Dynamic Spectrum Management in Multi-Access Systems moving towards 6G

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***Abstract*—This paper provides a survey of key innovations brought in the last ten years in the areas of both dynamic spectrum management and integration of diverse radio access technologies in heterogeneous and multi-access systems, taking into consideration also regulatory and standardization aspects. In particular, recent enhancements proposed by EU-funded research projects are detailed, showing the path towards forthcoming 6G networks.**

Keywords—Dynamic Spectrum Management, Frequency Bands, 5G, 5G Advanced, 6G, Regulation, Standardization, RAT.

I. Introduction

Since the start of commercial mobile services, a constant trend can be observed: on average each couple of years, a new set of mobile network features is launched. This set is defined by a so-called *Release* of the Third Generation Partnership Project (3GPP) standards [1], proposing new capabilities and enhancements to previously deployed sets. Such novel group of functionalities most of the times increases at each round the need for additional spectrum bands, to fulfil the always more demanding requirements of the proposed set of new services composing the new Release [2].

The currently under definition next generation (6G) of mobile networks foresees a future telecommunication network where different Radio Access Technologies (RATs) (i.e., cellular, Wi-Fi, low-power wide-area networks, and Non-Terrestrial-Networks (NTN)), together with their related communication protocols and resource management methods, converge to create a unique system of systems [3]-[6]. Such overarching network is supposed to better accommodate, in an environmental-friendly and sustainable way, the planned novel 6G features [7]. These features are expected to fulfil diverse market segments needs and are anticipated to open promising new business opportunities for big industrial players and Small and Medium Enterprises (SMEs) alike [8].

The heterogeneous and looked-for seamless integration of different RATs calls since a long time for a more intelligent, dynamic, and energy-efficient use of the expensive and scarcely available wireless spectrum resources [9]-[11]. Such additional spectrum is devised to be allocated in two main spectrum areas: i) the more traditional cellular and Wi-Fi bands, e.g., below 6 GHz, by refarming frequences not needed anymore by discontinued services or old technologies [12]; and ii) the newly allocated for commercial purposes of mobile networks lower millimeter-wave (mmWave) spectrum, e.g., in the already defined in 5G and currently being discussed for 6G new bands between 7 GHz and 100 GHz [13]. Those bands are expected to be used to unleash the potential of innovative applications launched by 5G Advanced and the forthcoming novel resource-demanding services, expected to be part of 6G deployments [14][15].

Several methods, frameworks, and tools have been proposed in the last years to alleviate the constant quest for new spectrum resources. Disregarding the actions proposed and partially implemented, as described in the comprehensive survey [16], to make available new spectrum resources the Information and Communication Technology (ICT) community keeps going on screaming for more spectrum at each introduction of a novel 3GPP Release or of a new generation of mobile networks (e.g., Wi-Fi 8) [17]-[19].

Based on such continuous interest from both research and industry in how either find ways to allocate new spectrum or make use in a more effective way of the existing spectrum bands, this paper provides a survey of key advancements proposed to make that happen. That is done taking into consideration some key and most visionary proposals coming from EU-funded collaborative research projects that concentrated their efforts in dynamic spectrum management and integrating heterogenous RATs. Scope of this paper is to provide the right references for interested readers to delve into topics addressed by those projects, which are of significance for research and industry ecosystems alike.

The remainder of the paper is structured as follows. Section II surveys key trends in literature in the last ten years, focusing on extending or creating new architectural blocks of a telco system so to allow for a dynamic spectrum allocation. Section III touches on the essential regulatory and standardization aspects of dynamic spectrum management. Finally, Section IV focuses on the very recent views of PREDICT-6G [20] and 6G-SENSES [21], two running EU-funded projects, working on the main challenges moving towards forthcoming 6G networks regarding: i) seamless integration of different RATs that involve different spectrum bands; and ii) main contributions in interference reduction for advanced dynamic spectrum multi-domain scenarios.

II. The 5G Evolution from Static to Dynamic and Flexible Spectrum Allocation

In 2014, when 4G was already fully deployed in commercial networks, the available terrestrial wireless spectrum was allocated in a static way, in a network structure made only of incumbents (i.e., entities that owned the spectrum resources) and a few other players. The latter could ask the incumbent for a limited time access to a spectrum band and needed to inform well in advance (several days) about the intention to rent spectrum, thus giving rise to a system of frequence management totally non dynamic in the time dimension.

The way such lease from an incumbent to a licensee could happen differed consistently among geographic regions, as the process was inadequately standardized and individually regulated among different countries. Moreover, only poor, when existing at all, guarantees of a Quality of Service (QoS) could be provided. That was mainly due to the fact that interference were not properly managed and misbehaving licensees could either create serious disruption to the services

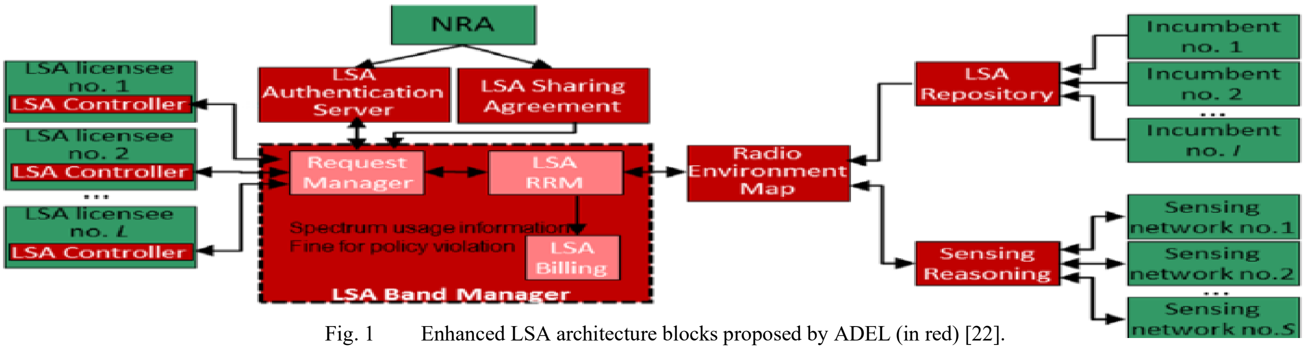

Fig. 1 Enhanced LSA architecture blocks proposed by ADEL (in red) [22].

provided to final users by the incumbent or strongly disturb the services provided by the other licensees [10].

First collaborative efforts in the research ecosystem towards a more effective usage of the available spectrum resources were taken thanks to a set of EU-funded projects. Among those, ***ADEL (Advanced Dynamic spectrum 5G mobile networks Employing Licensed shared access)***, running from 2013 to 2016, resulted to be one of the most visionary and ambitious ones. Back then (but the same is still valid nowadays) there were three main ways to share spectrum: i) Exploitation of TV white spaces (TVWS); ii) The Licensed Shared Access (LSA), aka Authorized Shared Access (ASA) approach; and iii) The Spectrum Access Systems (SAS) approach. Assessing pros and cons of the available options [22], ADEL realized that the most promising approach to add dynamicity to spectrum management was provided by LSA, which allows both Mobile Network Operators (MNOs) and non-MNOs licensees to make use of unused spectrum owned by the incumbent in a secure and effective way for both the incumbent and for one or more licensees.

Therefore, ADEL proposed a set of enhancements to an European Standards Telecommunications Institute (ETSI)-compliant LSA architecture, shown in Fig.1, aiming to:

i) increase the protection mechanism of the incumbent from any harmful interference caused by the licensees, thus providing a means to penalize the misbehaving entities;

ii) guarantee never experienced before QoS levels to the licensee;

iii) coordinate the access to the LSA band among a set of licensees;

iv) add to the system architecture a database-assisted collaborative spectrum sensing block to further improve the efficiency of the spectrum utilization;

v) add collaborative sensing networks on top of normal deployments (managed by an enhanced Radio Resource Management (RRM) layer located in small cells). Such networks allow in spectrum allocation procedures for: i) more flexibility and dynamicity, i.e., the capability to adapt to changes sensed in the radio environment in a more time-accurate way; and ii) much shorter time slots needed for the change of usage between licensees, and between a (set of) licensee(s) and the incumbent;

vi) introduce the new block Radio Environment Map (REM) taking care of storing updates of the radio environments provided by the sensing networks;

vii) add the LSA band manager block to the LSA architecture to introduce further features like a more refined and flexible billing scheme and enhanced security guarantees.

Simulations performed making use of the enhanced architecture showed evident QoS benefits for a set of licensees. The latter finally managed to more effectively share among themselves the spectrum made available by the incumbent, and to reduce the possibility for misbehaving licensees to get access to the available spectrum resources not originally assigned to them [23].

A different approach moving along the same stream of research came from the EU-funded project ***SPEED-5G (quality of Service Provision and capacity Expansion through Extended-DSA for 5G)***, running from 2015 to 2018 and focusing on the implementation of the concept of extended Dynamic Spectrum Allocation (eDSA). eDSA refers to a set of improvements to access stratum architectural blocks to more effectively make use of the available diverse spectrum bands accessible by the diverse RATs (cellular, Wi-Fi, and Internet of Things (IoT), as shown in Fig.2), with the aim of increasing the perceived QoS by final users [24].

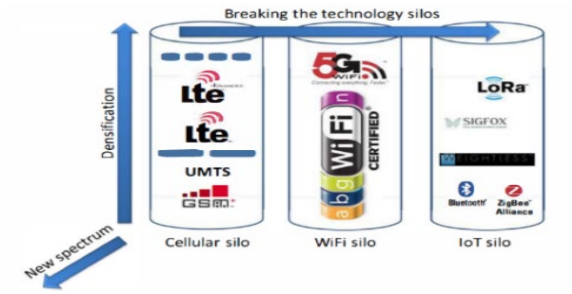

Fig.2 SPEED-5G approach to multi-RATs and multi-bands systems [24].

The enhancements brought by eDSA focussed on:

i) at the RRM in small-cells, regarding novel heterogeneous resource management techniques for Inter-RATs cooperation;

ii) at the Medium Access Control (MAC) in both terminal and small cell sides, regarding a smoother and tighter integration of 5G/5G Advanced flexible Physical layers.

The set targets of SPEED-5G were therefore to:

i) mitigate interferences in shared spectrum use cases by introducing novel Filter-Bank Multi Carrier (FBMC) modulation schemes, which manage to guarantee lower interference leakage compared to the standard Orthogonal Frequency Division Multiplexing (OFDM) approach. The proposed architecture accomplished to allow for a single MAC capable of handling both FBMC

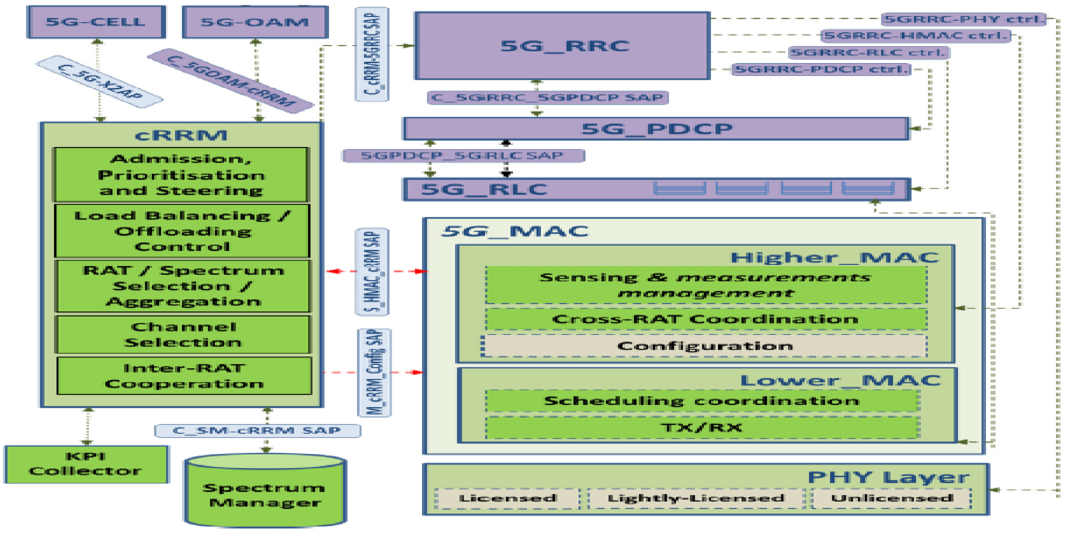

Fig. 3 SPEED-5G access stratum functional blocks both at small-cell (left) and terminal (right) side; in green the areas in focus [28].

and OFDM schemes with minimum-to-no changes to the SW stack;

ii) improve the QoS by adding the capability to harvest and aggregate fragmented spectrum chunks and introduce several improvements at the Radio Resource Control (RRC) and MAC layers of the SW protocol stack, also taking into consideration backhaul aspects [25] [26].

To achieve the above targets, SPEED-5G proposed to split the MAC layer architecture in two blocks, i.e., lower-MAC and Upper-MAC, each one containing a set of enhanced and novel functions compared to the existing 3GPP-defiened MAC capabilities. Also, the RRC block in small cells was split in two parts, centralized RRM (cRRM) and distributed RRM (dRRM) extended with new functionalities, to allow for seamless inter-RAT management and cooperation [27] [28]. Fig.3 shows the complex mapping of novel functionalities to a high-level architectural view of a cellular protocol stack.

A broad surveys of additional relevant methods and approaches to dynamic spectrum sharing obtained in that context can be found in the IEEE Special Issues on *Dynamic Spectrum Management for 5G* [29] and on *5G and Beyond—Mobile Technologies and Applications for IoT* [30].

A third luminary project was ***5GENESIS (5th Generation End-to-end Network, Experimentation, System Integration, and Showcasing)***, running from 2018 to 2022 and focusing on providing an experimentation facility made open to SMEs and the research ecosystem willing to perform end-to-end (E2E) trials. The project produced also tangible advancements in network automation, slicing, and advanced virtualization mechanisms serving 5G/5G Advanced use cases [31]. 5GENESIS introduced:

i) network automation mechanisms based on AI/Machine Learning (ML) methods for the automation of the resource management in spectrum sharing contexts [32];

ii) support to satellite access as another RAT to take into consideration for an improved load balancing and an extended remote areas coverage [33];

iii) support of virtualization and network slicing and an extension of RRC and other relevant procedures to ensure a user-defined QoS for the selected network slice [34].

The proposed AI/ML-based spectrum management architecture is shown in Fig.4 and assumes that a 5G base station can be split in three parts, i.e., Central-/Distributed-/Radio-Unit (CU, DU, RU), so to best optimize the streams of data coming from the different RATs, including a network slice. The state-of-the-art was extended by considering two spectrum sharing approaches, an *inter-network* one, in which a band is shared by several MNOs, and an *intra-network* one, where a single operator can make use of multiple bands coming from different RATs to fulfil the user-required QoS.

III. Regulatory and Standardization Aspects

Regulatory aspects of dynamic spectrum sharing have been constantly evolving in the last twenty years, since the first TVWB frequencies were re-allocated to make room for cellular services. Spectrum regulation is considered such an important topic that each country has its own dedicated agency dealing with that matter, deciding autonomously about which frequencies to share, how, for how long and between which incumbent and which kinds of licensees. The most active regulatory bodies driving the evolution and harmonization of spectrum bands in the world are the European Conference of Postal and Telecommunications Administrations (CEPT), in US the Federal Communications Commission (FCC), and in Australia the Communications and Media authority (ACMA) [35]. Each of them recommended a diverse set of bands for dynamic spectrum allocation for military or commercial services and a slightly different system architecture, involving a two- or a three-tiers approach for incumbent and licensees. All of the above has created a very much fragmented set of *spectrum allocation tables*, one per country. In addition, even within a single country there is usually a complex and scattered spectrum landscape, as nicely detailed in the *frequency allocation Chart* for the US [36]; more detailed information can be found in the *frequency allocation Tables* for the US [37] and the EU [38], as two exemplary cases.

To complicate the already very much fragmented scenario described above, with the advancement of the integration of NTN into the cellular network [39], new interference issues and spectrum sharing complexity have been added, topic addresses in the next section by the 6G-SENSES project.

On the ***standardization side***, the most important Working Groups (WG) producing specifications on LSA/DSA matters have been the WG1 of the Technical Committee on Reconfigurable Radio Systems of ETSI (TC RRS WG1) and several 3GPP WGs, especially the WG5 of the Technical

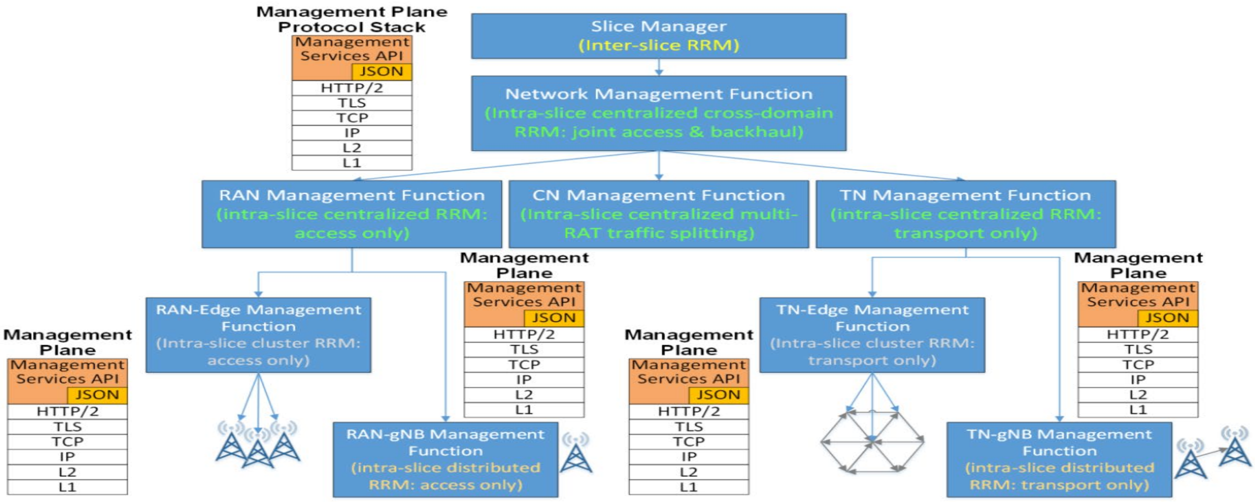

Fig. 4 5GENESIS spectrum management architecture [31].

Specification Group on Services and Systems Aspects of 3GPP (TSG SA WG5). ETSI has recently focused on proposing a spectrum sharing framework to take into consideration the always more important topic of Private Network (PN) deployments, considering their big impact on several vertical sectors like logistics and manufacturing [40] [41]. 3GPP started in Release 15 introducing features to add dynamicity to the spectrum management, and Release 18, recently (mid 2024) finalized, was the latest Release introducing a set of new features, as shown in Fig.5 [42].

IV. Towards 6G: two Views on how to improve dynamic spectrum allocation and RATs integration

On the path towards the definition of the forthcoming 6G system, some main trends can be spotted in the evolution of spectrum sharing methods. The inclusion of PN, pervasive AI/ML techniques, seamless integration of Satellite access with other RATs, slicing, adding time dynamicity and technology-usage flexibility in spectrum management procedures have been previously discussed. In the following, two running EU-funded research projects focusing on 6G are presented. The two projects propose further advancements in both RATs integration and spectrum management in innovative scenarios, stressing once more the importance of the capability of future systems to manage at the same time a dynamic spectrum allocation with the seamless usage of a set of underlying RATs and supported by different standards.

The vision of ***PREDICT-6G (Programmable AI-Enabled Deterministic Networking for 6G)***, running from 2023 to 2025, is to further advance the integration of different RATs and propose a system architecture capable of effectively be compliant with a set of standards (IEEE, IETF, 3GPP) of major importance in the manufacturing domain. In fact it is considered crucial to handle seamlessly the growing weight of Wi-Fi in Industrial IoT scenarios [43] and to leverage on the extension of Time-Sensitive Networking (TSN) technologies to be implemented on top of underlying 3GPP-compliant (cellular) and IEEE-complaint (Wi-Fi) networks. The main targets of PREDICT-6G, crystallized by the proposed system architecture and technology enablers shown in Fig.6, are therefore to:

i) emulate deterministic network capabilities on top of non-deterministic network segments;

ii) develop an AI-driven multi-stakeholder inter-domain control plane (AIPC) [4];

iii) develop a multi-technology multi-domain data plane (MDP) capable of integration deterministic and non-deterministic domains [44];

iv) enhance the predictability of the network via Digital Twins and advanced AI/ML mechanisms [45];

v) enhance cross-domain E2E deterministic service management automation.

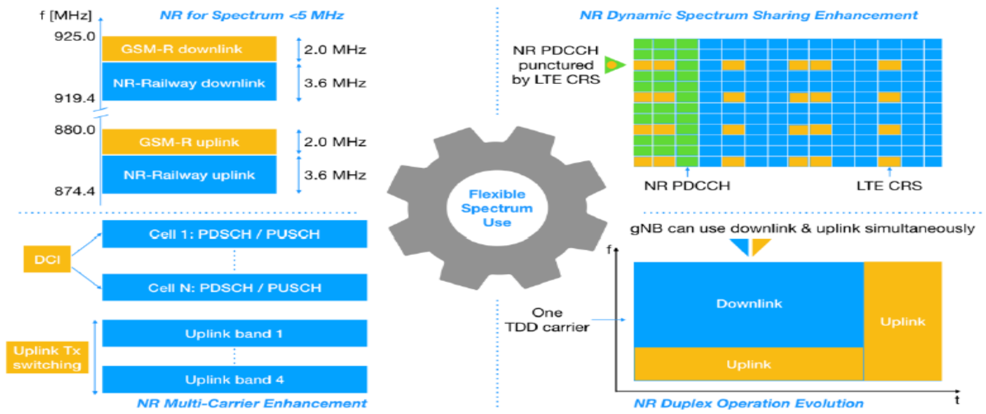

Fig.5 3GPP Release 18 features to improve dynamic spectrum sharing [42].

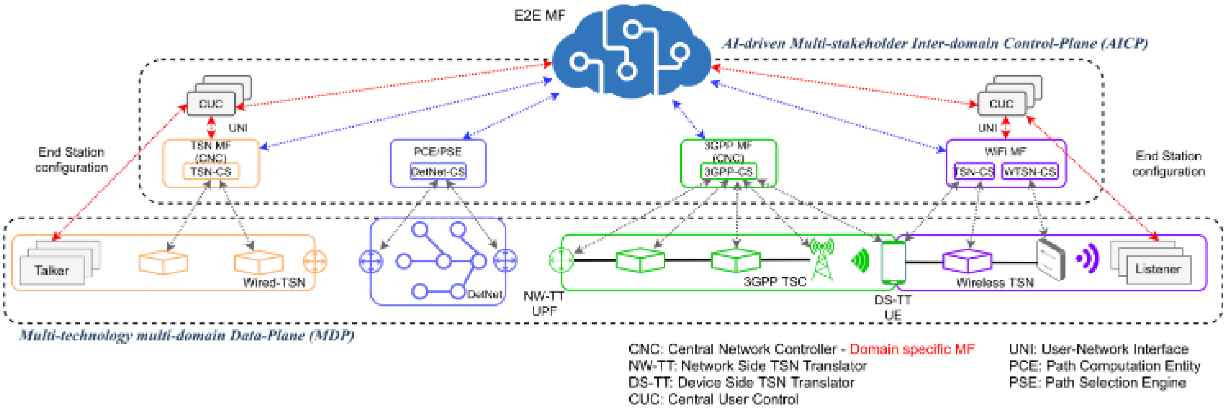

Fig. 6 Integration between MDP and AIPC among different RATs.

PREDICT-6G has demonstrated that the MDP jointly with the AICP can enable the creation of E2E deterministic paths, leveraging for the first time on both IETF Deterministic Networking (DetNet) and Reliable and Available Wireless (RAW) mechanisms on top of 3GPP-compliant wireless protocols and IEEE Wi-Fi access [46]. The increase predictability in wireless connections in factories is a long-time wished-for feature by the industrial ecosystem and is expected to have an important business relevance once broadly deployed [47].

Finally, the vision of ***6G-SENSES (Seamless integration of efficient 6G wireless technologies for communication and sensing)***, running from 2024 to 2026, is to integrate novel technologies, e.g. Cell-Free Massive Multiple-Input Multiple-Output (MIMO) and Joint Communication and Sensing (JCAS), towards 6G systems based on the 3GPP and Open-RAN (O-RAN) architectural frameworks, using both mmWave and Sub-6 GHz bands. The project acknowledges the high interest in spectrum sharing from both the Wi-Fi Alliance and the IMT Alliance in the 6-7 GHz frequency band, where Fixed Satellite Services (FSS) are currently operating. 6G-SENSES also assumes that the shared use of the spectrum is the best assumption to: i) reduce interference among the cellular, Wi-Fi and satellite communication technologies; and ii) avoid that coexistence issues among all three services could trigger a battle over frequencies among different industry vertical and frequency bands stakeholders. Unwanted interference is expected to worsen moving towards 6G, also considering the expected broad deployments of environmental sensing devices and Reflective Intelligence Surfaces (RISs), which can potentially cause unregulated signal radiation in unintended directions.

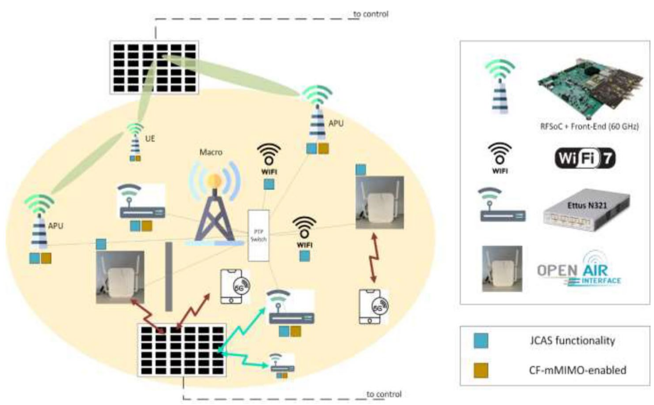

Fig.7 Data plane showing a set of interfering wireless technologies.

First simulations show that without an advance spectrum management capability, based on extensive use of AI/ML methods for intelligent and dynamic frequency allocation, the coexistence of services related to the different access technologies is endangered and not capable of guaranteeing the minimum expected QoS levels [48].

6G-SENSES proposes to address the above issues by design protocols that can enable cellular/Wi-Fi traffic steering and offloading in licensed/unlicensed spectrum and co-operative communications through RIS-based CF-MIMO in a centralised O-RAN controller. Moreover, an edge application on top of the 6G-SENSES control fabric will be developed for flexible and agile utilization of radio spectrum resource in heterogeneous networks, see Fig.7, to realize dynamic spectrum management in short time scale, i.e., down to mins.

In this context, [49] focuses on a reinforced-learning-based approach based on hypergraph interference model to both enhance network performance and mitigate the cumulative interface caused by massive deployments of IoT devices in a multi-domain and heterogeneous scenario.

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