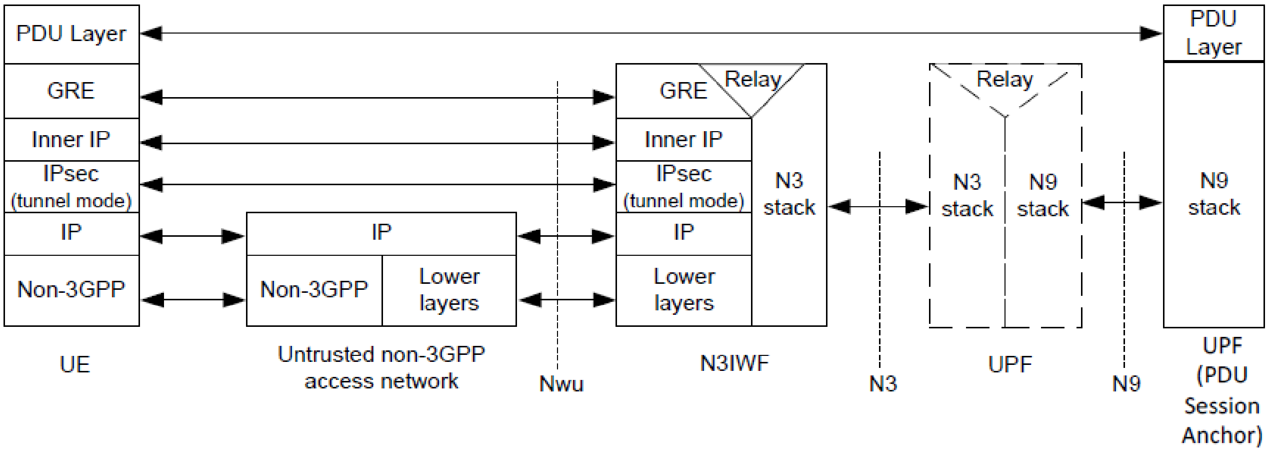


Figure 6.7: User plane for non-3GPP access [70]

6.2.2 Non-public and public network coexistence

6.2.2.1 Spectrum access

5G-CLARITY will enable a DSA paradigm based on the use of CBRS SAS architecture. This innovative regulatory regime albeit was initially the focus of the US market but might potentially be replicated in other geographies. Its intrinsic advantage is that since it is based on a 3-tier approach, it can be mapped to regulatory spectrum regimes spanning from usual traditional licensed ones to others where incumbent protection or local vertical licenses are granted to private network deployments. Figure 6.8 shows the logical CBRS architecture within the scope of 5GNR.

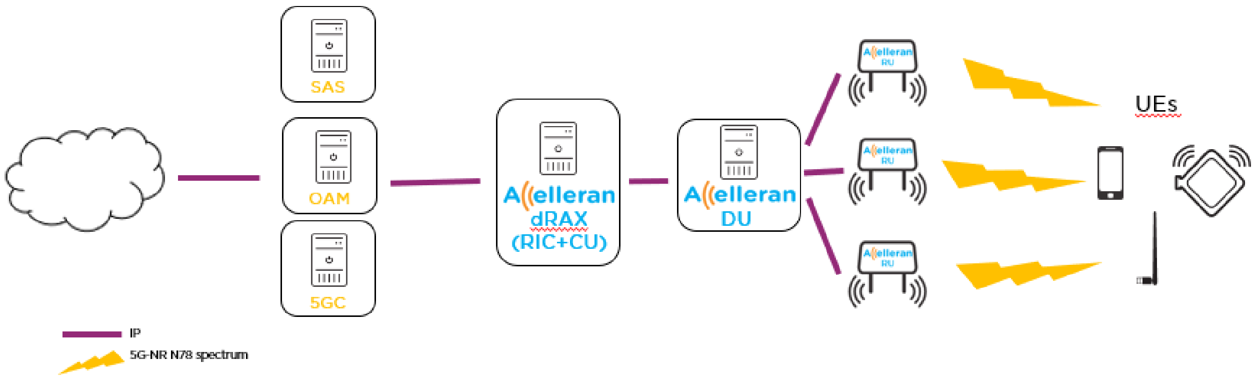


Figure 6.8: Overall CBRS logical architecture with 5G

The external SAS acting as an automated and intelligent dynamic spectrum management coordination entity will be simulated/emulated in order to provide the RF spectrum parameters that the 5G-CLARITY 5GNR SAS client require for operation. The current Accelleran integrated LTE SAS client used in CBRS Small Cell context will be implemented in O-RAN dRAX context as an xApp for 5G-CLARITY (See Figure 6.9) with the following enhanced functionality:

- Support grouping information and coexistence grouping so that the cluster of 5GNR DU/RUs can operate in co-channel deployment with minimal spectrum within cluster wide Interference Coordination Group.
- Align to upcoming CBRS Alliance Release 4 specifications to support 5GNR operation in SA mode and SA NPN/PLMN-integrated NPN.

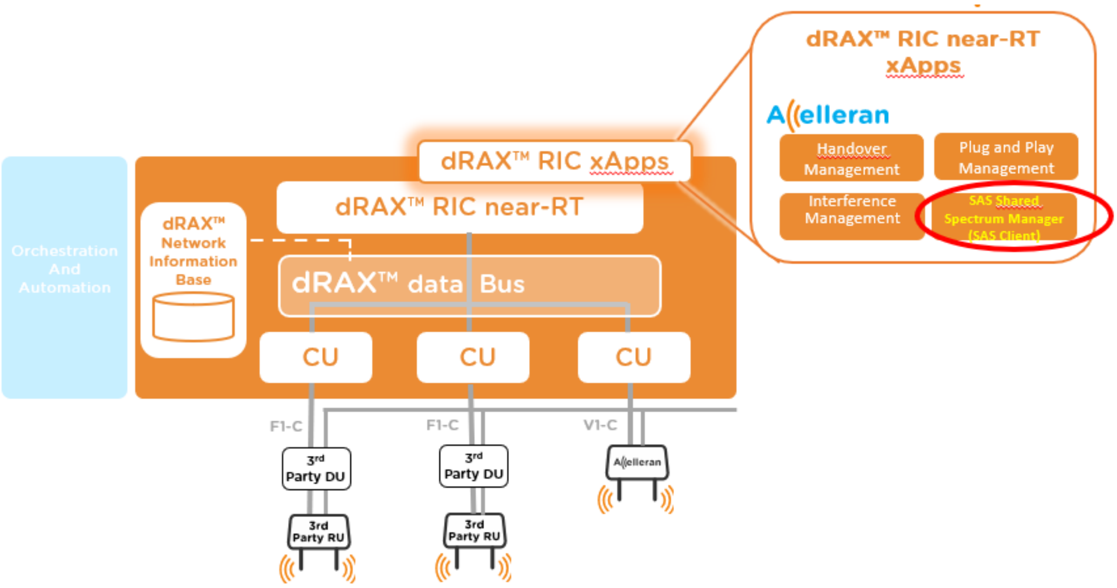


Figure 6.9: SAS client functionality as dRAX RIC xApp

6.2.3 Multi-access based multi-connectivity (MA-MC)

The 5G-CLARITY multi-access framework envisages an integrated convergence across a wide range of technologies, namely 3GPP 5GNR, 3GPP LTE (4G), IEEE 802.11 Wi-Fi and LiFi. The MA-MC framework is designed for allowing various traffic steering functionalities among the available access technologies in order to increase data-rate, reduce latency, or enhance reliability.

The available access technologies can be divided into three main categories, as shown in Figure 6.10, namely:

- All 3GPP: includes 3GPP-only access technologies, particularly LTE and 5GNR.
- 3GPP and non-3GPP: which comprises a combination of 3GPP and non-3GPP access technologies, such as LTE/5GNR with Wi-Fi/LiFi.
- Non-3GPP only, it includes non-3GPP access only technologies, namely Wi-Fi and Li-Fi.

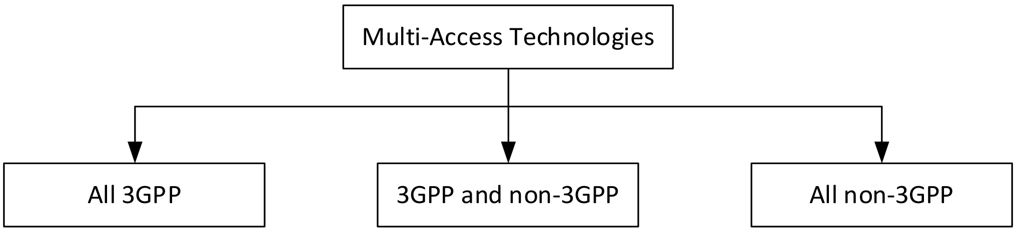


Figure 6.10: Access technologies scenarios

In the following sections two different approaches are discussed. First the multi-access design with only non-3GPP access, and then the multi-access design integrating 3GPP access. 5G-CLARITY implemented solutions will be based on 3GPP and non-3GPP access, but for completeness, the 'multi-access with non-3GPP access only' subsection describes how the solution could be integrated without 3GPP access or 5GC network.

6.2.3.1 Multi-access with non-3GPP access only

5G-CLARITY architecture supports the deployment of multiple wireless access technologies. The integration of a non-3GPP network such as Wi-Fi or LiFi requires inter-networking elements within the 5GC Network. Specifications for aggregation within 3GPP access networks, and between 3GPP and non-3GPP access networks have already been defined by various 3GPPP technical specifications. Section 6.2.3.2 discusses in detail 3GPP integrated multi-access multi-connectivity. This subsection considers a scenario outside the defined specifications for connectivity to the 5GC through LiFi and Wi-Fi access networks only.

There are several schemes to integrate an untrusted non-3GPP access to the core network. From [70] the AT3S offers steering, switching, and splitting functions for access traffic between a 3GPP and a non-3GPP access networks. AT3S is described in Section 3.1.2.3. An alternative is using the Access Network Discovery and Selection Function (ANDSF). It transmits traffic via a secure tunnel between the untrusted non-3GPP device and the core network. The ANDSF provides rules to guide the UE through routing traffic across separate access networks. Normally, this technique is deployed at the application level such as voice over Wi-Fi where the application establishes a reliable link.

The Multi-Access Management Service (MAMS) offers more flexibility for selection of network routes in a multi-access framework based on application requirements. MAMS uses network intelligence to dynamically adjust traffic selection between networks. This function is beyond the mere distribution of network policies and rules as employed by ANDSF. MAMS structures are independent of any specific access network type or user plane protocols like TCP, UDP, GRE, MPTCP [173].

However, the constraint of using the core network of an associated access network path remains problematic for a truly multi-access 5G deployment scenario. This is because the performance of an application in different scenarios depends on the chosen access network. Hence, to achieve the application performance in different scenarios a framework that permits flexible combination of access technologies and common network paths is required. Additionally, a flexible usage of DL and UL protocols is needed too. 3GPP Release 16 supports traffic aggregation at L3 via the multi-access 5G network, which has just been completed in July 2020.

The Multi-Path Steering Switching and Splitting (MP3S) function allows steering, switching and splitting operations in networks that are not connected to the 5GC, for instance private networks with Wi-Fi only. Like the 3GPP AT3S, the MP3S can be based on MPTCP implementation and the SSS operations are similar to 3GPP AT3S. The MP3S framework splits the MP3S functionality between UE and Network, where the MP3S in the UE is controlled by the UE policy controller, which is operating on access network control plane.

Real-time Telemetry function is collecting real-time measurements from each access technology. This telemetry is carried over to the Intelligent Telemetry Application Function which analyses the telemetry and proposes a policy change to the real-time policy-controller. The real-time policy-controller coordinates the dynamic policy changes that impact on MP3S function and eventually scheduling of the access network traffic. The functions presented in Figure 6.11 do not consider any particular deployment. One possibility is to deploy these functions on ETSI MEC platform.

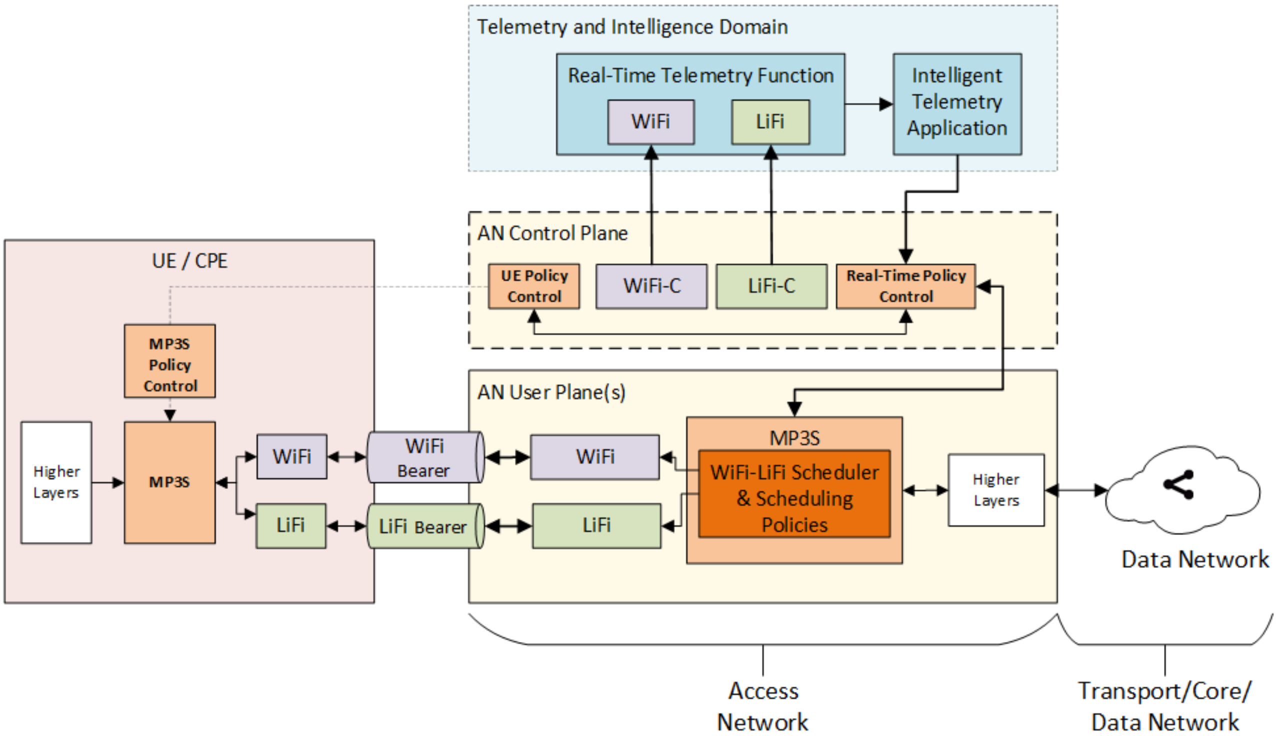


Figure 6.11: MP3S non-3GPP-access based framework.

6.2.3.2 3GPP integrated multi-access

There are two possible approaches to achieve 3GPP integrated MA-MC. One is based on an enhanced AT3S (eAT3S) at the core network level which can be applicable to co-located (on the same point of presence) and non-co-located (not on the same point of presence) access solutions, and another based on typical RAN integrations for unlicensed bands via carrier aggregation between licensed and unlicensed carriers or via some LWA/LWIP approaches.

Within the scope of 5G-CLARITY no RAN integration approaches will be used in the demonstration pilots since 5GNR and Wi-Fi will come from different partners. This would be also the normal case in private networks when cellular LTE/5GNR technology is brought into an already established Wi-Fi infrastructure.

The 5G-CLARITY solution will use and demonstrate a core-based eAT3S integration. This solution will effectively be a hybrid of both core side and RAN side approaches in the sense that the AT3S will be enhanced to incorporate near-RT RAN control of the AT3S policies behind the UPF by using multi-WAT telemetry at RAN level (not only UPF level) via near-RT RIC and xApps O-RAN framework. The motivation of eAT3S is to mitigate any increase on latency in case PCF and SMF are not located in the private venue. One of the near-RT RIC xApps will be the AT3S control. This O-RAN based reference architecture will be provided by Accelleran dRAX as shown in Figure 6.12. Telemetry data from the different access technologies will be published in Accelleran dRAX databus and made available to the AT3S control xApp, which will be able to control the AT3S policies near real time through appropriate exposure interfaces.

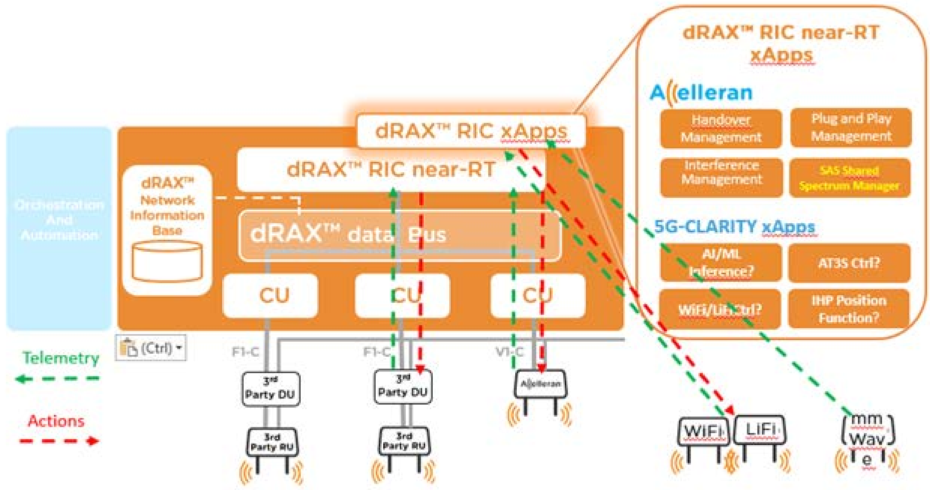


Figure 6.12: Accelleran dRAX multi-WAT reference architecture

In Figure 6.13, the control plane of the proposed 5G-CLARITY enhanced AT3S is depicted. The details of blocks/signal-flows marked by red-squared numbers are as follows:

1. AT3S rules are modified in order to include eAT3S procedure that enables real-time traffic steering. The real-time steering is going to be considered as the first AT3S rule among the list of AT3S rules. AT3S policy function pushes this rule to User Plane control AT3S Function (UPc-AT3SF) and User Equipment AT3S Function (UE-AT3SF) in the UPF and UE, respectively. Based on this rule, Rt-UPc-AT3SF and Rt-UE-AT3SF are going to be used for the upcoming traffic.
2. Rt-UPc-AT3SF enables adaptive modification of steering/splitting parameters within UPF.
3. Rt-AT3S Ctrl collects telemetry data from 5GNR, Wi-Fi and LiFi networks as well as AT3S performance measurements from PMF. Based on the collected data and network slice that is being served, Rt-AT3S Ctrl modifies the traffic routing parameters such as load per access network, priority of access networks or changes the considered active network type from/to 3GPP to/from non-3GPP and so on. These modifications are being done in real-time and applied for both downlink traffic (through Rt-UPc-AT3SF) and uplink traffic (through Rt-UE-AT3SF).
4. Based on the AT3S policy function, if Rt-UE-AT3SF is enabled, it gets network status related updates/modifications from Rt-AT3S Ctrl and routes the uplink traffic accordingly. The AT3S rules for the uplink direction are conveyed from Rt-AT3S Ctrl to UE as user plane in-band transmission from UPF via 5GNR, Wi-Fi and LiFi networks.
5. Wi-Fi/LiFi Ctrl provides seamless L2 connectivity for the integrated Wi-Fi/LiFi network that is considered as non-3GPP network in 5G-CLARITY. It maintains the bindings between the MAC addresses of the user devices and the Wi-Fi/LiFi APs that the user is attached to, and gathers Wi-Fi/LiFi-related telemetry.
6. The multi-path transmission performance results on RTT, received power level, channel utilization, etc., are provided to AT3S performance measurement function. AT3S performance measurement function compares the reported measurements with corresponding predefined measurement thresholds. It is important to note that this function can be a standalone function, as shown in Figure 6.13, or collocated within the UPF.
7. All the gathered telemetry data from 5GNR, Wi-Fi and LiFi access networks and path performance measurement results of AT3S are fed back to Rt-AT3S Ctrl for deciding whether modify or not the traffic flows.

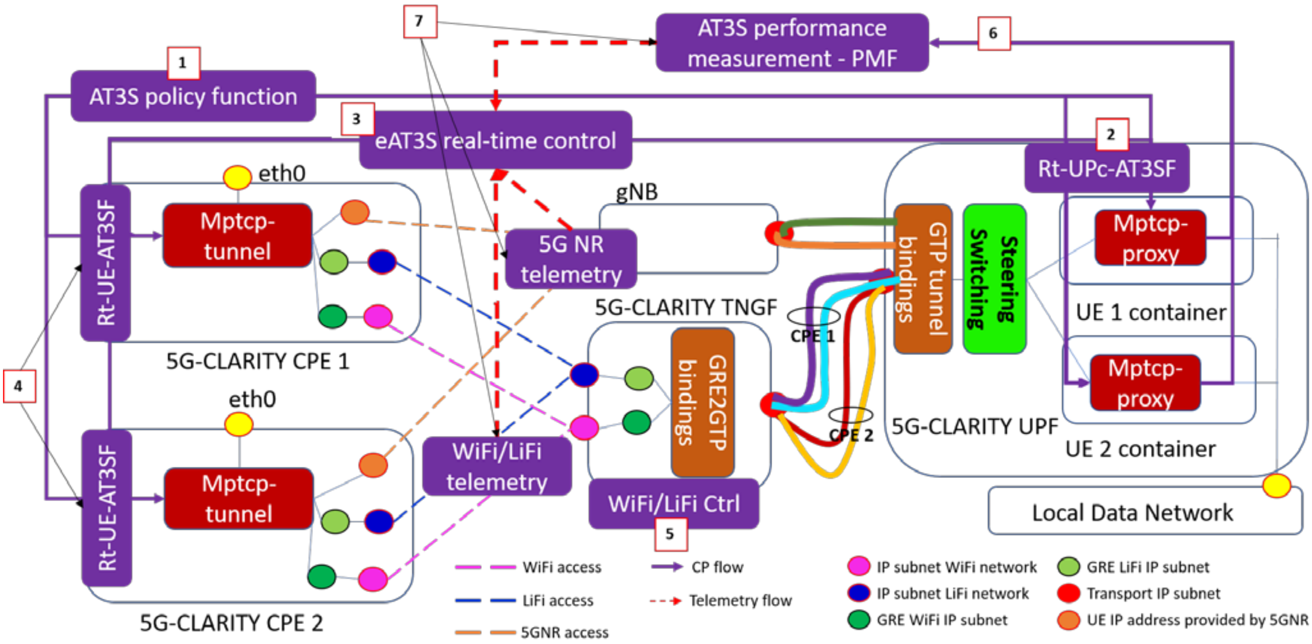


Figure 6.13: 5G-CLARITY eAT3S control plane – CPE/UE can be used interchangeably

In Figure 6.14, the user plane of the proposed 5G-CLARITY eAT3S is shown. The details of elements marked by red-squared numbers are as follows:

1. A container for each UE is considered in 5G-CLARITY UPF. Each UE container can have one IP interface and three destination paths for 5G, Wi-Fi and LiFi can be used to reach the UE from the single source UE container.
2. Static routes are required in the "Steering/Switching" function in order to point to the remote end-points of the MPTCP session. In other words, per UE per WAT routes are required.
3. "GTP tunnel bindings" function is used to bind GTP tunnels to UE containers.
4. Solid, colourful paths represent N3 interfaces which can be considered as one GTP tunnel per UE and per 3GPP/non-3GPP technology.
5. "GRE2GTP bindings" function is used to bind GRE tunnel IP to GTP tunnel ID, and vice versa. It needs to inspect *gre_key* and *gtp TEID*.
6. Any protocol (e.g. Ethernet) should be packaged over the MPTCP tunnel.

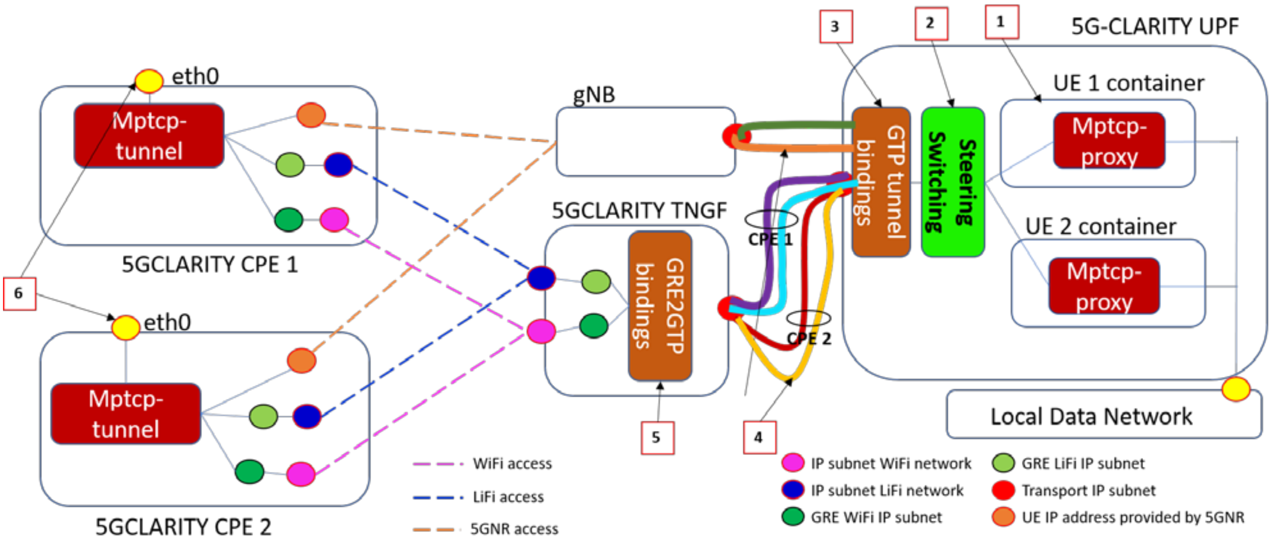


Figure 6.14: eAT3S user plane – CPE/UE can be used interchangeably

6.2.4 Resource Management

In 5G-CLARITY, non-3GPP access network is considered as an integrated Wi-Fi-LiFi SDN L2 network as described in Section 6.2.1. Since the non-3GPP access network will be integrated with 3GPP access network using AT3S as described in Section 6.2.3, how to route the traffic flows to 3GPP and non-3GPP access networks can be considered as a resource management problem. Moreover, as a 5G-CLARITY CPE/UE will be capable of using 5G, Wi-Fi and LiFi technologies [166], multi-user access to physical resources of those technologies can also be considered as a resource management problem. Therefore, resource management in 5G-CLARITY will be considered as a two-stage process namely 'traffic routing' and 'gNB/AP-level resource scheduling', as shown in Figure 6.15.

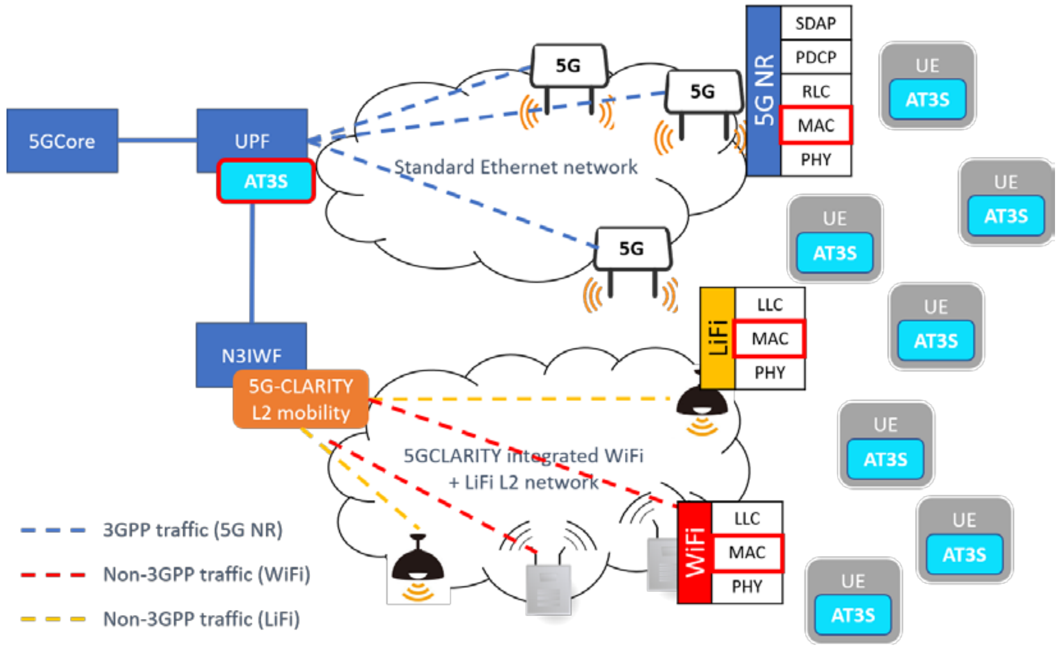


Figure 6.15: High-level network architecture of 5G-CLARITY

6.2.4.1 Traffic routing

Traffic routing is an AT3S-level problem. As described in Section 6.2.3.2, telemetry and performance measurements will be used to route traffic flows to non-3GPP and 3GPP networks in real-time by eAT3S. Within 5G-CLARITY real-time eAT3S, traffic routing is based on (i) comparing the predefined threshold values of network service related KPIs and the real-time performance measurements/telemetry data; and (ii) ML-based traffic routing onto different WATs by using the telemetry data and performance measurements. It is important to note that in the former routing method, the WAT-specific telemetry data is used along with the path performance measurements to decide traffic routing decision. Having a WAT-specific telemetry data and using it within AT3S routing leveraging O-RAN reference architecture is not considered/defined in the current 3GPP AT3S framework. Therefore, both of the noted routing methods are 5G-CLARITY novel solutions.

As noted, AT3S considers three different procedures namely, steering, switching and splitting. Steering procedure is going to be used to send a new flow through 3GPP (5GNR) or non-3GPP network (integrated Wi-Fi/LiFi network) in five different modes as described in Section 3.1.2.3. Switching procedure is going to be used to move an ongoing flow from one technology to another. Splitting procedure is going to be used to distribute an ongoing flow across different technologies to aggregate throughput. In order to effectively support the splitting procedure, a receiver must be able to reorder the flow packets.

The traffic steering, switching and splitting strategies enforced via AT3S rules are based on predefined values for either all traffic types or some specific traffic type such as UDP or TCP to a specific IP address or port. For example, if the load balancing steering mode is selected, a predefined percentage value has to be written for 3GPP and non-3GPP access networks, such as 20% for 3GPP and 80% for non-3GPP. In another example, the priority-based steering mode can be selected to prevent congestion over 3GPP network. Then, high priority is assigned to non-3GPP network to offload the 3GPP network traffic. All these rules are preconstructed and ordered in a way that as long as a data flow matches a rule, the data flow gets routed according to this rule and the remaining rules are not considered ([70], Figure 6.4.3.1). While traffic is routed according to a specific rule, sudden changes on the network status such as link availability due to CSI fluctuations or link blockage will not be incorporated to traffic routing. 5G-CLARITY eAT3S resolves this issue by introducing another steering mode, named real-time steering mode. The real-time steering mode is described as the AT3S rule with the highest priority (Rule #1) and will be adaptive to network status. For example, if there is a congestion on non-3GPP network and the load balancing mode is used to enforce 80% for non-3GPP network, the real-time steering mode will modify/overwrite the weight for each network to optimally utilize both networks.

In order to clarify the eAT3S based traffic distribution based on AT3S rules, Figure 6.16 and Figure 6.17 depict the flowcharts of traffic distribution based on 3GPP AT3S and 5G-CLARITY eAT3S, respectively. When RT-AT3S Ctrl is initiated, a new AT3S rule is defined with steering mode of “real-time”. Then, this rule is located at the beginning of the list of AT3S rules (Rule #1). The rest of the already defined AT3S rules are shifted one below and can be used in case a UE with no Rt-UE-ATSF capability is in the network. For the UE that is capable of utilizing Rt-UE-ATSF, AT3S rules are modified in real-time based on access network status.

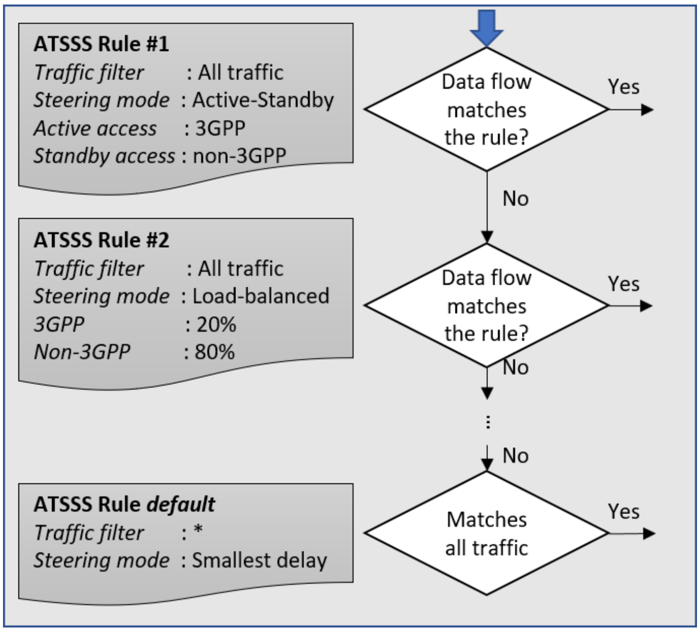


Figure 6.16: Flowchart of traffic distribution based on AT3S rules [70]

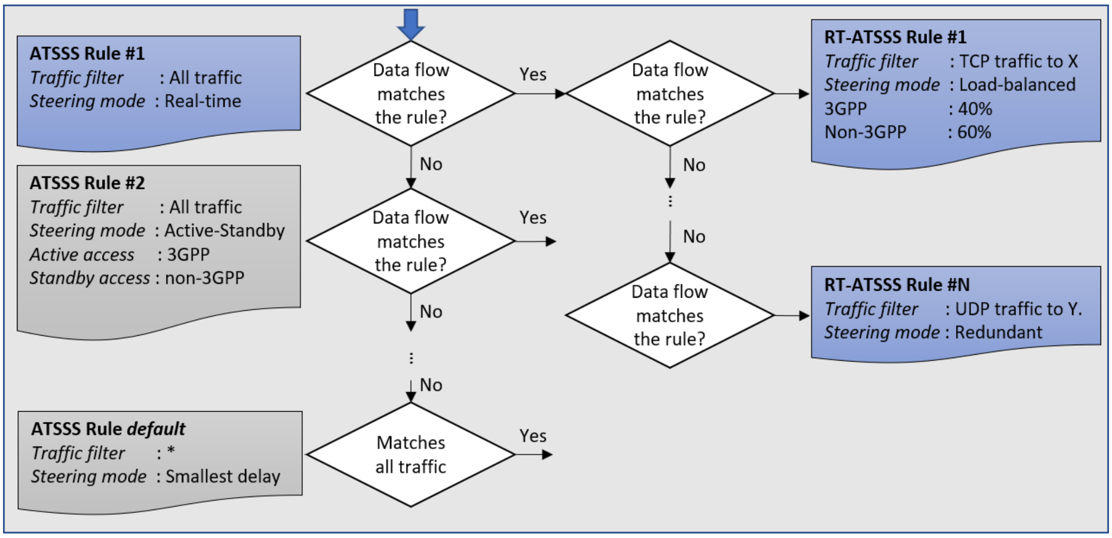


Figure 6.17: Flowchart of traffic distribution based on 5G-CLARITY eAT3S rules

There are four key components in the kernel module of the MPTCP implementation in Linux that can be leveraged by 5G-CLARITY. The first one is the path manager, a.k.a *net.mptcp.mptcp_path_manager*. It is the algorithm that tells MPTCP on how to incorporate new paths. By default, it does full mesh which means that all the available IP addresses for a UE are used. In 5G-CLARITY, the path manager will be modified in a way that it allows provision policies externally e.g. UE-x can use Wi-Fi but not LiFi. The second key component is scheduler, a.k.a *net.mptcp.mptcp_scheduler*. The MPTCP scheduler handles how packets need to be distributed among available interfaces/WATs. It uses three different policies as follows (i) "*default*" which uses the path with lowest RTT; (ii) "*roundrobin*" which sends packet through each interface based on Round Robin fashion; and (iii) "*redundant*" which sends copies of packets through all interfaces. In 5G-CLARITY, new scheduling policies will be defined. For example, a weighted Round Robin can be used to send a specific portion of packets through each interface. The weight of each interface can be updated in real-time. The third component of the MPTCP implementation is the congestion control. MPTCP runs an overall congestion controller to control the overall amount of data inserted by each subflow in the network. Several congestion control flows are available in Linux such as Cubic, OLIA, BALIA etc. In 5G-CLARITY, how the available congestion control algorithms work when combining 5GNR, Wi-Fi and LiFi and how these algorithms could be improved will be studied. The last component that can be leveraged in 5G-CLARITY is end-to-end metrics, a.k.a MPTCP_INFO. It provides detailed information per subflow. Within 5G-CLARITY, the end-to-end MPTCP metrics can be used as the performance measurement function that is required by AT3S.

In addition to MPTCP, possible alternatives to MPTCP such as MP-QUIC [70] and MLVPN[3] will also be considered as subject of studies in 5G-CLARITY. MP-QUIC is a user space implementation. In other words, each user container can have entirely different MP-QUIC modules. This is also the case for MLVPN, which can handle both UDP and TCP traffic.

6.2.4.2 Resource scheduling on AP/gNB

In 5G-CLARITY architecture, once a traffic flow is routed to 5G, Wi-Fi or LiFi network, either gNB, Wi-Fi AP or LiFi AP will take care of scheduling its physical resources for the intended user access. Therefore, each technology can use its preferred packet scheduler such as round robin or proportional fair to deliver the routed packets. Within 5G-CLARITY, off-the-shelf products will be used for 5GNRgNBs, Wi-Fi APs and LiFi APs.

6.2.4.2.1 ACC's gNB scheduler details

The 5GNR MAC protocol and scheduler functionality belongs to 5GNR DU as discussed in [166] and shown in Figure 6.18. The initial implementation of the first 5GNR DU integrated with Accelleran dRAX nRT-RIC and CU functions for 5G-CLARITY will be based on RR scheduling. Later on during the lifetime of the 5G-CLARITY project (subject to roadmap changes and DU supplier planning/ecosystem maturity) the scheduler will be enhanced to support configurable parameters and time-permitting more advanced scheduler algorithms such as QoS-aware RR or Proportional Fair scheduler.

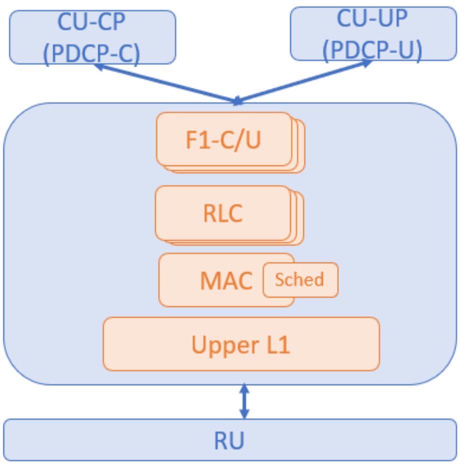


Figure 6.18: 5GNR DU Protocols

6.2.4.2.2 I2CAT's Wi-Fi AP scheduler details

In 5G-CLARITY, each Wi-Fi AP will support an uplink and downlink scheduling policy to assign different priorities on a per- virtual AP (vAP) basis, where each vAP is associated with a 5G-CLARITY wireless service[4]. The downlink scheduling policy will use a Deficit Round Robin airtime based scheduler, where airtime tokens are assigned to each device that is actively transmitting data. Thus, the local scheduler in each vAP monitors

[3] MLVPN is a software similar to OpenVPN that creates a network tunnel, encapsulates network packets and sends the encrypted packets over internet to another location. The primary use of MLVPN is to create aggregated network links. More details can be found on https://mlvpn.readthedocs.io/en/latest/what_is_mlvpn.html

[4] The interested reader is referred to D2.2 [166] for a definition of a 5G-CLARITY wireless service.

each transmission of each device and decreases the consumed airtime from the available tokens. When a device has consumed all its available airtime, the vAP starts transmitting frames addressed to the next device in the scheduler queue. By allocating an overall weight to each vAP instantiated in a physical AP it is possible to control the resources allocated to each wireless service. Within a given vAP or wireless service, the scheduler allocates the available resources fairly among the different devices. A notable feature of this local scheduler agent will be the availability of an API that allows to modify in real-time, e.g. on a per-second basis, the scheduling weight allocated to each vAP in each AP, for example to account for load variations in time and space. The focus in 5G-CLARITY will be in the design of global scheduling algorithms that control the downlink scheduling weights of each AP in order to deliver network wide SLAs. Figure 6.19 describes a scheduling architecture with a global scheduling algorithm controlling the scheduling weights of the physical APs.

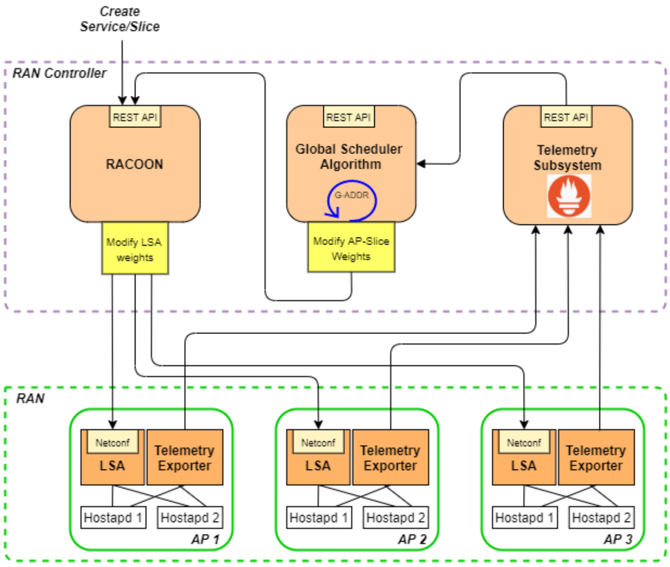


Figure 6.19: Tentative Wi-Fi downlink scheduling architecture in 5G-CLARITY

On the uplink side, less control is available due to the characteristics of the Wi-Fi technology. In particular, Wi-Fi does not allow to directly influence the scheduling function used in the user devices, which compete with the AP to access the channel. One mechanism to exercise indirect control though is the configuration of the channel access parameters (EDCA settings), including the contention windows used by the devices to access the channel, on a per-device (and therefore per vAP) basis. In 5G-CLARITY, we will study how to make use of the EDCA settings to implement slicing in the uplink direction.

6.2.4.2.3 PLF's LiFi XC AP scheduler details

Within pureLiFi LiFi XC product, an equal average channel time-based scheduling algorithm is used to allocate users. As depicted in Figure 6.20, a counter is associated with each user and during packet transmission to a user, CPU ticks are accumulated with the user-specific counter. When there is a new packet arrival, the counter values are compared and the user that has the minimum counter value is granted for transmission. Developing a scheduler that assigns weights for each user based on their network slice KPIs as well as SLA in order to support multi-tenancy and network slicing concepts will be a subject of study in 5G-CLARITY.

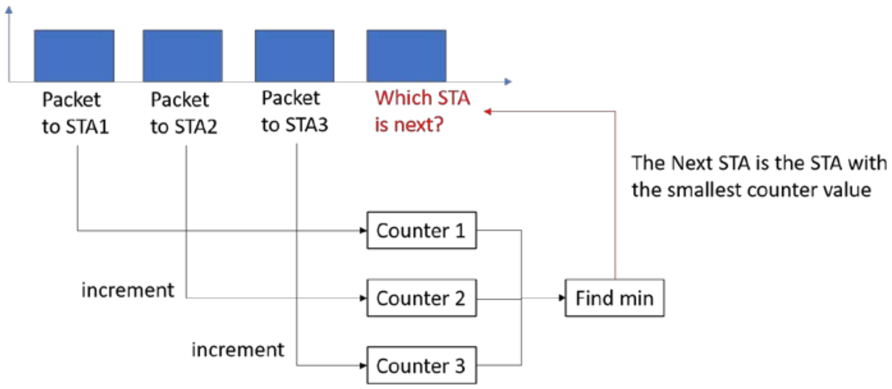


Figure 6.20: LiFi XC scheduling process

6.2.4.2.4 Utility-based scheduler

On the one hand, the network performance will be evaluated based on the noted supplier-based packet schedulers. On the other hand, a utility-based scheduler that effectively schedules the available physical resources of each technology in order to achieve the required KPIs for different service types and SLAs for different business models will also be a theoretical subject of study in 5G-CLARITY. The motivation of using a utility-based scheduler is to unify the scheduling weight parameter for different service/traffic types and improve the overall network performance. Therefore, different utility functions such as convex and sigmoid functions are used for different network slices that maps slice specific KPIs. For example, for an eMBB slice, the KPI is throughput, whereas for a URLLC slice, the KPI is latency and reliability. Then, the scheduler aims to maximize the network-wide utility. Figure 6.21 depicts the working principle of the considered utility-based scheduler.

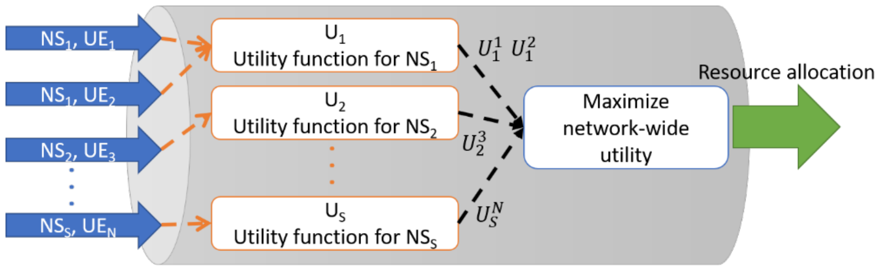


Figure 6.21: Utility-based scheduler working principle

6.2.5 Enhanced indoor positioning

Each technology presented in Section 5 can serve both communication and localization purposes. Regarding the latter, they offer distinct accuracies in the targeted service areas (see Section 5 for more details). However, 5G networks demand more intelligent means for computing the position of nodes to match specific requirements, e.g. possibly imposed by an SLA, which leads to the choice of the adequate technology that could achieve the desired positioning accuracy. For example, there will be cases where a relaxed position estimation (in the order of meters) of a node is desired (use of Sub-6 technologies would be enough), wherever in other cases a more precise position estimation of a node is mandatory (use of the capabilities of mmWave to achieve that desired precision).

This section presents the positioning framework design of the 5G-CLARITY project, leveraging a localization server that makes an intelligent use of different technologies in order to fulfill the desired positioning accuracy at any time. The proposed solution generalizes the positioning problem in a multi-connectivity framework, and fuse or combine different algorithms targeting position estimation.

6.2.5.1 Integration of positioning Information

In 5G-CLARITY we consider different technologies that may offer positioning estimates with different precision, on different areas and using different approaches (see Section 5 for more details). Depending on the UE behaviour, different scenarios can be expected leading to communication in LoS/NLoS conditions. Depending on the possibility that one technology faces a LoS scenario and the other a NLoS scenario, the positioning data from both technologies can be used with different confidence of the position estimate. The confidence of the position obtained from these WATs can be used based on the probability that a LoS/NLoS scenario occurs at a given moment.

The estimated UE positions are noisy by default, even in LoS scenarios. The level of this noise depends on the used WAT and the bandwidth. Most 5G-CLARITY technologies use limited bandwidth which means the noise in the position estimation is significant. If mmWave technology is used, the noise in the estimation of the position can be significantly reduced due to the larger channel bandwidth. Nevertheless, as mmWave technology availability would be limited and prone to blockage, it would be beneficial to use additional position estimates to reduce the positioning error. These redundant position estimates can come from different WATs or even a single WAT.

Figure 6.22 shows the localization server envisioned for 5G-CLARITY. It will be a piece of HW/SW function residing in the tenant venue and it will be in charge of managing the position estimates retrieved in such multi-WAT environment. Each candidate technology contributing to 5G-CLARITY positioning framework will have an interface towards the localization server. The localization server will encompass a set of methods that will allow the retrieval of requests, the control and intelligent combination of the position estimates, and will push the resulting position estimate to the 5GC.

One localization server feature is the acceptance of services requests, and it will be in charge of sending responses to the received requests. Another feature takes care of merging the localization data from different technologies. This can be performed in different ways, i.e. subject to the localization method employed and the underlying technology. The most general approach is to use Kalman filter (or extended Kalman filter) which would use the estimates from the different technologies in order to output a position estimate which is better compared to the estimates at its input. Another approach is to use least squares methods (i.e. Levenberg–Marquardt algorithm) if, for example, more than the minimum parameters for position estimate are available (overdetermined system of equations available). This last approach is usually straightforward when using a single WAT. The applicability of this approach to multiple WATs will be a subject of study in 5G-CLARITY.

The need of additional requests by the server for alternate WATs position estimates is also a subject of study, to match the required accuracy and precision [174]. For example, in some cases, the position estimates from a single WAT would be enough if the requirements are fulfilled during a specified time. A positioning function will perform the actual positioning of a specific target UE. The input to this function is a positioning request with a set of requirements. The function will output the location information of the target UE.

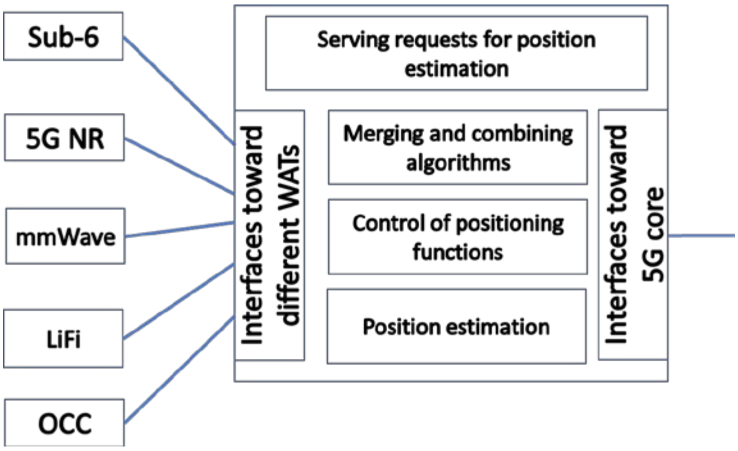


Figure 6.22: 5G-CLARITY localization server

6.2.5.2 Location management of 3GPP and non-3GPP access

3GPP positioning is based on the use of a location server, e.g. that of LTE. This server collects and distributes information related to positioning (UE capabilities, assistance data, measurements, position estimate, etc.) to the other entities involved in the positioning procedures. To retrieve the position estimates in 5G, the positioning methods listed in Section 5 are used in combination or separately to meet the accuracy requirements for different scenarios [175].

This section introduces the 5G-CLARITY localization server (Figure 6.22) as a potential source of information to complement the existing localization server in 5G. 5GNR Release 15 introduced basic positioning methods but defers high accuracy positioning methods to Release 16. In the latter, a combination of accurate estimates stemming from 3GPP and non-3GPP access network opens up an opportunity to improve user experience by better being able to integrate disparate networks. Harmonized with the standardization activities, 5G-CLARITY aims to formalize the concept of multi-WAT localization server from a theoretical and simulation point of view, i.e. to study the ways to combine the 5G-CLARITY localization server and the one considered in 5G [175].

The access network is involved in the handling of various positioning procedures including positioning of a target UE, provision of location related information not associated with a particular target UE and transfer of positioning messages between an AMF or Location Management Function (LMF) and a target UE (see Figure 6.23). Once the position estimation is available to the 5GC, the LMF should combine information fed from N3IWF and that calculated with 3GPP positioning methods as part of Release 16. More information on these studies will be included in deliverable D3.2.

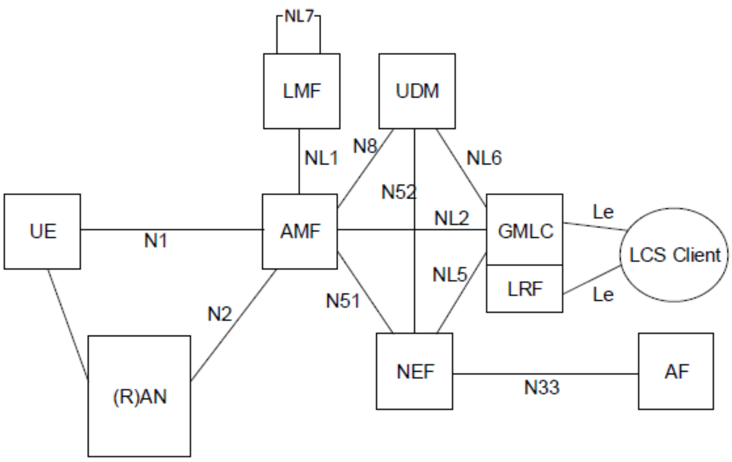


Figure 6.23: Non-roaming reference architecture for Location Services in reference point representation [175]

Nowadays, where location is computed within a network remains a hot research topic. In the past there have been trends that either delegated the position calculation and its storage to mobile devices themselves, or otherwise performed these procedures in centralized servers. This last option may present disadvantages like performance degradation in terms of delay, battery usage, and waste of network resources [176]. The use of hybrid approaches (e.g. maintaining separate location servers for 3GPP and non-3GPP access), may also impact the performance related to the calculation of the final position and the storage of training data sets. Offloading position information to a network edge [177] has been demonstrated as key to alleviate computing complexity and energy consumption happening at the BS. 3GPP Release 17 has a work-item on NR position enhancements that includes demanding positioning requirements of industrial IoT. 5G-CLARITY will consider this in the upcoming deliverable D3.2. Additional studies on this matter will also be part of D3.2.

6.3 Control/User Plane overall design

5G-CLARITY control and user plane architecture is described in detail within Section 6.2. In this section, the overall initial 5G-CLARITY user and control plane design is described. Figure 6.24 depicts the user and control plane network functions and interfaces that are defined by 3GPP, 5G-CLARITY and O-RAN. It is worth to note that more details on 5G-CLARITY proposals on private and public network integration can be found in D2.2 [166]. In the initial user and control plane design, it is assumed that 3GPP defined control plane functions are grouped to compose 5G core network and it can be either deployed within the venue or outside the venue, in public MNO’s premises. For the user plane functions namely UPF and N3IWF/TNGF, it is assumed that they are deployed within the private venue.

As it is shown in Figure 6.24, 5G-CLARITY architecture adopts the control and user plane separation by 3GPP and leveraged by the O-RAN reference architecture and interfaces. A 3GPP Service Based Architecture is used. Based on the O-RAN architecture described in Section 6.1, O1 interface is used to (i) provision and configure network functions; and (ii) receive telemetry from network functions. Whereas, A1 interface is used to provide policies to network functions. The role of the non-RT RIC shown in Figure 6.24 is to configure the 5GNR, Wi-Fi and LiFi APs using NETCONF, which is aligned with the O1 interface in O-RAN. In addition, the non-RT RIC also pushes policies to drive the operation of the xApps deployed in the near-RT RIC through the O-RAN A1 interface.

The near-RT RIC function processes policy instructions from the non-RT RIC and is in charge of the near real-time control and optimization of the CU-control plane, CU-user plane and DU functions via data collection and actions over the O-RAN E2 interface, which enables control loops in the ranging from 10 ms to 1 s. Following the O-RAN architecture, the near-RT RIC function hosts one or more xApps. The xApps are applications designed to run on the near-RT RIC, which can be provided by third parties. They consist of one or more microservices, e.g. a mobility optimization service, collecting near real-time RAN information, and providing added value data and control actions guided by the policies provided by the non-RT RIC through the O-RAN A1 interface.

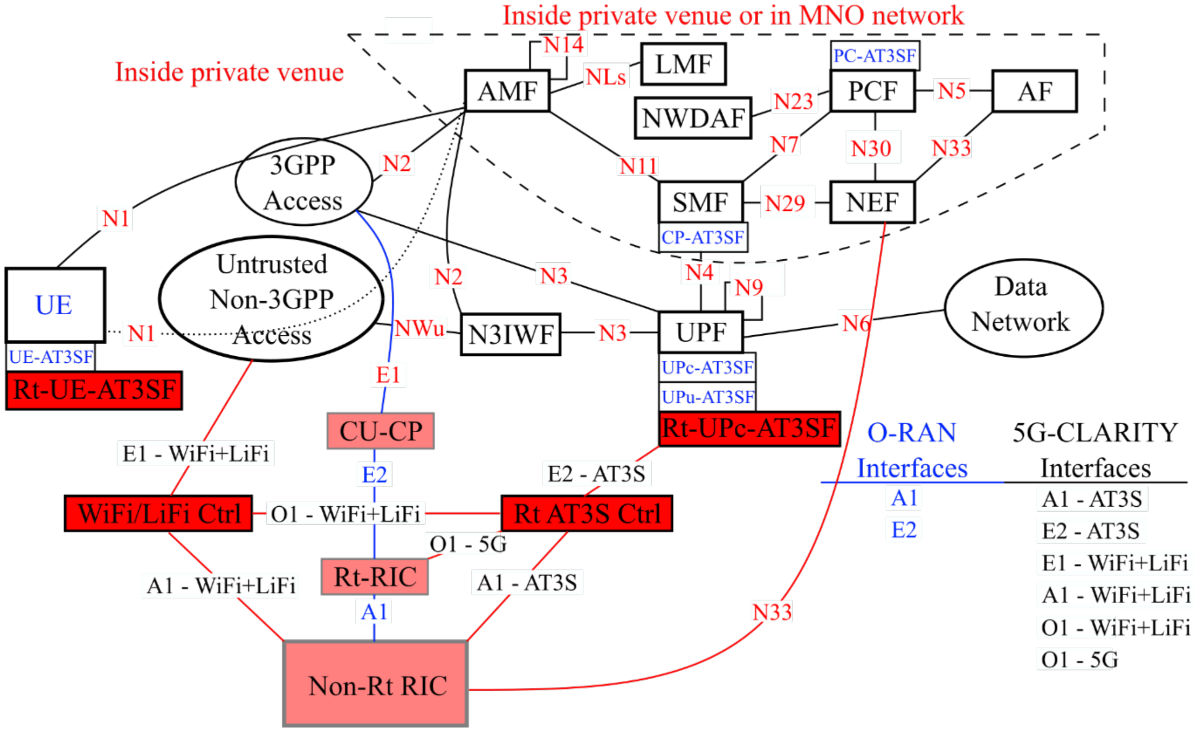


Figure 6.24: 5G-CLARITY **architecture for user and control planes**

In Figure 6.24, 5G-CLARITY specific functions are depicted in red boxes and their relevant interfaces are shown as red solid lines. Accordingly, Rt-UE-AT3SF, Wi-Fi/LiFi Ctrl, Rt-AT3S Ctrl and Rt-UPc-AT3SF are the 5G-CLARITY proposed control plane functions. The required interfaces for those functions can be listed as follows:

- A1-AT3S: Provides non-RT RIC policies to Rt-AT3S Ctrl.
- E2-AT3S: Enforces Rt AT3S Ctrl policies to Rt-UPc-AT3SF in UPF.
- E1-Wi-Fi+LiFi: Configures Wi-Fi and LiFi APs.
- A1-Wi-Fi+LiFi: Provides non-RT RIC policies to Wi-Fi/LiFi Ctrl.
- O1-Wi-Fi+LiFi: Receives telemetry from Wi-Fi and LiFi APs at Rt-AT3S Ctrl.
- O1-5GNR: Receives telemetry from 5GNRat Rt-AT3S Ctrl.
- N33: Provides access to the services and capabilities provided by 3GPP network entities/functions.

In the context of 5G-CLARITY, a key RAN optimization function is the combined use of multi-WAT (5GNR, Wi-Fi, LiFi) in such a way that they can be selected, aggregated and steered intelligently to optimize the overall network performance while addressing the diverse per-UE requirements in terms of latency, reliability and capacity.

7 Conclusions

This deliverable provides an initial overall design of the user and control plane architecture for the integrated 5GNR/Wi-Fi/LiFi network that is considered in 5G-CLARITY. A comprehensive state-of-the-art study on the existing approaches are provided in D3.1 for the four main tasks of WP3, namely T3.1, T3.2, T3.3 and T3.4. This is followed up with an initial design and a list of requirements for the proposed 5G-CLARITY solutions that enhance the existing approaches.

5G-CLARITY solution for T3.1 on spectrum sharing between the private 5GNR/Wi-Fi/LiFi network and other private/public networks is based on a CBRS-like framework, named Spectrum Access System (SAS). The features of the SAS are (i) automated and intelligent dynamic configuration by means of spectrum assignment and mapping regulatory spectrum regimes; (ii) efficient use of spectrum resources; and (iii) support for 5GNR operation in standalone mode and standalone NPN/PLMN-integrated NPN. The dynamic spectrum management coordinator is going to be simulated/emulated and the associated SAS client communicating with it from the multi-WAT dRAX will be implemented as an O-RAN dRAX RIC xAPP within 5G-CLARITY.

5G-CLARITY solution for T3.2 on multi-connectivity is a multi-access-based multi-connectivity framework that integrates 3GPP access networks such as 5GNR/4GLTE and non-3GPP access networks such as Wi-Fi/LiFi. The proposed multi-connectivity framework is going to allow the private networks to be deployed as (i) all 3GPP access technologies; (ii) integrated 3GPP and non-3GPP technologies; or (iii) all non-3GPP technologies. This feature is enabled via integration of Wi-Fi and LiFi networks that employs the two networks as a single non-3GPP access and enhanced AT3S functionality that provides real-time control on traffic steering/switching/splitting to each available access network according to KPIs of the networks services and SLAs.

5G-CLARITY solution for T3.3 on resource management is a two-stage process that firstly focusses on traffic routing to the available access networks, and secondly considers multi-user access to physical resources that are available in each access network. The proposed resource management approach is going to provide (i) an efficient routing/scheduling algorithm that utilizes the enhanced AT3S functionality and (ii) 5GNRgNB/Wi-Fi AP/LiFi AP-based resource scheduling algorithms that address fairness among users/network services to deliver network wide SLAs. In addition to that, a theoretical study on a utility-based scheduler that unifies the scheduling weight parameters for different service types is also going to be performed to investigate the overall performance of the integrated 5GNR/Wi-Fi/LiFi network.

5G-CLARITY solution for T3.4 on positioning is based on a localization server that makes an intelligent use of available access networks/technologies such as 5G NR, mmWave, LiFi and OCC to improve positioning accuracy. The localization server is going to (i) have an interface to each access technology; (ii) control and serve positioning request; (iii) intelligently merge position estimates that are retrieved from different access technologies; and (iv) estimate position of the targeted users. Based on the access network/technology availability, an extended Kalman filter or least squares method is going to be used to merge the position estimates fed by each available access network/technology.

All the proposed 5G-CLARITY solutions are integrated in an overall design for the user and control plane architecture. This overall design is aligned with the activities of the counterpart management plane in WP4 and aims to provide the defined KPIs for 5G-CLARITY technologies from WP2 and gathered in pilot demonstrations from WP5. The functions that are going to be used to employ 5G-CLARITY solutions are described and the interfaces needed for those functions to interact with the rest of the network functions are defined. Each of the proposed solution and the overall user and control plane architecture design will be further developed and evaluated in the upcoming WP3 deliverables.

8 References

[1] 5G-CLARITY, "D2.1 - Use cases and requirements," 2020.

[2] LS Telcom/VVA/PolicyTracker on behalf of the European Commission, "Study on Spectrum Assignment in the European Union," 2017.

[3] 3GPP, "TS 36.104 V16.4.0: Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception," 2019-12.

[4] GSA, "LTE FDD Frequency Bands Worldwide," November 2019.

[5] GTI, "GTI TDD Spectrum White Paper v4.0," 2019-05.

[6] 3GPP, "TS 38.104 V16.2.0 : Technical Specification Group Radio Access Network; NR; Base Station (BS) radio transmission and reception," 2019-12.

[7] GSA, "5G Market: Snapshot," March 2020.

[8] GSA, "5G Spectrum C-Band Snapshot," October 2019.

[9] B. Bellalta, "IEEE 802.11 ax: High-efficiency WLANs," *IEEE Wireless Communications,* vol. 23, no. 1, pp. 38-46, 2016.

[10] Wi-Fi Alliance, "https://www.wi-fi.org/news-events/newsroom/wi-fi-alliance-brings-wi-fi-6-into-6-ghz," [Online].

[11] FCC, "Report & Order & Further Notice of Proposed Rulemaking: Unlicensed Use of the 6 GHz Band - Expanding Flexible Use in Mid-Band Spectrum Between 3.7 and 24 GHz, GN Docket No. 17-183," April 24, 2020.

[12] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi and F. Gutierrez, "Millimeter wave mobile communications for 5G cellular: It will work!," *IEEE Access,* vol. 1, p. 335–349, 2013.

[13] S. Rangan, T. S. Rappaport and E. Erkip, "Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges," *Proceedings of the IEEE,* 2014.

[14] "IEEE 802.11bb Standard," [Online]. Available: http://www.ieee802.org/11/Reports/tgbb_update.htm.

[15] Disruptive Analysis,iBwave, Private LTE Networks & CBRS: Democratizing cellular for enterprise: New uses, new rules, new stakeholders.

[16] FCC, "Report and Order and Second Further Notice of Proposed Rulemaking," April 21, 2015.

[17] CEPT ECC, "ECC Report 216: Practical guidance for TDD networks synchronisation," August 2014.

[18] CEPT ECC, "ECC Report 203 - Least Restrictive Technical Conditions suitable for Mobile/Fixed Communication Networks (MFCN), including IMT, in the frequency bands 3400-3600 MHz and 3600-3800 MHz," 14 March 2014 .

[19] 3GPP, "TS 36.300 V16.0.0: 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; E-UTRA and E-UTRAN; Overall description; Stage 2," 2019-12.

[20] CEPT ECC, "ECC Report 296: National synchronisation regulatory framework options in 3400-3800 MHz: a toolbox for coexistence of MFCNs in synchronised, unsynchronised and semi-synchronised operation in 3400-3800 MHz," 8 March 2019.

[21] CEPT ECC, "ECC Report 281: Analysis of the suitability of the regulatory technical conditions for 5G MFCN operation in the 3400-3800 MHz band," 6 July 2018.

[22] 3GPP, "TR 38.828 V16.1.0: 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Cross Link Interference (CLI) handling and Remote Interference Management (RIM) for NR," 2019-09.

[23] 3GPP, "TS 38.300 V16.1.0: 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; NR and NG-RAN Overall Description; Stage 2," 2020-03.

[24] 3GPP, "TS 38.423 V16.1.0: 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NG-RAN; Xn application protocol (XnAP)," 2020-03.

[25] 3GPP, "TS 38.473 V16.1.0: 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NG-RAN; F1 application protocol (F1AP)," 2020-03.

[26] E. Khorov, A. Kureev, I. Levitsky and A. Lyakhov, "Testbed to study the capture effect: Can we rely on this effect in modern wi-fi networks," in *IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom)*, 2018.

[27] I. Selinis, M. Filo, S. Vahid, J. Rodriguez and R. Tafazolli, "Evaluation of the DSC algorithm and the BSS color scheme in dense cellular-like IEEE 802.11 ax deployments," in *IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, 2016.

[28] M. S. Afaqui, E. Garcia-Villegas, E. Lopez-Aguilera, G. Smith and D. Camps, "Evaluation of dynamic sensitivity control algorithm for IEEE 802.11 ax," in *IEEE Wireless Communications and Networking Conference (WCNC)*, March 2015.

[29] Y. Zeng, P. H. Pathak and P. Mohapatra, "A first look at 802.11 ac in action: Energy efficiency and interference characterization," in *IEEE IFIP Networking Conference*, 2014.

[30] A. Patro and S. Banerjee, "COAP: A software-defined approach for home WLAN management through an open API," in *Proceedings of the 9th ACM Workshop on Mobility in the Evolving Internet Architecture*, 2014.

[31] pureLiFi, "LiFi-XC: Fully mobile, networked LiFi communication system," pureLiFi, [Online]. Available: https://purelifi.com/say-hello-to-the-lifi-xc/. [Accessed June 2020].

[32] Z. Chen, D. A. Basnayaka, X. Wu and H. Haas, "Interference Mitigation for Indoor Optical Attocell Networks Using an Angle Diversity Receiver," *Journal of Lightwave Technology,* vol. 36, pp. 3866-3881, 2018.

[33] 3GPP, "TS 38.133 V16.3.0: 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; Requirements for support of radio resource management," 2020-03.

[34] GSA, "LTE in Unlicensed and Shared Spectrum: Executive Summary," March 2020.

[35] GSA, "LTE & 5G Market Statistics: Global Snapshot," March 2020.

[36] 3GPP, "TR 36.889 V13.0.0: 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on Licensed-Assisted Access to Unlicensed Spectrum," 2015-06.

[37] ETSI, "EN 301 893 V2.1.1: 5 GHz RLAN; Harmonized EN covering the essential requirements of article 3.2 of Directive 2014/53/EU," 2017-05.

[38] European Parliament/European Council, "Directive 2014/53/EU of the European Parliament and of the Council on the harmonisation of the laws of the Member States relating to the making available on the market of radio equipment," 16 April 2014.

[39] Qualcomm, "Progress on LAA and its relationship to LTE-U and MulteFire," February 22 2016.

[40] 3GPP, "TR 38.889 V16.0.0: 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on NR-based access to unlicensed spectrum," 2018-12.

[41] MulteFire Alliance, "MulteFire Release 1.1 Technical Overview White Paper".

[42] Qualcomm, "LTE in Unlicensed Spectrum: Harmonious Coexistence with Wi-Fi," June 2014 .

[43] DSA, "Automated Frequency Coordination - An established tool for modern spectrum management," March 2019.

[44] Ofcom, "Enabling wireless innovation through local licensing: Shared access to spectrum supporting mobile technology," 25 July 2019.

[45] Ofcom, "Shared Access Licence - Guidance document," 25 July 2019.

[46] Ofcom, "Local Access Licence - Guidance document".

[47] CEPT, "ECC Report 205 - Licensed Shared Access (LSA)," February 2014.

[48] ETSI, "TR 103 113 v1.1.1 - Electromagnetic compatibility and Radio Spectrum Matters (ERM); System Reference document (SRdoc); Mobile broadband services in the 2300 MHz - 2400 MHz frequency band under Licensed Shared Access regime," 2013-07.

[49] FCC, "Order on Reconsideration and Second Report and Order," May 2, 2016.

[50] Winnforum, [Online]. Available: https://cbrs.wirelessinnovation.org/standards.

[51] CBRS Alliance, [Online]. Available: https://www.cbrsalliance.org/.

[52] ATIS IOC, "International Mobile Subscriber Identity (IMSI) Assignment and Management Guidelines for Shared HNI for CBRS Range- Version 1.0," May 2018.

[53] OnGo/CBRS Alliance, "CBRS Network Services Use Cases and Requirements, CBRSA-TS-1001, V3.0.0," 18th Feb 2020.

[54] OnGo/CBRS Alliance, "CBRS Network Services Stage 2 and 3 Specification, CBRSA-TS-1002, V3.0.0," 18th Feb 2020.

[55] OnGo/CBRS Alliance, "CBRS Coexistence Technical Specifications, CBRSA-TS-2001, V3.0.0," 18th Feb 2020.

[56] Fierce Wireless, "Federated Wireless gets ready to enable sharing in 6 GHz band," [Online]. Available: https://www.fiercewireless.com/regulatory/federated-wireless-gets-ready-to-enable-sharing-6-ghz-band.

[57] 3GPP, TR 36.842 V12.0.0; Study on Small Cell enhancements for E-UTRA and E-UTRAN; Higher layer aspects, 2014.

[58] 3GPP, "TS 37.340 V15.8.0: 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA) and NR; Multi-connectivity; Stage 2," 2019-12.

[59] [Online]. Available: https://www.netmanias.com/en/post/reports/8532/laa-lte-lte-u-lwa-mptcp-wi-fi/analysis-of-lte-wifi-aggregation-solutions.

[60] B. Jin, S. Kim, D. Yun, H. Lee, W. Kim and Y.Yi, "Aggregating LTE and Wi-Fi: Toward Intra-Cell Fairness and High TCP Performance," *IEEE Transactions on Wireless Communications,* vol. 16, no. 10, pp. 6295-6308, Oct. 2017.

[61] I. G. Muriel, A. M. Heredia and P. M. Gomez, "Testbed to Experiment with LTE WiFi Aggregation," in *European Conference on Networks and Communications (EuCNC)*, Valencia, Spain, 2019.

[62] S. Thomas Valerrian Pasca, P. C. Amogh, D. Mishra, N. Dheeravath, A. K. Rangisetti, T. B. Reddy and A. A. Franklin, "Architectural challenges and solutions for collocated LWIP — A network layer perspective," in *Twenty-third National Conference on Communications (NCC)*, 2017.

[63] 3GPP, "TS 24.501 V16.4.1: Non-Access-Stratum (NAS) protocol for 5G System (5GS); Stage 3," 2020.

[64] W. 5. Workgroup, Unlicensed Integration with 5G Networks, 2018.

[65] 3GPP, "TS 23.502 V16.4.0 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Procedures for the 5G System (5GS) Stage 2," 3GPP, 2020.

[66] "Support of non-3GPP access [online]," [Online]. Available: https://itectec.com/spec/4-2-8-support-of-non-3gpp-access/.

[67] 3GPP, "TS 23.316 V16.3.0: Wireless and wireline convergence access support for the 5G System (5GS) (2020-03)".

[68] 3GPP, "TS 23.501 V16.4.0: 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; System architecture for the 5G System(5GS); Stage 2," 2020-03.

[69] CableLabs, "WR-TR-5WWC-ARCH-V01-190820; Wireless Convergence, 5G Wireless Wireline Converged Core Architecture Technical Report," 2019-08.

[70] 3GPP , "TR 23.793: Study on Access Traffic Steering, Switch and Splitting Support in the 5G System Architecture (Release 16)," 2018.

[71] 3GPP, "TS 29.244 V16.3.1: Interface between the Control Plane and the User Plane Nodes (Release 16)," 2020.

[72] "RFC0793," [Online]. Available: https://www.rfc-editor.org/rfc/rfc8684.html#RFC0793.

[73] "RFC6182," [Online]. Available: https://www.rfc-editor.org/rfc/rfc8684.html#RFC6182.

[74] "RFC8684," [Online]. Available: https://www.rfc-editor.org/rfc/rfc8684.html#name-introduction.

[75] H. Haas, L. Yin, C. Chen, S. Videv, D. Parol, E. Poves, H. Alshaer and M. S. Islim, "Introduction to indoor networking concepts and challenges in LiFi," *Journal of Optical Communications and Networking,* vol. 12, no. 2, 2020.

[76] M. B. Rahaim, A. M. Vegni and T. D. C. Little, "A hybrid radio frequency and broadcast visible light communication system," in *IEEE GLOBECOM Workshops*, Houston, TX, USA, 2011.

[77] X. Wu, M. D. Soltani, L. Zhou, M. Safari and H. Haas, “Hybrid LiFi and WiFi Networks: A Survey,” *arXiv:2001.04840v1.*

[78] S. Shao, A. Khreishah, M. Ayyash, M. B. Rahaim, H. Elgala, V. Jungnickel, D. Schulz, T. D. C. Little, J. Hilt and R. Freund, “Design and Analysis of a Visible-Light-Communication Enhanced WiFi System,” *IEEE/OSA Journal of Optical Communications and Networking,* vol. 7, no. 10, 2015.

[79] S. Naribole, S. Chen, E. Heng and E. Knightly, “LiRa: A WLAN Architecture for Visible Light Communication with a Wi-Fi Uplink,” in *14th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)*, San Diego, CA, USA, 2017.

[80] A. Tang, C. Xu, B. Zhai and X. Wang, “Design and Implementation of an Integrated Visible Light Communication and WiFi System,” in *IEEE 15th International Conference on Mobile Ad Hoc and Sensor Systems (MASS)*, Chengdu, China, 2018.

[81] A. Ford, C. Raiciu, M. Handley and O. Bonaventure, “TCP extensions for multipath operation with multiple addresses,” IETF RFC 6824, 2013.

[82] W. Zhang, L. Chen, X. Chen, Z. Yu, Z. Li and W. Wang, “Design and realization of indoor VLC-Wi-Fi hybrid network,” *Journal of Communications and Information Networks,* vol. 2, no. 4, pp. 75-87, 2017.

[83] E. Dahlman, S. Parkvall, J. Skold and P. Beming, 3G Evolution: HSPA and LTE for Mobile Broadband, 2nd ed., Academic Press, 2008.

[84] 3GPP, “TS 36.213: LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer Procedures”.

[85] 3GPP, “TS 38.211: 5G; NR; Physical Channels and Modulation v15.8.0”.

[86] 3GPP, “TS 38.213 V16.1.0: NR; Physical layer procedure for control,” 2020-04.

[87] 3GPP, “TS 38.321 V15.8.0: 5G; NR; Medium Access Control (MAC) protocol specification,” 2020-01.

[88] 3GPP, “TS 38.214 V15.8.0 5G; NR; Physical layer procedures for data,” 2020-01.

[89] Cisco, “802.11ac: The Fifth Generation of WiFi,” 2018.

[90] E. Khorov, A. Kiryanov, A. Lyakhov and G. Bianchi, “A Tutorial on IEEE 802.11ax High Efficiency WLANs,” *IEEE Communications Surveys & Tutorial,* vol. 21, no. 1, pp. 197-216, 2019.

[91] “IEEE Standard for Information technology—Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,” IEEE Std 802.11-2016 (Revision of IEEE Std 802.11-2012), 2016.

[92] W. Guo, S. Wang, X. Chu, J. Zhang, J. Chen and H. Song, “Automated small-cell deployment for heterogeneous cellular networks,” *IEEE Communications Magazine,* vol. 51, no. 5, pp. 46-53, 2013.

[93] 5G-PPP, “5GPPP use cases and performance evaluation models,” 2016. [Online]. Available: https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-use-cases-and-performance-evaluation-modeling_v1.0.pdf.

[94] S. Merlin and et al., “TGax Simulation Scenarios - IEEE 802.11-14/0980r16,” 2015. [Online]. Available: https://mentor.ieee.org/802.11/dcn/14/11-14-0980-16-00ax-simulation-scenarios.docx.

[95] M. Uysal, F. Miramirkhani, T. Baykas and K. Qaraqe, “IEEE 802.11bb reference channel models for

indoor environments - IEEE 802.11-18/1582r4," 2018. [Online]. Available: https://mentor.ieee.org/802.11/dcn/18/11-18-1582-04-00bb-ieee-802-11bb-reference-channel-models-for-indoor-environments.pdf.

[96] O. Boswarva, "Sitefinder mobile phone base station database," 2017. [Online]. Available: https://datashare.is.ed.ac.uk/handle/10283/2626.

[97] J. G. Andrews, F. Baccelli and R. K. Ganti, "A Tractable Approach to Coverage and Rate in Cellular Networks," *IEEE Transactions on Communications,* vol. 59, no. 11, pp. 3122-3134, 2011.

[98] C. Chen, D. A. Basnayaka and H. Haas, "Downlink Performance of Optical Attocell Networks," *Journal of Lightwave Technology,* vol. 34, no. 1, pp. 137-156, 2016.

[99] H. S. Dhillon, R. K. Ganti and J. G. Andrews, "Load-Aware Modeling and Analysis of Heterogeneous Cellular Networks," *IEEE Transaction on Wirelesss Communications,* vol. 12, no. 4, pp. 1666-1677, 2013.

[100] H. Jo, Y. J. Sang, P. Xia and J. G. Andrews, "Heterogeneous Cellular Networks with Flexible Cell Association: A Comprehensive Downlink SINR Analysis," *IEEE Transactions on Wireless Communications,* vol. 11, no. 10, pp. 3483-3495, 2012.

[101] M. A. Lema, E. Pardo, O. Galinina, S. Andreev and M. Dohler, "Flexible Dual-Connectivity Spectrum Aggregation for Decoupled Uplink and Downlink Access in 5G Heterogeneous Systems," *IEEE Journal on Selected Areas in Communications,* vol. 34, no. 11, pp. 2851-2865, 2016.

[102] V. Poirot, M. Ericson, M. Nordberg and K. Andersson, "Energy efficient multi-connectivity algorithms for ultra-dense 5G networks," *Wireless Networks,* vol. 26, pp. 2207-2222, 2020.

[103] Y.-D. Lin, C. C. Wang, Y.-J. Lu, Y.-C. Lai and H.-C. Yang, "Two-tier dynamic load balancing in SDN-enabled Wi-Fi networks," *Wireless Networks,* vol. 24, pp. 2811-2823, 2018.

[104] T. Sandholm and B. A. Huberman, "A Learning Approach to Wi-Fi Access," *CoRR,* vol. abs/1811.09946v1, 2018.

[105] C. Chen and X. Zhao, "Mobility-Aware Access Strategy in Multi-User HetNets," *IEEE Wireless Communications Letters,* 2020.

[106] B. Ma, B. Yang, Y. Zhu and J. Zhang, "Context-Aware Proactive 5G Load Balancing and Optimization for Urban Areas," *IEEE Access,* vol. 8, pp. 8405-8417, 2020.

[107] Q. Zhang, X. Wang, J. Lv and M. Huang, "Intelligent Content-Aware Traffic Engineering for SDN: An AI-Driven Approach," *IEEE Network,* pp. 12-19, 2020.

[108] L. Chen, B. Wang, X. Chen, X. Zhang and D. Yang, "Utility-based resource allocation for mixed traffic in wireless networks," in *IEEE INFOCOM Workshops*, Shanghai, China, 2011.

[109] A. Abdel-Hadi and C. Clancy, "A utility proportional fairness approach for resource allocation in 4G-LTE," in *International Conference on Computing, Networking and Communications (ICNC)*, Honolulu, HI, USA, 2014.

[110] Q. Ye, W. Zhuang, S. Zhang, A.-L. Jin, X. Shen and X. Li, "Dynamic Radio Resource Slicing for a Two-Tier Heterogeneous Wireless Network," *IEEE Transactions on Vehicular Technology,* vol. 67, no. 10, 2018.

[111] L. Diez, A. Garcia-Saavedra, V. Valls, X. Li, X. Costa-Perez and R. Aguero, "LaSR: A Supple Multi-Connectivity Scheduler for Multi-RAT OFDMA Systems," *IEEE Transactions on Mobile Computing,* vol.

19, no. 3, 2020.

[112] C.-Y. Chang, N. Nikaein and T. Spyropoulos, "Radio Access Network Resource Slicing for Flexible Service Execution," in *IEEE INFOCOM Workshops*, Honolulu, HI, USA, 2018.

[113] T. Guo and A. Suarez, "Enabling 5G RAN Slicing With EDF Slice Scheduling," *IEEE Transactions on Vehicular Technology,* vol. 68, no. 3, 2019.

[114] H. Alshaer and H. Haas, "Software-Defined Networking-Enabled Heterogeneous Wireless Networks and Applications Convergence," *IEEE Access,* vol. 8, 2020.

[115] A. Zappone, M. D. Renzo and M. Debbah, "Wireless Networks Design in the Era of Deep Learning: Model-Based, AI-Based, or Both?," *IEEE Transactions on Communications,* vol. 67, no. 10, 2019.

[116] Y. Sun, M. Peng, Y. Zhou, Y. Huang and S. Mao, "Application of Machine Learning in Wireless Networks: Key Techniques and Open Issues," *IEEE Communications Surveys & Tutorials,* vol. 21, no. 4, Fourth Quarter 2019.

[117] Z. DU, C. WANG, Y. SUN and G. WU, "Context-Aware Indoor VLC/RF Heterogeneous Network Selection: Reinforcement Learning With Knowledge Transfer," *IEEE Access,* vol. 6, 2018.

[118] 5G-CLARITY, "D4.1 - Initial Design of the SDN/NFV Platform and Identification of Target 5G-CLARITY ML Algorithms," 2020.

[119] P. Misra and P. Enge, Global Positioning System: Signals, Measurements and Performance, Lincoln, MA: Ganga-Jamuna Press, 2006.

[120] A. Brown and M. Sturza, "Vehicle Tracking System Employing Global Positioning System (gps) satellites". US Patent 5,225,842, 6 July 1993.

[121] O. J. Woodman, *An introduction to inertial navigation.,* University of Cambridge, Computer laboratory., 2007.

[122] A. Mylonas, V. Meletiadis, L. Mitrou and D. Gritzalis, "Smartphone sensor data as digital evidence," *Computers & Security,* vol. 38, no. 15, p. 51–75, 2013.

[123] W. Yi, W. Jia and J. Saniie, "Mobile sensor data collector using Android smartphone," in *Proceedings of the 2012 IEEE 55th International Midwest Symposium on Circuits and Systems (MWSCAS)*, Boise, ID, USA, 5–8 August 2012.

[124] P. Widhalm, P. Nitsche and N. Brändie, "Transport mode detection with realistic Smartphone sensor data," in *Proceedings of the 21st International Conference on Pattern Recognition (ICPR2012)*, Tsukuba, Japan, 11–25 November 2012.

[125] 3GPP, "TS 36.211 V15.3.0: E-UTRA physical channels and modulation," 2018-09.

[126] S. Fischer, "Observed time difference of arrival (OTDOA) positioning in 3GPP LTE," Qualcomm, 2014.

[127] R. D. Taranto, S. Muppirisetty, R. Raulefs, D. Slock, T. Svensson and H. Wymeersch, "Location-Aware Communications for 5G Networks: How location information can improve scalability, latency, and robustness of 5G," *IEEE Signal Processing Magazine,* vol. 31, no. 6, pp. 102-112, 2014.

[128] Y. Wang, Z. Shi, Y. Yu, S. Huang and L. Chen, "Enabling Angle-based Positioning to 3GPP NR Systems," in *16th Workshop on Positioning, Navigation and Communications (WPNC)*, Bremen, Germany, 2019.

[129] CATT, Intel Corporation, "Study on NR Positioning Enhancements," 2020.

[130] M. Husen and S. Lee, "Indoor human localization with orientation using WiFi fingerprinting," in *Proceedings of the 8th International Conference on Ubiquitous Information Management and Communication*, Siem Reap, Cambodia, 2014.

[131] E. Mok and G. Retscher, "Location determination using WiFi fingerprinting versus WiFi trilateration," *J. Locat. Based Serv.,* 2007.

[132] M. Choi and B. Jang, "An Accurate Fingerprinting based Indoor Positioning Algorithm," *Int. J. Appl. Eng. Res.,* no. 12, p. 86–90, 2017.

[133] C. Basri and A. E. Khadimi, "Survey on indoor localization system and recent advances of WIFI fingerprinting technique," in *5th International Conference on Multimedia Computing and Systems (ICMCS)*, 2016.

[134] X. Wang, L. Gao, S. Mao and S. Pandey, "Csi-based fingerprinting for indoor localization: A deep learning approach," *IEEE Transactions on Vehicular Technology,* vol. 66, no. 1, pp. 763-776, 2017.

[135] J. Barnes, C. Rizos, J. Wang, D. Small, G. Voigt and N. Gambale, "Locata: the positioning technology of the future," 2003.

[136] B. Campbell, P. Dutta, B. P. Kempke, Y.-S. Kuo and P. Pannuto, "Decawave: Exploring state of the art commercial localization," 2015.

[137] IEEE, "IEEE 802.11az Standard," [Online]. Available: https://standards.ieee.org/project/802_11az.html.

[138] T. Rappaport, R. W. H. Jr., T. Daniels and J. Murdock, Millimeter Wave Wireless Communications, Prentice Hall, 2014.

[139] C. Fiandrino, H. Assasa, P. Casari and J. Widmer, "Scaling Millimeter-Wave Networks to Dense Deployments and Dynamic Environments," *Proceedings of the IEEE,* 2019.

[140] F. Lemic, J. Martin, C. Yarp, D. Chan, V. Handziski, R. Brodersen, G. Fettweis, A. Wolisz and J. Wawrzynek, "Localization as a feature of mmWave communication," in *International Wireless Communications and Mobile Computing Conference (IWCMC)*, Paphos, Cyprus, 2016.

[141] N. Maletic, V. Sark, M. Ehrig, J. Gutiérrez and E. Grass, "Experimental Evaluation of Round-Trip ToF-based Localization in the 60 GHz Band," in *International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Pisa, Italy, 2019.

[142] V. Sark, N. Maletic, M. Ehrig, J. Gutiérrez and E. Grass, "Achieving Millimeter Precision Distance Estimation using Two-Way Ranging in the 60 GHz Band," in *European Conference on Networks and Communications (EuCNC)*, Valencia, Spain, 2019.

[143] H. Zheng, Z. Xu, C. Yu and M. Gurusamy, "A 3-D high accuracy positioning system based on visible light communication with novel positioning algorithm," *Optics Communications,* vol. 396, pp. 160-168, 2017.

[144] M. T. Taylor and S. Hranilovic, "Angular Diversity Approach to Indoor Positioning Using Visible Light," in *IEEE Globecom Workshops*, Atlanta, GA, USA, 2013.

[145] J. Vongkulbhisal, B. Chantaramolee, Y. Zhao and W. S. Mohammed, "A fingerprinting-based indoor localization system using intensity modulation of light emitting diodes," *Microwave and optical technology letters,* vol. 54, no. 5, pp. 1218-1227, 2012.

[146] Y. Zhuang, L. Hua, L. Qi, J. Yang, P. Cao, Y. Cao, Y. Wu, J. Thompson and H. Haas, "A survey of positioning systems using visible LED lights," *IEEE Communications Surveys & Tutorials,* vol. 20, no. 3, pp. 1963-1988, 2018.

[147] M. Yasir, S.-W. Ho and B. N. Vellambi, "Indoor positioning system using visible light and accelerometer," *Journal of Lightwave Technology,* vol. 32, no. 19, pp. 3306-3316, 2014.

[148] M. Aminikashani, W. Gu and M. Kavehrad, "Indoor positioning with OFDM visible light communications," in *IEEE CCNC*, Las Vegas, NV, USA, 2016.

[149] S.-H. Yang, H.-S. Kim, Y.-H. Son and S.-K. Han, "Three-dimensional visible light indoor localization using AOA and RSS with multiple optical receivers," *Journal of Lightwave Technology,* vol. 32, no. 14, pp. 2480-2485, 2014.

[150] B. Xie, K. Chen, G. Tan, M. Lu, Y. Liu, J. Wu and T. He, "LIPS: A light intensity-based positioning system for indoor environments," *ACM Transactions on Sensor Networks,* vol. 12, no. 4, 2016.

[151] L. Yin, X. Wu and H. Haas, "Indoor visible light positioning with angle diversity transmitter," in *IEEE VTC-Fall*, Boston, MA, USA, 2015.

[152] C. Danakis, M. Afgani, G. Povey, I. Underwood, "Using a CMOS camera sensor for visible light communication," in *IEEE Globecom Workshops*, Anaheim, USA, 2012.

[153] G. Woo, A. Lippman and R. Raskar, "VRCodes: Unobtrusive and active visual codes for interaction by exploiting rolling shutter," in *Proceedings of the 2012 IEEE Intern. Symp. on Mixed and Augmented Reality (ISMAR)*, Georgia, USA, 2012.

[154] J. Ferrandiz-Lahuerta, D. Camps-Mur and J. Paradells-Aspas, "A Reliable Asynchronous Protocol for VLC Communications Based on the Rolling Shutter Effect," in *Proceedings of the 2015 IEEE Global Communications Conference*, San Diego, USA, 2015.

[155] T. Nguyen, A. Islam, T. Hossan and Y. M. Jang, "Current status and performance analysis of optical camera communication technologies for 5G networks," *IEEE Access,* vol. 5, pp. 4574-4594, 2017.

[156] L. Li, P. Hu, C. Peng, G. Shen and F. Zhao, "Epsilon: A visible light based positioning system," in *Proceedings of the 11th USENIX Symposium on Networked Systems Design and Implementation*, Seattle, USA, 2014.

[157] Y.-S. Kuo, P. Pannuto, K.-J. Hsiao and P. Dutta, "Luxapose: Indoor positioning with mobile phones and visible light," in *Proceedings of the 20th international conference on mobile computing and networking*, Maui, Hawaii, USA, 2014.

[158] A. Jovicic, *Qualcomm Lumicast: A high accuracy indoor positioning system based on visible light communication,* 2016.

[159] Z. Yang, Z. Wang, J. Zhang, C. Huang and Q. Zhang, "Wearables can afford: Light-weight indoor positioning with visible light. In," in *Proceedings of the 13th International Conference on Mobile Systems, Applications, and Services*, Paris, France, 2015.

[160] Acuity Brands, "Indoor Positioning Services White Paper," 2017.

[161] A. Ghosh, A. Maeder, M. Baker and D. Chandramouli, "5G Evolution: A View on 5G Cellular Technology Beyond 3GPP Release 15," *IEEE Access,* vol. 7, pp. 127639-127651, 2019.

[162] M. Gapeyenko, V. Petrov, D. Moltchanov, M. R. Akdeniz, S. Andreev, N. Himayat and Y. Koucheryavy, "On the Degree of Multi-Connectivity in 5G Millimeter-Wave Cellular Urban Deployments," *IEEE*

Transactions on Vehicular Technology, vol. 68, no. 2, pp. 1973-1978, 2019.

[163] N. Maletic, V. Sark, J. Gutiérrez and E. Grass, "Device Localization Using mmWave Ranging with Sub-6-Assisted Angle of Arrival Estimation," in *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, Valencia, Spain, 2018.

[164] L. Yan, H. Ding, L. Zhang, J. Liu, X. Fang, Y. Fang, M. Xiao and X. Huang, "Machine Learning-Based Handovers for Sub-6 GHz and mmWave Integrated Vehicular Networks," *IEEE Transactions on Wireless Communications,* vol. 18, no. 10, pp. 4873-4885, 2019.

[165] O-RAN Alliance, "O-RAN: Towads an Open and Smart RAN, White Paper," October 2018.

[166] 5G-CLARITY, "D2.2 - Primary system architecture," 2020.

[167] O-RAN Alliance, "O-RAN Use Cases and Deployment Scenarios - Towards Open and Smart RAN, White Paper," 2020.

[168] Qualcomm, [Online]. Available: https://www.qualcomm.com/products/wi-fi.

[169] [Online]. Available: https://www.openvswitch.org/.

[170] R. Enns, "NETCONF Configuration Protocol (Technical Report) - RFC4741," IETF, 2006.

[171] 5GPICTURE, "D4.2 Complete design and initial evaluation of developed functions".

[172] M. Grandi, D. Camps-Mur, A. Betzler, J. J. Aleixendri and M. Catalan-Cid, "SWAM: SDN-based Wi-Fi Small Cells with Joint Access-Backhaul and Multi-Tenant Capabilities," in *IEEE/ACM IWQoS*, Canada, 2018.

[173] S. Kanugovi, F. Baboescu, J. Zhu, J. Mueller and S. Seo, "Multiple Access Management Services - draft-kanugovi-intarea-mams-framework-04," IETF, 2019.

[174] 5GENESIS, "D6.1 - Trials and experimentation - cycle 1," 2019.

[175] 3GPP, "TS 23.273 V16.3.0: 5G System (5GS) Location Services (LCS); Stage 2," 2020.

[176] M. D. Santambrogio, J. Santa, P. J. Fernández, R. Sanchez-Iborra, J. Ortiz and A. F. Skarmeta, "Offloading Positioning onto Network Edge," *Wireless Communications and Mobile Computing,* vol. 2018, pp. 1530-8669, 2018.

[177] J. Werner, M. Costa, A. Hakkarainen, K. Leppanen and M. Valkama, "Joint user node positioning and clock offset estimation in 5G ultradense networks," in *IEEE Globecom*, San Diego, CA, 2015.

[178] Small Cell Forum, "Network densification in the 5G era," 2017.

[179] 3GPP, "TS 36.300: LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Overall Description; Stage 2".

[180] Philips, "Indoor Positioning White Paper: Unlocking the value of retail apps with lighting," 2016.

[181] F. B. Tesema, et. al., "Mobility modeling and performance evaluation of multi-connectivity in 5G intra-frequency networks," in *IEEE Globecom Workshops (GC Wkshps)*, 2015.

[182] "IEEE 802.11bb Standard," [Online]. Available: http://www.ieee802.org/11/Reports/tgbb_update.htm.

[183] ETSI, TS 124 502 V15.0.0; Access to the 3GPP 5G Core Network (5GCN) via non-3GPP access networks,

ETSI, 2018.

9 List of Acronyms

3GPP	3rd Generation Partnership Project
5GNR	5G New Radio
5G-BRG	5G Broadband Residential Gateway
5GC	5G Core
5G-CRG	5G Cable Residential Gateway
5G-RG	5G Residential Gateway
AAS	Active Antenna System
ABS	Almost Blank Subframe
ADR	Angle Diversity Receiver
ADT	Angle Diversity Transmitter
AF	Application Function
AFC	Automated Frequency Coordination
A-GNSS	Assisted GNSS
AI	Artificial intelligence
AKA	Authentication and Key Agreement
AMC	Adaptive Modulation and Coding
AMF	Access and Mobility Management Function
ANDSF	Access Network Discovery and Selection Function
AoA	Angle of Arrival
AoD	Angle of Departure
AP	Access Point
ARP	Address Resolution Protocol
ARQ	Automatic Repeat request
ATSSS/AT3S	Access Traffic Steering Switching and Splitting
ATIS-IOC	Alliance for Telecommunications Industry Solutions IMSI Oversight Council
BFSK	Binary Frequency Shift Keying
BLER	BLock Error Rate
BNG	Broadband Network Gateway
BPSK	Binary Phase Shift Keying
BS	Base Station
BSS	Basic Service Set
BW	Bandwidth
BWP	Bandwidth Part
CBRS	Citizens Broadband Radio Service
CRE	Cell Range Extension
ECC	Electronic Communications Committee
CA	Carrier Aggregation
CAP	Contention Access Period
CBSD	Citizens Broadband radio Service Device
CC	Component Carrier
CCA-ED	Clear Channel Assessment-Energy Detection
CEPT	Comite Europeen des Postes et Telecommunications
CLI	Cross-Link Interference
CMOS	Complementary Metal Oxide Semiconductor
CoAP	Constrained Application Protocol
COTS	Commercial Off-The-Shelf
CPE	Customer Premise Equipment
CQI	Channel Quality Indicator
CRS	Cell-specific Reference Symbol
CSAS	CBRS Alliance SAS Entity
CSAT	Carrier Sensing Adaptive Transmission
CSI	Channel State Information
CSMA-CA	Carrier Sense Multiple Access-Collision Avoidance
CST	Carrier Sense Threshold
CTS	Clear To Send
CU	Central Unit
CxG	Coexistence Group
CxM	Coexistence Manager
DAS	Distributed Antenna System
dB	decibel
DC	Dual Connectivity
DCF	Distributed Coordination Function
DCI	Downlink Control Information
DFS	Dynamic Frequency Selection
DL	DownLink
DRX	Discontinuous Reception
DSA	Dynamic Spectrum Access
DSC	Dynamic Sensitivity Control
DSS	Dynamic Spectrum Sharing
DU	Distributed Unit
EAP-AKA	Extensible Authentication Protocol-Authentication and Key Agreement
eAT3S	5G-CLARITY enhanced A3TS
E-CID	Enhanced Cell ID
ECC	Electronic Communications Committee
EDCA	Enhanced Distributed Channel Access

eICIC	enhanced ICIC
EIRP	Effective Isotropic Radiated Power
eLAA	enhanced LAA
eLWA	enhanced LWA
eMBB	enhanced Mobile BroadBand
EMS	Element Management System
eMTC	enhanced Machine Type Communication
eNB	enhanced Node B
EN-DC	E-UTRAN New Radio Dual Connectivity
EPC	Evolved Packet Core
EPS	Evolved Packet System
ERP	EAP Re-authentication Protocol
ESC	Environmental Sensing Capability
ETSI	European Telecommunications Standard Institute
EU	Europe
EUD	End User Device
E-UTRA/N	Enhanced UTRA/N
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FDM	Frequency Division Multiplexing
feICIC	further enhanced ICIC
FN-RG	Fixed Network Residential Gateway
FOV	Field-of-view
FR	Frequency Range
FSS	Fixed Satellite Services
FTM	Fine Tune Measurement
FWA	Fixed Wireless Access
GAA	General Authorised Access
GBR	Guaranteed Bit Rate
gNB	Next generation Node B
GPRS	General Packet Radio Service
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRE	Generic Routing Encapsulation
GSA	Global mobile Suppliers Association
GSM	Global System for Mobile
GTI	Global TD-LTE Interest group
GTP/GTP-U	GPRS Tunnelling Protocol-User plane
Hetnet	Heterogeneous Network
HetWAT	Heterogeneous WAT
HLWNet	Hybrid LiFi Wi-Fi Network
HNI	Home Network Identity
HW	HardWare
ICIC	Inter-Cell Interference Coordination
IDC	In-Device Coexistence
IE	Information Element
IMSI	International Mobile Subscriber Identity
IP	Internet Protocol
IPSec	IP Security
ISM	Industrial, Scientific and Medical
IR	InfraRed
ISP	Internet Service Provider
KPI	Key Performance Indicator
LAA	License Assisted Access
LAN	Local Area Network
LBT	Listen-Before-Talk
LC	Link Convergence
LEC	Light Emitting Diode
LIDAR	Light Detection And Ranging
LiRa	Light Radio WLAN
LMF	Location Management Function
LoS	Line of Sight
LPPa	LTE Positioning Protocol annex
LSA	Licensed Shared Access
LTE	Long Term Evolution
LTE-U	LTE on Unlicensed
LWA	LTE WLAN Aggregation
LWAAP	LWA Adaption Protocol
LWIP	LTE WLAN Radio Level Integration with IPSec Tunnel
MAC	Medium Access Control
MAMS	Multi-Access Management Service
MCG	Master Cell Group
MFCN	Mobile/Fixed Communications Network
MIMO	Multiple Input Multiple Output
ML	Machine Learning
mMTC	massive Machine Type Communication
MN	Master Node
MNO	Mobile Network Operator
MOCN	Multi-Operator Core Network
MPTCP	Multi-Path TCP
MR-DC	Multi-Radio Dual Connectivity
MS	Mobile Station
MSC	Modulation and Coding Schemes
MSO	Multiple-System Operator
MU-MIMO	Multi User MIMO

N3AN	Non 3GPP Access Networks
N3IWF	Non-3GPP InterWorking Function
N5CW	Non-5G-Capable over WLAN
NAV	Network Allocation Vector
NB-IoT	NarrowBand Internet of Things
NE-DC	NR-E-UTRA-Dual Connectivity
NEF	Network resource Exposure Function
NF	Network Function
NFV	Network Function Virtualization
NGEN-DC	NG-RAN E-EUTRA NR-Dual Connectivity
NG-RAN	Next Generation Radio Access Network
NHN	Neutral Host Network
NLOS	Non Line Of Sight
NMS	Network Management System
NPN	Non-Public Network
NR	New Radio (5GNR)
NR-DC	New Radio Dual Connectivity
NR-U	New Radio in Unlicensed
OAM	Operations, Administration and Maintenance
OBSS	Overlapping BSS
OCC	Optical Camera Communication
OFDMA	Orthogonal Frequency Division Multiple Access
OTDOA	Observed Time Difference of Arrival
PAL	Priority Access License
PCF	Policy Charging Function
PDCP	Packet Data Convergence Protocol
PDU	Protocol Data Unit
PF	Proportional Fair
PHY	Physical Layer
PPP	Poisson point process
PRB	Physical Resource Block
PRS	Positioning Reference Signal
PRTC	Primary Reference Time Clock
PSCell	Primary SCell
PSDU	PHY SDU
PtP	Point-to-Point
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
QZSS	Quasi-Zenith Satellite System
RA	Resource Allocation
RAN	Radio Access Network
RB	Resource Block
RBG	Resource Block Group
RF	Radio Frequency
RIC	Radio Interface Controller
RIM	Remote Interference Management
RIV	Resource Indication Value
RLAN	Radio LAN
RLC	Radio Link Control
RLM	Radio Link Monitoring
RMS	Root Mean Square
RR	Round Robin
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RT	Realtime
RTK	Real-Time Kinematic
RTOA	Relative Time of Arrival
RTS	Request To Send
RTT	Round Trip Time
SA	StandAlone
SAS	Spectrum Access System
SCell	Secondary Cell
SCS	SubCarrier Spacing
SDN	Software Defined Networking
SDR	Software Defined Radio
SDU	Service Data Unit
SeGW	Security GateWay
SISO	Single Input Single Output
SINR	Signal to Interference plus Noise Ratio
SLA	Service Level Agreement
SMF	Session Management Function
SN	Secondary Node
SNR	Signal to Noise Ratio
SRS	Sounding Reference Signal
SU-MIMO	Single User MIMO
SW	SoftWare
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDOA/TDoA	Time Difference of Arrival
TNGF	Trusted Non-3GPP Gateway Function
ToA	Time of Arrival
ToF	Time of Flight
TSG	Technical Specification Group
TTI	Transmission Time Interval

TV	TeleVision
TWIF	Trusted WLAN Interworking Function
UDP	User Datagram Protocol
UE	User Equipment
UK	United Kingdom
UL	UpLink
UMTS	Universal Mobile Telecommunications System
UPF	User Plane Function
URLLC	Ultra Reliable Low Latency Communications
URSP	UE Route Selection Policy (URSP)
US	United States
USB	Universal Serial Bus
UTC	Universal Time Coordinated
UTDOA	Uplink Time Difference of Arrival
UTRA/N	UMTS Terrestrial Radio Access/Network
UWB	Ultra Wide Band
V2X	Vehicle-to-everything
vAP	Virtual AP
VL	Visible Light
VLC	Visible Light Communication
VLP	Visible Light Positioning
VRB	Virtualised Resource Blocks
W-5GAN	Wireline 5G Access Network
W-AGF	Wireline Access Gateway Function
WAS	Wireless Access System
WAT	Wireless Access Technology
WDM	Wavelength Division Multiplexing
WLAN	Wireless LAN
WT	Wireless Termination