

Sharing Distributed and Heterogeneous Resources toward End-to-End 5G networks: A Comprehensive Survey and a Taxonomy

Nina Slamnik-Kriještorac*, Haris Kremo†, Marco Ruffini‡, and Johann M. Marquez-Barja*

* University of Antwerp - imec, IDLab research group, Sint-Pietersvliet, 2000 Antwerp, Belgium.

E-mail: {name.surname}@uantwerpen.be

† RWTH Aachen University

E-mail: kremo@ice.rwth-aachen.de

‡ CONNECT Center, Trinity College Dublin, Ireland.

E-mail: marco.ruffini@scss.tcd.ie

Abstract—Regardless of the context to which it is applied, sharing resources is well-recognized for its considerable benefits. Since 5G networks will be service-oriented, on-demand, and highly heterogeneous, it is utmost important to approach the design and optimization of the network from an end-to-end perspective. In addition, in order to ensure end-to-end performance, this approach has to entail both wireless and optical domains, altogether with the IoT, edge, and cloud paradigms which are an indispensable part of the 5G network architecture. Shifting from the exclusive ownership of network resources toward sharing enables all participants to cope with stringent service requirements in 5G networks, gaining significant performance improvements and cost savings at the same time. The main objective of this paper is to survey the literature on resource sharing, providing an in-depth and comprehensive perspective of sharing by recognizing the main trends, the techniques which enable sharing, and the challenges that need to be addressed. By providing a taxonomy which brings the relevant features of a comprehensive sharing model into focus, we aim to enable the creation of sharing models for more efficient future communication networks. We also summarize and discuss the relevant issues arising from network sharing, that should be properly tackled in the future.

Index Terms—sharing resources, end-to-end future communication networks, 5G, wireless domain, optical domain, IoT, edge, cloud, sharing challenges.

I. INTRODUCTION

The widespread concept of *sharing* can be defined as a joint use of resources enabled by on-demand exchange, or by loaning of valuable goods [1]. Sharing brings its beneficial nature in many domains including social and economic systems, as well as in nature. Based on that fact, we anticipate and envision that provisioning of the models and methods for sharing of network resources represents one of the fundamental steps in designing Future Communication Networks (FCNs).

As a pioneer among FCNs, 5G represents the fifth generation of wireless technologies for digital cellular networks. Built upon 4G systems, 5G is an evolution considered to be the convergence of Internet services with legacy mobile networking standards leading to the mobile Internet over heterogeneous networks with high-speed broadband [2].

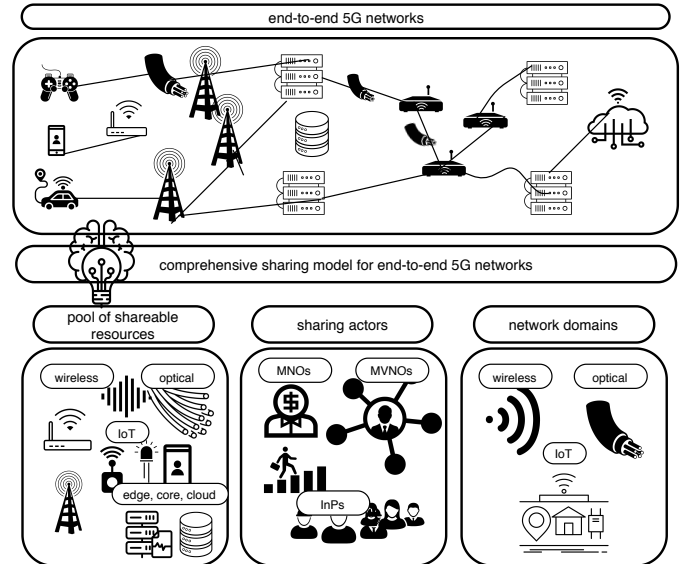


Fig. 1: Extensive and comprehensive sharing of distributed and heterogeneous resources

The main focus of our survey is on the applicability of sharing in the context of FCNs with the goals to: 1) present current trends in sharing of network resources, 2) provide research community with knowledge on the existing sharing techniques, 3) outline the challenges in the implementation of these techniques, and finally and most importantly 4) provide a taxonomy which brings the main features of a comprehensive sharing model into focus, facilitating the creation of models suitable to build more efficient FCNs.

Given Fig. 1, the aforementioned comprehensive sharing models span both physically tangible and intangible types of network resources (pool of shareable resources) in the *wireless* as well as in the *optical domain*, altogether with *Internet of Things (IoT)*, *network edge*, and *cloud domains*. Moreover, sharing actors (Fig. 1, e.g., network operators (i.e., Mobile Network Operators (MNOs)), Service Providers (SPs), Infras-

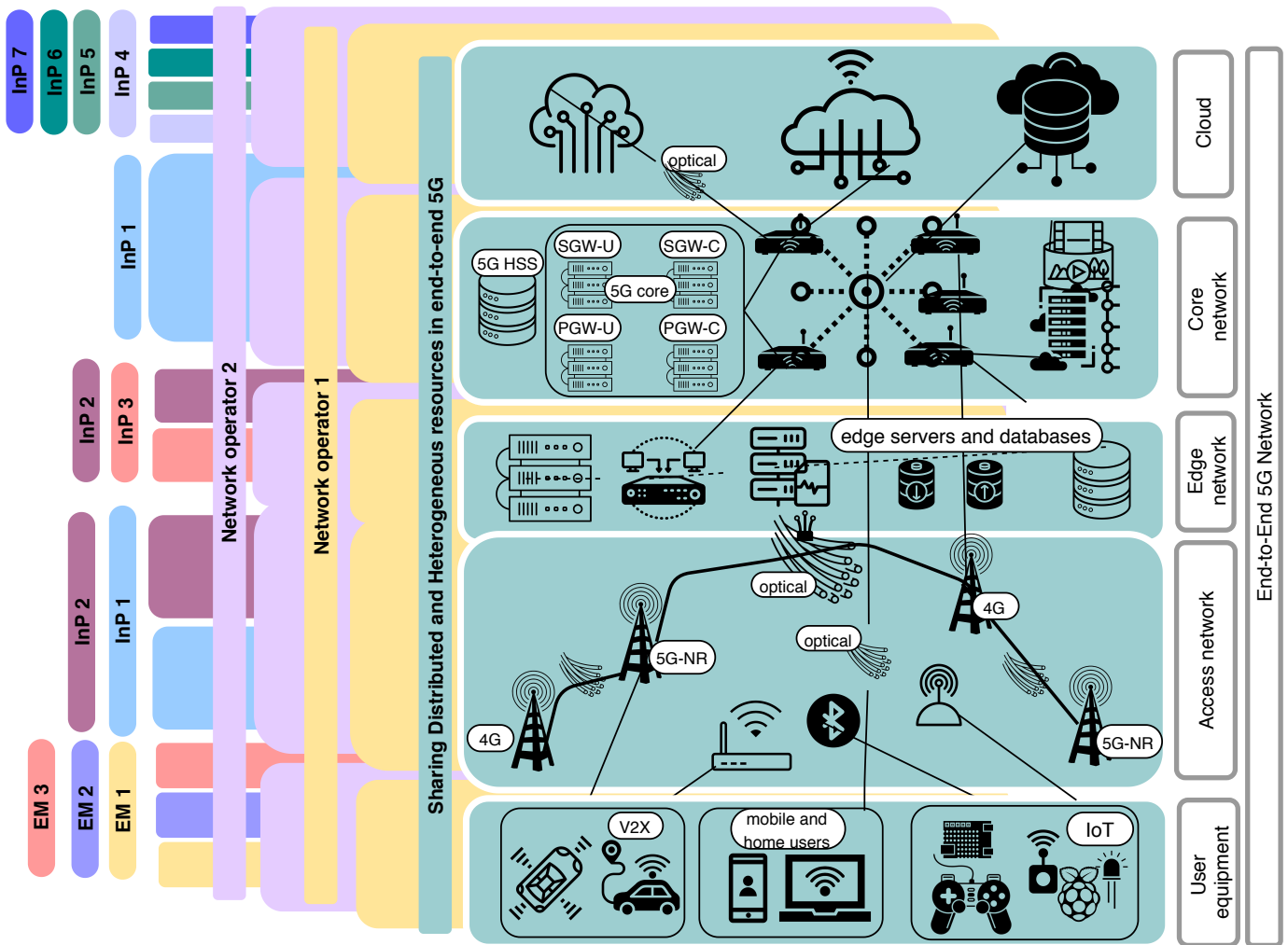


Fig. 2: The End-to-End 5G networks perspective starting from user domain, through access and edge networks, towards core and cloud (Equipment Manufacturer (EM), Infrastructure Provider (InP))

structure Providers (InPs), Mobile Virtual Network Operators (MVNOs), users, etc.) can increase both revenues and users' satisfaction with their services if they share resources from an end-to-end perspective. Such concept is shown in Fig. 2, illustrating it from a 5G network perspective.

Due to the strong heterogeneity in terms of network resources and technologies, it is utmost important for such sharing models to have an *end-to-end perspective* of 5G networks. As shown in Fig. 2, the scope of a 5G network as an FCN spans different network segments, such as users' domain (i.e., User Equipment (UE)), Radio Access Network (RAN), edge (depending on the deployment, it can be part of RAN, with edge servers deployed within Base Transceiver Stations (BTSs)), and finally core, and cloud. Furthermore, each of these network segments are deployed/developed/hosted by different InPs, operators, manufacturers, SPs, etc. (represented by colored boxes in Fig. 2), making a 5G network resourceful but highly heterogeneous ecosystem. Besides different network segments starting from user domain all the way to the cloud, 5G takes advantage of different communication technologies

such as wireless and optical, as shown in specific network segments. Finally, it includes a wide variety of IoT devices that are key components in Industry 4.0 or Smart cities domains. Hence, a vast end-to-end perspective of 5G network is a cohesion of wireless and optical technologies, connecting IoT and non-IoT devices from user domain to the core and cloud, taking advantage of edge computing which aims at reducing the overall end-to-end latency by exposing resources to the network edge. Therefore, the end-to-end perspective in the context of resource sharing means that the design and the optimization of networks should be achieved by sharing a wide variety of resources, starting with users' domain, through RAN and edge towards core network and cloud. In this way, instead of having a full ownership of the specific network segment, all of the sharing actors make their pool of resources available for sharing.

In Fig. 2, we also use a comprehensible color code followed by explanatory boxes (e.g., Network operator 1, Infrastructure provider 2, Sharing Distributed and Heterogeneous resources in end-to-end 5G, etc.), clearly differentiating scenarios:

- in which all resources from user domain to the cloud, including wireless, optical, and IoT, are shared (green color in Fig. 2),
- and those where different network segments (i.e., edge network, access network, etc.) are supplied, maintained, and/or owned by different parties (e.g., network operators, infrastructure providers, equipment manufacturers, etc.) (other colors in Fig. 2).

Sharing provides tremendous benefits regardless of the environment in which it is applied, and its benefits are especially known in economics. In the sharing economy, the participants (i.e., sharing actors), share and use valuable items like cars or houses without the need for exclusive ownership [1]. At the same time, sharing creates opportunities for others to extract value from idle possessions or talents [3].

In the emerging sharing cities paradigm [4] - including increasingly popular smart cities - goods such as spaces or venues for collaboration, parking spots, and publicly owned handy bikes are shared. For example, the National Industrial Symbiosis Program (NISP) is a model to optimize use of resources in commercial business and move toward circular economy through sharing. In an eight year period, in Europe and around the world, NISP has helped businesses to: 1) save £1 billion in costs, 2) generate £993 million in additional sales, 3) safeguard over 10,000 jobs, 4) recover and reuse 38 million tons of material, 5) reduce 39 million tons of industrial carbon emissions, and 6) save 71 million tons of industrial water [1].

Another interesting example comes from the microscopic world, in which the same species of bacteria compete for the same resources when living in homogeneous communities. Such competition results in their decreased growth. However, when they change their feeding habits to share the resources more effectively by coexisting in mixed communities with other species and by reusing each other's waste products, the operation and well-being of the whole heterogeneous community is greatly improved [5]. With the introduction of 5G now is the right time to look up to such fascinating examples [6], and to exploit the resource sharing potential of communications networks.

Complementary to sharing of goods, network sharing is a paradigm which embraces a set of strategies that enable network operators to use their resources jointly in order to reach their common goal: to provide and guarantee user services while achieving energy and cost reduction [7]. As an illustration of the benefits of such sharing, Bousia *et al.* [7] report considerable improvement (increased energy efficiency by 174% and cost reduction by 86%), when the number of operators who share their underutilized network elements increases from four to six.

Moving our focus to the digital world, there is a prediction in Cisco Forecast and Trends paper [8] that an ever-increasing number of devices that are wirelessly connected to the Internet (smart-phones, tablets, IoT devices, etc.), will reach approximately 12.3 billion by 2023. As a consequence, such growth unavoidably leads to tremendous increase in service requests for applications like video, interactive gaming, Machine-to-Machine (M2M) communications, etc. In the 5G community these applications fall into the three main areas: mas-

sive Machine Type Communication (mMTC), ultra-Reliable Low Latency Communication (uRLLC), and enhanced Mobile Broadband (eMMB) [9]. Applications falling into these categories impose highly specific and stringent Quality of Service (QoS) requirements. For the network operators, these QoS requirements are then tied to provisioning of different network resources. Consequently, the excessive growth in service requests becomes a heavy technological and economic burden for the operators.

From the purely technical perspective, once the service request arrives, the pool of heterogeneous and distributed resources is invoked. Then, selection and chaining of adequate portions of the network resources is performed. These resources are then provided to the service which initiated the request. The resources are carefully selected from the resource pool and customized to the service request. However, these resources are not localized within a centralized pool. In reality the resources are widely (geographically) distributed across the entire network (Fig. 1, and Fig. 2). The conflict between widely disseminated network infrastructure and its strict ownership boundaries clearly and urgently presses to create and implement new sharing models for the network resources. Several important points should be emphasized:

- 1) In such dynamic and challenging environment as 5G, it is essential to enable coexistence of diverse existing services and facilitate easy creation of new ones [10].
- 2) When all network operators have static amount of dedicated resources, a significant percentage of those resources can go to waste if the excess is not shared among the operators [10]. Hence, once the heterogeneous network resources are not needed, they should be released for sharing and temporarily given to other entities.
- 3) Operators should rethink their traditional business models, evolving from owning all the resources (from very intangible items like spectrum to physically tangible ones like electronic equipment, radio masts, and towers) to sharing of these resources [11]. However, a corresponding model made of rules for sharing (such as the operators' business model) should be established and used wherever and whenever sharing is an option. While formal business models are out of scope of our work, we want to provide the research community with an extensive overview and knowledge base of resource sharing that will enable future dynamic network environments. The importance of the aforementioned approach is also emphasized in Fig. 3, where the red-framed Section IV-A elaborates the comprehensive sharing model and its features, with a specific focus on the technical sharing model in Section V.
- 4) The advent of emerging technologies, such as Software Defined Network (SDN), and Network Function Virtualization (NFV) provide momentum for new design principles toward software-defined 5G networks that are expected to facilitate resource sharing, and resource management in general. The aforementioned is viable since virtualization is a technique that abstracts

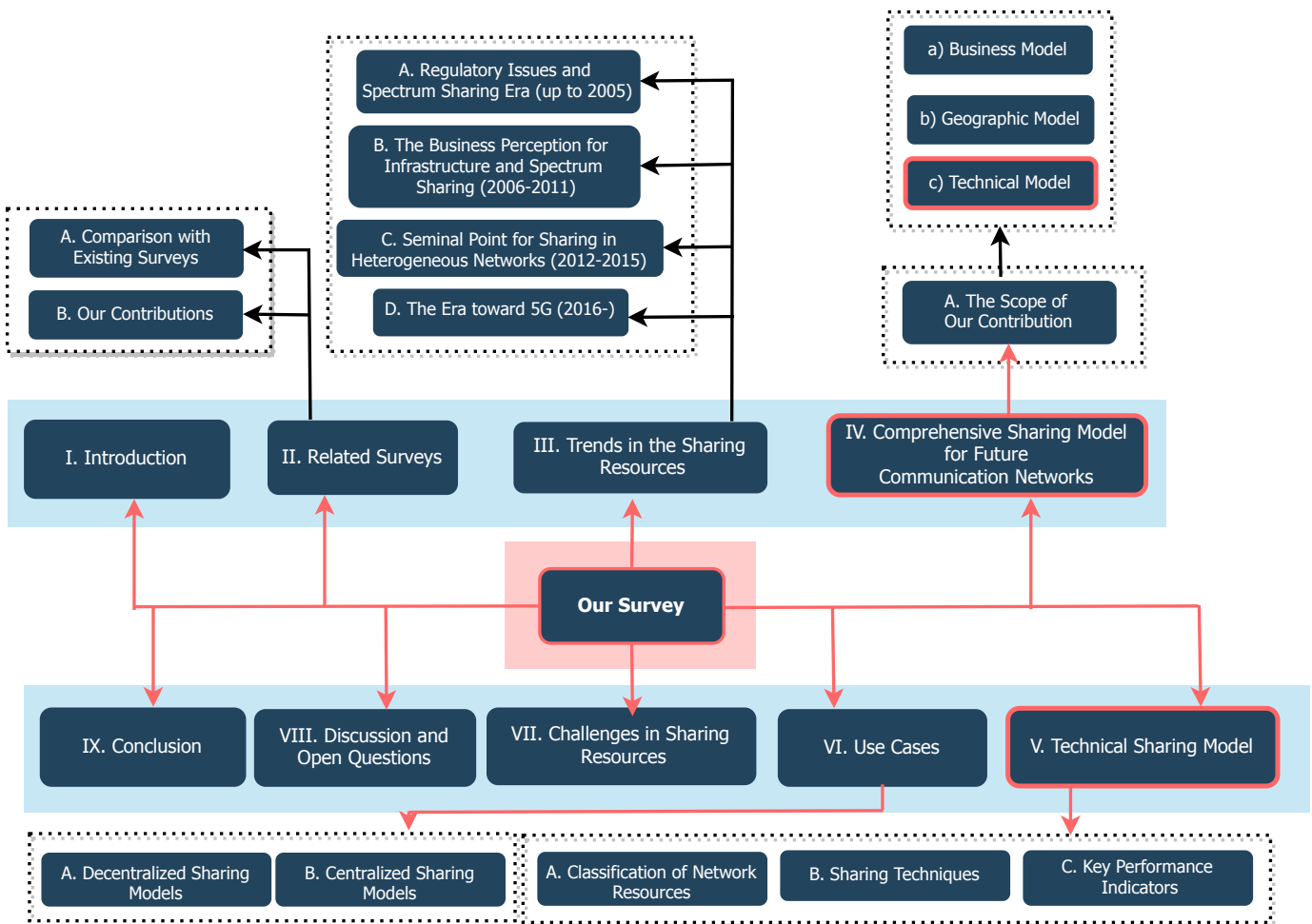


Fig. 3: Organization of This Paper

network resources, making them independent from the underlying physical infrastructure. On the other hand, SDN simplifies resource management by decoupling the control and data, positioning them into two distinct planes via logically centralizing network intelligence. As both SDN and virtualization are recognized as crucial enablers for network sharing, we elaborate on their impact on resource sharing in Section V-B.

Observing how resource sharing has evolved over time, one can recognize the transition from only hardware-based sharing to overall softwarization, which is discussed in greater detail in Section III. This specific transition from hardware-based to software-based sharing evolved into different models that at first identify and distinguish all shareable resources, and then offer them for sharing. Our perspective on this shift toward softwarization will pave the way for new contributions in diverse research domains, such as dynamic network configurations and slicing, new service creation and delivery, and techno-economics.

The overall organization of this paper is presented in Fig. 3, which clearly shows the structure of the sections, briefly announcing the content related to each of them. Within Section II, we present related work by comparing our views to other related surveys. Then, based on that comparison, we

specify the contributions which our survey provides to the research community. Importantly, Sections III and IV address resource sharing from two different viewpoints: one showing the evolution of sharing over time, and another presenting dimensions of the sharing model that have to be carefully considered and designed prior to sharing. In particular, the trends in resource sharing over the period of the last 20 years are discussed in Section III. Section IV defines the position of the sharing paradigms in a generalized end-to-end FCN architecture, providing an in-depth taxonomy of this area. The taxonomy brings relevant features of sharing models into the focus, pointing at all the dimensions that have to be carefully designed and synchronized in order to create more efficient FCNs. It presents a hierarchical view of the issues and solutions, per model: business, geographic, and technical; and per layer: infrastructure, orchestration, and service. In Section VI, we present specific use cases which exemplify the resource sharing. After this, section VII reports the main research challenges that need to be taken into consideration during careful design of any sharing model. A baseline for open research questions and the following discussion is presented in Section VIII. Finally, Section IX concludes the paper. In addition, we acknowledge that due to the complexity of the topic, which resulted in many acronyms throughout the paper,

we guide the reader to the annex with the list of all acronyms at the end of the manuscript (pages 31, and 32).

II. RELATED SURVEYS

In this section, we present an analysis of the existing surveys available in the literature addressing sharing-related topics. Moreover, we highlight the new and complimentary contributions that our survey brings to the research community. Fig. 4 provides our insight into the classification of existing surveys on sharing for next generation communication networks. The figure illustrates lack of an overall end-to-end approach in the research community. The analyzed work only considers specific parts of the network infrastructure, such as spectrum sharing in wireless networks.

A. Comparison with Existing Surveys

This section provides insight into current research through the analysis of existing survey papers on the topic of sharing resources in end-to-end next generation communication networks (Fig. 4). Our approach takes into account a challenging end-to-end overview of FCNs, considering surveys in both wireless and optical domains, and including IoT, edge, and cloud.

a) Sharing of Radio and Optical Spectrum: According to prior surveys [12–20], sharing of resources in communication networks usually entails spectrum as the bottleneck commodity with the highest demand and the smallest availability. The imminent shortage of this type of resource, coupled with the increasing demand for higher capacity, is a strong motivation for researchers to study practical solutions for efficient spectrum sharing. During the last 15 years, and more recently with anticipated deployment of 5G wireless networks [12], the interest for spectrum sharing has grown even larger, resulting in a vast number of publications investigating and presenting new sharing solutions for this intangible resource.

As Fig. 4 shows, under the roof of the wireless networks and depending on the spectrum ownership, the existing surveys address spectrum sharing in: i) *licensed* bands, ii) *unlicensed* bands, and iii) *both*. Tehrani *et al.* [12] study the main concepts of dynamic spectrum sharing and different sharing scenarios, with the focus on practical solutions which efficiently utilize scarce licensed bands in a shared manner. They also recognize and present the major challenges related to sharing in licensed parts of the wireless spectrum. With respect to unlicensed bands, the Cognitive Radio (CR) has received the prominent attention [13–15,17,20].

The CR paradigm addresses the issue of spectrum scarcity and underutilization by enabling a technique called Dynamic Spectrum Allocation (DSA), which allows users to opportunistically access unlicensed bands [13]. The most general classification of CR network paradigms is given by Goldsmith *et al.* [20] as follows: 1. *underlay*, 2. *overlay*, and 3. *interweave*, characterized by the rule cognitive users follow in their operation. Furthermore, Nair *et al.* [13] provide a comprehensive overview of the use of game theory as the enabler for DSA. A survey on full spectrum sharing in CR networks, but with main focus on its implementation in 5G networks,

is presented by Hu *et al.* in [14]. The authors discuss further expansion of the spectrum range (from 1GHz to 100GHz), motivated by the demand to meet all the critical service requirements in 5G networks, such as wider coverage, massive capacity, massive connectivity, and low latency. Similarly to the approach adopted by Nair *et al.* in [13], the problems with spectrum allocation are discussed under the game theory umbrella in [14]. Beside other spectrum sharing schemes, such as: Device to Device (D2D) spectrum sharing, In-Band Full Duplex (IBFD), Non-Orthogonal Multiple Access (NOMA), LTE-Unlicensed (LTE-U)-based spectrum sharing, Zhang *et al.* also present CR as an intelligence layer on top of the aforementioned approaches, first in a specific IoT context in [15] and then as an advanced technique for spectrum sharing in 5G networks in [17].

When considering spectrum sharing across both bands, it can be observed that these are typically utilized by a diverse pool of wireless devices [16,17], rather than single-technology devices. Their difference in terms of technologies and traffic requirements implies interaction across technologies, which is gaining momentum [16]. Voicu *et al.* address spectrum sharing mechanisms for wireless inter-technology coexistence (e.g., WiFi/Long-Term Evolution (LTE), WiFi/Bluetooth, LTE/D2D or Narrowband Internet of Things (NB-IoT)), surveying both technical and non-technical aspects. As non-technical aspects that are the most influential on the design of the spectrum sharing mechanisms, they identify the business models and the social practices. The authors observe that sometimes the best technical solutions for sharing may not be adopted due to non-technical concerns like the lack of agreement among sharing participants [16]. For instance, the primary spectrum owners must be incentivized to yield exclusive spectrum rights [21,22].

Regarding the heterogeneity of 5G networks, Zhang *et al.* [17] present the idea to study multiple spectrum sharing techniques jointly, in order to provide a global spectrum sharing approach which encompasses multiple radio technologies. In order to better discern the concept and all the practicalities of spectrum sharing in upcoming 5G networks, a profound understanding of spectrum sharing in LTE is a must. To that goal, Ye *et al.* [18] present the overview of LTE spectrum sharing techniques, with the focus on three spectrum segments: i) TV white space channels, ii) frequently unused service-dedicated 3.5GHz, and iii) 5GHz unlicensed band [18]. Finally, Ahmad *et al.* present a thorough review of recent advances in spectrum sharing in 5G networks [23]. *However, all of the above-mentioned surveys solely tackle the wireless domain.*

In optical communications networks, spectrum is by itself not a scarce resource, as each individual fiber strand can carry several THz of capacity. In addition, optical transmissions networks are typically closed systems in two ways. Firstly there is usually only one operator running services over each fiber pair; secondly, optical systems are mostly deployed using technology from a single vendor. However, recently the trend is changing, as the possibility to open up an optical system to operate with components from more than one vendor is being investigated across several industry-drive

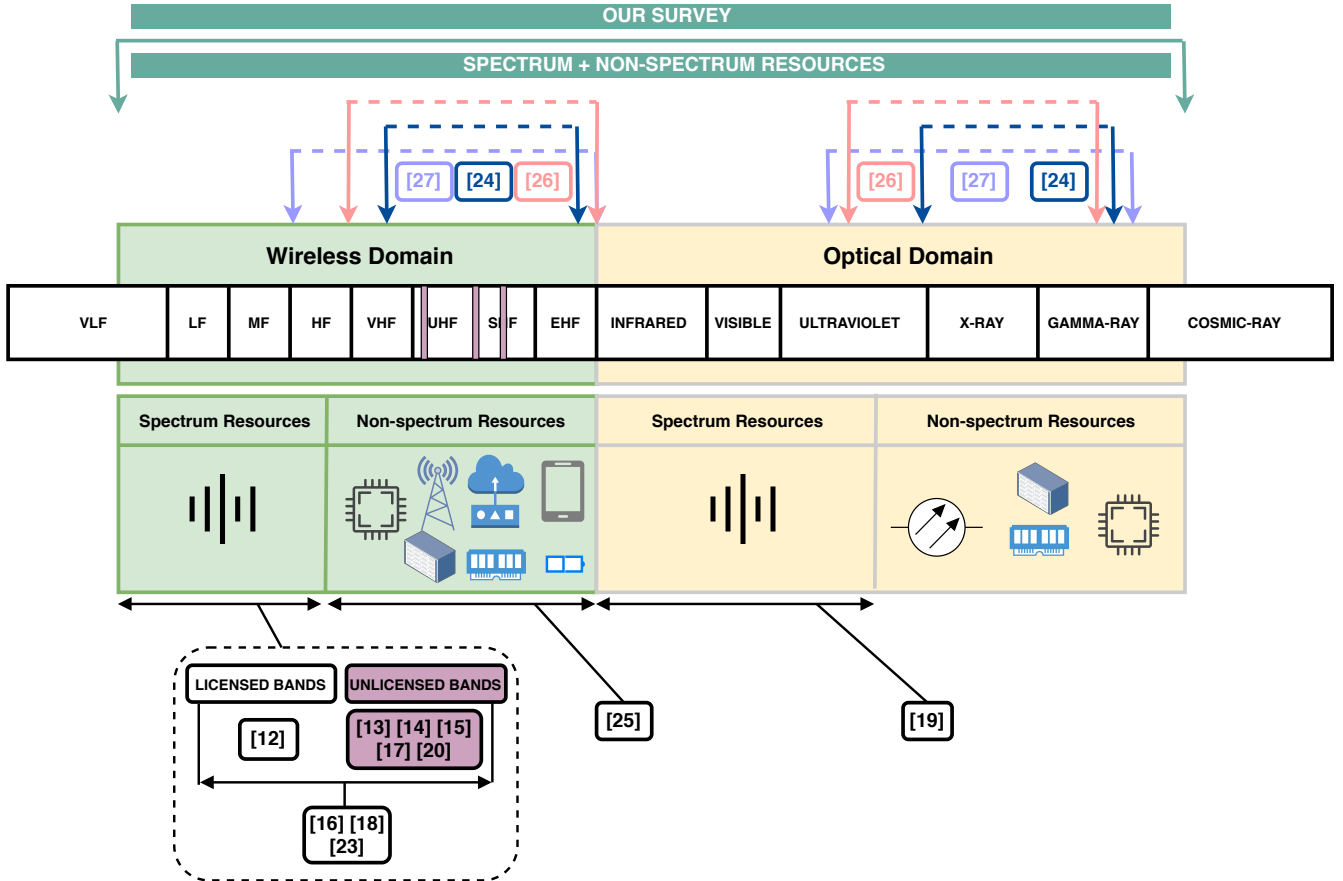


Fig. 4: Overview of existing related surveys

consortia (most notably, the Optical Networking Foundation (ONF), the Open ROADM Multi-Source Agreement, which defines interoperability specifications for Reconfigurable Optical Add/Drop Multiplexers (ROADM), and the Telecom Infra Project (TIP)). Considering also that using additional optical fibre is expensive, especially in long-haul links that require the addition of several in-line amplifiers, the concept of fiber spectrum sharing has been recently explored, especially with the rise of Elastic Optical Networks (EONs). Spectrum management techniques for EONs were recently addressed in [19] by Talebi *et al.*, where they show, for example, the importance of efficient spectrum sharing across backup optical paths.

b) Sharing of Resources Other than Spectrum: Virtualization is recognized as a technique that enables efficient resource sharing among different operators, services, and applications [24–26]. According to Kliks *et al.* [24], the broad idea of virtualization is that it enables separation of services or service requests from the actual resources. Considering non-spectrum resources (although confined only to the wireless domain) Zahoor and Mir [25] present the survey on virtualization in the context of IoT resource management, providing the insight into how IoT infrastructure can be virtualized in order to be shared. Here we elaborate on several publications, which study both wireless and optical domains. For instance, Bianzino *et al.* [26] depict the key paradigms, including virtualization of the FCN infrastructure, which can

be exploited to reach network "greening" (i.e., reduction of energy consumption). Although Bianzino *et al.* [26] mainly consider the wired domain, they also outline insights on how to deploy the paradigms they introduce in the wireless domain. Mamushiane *et al.* in [27] offer an overview of the concept of SDNs as an enabler of sharing, together with an assessment of its impact on Capital Expenditure (CapEx) and Operational Expenditure (OpEx). They tackle both the optical and the wireless domain, and with respect to the optical domain they investigate how sharing of the active backhaul through softwarization reduces both costs.

Finally, Kliks *et al.* [24] provide a comprehensive study of all the perspectives for resource sharing in 5G networks, considering both the wired and the wireless domains. Regardless of the fact that the above reference is not a survey, but rather a literature overview, it is one of the rare attempts to examine resource sharing in 5G networks from a broader perspective. Hence, it presents an overview of the concepts for 5G implementation in a flexible and programmable manner through virtualization. Most notably, the authors provide a generalized architecture for FCN, but only in the context of sharing resources in the wireless domain. We adopt and expand their architecture and try to exploit it in a broader sense by surveying network sharing from an end-to-end perspective, and in both wireless and optical domains, while also including IoT, edge and cloud resources.

B. Our Contributions

From the previous section we conclude that the existing surveys do not cover sharing of network resources from the end-to-end standpoint. In particular, Fig. 4 depicts a quite unbalanced scenario, where the majority of the surveys solely tackle spectrum sharing in wireless networks. To the best of our knowledge, this work is the first attempt to research and survey network sharing in an end-to-end manner, thereby considering heterogeneous network resource sharing that crosses both the wireless and optical network domains, and extends to IoT, edge, and cloud paradigms, which altogether coexist and define the 5G network. The impact of our survey is in providing an extensive taxonomy on the sharing of heterogeneous resources in FCN with a viewpoint that goes beyond the boundaries between networks and operator domains. We examine the sharing potential of all resources from users' domain, RAN, edge, and core network. Gathering information on how resources of these separate domains used to be shared, and up to what extent, as well as determining the similarities between sharing models, can help us understand the true potentials of each technology and domain.

Thus, the overall impact of this survey consists of the following contributions:

- 1) Helping the research community to identify up to what extent can network resources be shared, answering the questions on what could be and what should be shared.
- 2) Presenting the existing use cases and techniques used to enable sharing of distributed and heterogeneous resources.
- 3) Recognizing and presenting sharing challenges and requirements arising from the highly dynamic, heterogeneous, and highly diverse 5G environment.
- 4) Providing a taxonomy which will help researchers design new sharing models, by thoroughly investigating current network sharing challenges.

Another contribution of this survey is that it will provide a solid reference for researchers willing to address the following topics:

- Creating a flexible environment as enabler for new diverse services for the end users.
- Implementing comprehensive sharing model in real-life scenarios, which includes collaboration with group members working on NFV and softwarization.
- Developing techno-economic models for sharing.
- Extending and enhancing existing sharing approaches by leveraging the Artificial Intelligence (AI) umbrella.

III. TRENDS IN THE SHARING RESOURCES

This section describes how the concept of resource sharing has evolved over time and classifies publications both by time and topic, which we summarize in Fig. 5. Studying these topics, we identified that sharing resources in wireless and optical domain [28,29] have always been considered separately, despite the fact that at times they used similar techniques [30–32]. One of the most important tendencies, not only in resource sharing but also in computing, can be recognized from the illustrated timeline. Namely, the tendency

to share physical resources has changed over time, following the emerging popularity of ubiquitous techniques such as virtualization and software defined networking. Thus, it can be clearly observed that in the early 2000s and even before the trend was to share physical resources (i.e., hardware), while recent trend is to share logical resources which are the result of softwarization/abstraction of physical resources. If the tendencies related to the specific types of resources are taken into consideration, one can primarily notice that spectrum has always been considered a bottleneck. Supported by the fact that spectrum is an enabler of wireless communication, it is not surprising that it still receives considerable attention among researchers [33–36]. The following sections go into detail of the different phases, shown in Fig. 5, taking into account a vast pool of heterogeneous and distributed network resources. In this section we briefly introduce these trends, which are then further elaborated in subsequent sections, where we describe use cases, sharing techniques, and more specific challenges.

A. Regulatory Issues and Spectrum Sharing Era (up to 2005)

One of the first attempts to approach spectrum sharing is presented by Gould and Kelleher [37], addressing the issue of frequency sharing between broadcasting satellites and other radio communications systems. This approach is followed by Prosch's in [38], which showed the possibility to increase spectrum efficiency by 30% when the Very High Frequency (VHF) spectrum band (30-300MHz) is shared between the FM radio band (88-108MHz) and the digital audio broadcast. Furthermore, an interesting analysis of interference caused by multiple uncoordinated low-power transmitters for wireless network access towards fixed Point-to-Point (P2P) microwave receivers is given by Varma *et al.* in [39]. They determined and discussed the factors which directly impact the density of such uncoordinated users.

However, spectrum sharing was not emerging solely in the wireless domain, but also in optical, where for example Tridandapani and Mukherjee [40] examined channel sharing techniques in multi-hop optical networks. Another example of spectrum sharing is provided by Foschini in [41], which investigated the possibility of sharing optical bands among large numbers of high-speed users.

In early 2000, Papadimitratos *et al.* [42] proposed an overlaid ad-hoc secondary network to share underutilized bandwidth resources in the primary cellular system. Here the authors also defined the Medium Access Control (MAC) protocol which enabled such scenario.

In this early phase, before 2006, a step further from spectrum sharing is provided by Ali in [28], who recognized optical node device as the dominant cost factor in overall backhaul network. At the same time, other researchers were exploring regulatory issues and the necessity for suitable business models. Beckman and Smith [43] identified regulatory issues as the crucial part for their feasibility study of resource sharing. Moreover, the importance of adequate business models for shared wireless networks is emphasized by Hultell *et al.* [44]. They recognized the need for a technical sharing framework, which enables sharing between multiple

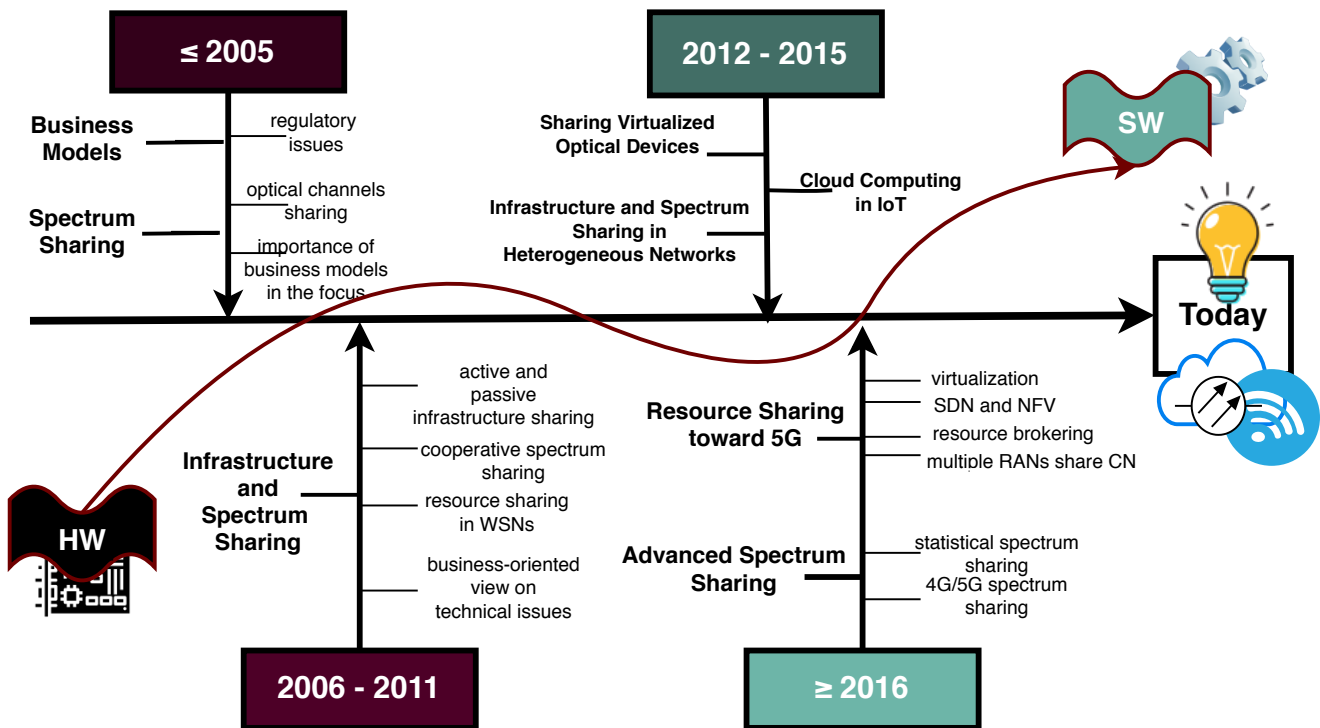


Fig. 5: Timeline of Resource Sharing; Sharing Trends

operators and service providers with strong focus on Service Level Agreements (SLAs). The end of this era ceases with a critical review of controversial regulation rules provided by the U.S. Federal Communication Commission (FCC) [45], regarding the regulatory framework for sharing of landline access. In his review, Jones [46] provides a criticism towards regulations that fixed the price for access to the incumbents' switching facilities only for local voice service, while the price for accessing broadband equipment was left negotiable.

B. The Business Perception for Infrastructure and Spectrum Sharing (2006-2011)

At the beginning of the next period in our resource sharing timeline, CR started gaining momentum as a new Software Defined Radio (SDR) approach to radio spectrum sharing. The fixed spectrum assignment policies unavoidably led to unacceptably low spectrum utilization [47,48]. With this in mind, Akyildiz *et al.* [47] presented one of the first concise overviews of all the characteristics of the CR concept and enabling technologies. Later, Akyildiz *et al.* surveyed the topic of spectrum management in CR networks, identifying developments and open research questions with focus on CR deployment without the need for modifying existing networks (i.e., primary spectrum owners) [49].

In that period, from 2006 to 2011, CR along with other enabling technologies like the software radio, spectrum sensing and mesh networks, was considered capable to facilitate new forms of spectrum sharing that could considerably improve spectral efficiency and alleviate scarcity [50]. However, any new technology would have no or little impact if inconsistent with spectrum policies, regardless of the opportunities and

benefits it could bring. Accordingly, Peha in [50] discussed regulatory policies as the ultimate enablers for these emerging technologies, which can further facilitate spectrum sharing and increase spectrum utilization.

Furthermore, the importance of the CR paradigm was corroborated by many other papers, related to dynamic spectrum leasing [51], cooperative spectrum sharing [52], and opportunistic spectrum sharing in cognitive Multiple Input Multiple Output (MIMO) wireless networks [53]. In [54], while pointing at the opportunities and challenges in sharing the mostly underutilized government spectrum with private users, Marcus claimed again that research in this period was highly dependent on business and regulatory domains. Other business-oriented perspectives are provided by Frisanco *et al.* [55] and Meddour *et al.* in [56], but for infrastructure sharing. The authors studied both technical and business-related challenges in infrastructure sharing within the multi-vendor landscape of mobile communication networks.

One of the first attempts to apply sharing in Wireless Sensor Network (WSN) is presented by del Cid *et al.* in [57], aiming to resolve issues on concurrent use of WSN services, which leads to excessive contention of sensor node's resources for radio channel access. Also, Shi *et al.* in [33] studied resource management in IoT networks, from the perspective of scarce and non-renewable spectrum. Regarding the optical domain, an example of sharing is adopted and presented by Darcie *et al.* in [58]. They explored wavelength sharing on Passive Optical Networks (PONs) through the Wavelength Division Multiplexing (WDM). This approach enables variable degrees of wavelength sharing by combining different wavelengths from multiple PONs.

C. Seminal Point for Sharing in Heterogeneous Networks (2012-2015)

The period from 2012 to 2015 has a significant impact on today's research, since it includes studies of sharing of heterogeneous networks, providing a crucial asset for further research. Many technologies which are widely utilized for sharing toward FCNs were developed during this phase. We identify this period in our timeline (Fig. 5), as a potential cornerstone for exploiting sharing of many different types of resources, including spectrum. Accordingly, Kibilda and DaSilva in [59] introduced the so-called *Networks without Borders*, as a mode of sharing infrastructure among both homogeneous and heterogeneous networks. Further advances in spectrum sharing are presented by Jorswieck *et al.* [60] and Park *et al.* [61]. Despite all the technology advances which reflect positive feedback from spectrum sharing [60], Park *et al.* point at severe security and privacy problems that have arisen as a consequence of sharing. Focusing on the framework of CR, they accentuated the importance of these problems, reviewing some of the critical security and privacy threats that impact spectrum sharing and its outcomes. These issues are classified into two categories: threats to sensing-driven spectrum sharing (such as PHY-layer threats, MAC-layer threats, and cross-layer threats) and threats to database-driven spectrum sharing (i.e., database interference attacks and threats to database access protocols) [61].

In spite of the ubiquitous popularity of virtualization techniques and SDN in today's wireless networks, the first attempts to virtualize network resources occurred made in the fixed network domain. For instance, De Leenheer *et al.* [62] introduced sharing bandwidth among virtual optical networks grouped into clusters, followed by Vilalta *et al.* who introduced the concept of a virtual optical network resource broker [63]. Along with the popularity of virtualization techniques, the key enabling technique for the next generation of optical networks - Software Defined Optics (SDO) was introduced in [64,65]. Wang *et al.* in [66], as well as Khandaker *et al.* in [64,65], studied the concept of statistical spectrum sharing in the optical domain, enabling switching between base and peak rates through SDO. Many other researchers recognized the potentials in sharing optical devices [66–68] and in cooperative spectrum sharing [69,70].

As the final point in this section, we recognize the trends related to the IoT ecosystem, which belongs to the heterogeneous communication networks area. Heterogeneity of resources is not specific to IoT, but it appears to be most challenging in this domain due to the wide range of different devices, network connectivity options, communication protocols, communication methods, and so on. Hence, Silva *et al.* presented their attempt to bridge the heterogeneity among devices and to take advantage of it by symbiotic sharing between constrained IoT devices and unconstrained cellular devices [71]. At the same time, Kliem and Kao [72] applied the cloud computing paradigm to the management and sharing of resources in IoT, providing system design guidelines for specific use cases.

D. The Era toward 5G (2016-)

5G networks are supposed to offer new spectrum in the millimeter wave (mmWave) bands [73,74], which can potentially move focus away from spectrum sharing. However, the deployment of services on such high frequencies has to be studied with attention, especially because of several open challenges. In accordance to that, Wan *et al.* [75], Al-Khatib *et al.* [76], and Shah *et al.* [77] briefly discuss spectrum sharing towards 5G, presenting the idea to reuse existing LTE spectrum together with new frequency bands used by 5G New Radio (NR).

In the period from 2016 onwards, we find many publications focusing on virtualization of resources [78] empowered by SDN and network programmability [79] (Fig. 5). This statement is supported by various references in both wireless and optical domains, which discuss sharing opportunities arising from virtualization and SDN.

As one of the examples from the wireless domain, in [30] Zhang presents a wireless virtualization scheme, which offers abstraction and slicing as the base for their virtual network slicing/sharing framework. In particular, network slicing is a network concept that represents the whole network as a set of complete logical virtual networks, i.e., network slices, based on the physical shared infrastructure that is allocated to meet QoS demands [30,80–82]. Extracting the potential from recent advances in SDR, SDN, and NFV, InPs can create virtual networks customized to the specific QoS requirements for different tenants, deploying application-driven network slicing [83]. In their work, Han *et al.* [83] propose a system for orchestrating resources and services in heterogeneous networks that leverage SDN-supported network virtualization, and NFV-based Multi-Access Edge Computing (MEC) to realize application-driven end-to-end slicing. Providing a programmable SDN switch for flexible virtualization of radio resources by creating/removing virtual WiFi access points with dynamic bandwidth allocation, the work Han *et al.* presented in [83] can serve as a guideline for practices in radio resource sharing, enabled by network virtualization. Furthermore, Rawat [84] has introduced the concept of wireless virtualization as a technology that enables infrastructure sharing to multiple MVNOs, being considered as the best alternative to cognitive radio networks since it improves spectrum utilization efficiency, wireless network capacity, and coverage, with a special focus on wireless security (discussed in Sec. VII). Thus, the sharing framework presented in [84] enables moving/switching users from one virtual network to another using hand-off techniques while maintaining a secure connection.

Fog computing and MEC are promising network paradigms that bring cloud resources closer to the end-users, i.e., to the network edge [84,85], in order to decrease the end-to-end latency. Altogether with NFV and SDN, edge computing is gaining significant attention recently, and represent an inevitable component of 5G networks. Therefore, an interesting sharing scheme where fog nodes share spare edge resources to help pre-process raw data of applications hosted in the cloud is presented in [85]. Under the decision control from an SDN

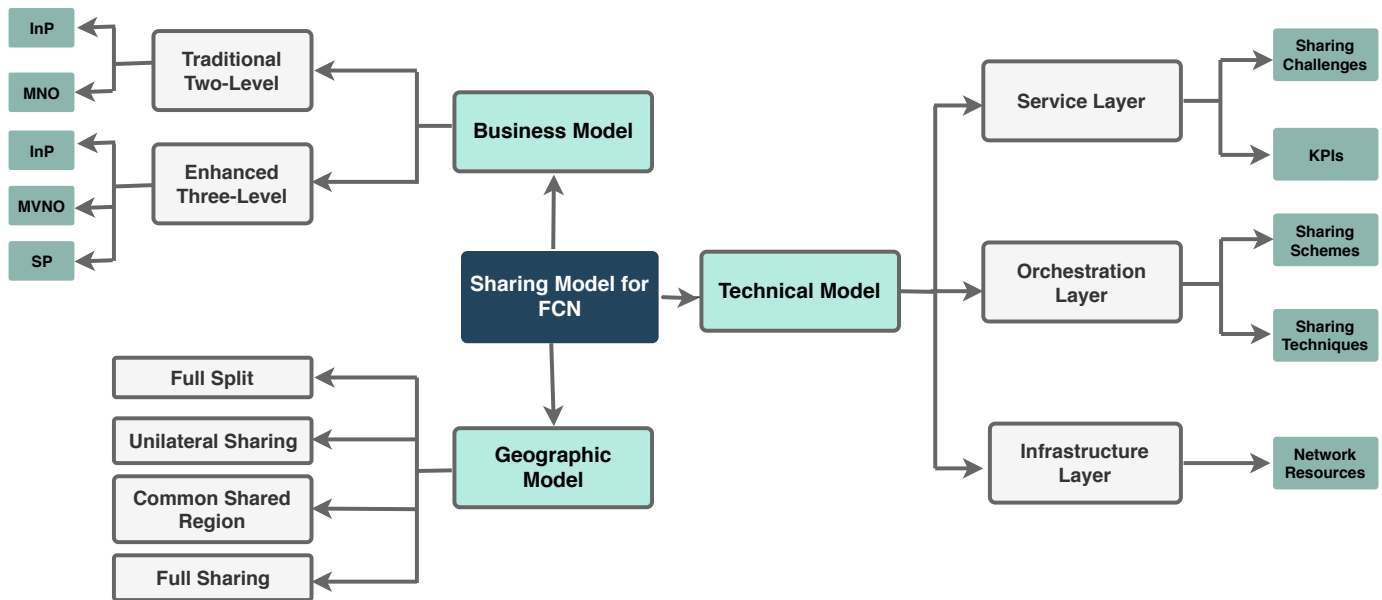


Fig. 6: Our comprehensive taxonomy for sharing of network resources in FCN

controller, the volume of application data for pre-processing at the network edge is dynamically adjusted by using resources from all fog nodes.

In parallel, Afraz *et al.* [32] discuss how PON virtualization techniques introduced in [86,87], together with SDN, impact the optical domain in terms of enabling multi-tenancy. Also, the role of a resource broker from Zhang’s [30] and similar approaches used in the wireless domain, is replaced by a global orchestrator which orchestrates radio and transport resources jointly in Centralized Radio Access Network (C-RAN) using optical backhaul and fronthaul. The optical C-RAN is a centralized RAN with an optical transport whose wavelength resources can be dynamically shared among multiple BTSs [88]. Accordingly, significant contributions to the research community are provided by Marques *et al.*, Domincini *et al.*, Alvarez *et al.*, and Slyne *et al.* since their work represents the integration of wireless and optical domain, enabled by SDN and virtualization of different wireless, optical, and edge/cloud resources [89–92].

In addition to the huge increase in popularity of SDN in both wireless and optical domains, Municio *et al.* [93] present the “Whisper” architecture, as an enabler for SDN-based IoT networks. The Whisper is a centralized SDN controller of a network which remotely controls nodes’ forwarding and cell allocation. In line with the increase in IoT deployment and in the overall usage of IoT devices, sharing of IoT resources has become an immensely popular research topic in this period.

For instance, Kouvelas *et al.* in [94] introduced an interesting theoretical foundation for resource sharing among IoT devices by exploiting graph theory. Furthermore, Yildirim and Tatar [95] present the two ways of sharing resources in WSNs: WSN virtualization and Middleware Based Server Systems (MBSSs), and discuss all advantages and disadvantages of both. Importantly, Vo *et al.* [96] spot the huge potential in integrating WSN into 5G, providing interesting point of views.

In line with the popularity of 5G networks, significant

research on edge and cloud computing is continuously being conducted. According to Bolivar *et al.* [97], the scarcity of network resources at the edge is severe, despite the benefits brought by edge computing. Thus, the amount of network resources is notably limited and efficient resource utilization is necessary. As demonstrated by these examples, virtualization techniques and SDN have gained incredible momentum in the past few years, and we expect this to continue steadily in the future.

IV. COMPREHENSIVE SHARING MODEL FOR FUTURE COMMUNICATION NETWORKS

Having examined resource sharing from a time evolution perspective, now we provide a classification based on research topics. This will answer the questions of what can be shared, how, and why. In this section, we propose a comprehensive taxonomy, summarized in Fig. 6, which incorporates the commonly adopted general FCN architecture presented by Kliks *et al.* [24]. The taxonomy summarizes all the dimensions that have to be carefully designed and harmonized in order to create more efficient FCN. The first part of this section contains general overviews of sharing models for FCN, from technical, business, and geographic perspectives. The rest of the section further expands the resource sharing model from the point of view of infrastructure, orchestration, and service layers. Since a detailed review of the business and geographic models is beyond the scope of this survey, we provide only general information and point at the gaps which should be further addressed by research in these areas. The taxonomy presented in this section will help the readers identify what are the current gaps for sharing FCNs.

A. The Scope of our Contribution

Sharing of goods and means like heterogeneous network resources, goes beyond the technical tasks and assets. Questions

such as: who to share the resources with, how to share, under which conditions, to what extent and where, require further attention before approaching technical aspects of sharing. Following the early effort of Frisanco *et al.* [55] to explain the relevance of considering the business, and the geographic models altogether with the technical design, in Fig. 6 we propose an extended taxonomy which portrays the flow of our survey. Following the guidelines to implement sharing in an existing network elaborated by [55], our comprehensive sharing model comprises three mutually coupled and heavily dependent parts: business, geographic, and technical models. Once these three components are selected, it is necessary to deploy the network assets in an optimal way. The first choice is to select which existing geographic sites will survive and which will be decommissioned. Concurrently, locations for new sites must be selected. Secondly, the existing equipment and technologies must be consolidated for sharing.

a) Business Model: The business model describes the parties which are directly or indirectly involved in sharing, as well as the contractual relationships between them [55]. In a broader sense, it describes the rationale that governs and constrains the design of a technical sharing model. The sharing of heterogeneous resources is always enabled and performed by the technical model, but under the regulations, pre-defined rules, and criteria adopted by the corresponding business model. According to recent research [30], the resolution among network operators and their businesses, which agree on resource sharing based on virtualization techniques, can be obtained by two possible types of business models:

- *Two-level:* The traditional business model consists of the two entities: the MNO as a business entity which has subscribers but no infrastructure resources, and the InP as an entity with infrastructure resources but no subscribers. In such model, the virtualization tasks are assigned to InPs, which further manage those resources together with the MNO.
- *Three-level:* The enhanced business model consists of three entities: the MVNO, which now has the role of an intermediary between the InP and the SP; the SP which does not have enough infrastructure resources and thus has to lease and share resources from the InP's pool; and the InP.

Interestingly, Hultell *et al.* [44] envisioned that prospective business models should include network operators that can offer resources to specialized SPs many years before the development of above-presented three-level business model. Thus, another example of a potentially successful business model is the one which assigns the role of inter-connection provider to an arbitrary entity, which then supplies resources to SPs and MNOs [44]. Moreover, the idea to incorporate the Pay As You Go (PAYG) business model to enable sharing of resources that belong to IoT devices is presented by Kliem and Kao [72]. Such business model dictates resource pooling, which makes feasible the on-demand provisioning [72]. Concerning network slicing, in order to adequately address the requirements of managing different services and applications that are available within 5G network slices, Barakabitze *et al.* [80] list three

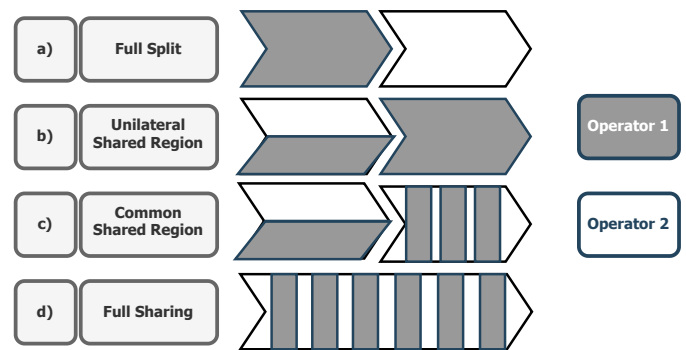


Fig. 7: The variants of the geographic model for infrastructure sharing

[55]: a) Full split, b) Unilateral shared region, c) Common shared region, and d) Full sharing.

possible business models for network slice commercialization: i) Business to Business (B2B), ii) Business to Consumers (B2C), and iii) Business to Business to Consumers (B2B2C). In the B2B model, resources are usually sold to enterprises by MNOs, while enterprises retain full control over their subscriptions. However, the B2C model allows customers to directly purchase resources upon their needs in an MNO-agnostic manner (i.e., the provision of communication services is generalized, and users have a neutral attitude towards the MNOs). For this reasons, B2C poses significant challenges to overcome different requirements of different MNOs. Finally, B2B2C includes an intermediary between MNOs and customers, i.e., network slice broker, that allows different verticals to lease resources from InPs in a dynamic manner [80].

Furthermore, Akhtar *et al.* [34] observe the non-existence of corresponding business models as one of the potential reasons for failure to implement spectrum sharing, justifying the huge importance of business models in any sharing scenario. In this fashion, network operators or any sharing entity are not provided with sufficient incentive to share spectrum. Lastly, as a potential research direction, Rebato *et al.* [73] envision introducing innovative business models for resource sharing to better quantify a potential economic impact. Accordingly, it is clear that the development of adequate business models should keep the pace with technical models in order to increase performance gains (i.e., Key Performance Indicators (KPIs)), anticipated from sharing resources.

b) Geographic Model: According to Frisanco *et al.* [55], the geographic model describes each operator's physical footprint in a nutshell. In order to enable sharing, certain locations, operator's domains, and preferences based on the geographic position have to be known and established. In particular, for the infrastructure sharing, [55] and [56] gather and sum up the sharing scenarios with regard to the operators' geographic footprint. According to the area each operator covers in a multi-tenant scenario, a geographic model might include: standalone, full split, unilateral shared region, common shared region, and full sharing. Based on the studies in [55] and [56], we illustrate each of these cases for the simple scenario with two network operators tasked to provide coverage in a geographic area (Fig. 7). Thus, Fig. 7 shows two separate

geographic areas which are covered either by one of the operators or by both of them. Respectively, the full split stands for only one operator, solely covering the whole area (Fig. 7 a)). Within the case of unilateral shared region, despite the presence of both operators, the geographic territory is split between them following certain regulations and without sharing, but with opportunities to establish mutual service agreement (Fig. 7 b)). Furthermore, if a certain operator has a full-coverage infrastructure and aims at leveraging it in order to gain additional revenues, then the unilateral sharing case would also apply. The small-scale operator is then allowed to enter the market without investing in infrastructure and suffering from risk related to small initial number of subscribers (e.g., large CapEx). On the other hand, if operators are of similar scale and, thus, want to operate jointly in a certain area, they can approach sharing of their resources in a common shared region (Fig. 7 c)). Finally, the full-sharing scenario is a theoretical base for deploying a technical model which can entail sharing heterogeneous resources in an end-to-end communication network [55], since it enables sharing of all resources between all network operators (Fig. 7 d)). The goal of this brief review of business and geographic models is to emphasize that the paradigm of resource sharing combines several dimensions, whose common denominator needs to be identified. The performance of a shared network is deeply affected by other factors included in the business and geographic models. The overall choice upon any of the technical, business or geographic models limits the degrees of freedom for selection of the two remaining models [55].

c) *Technical Model*: The taxonomy for the technical model can be seen in Fig. 6 and its elements are discussed in detail throughout the paper. Since the main focus of this survey is on the technical aspects of network sharing, we dedicate the entire next section V to it.

V. TECHNICAL SHARING MODEL

This section elaborates on the functional blocks drawn in the right hand side of Fig. 6, which consists of the following three branches: 1. Infrastructure Layer, 2. Orchestration Layer, and 3. Service Layer. The detailed structure of our technical model is shown in Fig. 8. First, the infrastructure layer consists of all shareable heterogeneous resources. Second, the orchestration layer consists of dedicated software platforms responsible not only for management, operation, and orchestration of heterogeneous resources in general as in [24], but also for sharing of those resources. Third, the service layer includes sharing challenges and KPIs, because the stakeholders, which are responsible for service management and delivery, must be aware of the benefits and the overall performance of resource sharing. Below, we first present the meticulous classification of network resources with respect to the network layers, followed by the most utilized sharing techniques, which are classified and described as the enablers of resource sharing. Finally, we point at widely used KPIs, which measure the success of the adopted and deployed sharing techniques.

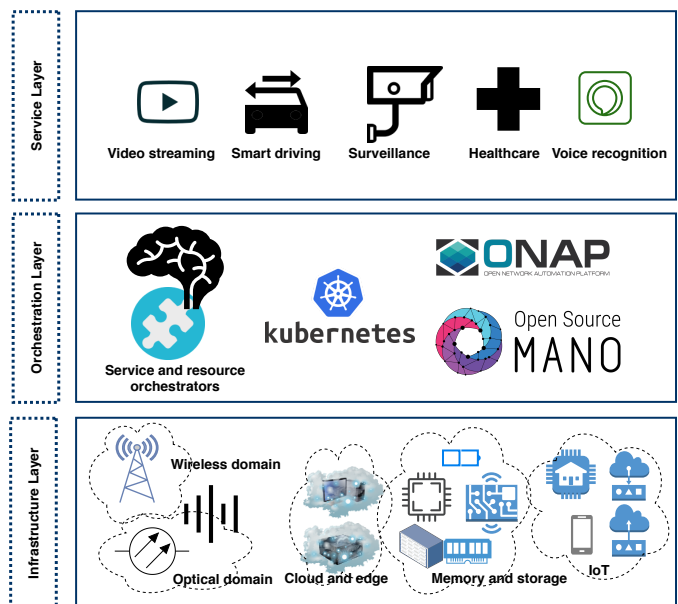


Fig. 8: The detailed structure of our technical model

A. Classification of Network Resources

In this section, we attempt to answer the question on which distributed and heterogeneous assets could and should be shared, in order to increase utilization of such shareable assets. Based on the studied literature, we provide the classification of resources and present it in Table I.

We categorize network resources with respect to the network layers introduced by Li *et al.* in [117]. The authors classify the network assets into four groups, depending on whether they belong to the physical layer, MAC, Internet Protocol (IP), or Virtual Private Network (VPN). Examples of classification criteria they use are isolation and customization among operators, efficient bandwidth utilization, etc. Rather than being requirements which must be fulfilled to enable sharing, we see these as the challenges, which we further discuss in Section VII. We collected all remaining types of resources which could not fit directly into any of the categories in a fourth group, labelled "Other".

Within each of these categories, we provide a further classification based on the nature of the shared resource, ranging from intangible (i.e., immaterial) resources, such as spectrum, to more tangible ones, such as network devices. From the perspective of Sarvanko *et al.* [48], immaterial resources are those that can be represented as abstract physical magnitudes. On the other hand, concrete resources are those such as real hardware, with processing capacity and ability to perform actions [48].

a) *Physical layer resources*: The first group in Table I classifies all physical layer resources. As one of the most pervasive, and yet the most influential asset, *spectrum* can be simply defined as a set of frequency bands with ability to enable electromagnetic signals to propagate.

The significance and the impact of radio spectrum is recognized by both researchers and network operators. For instance, in the work presented by Tridandapani and Mukherjee [40]

TABLE I: Classification of Network Resources

Network Resource Group	Type of Network Resource		Domain	Works		
Physical Layer	Spectrum	General resources (channels)	All*	[12–19,24,29,34–36,39,40,42,43,47,49–54] [60,61,64,65,69,70,73–75,75,76,81,98–109]		
		Path protection resources		[28,64–66,68,100,101,110,111]		
	Infrastructure	Transponders			[66]	
		OEO regenerators	shareable		[28,68]	
			idle		[28,68]	
		Line cards			[66]	
		Pure all-optical converters			[28,67]	
		OLT			[112]	
		ONU				
		ODN			[32]	
		Analog broadband repeaters				
		Optical fiber			[113]	
		User interface	Sensors			
			Actuators			[48,114]
		Sites				
	Towers					
	Air conditioning systems					
	Leased lines					
	Microwave links					
	BTS					
RNC						
SGSN						
MSC						
BNC						
eNodeB						
Energy				[55,114,116]		
Connectivity (Air interface)				[48]		
Built-in	Memory	Storage capacity	All*	[114,116]		
		Buffer space				
	Processing power			[48,71,116]		
Battery						
MAC Layer	Bandwidth					
IP Layer (VPN Level)	N/A					
Other	Network functions	Access	All*	[68,117,118]		
		Transportation				
		Core				
	Functionality	Signal regeneration				
		Wavelength Conversion				
	Functionality extender	Localization engines				
		Security accelerators				
Social resources	Individual (user)					
	Group (community)					
Computation burden						

* All comprises wireless, optical, IoT, edge and cloud domains.

sharing of spectrum is analyzed from the perspective of insufficient number of channels to orthogonalize all interconnecting network lines. In optical communications, most of the work on fiber spectrum sharing has focused on network redundancy, as link survivability is considered as one of the key concerns in network design, aiming to achieve fast service restorability against network failures [111]. When a failure such as fiber cut happens [100], back-up path should be available to restore the service. However, providing backup paths wastes resources, and thus they should be reused (i.e., shared) by services that can be preempted. In the context of EONs [64,65,101] Satkunarajah *et al.* [100] studied sharing of back-up resources in a pre-configured manner. This means that the backup paths are configured for sharing in advance. However, the multiple backup paths can share a given optical channel only if their corresponding primary routes are not expected to fail simultaneously [28] (i.e., they belong to the same Shared Risk Link (SRLG) group).

In the optical domain, statistical spectrum sharing can be implemented through the use of software-defined variable

bandwidth transponders which can support variable data rates (base and peak), leading to variable bandwidth occupation. Khandaker *et al.* [64,65] considered in their cost study the use of transponders and 3R regenerators capable of switching between multiple rates, while Wang *et al.* extended the idea further, by considering shareable regenerators and line cards [66]. In particular, Wang *et al.* [66] proposed a method that enables optical transceivers to change bandwidth dynamically without service interruption. Their aim is to provide a mechanism for optical channels to match the statistical behaviour of network traffic, so that wavelength can vary dynamically between a base and peak rate. Their simulation study, based on well known optical topologies, show that statistical wavelength sharing can provide up to 200% gain in network capacity.

Two other shareable optical devices are presented by Ali [28] and Pedrola *et al.* [67], namely Optical-Electrical-Optical (OEO) regenerators and the pure all-optical converters. OEO regenerators are necessary for dealing with optical transmission impairments and/or realization of wavelength conversion [28]. In the implementation, one set of OEOs is shareable,

while the another set is left idle [68]. The idle group is reserved for backup paths, as the other shareable devices are meant to be operational at any time. This type of resource sharing does not include multiple operators, and rather refers to sharing of costly components across multiple backup paths belonging to the same operator, enabling a reduction of capital costs for the operator. Nonetheless, sharing components increases the complexity of the network and control system, generating a trade-off between added complexity and reduction of total cost of network ownership, which needs to be studied.

Almost 10 years later, Pedrola *et al.* [67] tackled this issue of complexity increase due to sharing. They consider FCNs as networks that require high agility, for example implementing Sub-Wavelength Sharing (SWS), in order to cope with highly dynamic traffic patterns. They proposed an optical translucent network architecture, based on a mix of electrical regenerators and optical wavelength converters. The main issue is that sharing converters increases the complexity of the optical switches, which increases the number of optical gates required. The trade-off thus becomes one of relative costs between converters and optical gates. The outcome of their study highlight the conditions that need to be met in order for the sharing architecture to pay off: the cost of pure all-optical converters has to be at least two orders of magnitude higher than that of the optical gates, and similar or lower than the cost of 3R regenerators [67].

Moving towards optical access networks, Ruffini *et al.* [119] addressed sharing of optical devices in PONs. These networks are made up of: 1. Optical Line Terminals (OLTs), which are located in the Central Office (CO) of the InP, 2. Optical Network Units (ONUs), located at the user premises, and the 3. Optical Distribution Network (ODN) which consists of fiber cables and optical splitters deployed in the field. Their work, based on PON virtualization [120] enables multiple operators to independently schedule their capacity allocation. However, this creates a new issue, as virtual operators have no incentive to give away their unallocated capacity to their competitors. Thus they propose a novel mechanism [10] based on auctioning capacity between Virtual Network Operators (VNOs), thus restoring the sharing performance of PONs. In [121], they further extend their work to consider scenarios where the InP also operates as one of the VNOs, so that it cannot be considered a trusted third party. They thus reformulate their auction as a distributed operation and demonstrate its feasibility on a blockchain implementation based on the Hyperledger Fabric.

In the wireless context, infrastructure sharing is mainly divided into passive and active [24,55,78]. Example of devices that can be shared passively are the RAN components, such as BTS and eNodeB. Site sharing is recognized as favorable from the perspective of operators, due to the fact that lower overall number of occupied locations results not only in lower costs but also provides better environmental and aesthetic conditions [55]. Microwave links and leased lines, which usually form transmission networks between Base Station Controller (BSC) and BTS in 2G, and eNodeB and Radio Network Controller (RNC) in 3G and 4G, are considered as shareable and belong to the passive domain [55]. The RAN components such as

BTS, BSC, RNC, and eNodeB can be shared actively as well. Multiple virtual radio access network instances are implemented by splitting the RAN elements into logically independent units running in one single physical device [55,56]. In general, RAN virtualization supported by SDN provides isolation in terms of control plane functionalities for each sharing actor [80]. Due to the lack of practical SDN-based solutions for RAN sharing, Foukas *et al.* [122] developed a flexible and programmable SDN-supported RAN platform, i.e., SD-RAN FlexRAN. This platform offers southbound APIs for separating data and control planes, making the control plane programmable, technology-agnostic, and customizable to different sharing entities through the programmability of virtualized network functions. FlexRAN aims at facilitating resource sharing by exploiting the virtualization capabilities, which enable dynamic introduction of new MVNOs to the RAN, as well as on-demand customization of scheduling policies per each MVNO. Furthermore, Shantharama *et al.* [123] introduce LayBack, an SDN-based platform for extending sharing capabilities of RAN towards edge resource sharing. For the context specific to network slicing, additional SDN-based mechanisms for RAN virtualization are presented in [80,124–126].

Besides the RAN, the core network can also be shared, but to a limited extent. This is restricted due to the confidentiality and performance requirement of the operator, because sharing the core network would imply sharing servers and network functionalities that are critical for running the network services [56]. These core network functionalities often contain confidential information pertaining the operator's business operation, and thus has to be kept within the operator's boundaries, which limits the level of shareability. Upon advances in NFV and SDN, and their inseparability from FCNs, sharing of core network resources has gained momentum. In particular, Meddour *et al.* pose an important design constraint for core network sharing: they propose the idea of FCNs with separated control and data planes through use of SDN. With such data and control plane separation, they state that core network elements such as Home Location Register (HLR), Gateway Mobile Switching Center (GMSC), and Gateway GPRS Support Node (GGSN) remain separate in one operator's core network, while at the same time Serving GPRS Support Node (SGSN), RNC, and Visitor Location Register (VLR) are available for sharing. This enables sharing the data plane of the core FCN but not the control plane, enabling service differentiation while maintaining confidentiality [56]. Likewise, but in LTE, both the control plane (MME and Home Subscriber Server (HSS)) and user plane (Serving Gateway (SGW) and Packet data network Gateway (PGW)) entities of the Evolved Packet Core (EPC) can now be developed as services on sophisticated GPP servers [126] that bring more flexibility in operation, enabling the opportunities for operator-specific requirements and customizations. The aforementioned is possible due to the fact that network operators can deploy multiple virtual instances of EPC at the same time, serving different categories of users [126] and sharing those resources with VMNOs or other sharing parties. In particular, such on-the-fly creation of virtualized core networks is enabled by

virtualization technologies such as VMs and containers, and e.g., OpenStack as a platform for pooling of resources on demand [127].

From the IoT perspective, Pagani and Mikhaylov [114] consider WSNs composed of myriads of nodes with highly heterogeneous characteristics, differing among each other in: structure and hardware components, processing and storage capabilities, communication interfaces, software applications, and available services. All these heterogeneous features provide a set of specific resources which belong to a certain IoT node (actuator, sensor, etc.). However, these resources are usually very limited, while devices are constantly being exposed to plethora of service requests [116]. Pagani and Mikhaylov also emphasize the importance of awareness of each other's resources and tasks among IoT nodes, in order to trigger mechanisms for sharing. Angelakis *et al.* [116] adopt similar approach by considering sharing in the context of splitting service requests into different interfaces with different resources. Furthermore, energy as a shareable resource among IoT devices is examined by Kouvelas *et al.* [94] in their theoretical graph theory-based sharing algorithm. This specific algorithm is created under the assumption that excess energy transmission between microgrid interconnected IoT devices is feasible.

b) MAC layer resources: Li *et al.* [112] introduce slice and frame schedulers to enable bandwidth sharing in XG-PONs. In this context, slice scheduler decides on the slice owner for each frame, while the frame scheduler enables the operator to schedule the bandwidth resources of the frame for its subscribers with customized bandwidth allocation schemes [112]. However, isolation and customization problems have arisen in such scenario, for which a novel solution based on intra-frame sharing was developed in [86], as discussed later in the paper.

c) Other resources: As the last but certainly not least, we refer to other resources that could not fit into designated network layers. First, we briefly turn to the *social resources* mentioned, for instance, by Sarvanko *et al.* [48]. Although this type of resources is beyond our scope, social resources can be perceived as an integral part of the users or users' perception, since they are important for the cognitive and cooperative sphere of sharing. Sarvanko *et al.* underline the importance of users' decisions on what, when, and with whom to share, in alignment with the corresponding KPIs which are the outcome of such sharing process. Meddour *et al.* [56] also refer to this type of resources, but in the form of Radio Frequency (RF) engineering support in the sharing resources chain.

We further present some explicative attempts to share the *functionalities* among different sharing entities in IoT, and optical networks. The IoT devices can share not only excess energy, as presented by Kouvelas *et al.* [94], but also functionalities. One example is presented by Silva *et al.* [71], in which cellular unconstrained and IoT constrained devices share resources and functionalities. Thus, the benefits are mutual, because unconstrained devices can assist constrained ones during the service operation by proper task offloading [71]. Furthermore, such offloading of computation-intensive tasks from the resource constrained devices to the cloud envi-

ronment is recognized as a beneficial and promising solution for FCNs in general. It is supported by MEC, which is one of the key technology pillars for 5G networks [118]. As stated by Taleb *et al.* [118], MEC provides a shared pool of resources, which can be scaled dynamically. Interestingly, sharing of functionalities is studied in the optical domain as well. For example, Manolova *et al.* [68] propose the use of regenerators both for signal regeneration and wavelength conversion, providing additional flexibility to their resource allocation algorithm.

An important elaboration of network functions as a resource that can be shared is given by Taleb *et al.* [118]. In the context of MEC, Virtual Network Functions (VNFs) deployed in the form of virtual machines and containers can be dynamically allocated and re-allocated, and thus shared. Since traditional access, transportation, and core network functions can be transformed into virtual network functions, we list some of the general mechanisms to share VNFs. 5G-Transformer project¹ aims to transform today's mobile transport network into an SDN/NFV-based platform that manages slices tailored to the specific needs of vertical industries, by customizing VNFs. This project recognizes the potential in developing new mechanisms for sharing VNFs by multiple tenants and slices. As VNFs are today base components of network services, it is not unusual that they are common for various network services in parallel. Therefore, Malandrino *et al.* [128] study the opportunities of VNF sharing by considering multiple criteria, such as: i) conditions upon which VNFs can be shared, ii) distribution of the workload per virtual machines that run shared VNFs, and iii) possibilities to prioritize service traffic within shared VNFs. Thus, authors propose FlexShare optimization algorithm for VNF sharing, and show that this algorithm outperforms baseline solutions in terms of achieved KPIs such as service deployment cost, and total delay [128].

At this point, all of the resources that we recognized as shareable in the considered literature scope have been introduced. The rest of the section is dedicated to illustrating their sharing potential and how can these be exploited to achieve target KPIs.

B. Sharing Techniques

In this section we discuss some of the most frequent techniques (Table (II)), use to pool and share network resources.

It is important to acknowledge that a large variety of available network resources, such as different technologies and services in FCNs, and in particular in 5G network, bring huge heterogeneity to the network. To achieve the promised connectivity, new services and applications, and the benefits of full capacity in 5G networks, the users need the ability to access infrastructure deployed by different operators, not only the one for which they have a subscription. Multi-tenancy plays a key role to enable such scenario.

a) Virtualization: In order to keep up with the agility required to deliver the 5G KPIs across heterogeneous networks, 5G networks introduce virtualization and softwarization [76,132]. Although the definition of *virtualization* depends

¹5G Transformer: <http://5g-transformer.eu/>

TABLE II: Classification of Sharing Techniques

Sharing technique		Domain	Works
Virtualization		All*	[24,25,30–32,62,73,76,78,80–83,88,95,98,105,124,126,127,129–138]
Software defined networking			[24,25,30–32,62,76,78,80,82,83,88,98,124,126,127,130–138]
Resource brokering			[24,30,31,129,133,139]
Network slicing			[80–83,124,126,127,129,133,135–138,140–142]
WSN management middleware		IoT	[57,95]
On-demand provisioning			[72]
Resource pooling			[71]
Registration and resource provision accounting	ranking		[71]
	earning credits		
Assigning services to interfaces with heterogeneous resources			[116]

* All comprises wireless, optical, IoT, edge and cloud domains.

on the application domain, a quite general and straightforward rationale is provided by Van De Belt in [143]. Van de Belt *et al.* interpret it as a technique which enables network services to observe and use network resources in a manner which is independent from the underlying physical infrastructure. Importantly, a likely outcome of this ability is the possibility to use these resources in a scalable and customizable way. The utilization of resources can be aligned with the service requirements, gaining significant reduction in time and resources for network deployment and operation [78]. Regardless of the domain it applies to, virtualization can be comprehended as abstraction, isolation, and sharing of heterogeneous resources among multiple actors (network operators or users) in both wireless [30,129] and optical domain [31,144], achieving a certain degree of isolation between all sharing units [30].

For the wireless domain, Zhang [30] emphasizes one important characteristic of virtualization, which is the capability to approach abstraction and isolation of physical layer resources, and to map them into specific virtual networks. Zhang’s consideration of virtualization as an umbrella which covers several different realms designated according to the part they play in the end-to-end FCN is presented in [30]. Based on his approach as well as Liang’s and Yu’s work [78], one can notice that the RAN as well as the core network can be virtualized completely or up to a certain level. Indeed, sharing of wireless access and infrastructure have become easier to achieve after the development of virtualization techniques. Regarding core network sharing, various sources [88,145–147] propose techniques for virtualization of EPC in a mobile network, as well as corresponding SDN-based control architectures. Such control architectures are capable of dynamic reconfiguration of the transport network in order to reroute the traffic dynamically to the closest available virtualized EPC [88]. For instance, the virtualization techniques presented by Costa-Requena *et al.* in [145] and [146], have proved their beneficial nature, since they provide better utilization of resources and cost reduction of 7.7%.

Furthermore, many authors indicate that isolation among resources represents a crucial part in the virtualization process [30,62,72,78,82,112,117], since it directly impacts the sharing. Thus, the isolation has to be studied with a more prominent attention and as an essential challenge.

Moreover, Li briefly explains the difference between applying virtualization techniques in optical and wireless domains, and illustrates necessary modifications which have to be made

in wireless networks in order to make virtualization functional [148]. He also anticipated that the SDR is a valuable asset which can further enhance the performance of virtualization techniques.

Some of the advantages enabled by virtualization are flexible and dynamic management of resources that can enable network operators to provide new types of services [78]. Such flexibility could not be possible without certain set of previously inaccessible virtualized resources. Furthermore, Van De Belt *et al.* accentuate improved security and protection when virtual networks are deployed on top of the existing infrastructure thanks to the inherent isolation of network resources [143]. Another important improvement brought by virtualization techniques is examined by Afraz *et al.* [32]. Since these techniques provide dynamic control and management [78], which the network operators can further align to the users’ requirements, the concept of multi-tenancy would be more acceptable and trustworthy solution than ever before. Empowered by SDN, network programmability and control plane centralization, virtualization of network resources, and functions can facilitate multi-tenant scenarios by providing the VNOs with immediate access to network functions without any intervention from the InP [32,129]. Afraz *et al.* focused on optical domain and concluded that virtualization of devices such as ONU and OLT can make the PON significantly flexible.

From a business perspective, Chowdhury and Boutaba in [149] envision network virtualization as the decoupler of the traditional Internet Service Providers (ISPs) business model into two separate and independent entities, namely the InPs and the SPs. The specific roles of these two entities are to manage physical infrastructure and to create virtual networks by aggregating various resources from different InPs, respectively.

Recently, [25,95] studied how virtualization can be applied in the IoT ecosystem. Due to the fact that IoT networks suffer from resource constraints, virtualization seems to provide many opportunities in their deployment and operation. In their survey on virtualization techniques in the context of IoT resource management, Zahoor and Mir in [25] see virtualization as the approach that can play an important role in maximizing resource utilization and managing the resources. Yildirim and Tatar [95] propose Node-based Virtualization (NoBV) and Network-based Virtualization (NeBV) as a way to apply virtualization into WSNs, and these specific use cases

are further elaborated in the Section VI. In the latter part of this subsection we refer to other techniques listed in the Table II.

b) SDN: According to plentiful of sources, SDN can be defined as an emerging programmable architecture which decouples network control from data (sometimes also referred as forwarding) plane. However, the seminal point for such control and data plane separation lays in the need for effective and dynamic resource and processing power management in modern computing environments [24]. Zhang [30] concisely elaborates the key features of an SDN architecture, explaining that the centralized control in 5G networks supports and enables service-oriented operation, which is dynamic, easily manageable, cost-effective, and customizable to the emerging and 5G-specific applications (i.e., eMMB, mMTC and uRLLC). An example of control plane implementation is presented by Raza *et al.* [88], within their approach of dynamic resource sharing for C-RAN with optical transport network. This approach takes advantage of a hierarchical SDN controller as a global orchestrator which harmonizes transport resources, in line with the spatial and temporal variations of the wireless traffic. Focusing on the wireless access, Rebato *et al.* [106] emphasize its sharing opportunity through joint utilization of SDN and NFV, as a viable option to leverage macro-diversity in mmWave bands.

Another perspective of applying SDN in 5G heterogeneous networks is presented by Akhtar *et al.* in [34]. Their approach embraces principles of centralized management with hierarchical control domain in order to globally control the entire network despite distributed inputs arriving from users. The centralized approach inevitably raises concerns on scalability and latency, but the authors address them by balancing the task distribution among the controller and the BTSs. This can be achieved by limiting the controller to manage only global network rules in the back-end, while the BTSs form the front-end interacts with and manages the user devices [34].

c) Network slicing and Resource brokering: Crippa *et al.* [130] introduced the project 5G NOvel Radio Multiservice adaptive network Architecture (5G NORMA) and its network-of-functions-based architecture suitable for supporting a wide variety of services with various requirements. This architecture is one of the first applications of novel concepts such as *network slicing* and multi-tenancy [130]. According to European Telecommunications Standards Institute (ETSI)'s NFV Management and Orchestration (MANO) [150], network slice is defined as a set of network functions and resources which are necessary to run these functions, forming a complete logical network capable to meet the network characteristics required by end-to-end services. Thus, network slices are nothing else than logical virtual networks based on the physical shared infrastructure, allocated and customized according to the QoS demands [30,81,82].

Network slicing as a technique for enabling resource sharing among multiple tenants is considered a key functionality of next generation mobile networks [136]. Cabellero *et al.* [136] provide an illustrative practical exemplification of creating network slices, explaining that each slice consists of VNFs that jointly form the network services that run on top of

heterogeneous infrastructure. According to Caballero *et al.*, the deployment of network slicing starts with a slice creation phase (i.e., an end user requests a slice from the NS catalogue and tenants responds with slice instantiation), and continues with a runtime phase (i.e., triggering operation of functional blocks allocated within slices).

The concept of network slicing is gaining significant attention from the telecommunication industry, with an accent on providing network as a service for different use cases [82]. Khan *et al.* [102] present the core modules that enable dynamic allocation of RAN network slices with dedicated spectrum and resource scheduling functions. Their results show benefits and trade-offs of spectrum sharing between RAN tenants. Similarly, based on the 3GPP's DÉCOR technology, Kiess *et al.* [147] investigate methods to upgrade existing heterogeneous networks with a slicing mechanism that requires minimal changes to select and configure the slices. In the scope of resource sharing, the SDN controller plays the role of either an *orchestrator* or a *resource broker*. The actual role depends on the architectural designer's preference. As an example, Samdanis *et al.* [129] introduce the on-demand capacity broker, whose role is to facilitate on-the-fly resource allocation. In this paper, the authors provide a detailed overview of the new control architecture installed on the top of existing 3rd Generation Partnership Project (3GPP) networks with a network slice broker as brain. Their approach is similar to those presented in [30,34,68], since they also adopt a hierarchical control architecture.

The compound of stringent QoS requirements for advanced 5G services and applications, and dynamic wireless environment poses a significant challenge to existing management techniques [140]. Therefore, Isolani *et al.* raise the importance of performing slice orchestration and IEEE 802.11 MAC management at runtime for the end-to-end QoS [140–142]. In [142] they propose an algorithm for on-the-fly end-to-end slice orchestration and IEEE 802.11 MAC management based on the application's QoS requirements. The main purpose of this algorithm is to periodically re-calculate and adjust the resources allocated to each network slice based on the current QoS demand. In their realistic experimentation within the testbed environment consisting of one centralized SDN-based controller, one Access Point (AP), and two clients, Isolani *et al.* [142] show that their algorithm brings significant improvements in QoS, i.e., throughput, latency, and reliability. Furthermore, in [140] Isolani *et al.* go further and exploit the flexibility of slice airtime allocation considering both resource availability and stringent latency requirements for uRLLC, towards achieving the optimal allocation of network slices in IEEE 802.11 RANs. To assign different airtime configurations per network slice, Isolani *et al.* [140] use a scheduling policy, enabling prioritization among slices. As expected, the optimal allocation of slices depends on the number of slices to be allocated, and the strictness of QoS requirements for each of the slices [140]. In order to improve the allocation of slices in an SDN-enabled 5G network infrastructure, Isolani *et al.* [141] have recently upgraded their SDN-based management framework by gathering fine-grained end-to-end network statistics via advanced monitoring techniques - Inband Net-

work Telemetry (INT), that enable higher level of granularity in monitoring dynamics of wireless environments. Given the monitoring reports, the slice orchestrator performs slice re-arrangement to meet QoS requirements, and SDN management entity distributes the flows to the isolated slices.

Considering network slicing from a federation perspective that includes multiple administrative domains, Taleb *et al.* [138] develop a federated management architecture with multi-domain Service Conductor plane that consists of: i) service broker, which performs the admission control and negotiation once a tenant requests slice, and ii) service conductor, which analyzes successful requests forwarded by service broker, and selects corresponding domains before instantiating a cross-domain slice coordinator for an allocated network slice instance [138].

As every solution comes at a price, the concept of network slicing is not an exception. A likely issue in network slicing for virtualized FCN is a potential underutilization of network resources, which, for example, can occur during network congestion [131]. In order to cope with this challenge, Gang and Friderikos [131] propose optimal and near-optimal inter-slice sharing between tenants. For instance, Vlachos *et al.* [133] reinforce sharing models that result in better resource utilization, with a specific focus on so-called cross-slice coordinator, which is presented as an extension to the SDN/NFV framework.

d) On-demand provisioning and Resource pooling: Given the enormous increase in number of devices, the users' IoT environment will suffer from scalability issues. One of the attempts to address issues directly caused by the IoT proliferation, is presented in [72] by Kliem and Kao. To resolve the resource management issues, they map the concepts which are characteristic to the cloud computing domain like on-demand provisioning, elasticity, and resource pooling onto the IoT ecosystem.

e) Assigning services to different interfaces: Due to the fact that almost every IoT device is equipped with numerous interfaces, Angelakis *et al.* [116] tackled the problem of *assigning different services to different interfaces*, in order to customize heterogeneous resources to the services requirements.

C. Key Performance Indicators

As Table III indicates, we recognize numerous KPIs widely used in the research community. These indicators are used to evaluate and compare the performance of proposed and existing use cases, algorithms, or architectures.

The summary in Table III, shows that the authors mostly use CapEx and OpEx to emphasize *cost efficiency*. According to [10], there is an assumption that network sharing can provide the required economic incentives if properly implemented. In the wireless domain, Oliva *et al.* [159], within the scope of the 5G Transformer project, state that infrastructure sharing among tenants, based on the network slicing, is supposed to reduce OpEx. Furthermore, in the optical domain, Afraz *et al.* in [32] convey the statement from the Broadband Forum

(BBF) standardization body¹, in which sharing of network infrastructure is a preferred means to reduce network costs and to make network scalable.

In particular, CapEx includes all expenses related to the initial investments that the operators face during equipment purchase and installation. On the other hand, OpEx is related to the network maintenance and other expenses which are necessary for proper operation of the communication network on a daily basis.

Costs play a very important role for any market player such as MNO, InP, MVNO, SP, end users etc. in the business model of a communication network. However, other KPIs, such as QoS parameters and spectral efficiency are also widely exploited to evaluate sharing of network resources from technical perspective. Since *spectrum* is a highly limited and precious resource, it is not surprising that many publications tackle spectral efficiency as a KPI.

The remainder of the section shortly presents how the authors incorporated different KPIs into their specific use cases, algorithms, or architectures in order to evaluate their performance.

a) Wireless domain-related KPIs: Since the idea of FCN is created to support the three generic classes of services, namely mMTC, uRLLC, and eMMB [9,160], it is important to understand how resource sharing affects their *QoS* parameters. The services falling into these three categories most importantly differ with respect to required latency, number of connected devices, and throughput. In the context of throughput requirements in 5G networks, an interesting approach presented by Khan *et al.* in [102] facilitates specific radio resource segmentation and management through distinct slice-specific MAC procedures to enable granular spectrum sharing. Their results confirm that achieving more granular spectrum sharing ultimately leads to increased throughput.

Bousia *et al.* [7] justify significant improvements in the *network energy efficiency*, and QoS for MNOs which share infrastructure according to their proposed algorithm. Adopting a game theory approach, their algorithm facilitates switching off of the redundant BTSs while achieving high reduction in the total expenses. Due to the probabilistic nature of arrivals of service requests, switching off of the BTSs can increase probability of a service request being blocked. Therefore, for such systems the case of any general service requests not being successfully established in the network becomes the most important KPI. In [161] Bluemm *et al.*, demonstrated a similar concept on a testbed prototype, where an SDN controller could selectively put into sleep mode Baseband Unit (BBU) and Remote Radio Head (RRH) of an SDR-based C-RAN.

Farhat *et al.* [151] investigated resource sharing in a multi-operator 5G network, where VNOs agreed on the percentage of the resources shared with guest users. The incentive for sharing in this case is the increased user satisfaction due to lower blocking rates. Their simulations point to an additional advantage in higher profits as the operators share more capacity, although they also recognize a trade-off between users' and operators' satisfaction (i.e., higher revenue/lower

¹<https://www.broadband-forum.org/>

TABLE III: Classification of Key Performance Indicators (KPIs)

Key Performance Indicators	Domain	Works	
Blocking probability/Blocking rate	All*	[63–65,68–70,73,100,101,110,151,152]	
Capacity Gain		[10,24,33,40,66,98,117,130,139,147,153,154]	
Quality of transmission		[68]	
Quality of data		[57]	
Resource utilization ratio		[24,34,62,68,73,88,98,110,110,130,154]	
Control plane scalability		[62]	
CapEx		[7,10,24,28,30,32,56,57,62,66–68,73,75,88,94,95,112,113,116,117,129,139,147,151,153–155]	
OpEx		[7,10,24,28,30,32,56,57,62,66–68,73,75,88,94,95,107,112,113,116,117,129,139,147,151,153–155]	
Coverage area		[44,56,73,75]	
Data rate		[10,34,44,60,73,152–155]	
Network energy efficiency		[7,67,94]	
Spectral efficiency		[12,14–19,39,42,43,47,49–54,60,61,64,65,69,70,74–76,99,101,102,104,106–108,111,135,156–158]	
Quality of service		[10,24,33,40,75,95,98,102,117,130,139,147,153,154]	
Quality of experience		[60,98,130,151,153,156]	
Probability of achieving peak rate		[64,65]	
Duration of investment payback period		[75,129,155]	
Mobility		[75]	
Complexity of site acquisition		Wireless	[75,129,155]
Survivability		Optical	[68,100,111]
Regenerator availability			[68]
Average regenerator usage	[68]		

* All comprises wireless, optical, IoT, edge and cloud domains.

expenses) [151]. Another example which corroborates the benefits of spectrum sharing is presented by Hultell *et al.* [44], showing the scenario in which two or more license holders cooperate and share frequency carriers. Besides improved spectral efficiency, sharing also provides higher data rates with wide-area coverage.

An interesting evaluation of case studies for cost savings across different user density scenarios, is presented by Meddour *et al.* [56]. They based their evaluation on comparing different infrastructure sharing models, such as Multi-Operator Core Network (MOCN) and Gateway Core Network (GWCN), presented in Section VI, including model sub-types based on whether they include backhaul or spectrum sharing. The importance of their contribution lays in the conclusion that *the highest savings in CapEx and OpEx are provided by the GWCN implementation*, since it allows maximum degree of sharing between the operators [56]. With similar use cases, Samdanis *et al.* [129] inspect 3GPP sharing principles and mechanisms for FCNs with multi-tenancy. They argue that in urban areas, sharing can greatly simplify the complex and long processes of site acquisition due to spectrum regulation limitations. Similarly, sharing can reduce the *network investment payback period* in rural areas [129].

Adding to the arguments in favor of infrastructure sharing, Nokia estimated that 20-30% cost savings from site sharing, and 30-40% cost savings from sharing both sites and RAN can be achieved [113]. Likewise, but from the perspective of Enhanced Cloud RAN (EC-RAN), Yu *et al.* [107] provide illustrative results showing that resource sharing between cloudlets can significantly improve the performance of 5G-enabled vehicular networks, and reduce system operation cost.

Authors usually approach the resource sharing problem by creating a suitable use case, sharing algorithm, or architecture, and testing its performance in terms of sharing benefits against a choice of different scenarios (i.e., varying their input simulation parameters). Except for two notable examples, we will not go into details of many such approaches and KPIs used

therein, since they can be easily found within the taxonomy provided in Table III. In the first example, Kibilda and DaSilva [59] introduced an innovative regime for infrastructure sharing — so-called Networks without Borders, which aims at efficient provisioning of *coverage* among all involved operators. Their idea in the background of regime’s operation is to dynamically select a wireless network which: 1. represents the most suitable choice for the upcoming user service request, and 2. provides the lowest possible cost for an operator [59]. Similarly, Cano *et al.* [155] utilize Mixed Integer Linear Programming (MILP) to find the most suitable solution for resource sharing among the network operators, given as input techno-economic parameters, such as throughput for the end users, Return of Investments (ROI), pricing models, etc.. Their output is expressed in terms of most suitable solution for sharing resources among operators. Numerous publications reflect the huge interest in sharing network resources in mmWave bands, and some of them also point at their essential advantages in terms of KPIs. For instance, Rebato *et al.* [73,106] studied the potential of mmWave spectrum and infrastructure sharing by assessing the achieved capacity gain. They point at two major benefits of sharing: 1. super-linear increase in user rate with increase in cell density due to signal being power-limited, 2. decrease in *blocking probability* [73,106]. They also present how to cope with increased interference in mmWave bands when it comes to sharing.

Georgakopoulos *et al.* [154] and Kostopoulos *et al.* [98] agree that energy and *resource utilization efficiency* are key factors for sustainability in 5G networks. To support the previous statement, Georgakopoulos *et al.* conducted simulations that resulted in significant energy gains in comparison to the scenarios without sharing. From the perspective of the COHERENT project, Kostopoulos *et al.* developed a programmable 5G control plane, which pointed at huge opportunities in efficient control of network resources in the form of programmable 5G control framework, mostly because of increased capacity, spectrum and energy efficiency, as

well as *Quality of Experience (QoE)* that can be achieved. In their multi-operator resource allocation scheme, Marzouk *et al.* [158] studied static and adaptive spectrum sharing among MVNOs, by providing them with fair distribution of resources, and adaptive amount depending on their bandwidth requirements, respectively. Similarly to Marzouk *et al.* [158], Gang, Frederikos *et al.* [135] introduce tight and loose coupling, based on whether shareable resources are predefined or dynamically allocated. Although based on theoretical assumptions, Marzouk *et al.* [158] present an interesting way on studying how different distribution of shared resources can affect spectrum utilization efficiency, average throughput, and users' satisfaction. Through their simulation results, Marzouk *et al.* [158] show that adaptive sharing utilizes spectrum more efficiently in case of low density of users. Such approach might be interesting to test in the case of network slicing, where potential underutilization of resources in specific slices might occur.

b) Optical domain-related KPIs: Regarding the previously discussed resource utilization efficiency, Zhang *et al.* [157] investigated how to reuse idle fiber spectrum. Their simulations emphasize that resource utilization efficiency can be improved to a greater extent if the interference is reduced in optical networks that adopts flexible bandwidth allocation. As already mentioned, installation and operation of devices such as optical transponder cause significant cost to the network operators. In this respect, Raza *et al.* [88] proposed and tested a novel strategy that resulted in up to 31.4% of cost savings from decreasing the number of optical transponders through dynamic sharing. They also mentioned that this would increase even further with 5G networks, due to the use of high-density by small cells [88]. Cost-effectiveness can be achieved not only by sharing optical devices but by sharing network functionalities as well. As previously mentioned, Manolova *et al.* [68] used this approach with the specific objective to ensure requested Quality of Transmission (QoT) and backup resources for improved survivability. Several KPIs are tightly coupled with efficient use of backup resources, which are typically required to provide high level of resilience in optical networks, but pose a trade-off between level of availability and efficiency in spectrum utilization. Similarly, Ning-Hai Bao *et al.* [110] and Chen *et al.* [101] evaluate sharing of backup resources in order to achieve higher spectral efficiency, and to decrease the probability of blocking service requests.

Blocking probability is widely used to evaluate the performance of network optimization algorithms, such as routing and wavelength assignment, in optical networks [31,63]. These references utilize blocking rate of service requests in virtualized EONs to experimentally prove the performance of their sharing framework. Furthermore, an essential and yet quite general question has arisen from the study of isolation among virtualized optical networks provided by DeLeenheer *et al.* [62]. This work tackles the importance of trade-off between network resources utilization and control plane scalability and proposes a resource sharing algorithm that reduces the number of wavelength channels required by 10%. Due to its significance we will discuss this work in Section VII, as an implementation challenge.

With regard to the network slicing, Crippa *et al.* [130] provide a detailed architecture of network slicing management framework. They propose the use of a controller for each slice, which is responsible for preparing the resources for a given slice and to manage those resources. These controllers set the input values according to the specific service QoS/QoE requirements and constraints.

c) IoT-related KPIs: Although IoT devices are typically low cost, they are deployed in large number, thus it is important to consider all their operational costs (e.g., including energy consumption). Yildirim and Tatar [95] state that resource sharing between heterogeneous WSNs leads to significant cost savings and reduction in latency, in particular for large IoT systems such as smart cities. Likewise, Kouvelas *et al.* [94] facilitate micro-grid within IoT systems for the sake of sharing energy locally and reducing the overall costs. In their already mentioned work, in which they assign different service requests to interfaces with heterogeneous resources, Angelakis *et al.* [116] also strive to meet QoS requirements and to minimize costs. Accordingly, their numerical cost analysis considers both costs of activation of services' splitting, and their distribution among interfaces. Their MILP-based algorithm demonstrates the impact of the total number of algorithm iterations, focusing on the trade-off between the minimum number of iterations and minimum cost. Looking back at the approach presented by Yildirim and Tatar in [95], time savings in time-critical IoT systems are achievable if the client evaluation entities (i.e., command/queries, data aggregation, and data fusion algorithms, etc.) are brought closer to the MBSS because the time needed to notify that resources will be shared is ultimately shorter [95].

In wireless networks, the time-variant nature of the transmission medium can strongly affect IoT applications and their strict QoS requirements [33]. Thus, similarly to the sharing architectures presented by Kunst [139] and Crippa *et al.* [130], Shi *et al.* [33] provide an IoT architecture with two-layer information base. The user level is indicated as a resource management level, which tracks QoS as well as QoE, and according to the predefined threshold coordinates new service requests seeking for new and more reliable routes. The network level instead reconfigures the networking resources to overcome the negative effects caused by changes in network states. Since the resources in IoT networks are shared by all users, the resource requests from one user might affect the network state, and the network level thus either performs resource adjustments limited to network, or provides a dynamic share or rent of frequency from other networks [33].

To sum up the section, we briefly mention spectral efficiency approaches related to IoT. For instance, Zhang *et al.* [15] claim that advanced spectrum sharing schemes such as CR, NOMA, D2D, IBFD, and LTE-U improve spectral efficiency for IoT applications. Other approaches include the use of unlicensed mmWave band. The authors also suggest new research directions in investigating the integration of multiple spectrum sharing techniques to address the highly heterogeneous nature of 5G networks. Finally, there are several observed and yet very important challenges related to LTE/NR uplink

(UL) sharing which is expected to benefit IoT applications [75]. In particular, this approach generates trade-offs between spectrum availability and coverage, spectral efficiency and downlink (DL)/UL coverage balance, transmission efficiency and latency, and seamless coverage and deployment investment [75]. Due to their relevance for incorporating IoT into FCNs, they are elaborated within Section VII.

VI. USE CASES

In this section we aim to present practical use cases, taken from the literature, that exemplify the sharing of heterogeneous and distributed resources. Here, the term use case refers to the specific model for resource sharing, which assigns roles to the participants and specifies steps in the sharing procedures. Such participants then follow these procedures to improve their KPIs. Tables IV, V, and VI summarize the studied use cases.

While inspecting the features of various use cases presented by different authors, we noticed that sharing models primarily differ among each other in the way the control and management entities are organized and implemented. Accordingly, we group them into two categories: *decentralized/distributed* and *centralized*, which are presented in Tables IV, V, and VI. Furthermore, we evaluated both categories from the perspective of infrastructure and spectrum sharing.

The reason we apply this differentiation between sharing models, is to better suit the typical organizational structure of FCNs' control planes. Due to the synergy of SDN and NFV, FCNs' control planes can be organized in a centralized, hierarchical, and distributed manner [30]. In the first case, the whole control entity is made of only one SDN controller having a global view of the whole network, which makes it easier to implement but hard to scale. The distributed case, however, reflects the spread out nature of the control entity, consisting of several SDN controllers which communicate among each other to increase their local knowledge [30]. This distributed control plane architecture is suitable for stringent 5G service requirements, especially because of the reduced latency, but at the same time it is very hard to maintain due to the significant network heterogeneity. Lastly, the hierarchical control plane, having low-level and high-level controllers, combines benefits such as the simplicity of the implementation and the reduced latency, from both centralized and distributed architectures [30]. In the following, we discuss both distributed and hierarchical models of control and management entities within decentralized sharing models.

A. Decentralized Sharing Models

a) Infrastructure sharing: Infrastructure sharing is a well investigated topic in wireless networks. Based on the deployed resource control and management architecture, RAN sharing can be performed either as a distributed (Distributed Radio Access Network (D-RAN)) or centralized RAN (C-RAN). In order to enable and support multi-tenancy in FCNs, Kostopoulos *et al.* [98] note that D-RAN requires sharing of the legacy RAN infrastructure, as well as the whole or parts of the core network. Much earlier, Frisanco *et al.* [55] presented details of different sharing models according to the part of the

infrastructure that is about to be shared in 3GPP. The Multi-Operator Radio Access Network (MORAN) realizes sharing of active RAN infrastructure (i.e., BTSs and BSCs in 2G, as well as eNodeBs and RNCs in 3G and LTE), allowing network operators to maintain their independent control over their traffic and its QoS. With the arrival of the third generation of communication networks (i.e., 3G), another solution for sharing active RAN infrastructure - MOCN was proposed by Frisanco *et al.* [55]. It represents an extension to MORAN, adding the possibility of frequency pooling. In particular, each network operator possesses its own core network (e.g., EPC in LTE), which is connected to a shared Evolved Universal Terrestrial RAN (eUTRAN) via the S1 interface [56]. Given additional cost savings of frequency pooling, MOCN shows its superiority over MORAN. Stemming from MORAN and MOCN, and exploiting the synergy between SDN and NFV, the FlexRAN platform [122] follows a decentralized principle, having two main components: FlexRAN control plane and FlexRAN Agent API. While each eNodeB has an Agent API installed, the control plane is organized in a hierarchical manner, distributing control decisions from Master Controller to each Agent. As already discussed in Section V-A, the hardware elements in the future core networks are envisioned to be functions that can be virtualized [30,123,126,127] and thus shared. Furthermore, GWCN enables sharing of the Mobility Management Entity (MME) entity, allowing the core network to be shared as well.

Although originally presented much earlier, an alternative approach to the "conventional" sharing of RAN cells is studied by Beckman and Smith [113]. They argue that benefits can be obtained by distributing the RF power from the operators' BTSs via common shared Distributed Antenna System (DAS), usually made up of analog broadband radio repeaters and optical fibers. Thus, they clearly point at its potential to reduce CapEx and OpEx, which is not exploited enough due to the absence of network sharing.

An important decentralized model for sharing resources toward 5G networks is presented in [30]. Zhang [30] developed auction-based and contract-based algorithms for virtualization that can run in SDN controllers. In the model the InPs act as sellers, MVNOs act as buyers and SDN controllers are used to manage the virtualization process as well as signaling, forwarding, and pricing. The so-called regional controller - which executes the long-term optimization, and local controllers which provide short-term optimization in network are elaborated in great detail in [30]. Another decentralized SDN NFV-based approach to resource sharing, this time in dynamic wireless backhaul networks, is presented by Lun and Grace [156]. In order to establish balance between scalability and system performance, Lun and Grace [156] present a hierarchical architecture with two tiers of SDN controllers. In this way the communication burden is offloaded from one central to multiple local logically distributed controllers. In their multi-tenant scenario, Lun and Grace tested a resource sharing algorithm, demonstrating that their proposed architecture results in up to 40% of energy savings compared to a centralized scenario while maintaining satisfactory levels of QoS [156].

TABLE IV: Classification of Decentralized Sharing Models - Infrastructure Sharing

Type		Description	Domain	Works	
RAN-only Sharing	Passive RAN Sharing		Wireless	[7,24,30,32,55] [56,73,98,106,122,156]	
	Active RAN Sharing	MORAN			no core network sharing
		MOCN			MORAN + frequency pooling
RAN + Core Network	GWCN	MORAN + core network			
RF power distribution	Common DAS	Sharing Analog Broadband Radio Repeaters		[113]	
		Optical Fibers			
Sharing RF Power Among Operators via DAS					
Sharing OEO Tables			Optical	[28]	
IoT-related			IoT	[33,71,94,95,114]	

In the optical domain, Ali [28] devised a two-layered management architecture for sharing resources in terms of: 1. sharing back-up path resources, 2. sharing regenerators among back-up paths. The whole sharing procedure is governed by the intermediary switching nodes. Thus, for every shared object in the network, a sharing table is employed, containing an identification of the object as well as a list of numbers for unique optical fibers. Although two different types of tables are utilized for channels and OEOs, the constraints in Ali's approach are directly related to its scalability, because of the sharing tables can become excessively large. Another example of infrastructure sharing for protection purposes is that introduced by Ruffini *et al.*, in [163] for converged access/metro networks. Considering a nation-wide deployment of Long-Reach PON [164], the authors devised a mechanism, based on a geometrical network coverage technique, to share backup optical transceivers across the entire country. The mechanism is based on the pre-planned disconnection of selected transceivers, which trigger a fast protection mechanism that enables load balancing, by sharing a failure across devices located in different parts of the network. Their fast protection mechanism was also experimentally demonstrated in [165].

Turning to the IoT ecosystem and its sustainability within FCNs, we briefly point out several significant attempts to share resources in this environment, in a distributed manner. In order to cope with the challenge of energy consumption in constrained IoT devices, we have already referred to [94], in which Kouvelas *et al.* have proposed to share energy between IoT devices, that can be receivers and providers but not at the same time. Tackling the management structure of their solution, several control/management nodes are distributed among the entire IoT ecosystem. While numerous approaches to share resources in IoT environments are strictly theoretical, Pagani and Mikhaylov [114] presented one of the rare attempts to practically approach sharing in WSNs. Their sharing model includes dynamic discovery, negotiation, and sharing of tasks and resources between neighboring heterogeneous IoT nodes, allowing each of them to discover, request, and reserve other nodes' resources in a distributed fashion.

Yildirim and Tatar [95] also present two decentralized approaches to resource sharing: NoBV and NeBV. Their com-

parison of NoBV and NeBV with a centralized middleware-based model (which will be further discussed later) brings up some interesting differences between decentralized and centralized approaches, that can be considered of general validity. In NoBV virtualization is performed at each node, which is desirable for time-critical applications due to the short response time. In NeBV the authors also adapt the network virtualization protocol to the type of network considered. However, compared to centralized models, they both suffer from excessive energy consumption at the decentralized nodes, which are typically energy constrained in IoT environments.

b) Spectrum sharing: Beside the extensive overview of infrastructure sharing models, we pay special attention to those use cases which tackle spectrum sharing, from various perspectives. Hence, authors in [17] gather all the advanced sharing models, such as D2D, IBFD, NOMA, LTE-U and CR on top of them, and present their features and potential for deployment within 5G networks. Furthermore, Khan *et al.* [102] extend previously published lists of advanced sharing models with License Assisted Access (LAA), Licensed Shared Access (LSA), LTE-Wi-Fi Aggregation (LWA), and Multe-fire. However, the authors accentuate that these models are coarse-grained and thus not suitable for achieving significant improvements in spectrum utilization efficiency.

Furthermore, two decentralized sharing trends can be recognized in the optical domain: statistical spectrum sharing and dynamic cooperative spectrum sharing. As a representative of the first one, Wang *et al.* [66] introduce dynamic modification of channel capacity between base and peak rates, flexibly mapping the client traffic onto an arbitrary number of universal line cards in order to compose the optical superchannel which supports the required data rate. On the other hand, dynamic spectrum sharing is extensively studied in [69,70], presenting a spectrum expansion/contraction policy. The concept of such sharing is considered dynamic because the policy takes into account the spectrum allocation of the neighbouring connections which compete among each other for the same spectrum resources. In fact, when a request for spectrum resources arrives: 1. the relevant spectrum expansion procedure is invoked, 2. in case there are no available spectrum slots in the largest expansion region, the spectrum re-allocation procedure is trig-

TABLE V: Classification of Decentralized Sharing Models - Spectrum Sharing

Type		Description	Domain	Works	
General	LAA	standardized version of LTE-U	Wireless	[15,17,102]	
	LTE-U	coexistence between LTE and WiFi users on the same WiFi 5GHz channel			
	LTE-WiFi Aggregation	LTE signal uses WLAN connections to increase capacity			
	Multifire	operates only in unlicensed band and combines LTE performance with WiFi simplicity of deployment			
	Cognitive Radio	Overlay			
		Underlay			
	D2D	direct communication between two nodes when BTS is far away			
	IBFD	signal transmission and reception at the same time on the same frequency band enabled			
	NOMA	BTS allows connection on the same spectrum band to multiple users			
	Statistical Spectrum Sharing	switching between basic and peak rate			
Sharing Tables			[28]		
Cooperative Spectrum Sharing	CSA	fixed number of spectrum slots per connection	All*	[68–70]	
		Expansion			DAD
	ACN				- spectrum re-allocation not allowed - consumption of resources from connections with potentially more available resources
	Re-Allocation	Shift ACN			spectrum re-allocation allowed with restrictions
		Float ACN			no restrictions on spectrum re-allocation
		k-Float ACN			re-allocation of neighbors of k-th order
		Iterative k-Flow ACN			re-allocation of neighbors of any order
IoT-related	Licensed Spectrum	eMTC-related		IoT	[15]
		NB-IoT-related	stand-alone operation		
			in-band operation		
	guard-band operation				
	Unlicensed Spectrum	Bluetooth-related	AFHSS scheme		
			Collaborative Spectrum Allocation Scheme		
		Zigbee-related	DSSS		
		LoRa-WAN-related			
	Both Licensed and Unlicensed	SigFox-related			
		Ambient Backscatter Communication			
New LTE/NR Frequency Sharing	Semi-static		All*	[75]	
	Dynamic				

* All comprises wireless, optical, IoT, edge and cloud domains.

TABLE VI: Classification of Centralized Sharing Models

Type		Domain	Works	
Infrastructure Sharing	RAN Sharing	C-RAN	[98,123]	
		Game-theory based BTS Sharing	[7]	
		EC-RAN	[107]	
		Resource Broker-based Schemes	[88,129,130,139]	
	IoT-related sharing	MBSS	Digi Device Cloud	[95]
			Sentille	
			Libelium	
			IoTSense	
			Sensor Rush	
		Caching and DL Resources Sharing	[96]	
Spectrum Sharing	TV White Spaces	[18]		
	Centralized Network Control and Coordination Framework	[102,162]		
Sharing Among Network Slices	ICIC	All*	[130]	
	Network Slice Brokering			
	Spectrum Sharing			
	VNF Placement Consideration			
	Authentication			

* All comprises wireless, optical, IoT, edge and cloud domains.

gered, 3. if spectrum re-allocation is not allowed, the request is refused [69,70]. Based on the feasibility of each of these three steps, Palkopoulou *et al.* [69] define several different dynamic spectrum sharing models, such as: Constant Spectrum Allocation (CSA), Dynamic Alternate Direction (DAD), Avoid Close Neighbors (ACN), Shift ACN, and Float ACN. They evaluate the performance of the proposed models defining case studies, conducted using Deutsche Telekom reference network [69]. Lastly, Stiakogiannakis *et al.* [70] extend previous study with the following models: k-Float Blocking Neighbors and Iterative Float Blocking Neighbors.

Finally, an important distinction between spectrum sharing in IoT and conventional networks is presented in [15]. The spectrum sharing models used in conventional communication networks are mainly designed for DL long-packet communication, which is contrary to the mostly UL short-packet traffic of IoT. Thus, conventional sharing models cannot be reused for IoT applications. Another fundamental difference lays in different capabilities of the devices used in conventional and IoT networks. The conventional mobile devices are much more resourceful than IoT devices, designed with strong signal-processing capabilities and rechargeable batteries. With these differences in mind, and in order not to overload IoT devices, Zhang *et al.* [15] emphasize the importance of adopting simple techniques when designing spectrum sharing models for IoT. They propose a set of sharing models suitable for licensed and unlicensed bands separately, together with models that can be utilized in both licensing regimes. Interesting to notice is that there is a certain overlap in these models, since CR, NOMA, D2D, and LTE-U can be used either for conventional or IoT networks.

B. Centralized Sharing Models

Typically, sharing models where a mediator is interposed between the sharing actors and the pool of shareable resources, are characterized by higher latency and signal overhead. In this section, we present various sources which study centralized sharing models and tackle the aforementioned disadvantages,

with some of them striving to prevent service disruptions potentially caused by existence of the intermediary node.

a) *Infrastructure sharing*: With regard to the infrastructure sharing, we refer to several important publications and their main contributions. Using the game theory, Bousia *et al.* [7] propose sharing of BTSs under unrealistic assumption of a non-competitive multi-tenant scenario, in which no network operator acts selfishly and/or greedily. Nevertheless, in order to save energy and decrease expenses, redundant BTSs are being switched off upon decisions made at an arbitrarily-defined central point. However, this sharing scheme also assumes that roaming costs are low, otherwise the operators would be less likely to switch off underutilized BTSs and revert to roaming. In the context of network slicing, the CellSlice architecture is proposed by Kokku *et al.* [166], providing a gateway-level solution for slice-specific resource virtualization that impacts the individual BTS scheduling decision.

For the purpose of RAN sharing, Kostopoulos *et al.* [98] propose an approach to use C-RAN to improve sharing of eNodeBs. C-RANs are based on the disaggregation of eNodeBs, physically separating the RRH devices consisted of RF elements and the BBU that carries out all baseband digital processing functions. In particular, RRH devices are usually employed to extend the coverage of BTSs and eNodeBs, which are located in challenging environments (e.g., tunnels, rural areas, etc.). The two are typically connected using a Common Public Radio Interface (CPRI) protocol operating over optical fibre. When virtualized, the BBU can run as software over General Purpose Processors (GPPs) servers, located in a central office or in the cloud (BBU pool). Such virtualization enables sharing of computational resources, as the BBUs, hosted in virtual machines or containers (e.g., Linux, Docker), can be dynamically migrated over different physical hardware.

From a perspective of RRH distribution among MNOs, Narmanlioglu and Zeydan [167] propose hierarchical SDN-based C-RAN architecture, having a RAN controller to control eNodeB functions, and a virtualization controller which

performs core network sharing. In particular, they propose an RRH assignment based on load balancing algorithm for sharing RRH resources among MNOs, executed on the top of C-RAN controller. Such algorithm assigns RRHs to a particular MNO based on the number of connected UEs, unlike the traditional RRHs distribution which homogeneously distributes available RRHs. The results presented in [167] show that such load-balancing aware approach outperforms traditional RRH distribution, enabling more efficient RRHs usage. However, as resource sharing might cause insufficient isolation between operators, Niu *et al.* [168] present a multi-timescale dynamic resource sharing mechanism with a given level of isolation in order to decrease interference between RRHs. The output of their algorithm proves it to be robust under user mobility, while achieving the service isolation and efficient resource sharing among service providers.

An advanced version of C-RAN is the EC-RAN, designed for the stringent QoS requirements for augmented reality applications in 5G-enabled vehicular networks [107]. The EC-RAN combines C-RAN and cloud computing, and consists of numerous cloudlets which are geographically distributed to support local vehicular services.

A similar, although generalized, resource sharing architecture is presented by Kunst [139]. The resource broker is defined as a centralized entity, which is constituted of three interconnected levels: 1. update level, 2. resources level, and 3. decision level. The update level is in charge of parameter collection across the whole multi-tenant network, consisting of multiple network operators which share resources. Furthermore, the resource level provides information about all available resources, while the decision level takes care of resource leasing requests and takes into account adequate pricing mechanisms and resource availability. Another example of such resource broker-related approaches, is provided by Samdanis *et al.* [129] with the design of an on-demand capacity broker, which facilitates on-the-fly resource allocation, thus allowing InP to allocate given portions of network capacity to an MVNO, Over The Top (OTT) operator, or any vertical market player. The layered architecture for sharing RAN and edge resources presented by Shantharama *et al.* [123], so-called LayBack, disseminates all resources into three layers (i.e., device layer, radio node layer, and gateway layer) which are jointly managed by an SDN orchestrator that implements SDN-based management framework in a centralized fashion, thereby coordinating the cooperation between different wireless operators and technologies. Since the SDN orchestrator decouples fronthaul from backhaul, fronthaul resources can be shared among different sharing parties. We close the elaboration of centralized infrastructure sharing in wireless domain by pointing at inter-slice sharing frameworks, which are in line with those previously elaborated.

Within the sphere of resource broker solutions, in the optical domain, a resource sharing model is presented by Raza *et al.* [88]. Their centralized RAN architecture with hierarchical SDN control plane is characterized by the presence of a global orchestrator, that performs sharing and optimization of resources. They show how adopting the concept of dynamic resource sharing to a limited pool of optical resources that

can be shared among BTSs, results in considerable savings in overall cost of network ownership. This result was obtained by both simulating and emulating shared network environments.

As we have already mentioned, in Section VI-A, that the IoT-related centralized solution provided in [95] proves superior to the decentralized NoBV and NeBV approaches, we now further explore this aspect. Yildirim and Tatar [95] present their sharing model which is based on MBSS, but with significant improvements in comparison with traditional MBSS-based models. In order to prevent increase in delay and volume of signaling-related traffic, they rely on bringing the client evaluation entities closer to the shared resources. To that goal, they place client evaluation to the MBSS as the closest location. This approach requires to implement and execute the client algorithms under the same software framework. The detailed description of such software framework is provided in [95].

Considering that WSNs will become an indispensable part of 5G networks, due to the omnipresence of smart cities and their massive exploitation in FCNs, Vo *et al.* [96] attempt to address issues related to the limited resources of WSNs by provisioning adequate assistance from other network devices with stronger processing potential. Thus, they have designed a joint caching and DL resource sharing optimization framework, which exploits the caching storage of all existing Macro BTSs (MBSs) and Femto BTSs (FBSs), as well as the DL resources of control units in 5G networks. We associate this sharing framework to the group of centralized sharing schemes, since MBS performs collection and optimization procedures of all system parameters and then deploys the framework to cache the multimedia content in the proper FBS and to share the DL resources between the control units.

b) Spectrum sharing: Within the topic of spectrum sharing, we shortly present three approaches which differ in philosophy as well as in the period of time when they were studied. One of the first radio bands to be considered for sharing was the TV White Space (TVWS), the broadcast channels which are unused in a certain geographic area and during a certain period of time. One approach to determine unused TV channels relies on spectrum sensing, but it was quickly recognized that in order to reliably detect incumbent TV stations the sensing threshold must be set below the noise floor. Alternatively, the FCC requires geolocation capable secondary spectrum users which then need to communicate with the TVWS databases to determine available channels. Due to excessive interference protection margins however, the potential for spectrum reuse is not fully exploited [18].

To achieve efficient and elastic spectrum utilization among multiple operators in LTE networks, Shrivastava *et al.* [162] designed a centralized SDN Controller, which acts as a resource brokering entity with global resource knowledge. Their approach assumes that heterogeneous LTE environments consists of FDD macro-cells, accompanied by multi-tenant TDD pico-cells, allowing spectrum sharing across both. Having a TDD frame reconfiguration algorithm that dynamically adjusts UL/DL ratio for pico-cells, the trade-off between resource utilization and bandwidth is treatable and customizable. The preliminary results presented in [162] show how their SDN-

based architecture significantly reduces DL delay of both FDD macro-cells, and TDD pico-cells.

Recently, Khan *et al.* [102] recognized the potential for fine-grained spectrum sharing aimed at achieving very stringent requirements for spectrum utilization efficiency in 5G networks. In particular, this can be realized if micro-transactions of spectrum are carried out among network tenants, while a centralized spectrum management application controls the overall sharing from a higher perspective [102].

VII. CHALLENGES IN SHARING RESOURCES

Despite the undeniable benefits of sharing of network resources and recent developments in its implementation, there are indeed plenty of significant challenges remaining to be addressed.

Our presented literature review consists of numerous publications which approach sharing of network resources in various manners, and from the most diverse perspectives. According to the challenges that we have recognized by studying the literature, Table VII reassembles, to the best of our knowledge, all relevant sources describing various challenges related to sharing of heterogeneous resources. As Table VII clearly depicts, we group all sharing challenges into two non-overlapping categories, based on their technical vs. non-technical nature. In the technical category, we pay attention to the general challenges which impact both wireless and optical domains, supported by the overview of the challenges related to the IoT, edge, and cloud. Furthermore, we elaborate on the challenges which are specific for spectrum as a shareable resource and then consider non-technical challenges, such as government regulations, operators' negotiations, trust, and competition. Interestingly, we found that most of the challenges are common to wireless, optical, edge, and cloud domains.

a) Heterogeneity: Nowadays, communication networks are characterized by highly heterogeneous types of devices, hardware equipment and platforms, radio access and backhaul technologies, configuration interfaces, actors, etc., all co-existing and cooperating in order to meet the most stringent service requirements. Silva *et al.* [71] and Kliem *et al.* [72], for instance, perceive heterogeneity as one of the main challenges that has to be overcome in the IoT world. Similarly, Taleb *et al.* [118] discuss heterogeneity in the context of dynamic service provisioning over distributed edge networks as a part of 5G networks.

For example, trying to exploit mechanisms derived from cloud computing [72], which usually includes pools of homogeneous resources, in the context of IoT is problematic, due to the need for each user to be able to handle any type of device [72]. Although virtualization techniques should enable tolerance to heterogeneity by enabling abstraction and isolation of resources, this comes at a price, as further discussed below.

b) Abstraction and Isolation: Virtualization is probably the main technique to enable seamless resource sharing in 5G and FCNs, as previously discussed in subsection V-B. The two indispensable terms and yet inseparable from virtualization, *abstraction* and *isolation* represent the key challenges in

implementing sharing models in FCN scenarios. Isolation can be considered in the context of: i) isolation of resources in general, and ii) specific isolation among network slices. As defined by Liang and Yu [78], isolation should in general ensure that any change in configuration, customization, or topology should not affect other coexisting parts of the network. Similarly, *slice isolation* refers to the cases where any failure or security attack on one network slice does not cause consequences on regular operation of other network slices [82].

Li *et al.* [117] consider isolation from the perspective of network operators, with a specific focus on the impact that one operator has on other operators, while sharing the same resources. Regarding the customization among operators in XG-PONs, Li *et al.* [117] emphasize the importance of operators being able to implement their desired scheduling algorithms, independently of the other VNOs.

Moreover, Zhang [30] and Liang and Yu [78] point at the differences between abstraction and isolation of physical resources between wireless and wired networks in general. These two virtualization procedures are particularly challenging in the wireless domain since they cannot be easily implemented due to the fact that the wireless channel is inherently broadcast and with stochastic fluctuations [30,78]. Liang and Yu [78] further elaborate on the undesirable properties of wireless networks, such as time-various channels, attenuation, mobility, broadcast, etc., with a special focus on cellular systems. They convey within their survey that any change in one network cell can cause significant interference to the neighboring cells, making isolation even more difficult and complicated [78]. Their comprehensive elaboration of virtualization as a sharing technique, together with the challenges and details of implementation can be found in [78].

The way in which physical resources are abstracted (and the granularity of their isolation) directly impact the efficiency of resource utilization. According to DeLeenheer *et al.* [62], a complete isolation is wasteful in terms of resource utilization. Their results confirm that intelligent isolation can lead to substantial savings and improved resource utilization, due to the fact that total isolation usually leads to overprovisioning of resources. The latter occurs simply because of resources being separately allocated to different network slices. In addition, having a smaller number of isolated virtual networks affects control plane scalability, because the number of control plane messages increases with the number of nodes in the network [62]. Their approach to reduce message exchange rate can be generalized and used as a template to address similar problems in other networking domains.

c) Isolation granularity: *Isolation granularity* refers to how precisely are the resources committed to a given slice defined, impacting the level of aggregation of services or customer data into the same slice. Accordingly, Zhang [30] defined four levels of isolation, which are, from coarser to finer: i) *spectrum-level slicing*, ii) *infrastructure-level slicing*, iii) *network-level slicing*, and iv) *flow-level slicing*.

The first, coarsest level, aggregates all services delivered through a certain frequency band into the same slice. The associated methods thus simply target spectrum-level isolation. The infrastructure-level slicing instead, within a given

TABLE VII: Sharing Challenges

Group		Type		Domain	Works	
Technical	General	Abstraction of resources		All*	[30,72,78,112,117]	
		Isolation among operators	Fully		[62,82,122,127,136]	
			Limited			
		Isolation granularity				[30,122,127,136]
		Efficient resource utilization				[112,117]
		Customization among operators				
		QoS requirements				[59,155]
		Required signal strength				
		Required CapEx and Opex				
		Compatibility				[56]
		Interoperability	Additional losses caused by connecting equipment of different operators		Wireless	[44,55,56,72]
			Risk of incompatibility between manufacturers of eNodeBs and RNCs			
		Security			[71,72,80,126,136,138]	
		Privacy			[71,80,126,136,138]	
	Heterogeneity	Hardware		All*	[71,72,78,118]	
		Operating systems				
		Programming languages	Programming style			
	Electromagnetic compatibility			Wireless	[56,72]	
	Access and safety during installation of shared equipment			All*		
	Deployment schedule for operators					
Maintenance and monitoring						
Mobility of sharing entities			IoT			
Longer response time in centralized sharing solutions			All*	[95]		
Spectrum-related	Technical complexity caused by significant difference between operating frequency domains	Linearity of power amplifiers		Wireless	[55,56]	
		Different antenna design requirements				
	Coverage			All	[75]	
	Wideband spectrum availability vs coverage			IoT		
	Spectrum utilization vs UL/DL coverage balance					
	TDD DL/UL switching period					
Seamless coverage vs deployment invest						
Non-technical	Government regulations		All*	[30]		
	Operators' negotiations			[30,56]		
	Trust among operators			[44,56]		
	Competition	Enabled competition among operators		[44,56]		
		Concurrency between sharing entities		[71]		

* All comprises wireless, optical, IoT, edge and cloud domains.

spectrum band, assigns infrastructure resources (e.g., antennas, BTSs, backhaul, etc.) to a slice, across a shared infrastructure owned by an InP. Slicing on the network level is based on the virtualization of the whole, i.e., end-to-end network, including RAN, core network, and computing nodes within a close geographical area. Thus, all network resources are exposed in the form of packages tailored for different sharing actors and their users' demands. Within the last level, InP forms a slice of virtual resources (e.g., traffic flow), and provide it to MNOs and MVNOs. Such slice contains resources gathered with a fine granularity, and can be formed based on specific service-level requirements, such as data rate, bandwidth, latency, etc.

d) *Spectrum-related challenges*: Given the characteristics and requirements for 5G-specific IoT technologies, such

as eMMB and uRLLC, Wan *et al.* [75] discuss various challenges related to extending available spectrum to mmWave bands, and sharing UL frequency of LTE Frequency Division Duplex (FDD) frequency band as a supplemental UL carrier in the Time Division Duplex (TDD) band above 3GHz. In this approach, challenges are represented by trade-offs between requirements that have to be reconciled and adjusted to the service requirements. For instance, the trade-off between wideband spectrum availability and coverage in 5G is a concern, since bands below and above 3GHz reflect reciprocal relationship between coverage and data rates. The greater coverage in bands below 3GHz leads to its limited availability and lower bandwidth, which significantly constrains achieving high data rates. On the other hand, despite high data rates, bands above

3GHz suffer from significant propagation loss which reduces coverage.

The other spectrum-related challenge is also critical and refers to the balance between efficient spectrum utilization and TDD DL/UL coverage. Simply increasing the number of slots for UL up from the one slot which is currently adopted in 5G NR, does not solve the issue. Since the UL traffic is not in balance with the DL, additional slots will increase the UL coverage but significantly decrease the spectrum utilization efficiency. Wan *et al.* [75] also discuss the problem that dynamically switching between TDD DL and UL would create, because of the additional delay this introduces. Finally, their consideration spans the trade-off between seamless coverage and investment into deployment [75], as the signal propagation is exposed to significant losses above 3GHz, and thus additional sites and cells will be required. It is questionable whether the operators are ready to invest more in order to enhance coverage at such high frequencies.

e) Interoperability: The attempt to address challenges related to interoperability among different sharing actors is provided by Meddour *et al.* [56]. The authors address constraints related to active and passive infrastructure sharing. Active sharing entails various challenges such as those with design and configuration of antennas, since linearity of power amplifiers significantly varies across different frequency bands. According to our classification in Table VII, such variation belongs to the spectrum-related challenges, since it is caused by operation in various frequency bands. Furthermore, the additional signal losses when interconnecting equipment of different operators, different demands on antenna design, and potential risk of incompatibility between manufacturers of eNodeBs and RNCs might lead to additional technical complexity in sharing of network resources [56]. On the other hand, Electromagnetic Compatibility (EMC) of sites, access, and safety during the installation of equipment on the shared sites, as well as deployment schedules for different operators, maintenance and monitoring of sites, are representatives of challenges in passive infrastructure sharing [56].

f) Security and privacy: Since resource sharing includes different sharing parties (e.g., MVNOs, MNOs, InPs, SPs, different verticals, etc.) it is inevitable to preserve security and privacy requirements that are specific to each of these parties. Security is typically achieved through authentication, access control, and integrity assurance [71]. As an example, Silva *et al.* [71] present a detailed vision of security in sharing of resources among constrained and unconstrained devices, which provides two security levels. The more restrictive security level requires the encryption of the whole communication channel between constrained devices and endpoints, giving unconstrained devices the role of gateways with no permission to access the data. In case of less restrictive level of security, the unconstrained devices are provided with certain level of permission to access some critical resources from the sharing platform. Another example is the cloud computing-based IoT ecosystem proposed by Kliem *et al.* in [72] which uses Public Key Infrastructure (PKI) for this purpose.

Specifically in 5G networks, network sharing and network slicing might incur various security and privacy issues due

to the transparency in operation of any sharing paradigm. Therefore, Barakabitze *et al.* [80] point at the necessity for development of new 5G security and privacy protocols, which maintain the security and privacy mechanisms among slices, while enabling higher security and privacy granularity, i.e., per slice that serves various sharing actors. Furthermore, Afolabi *et al.* [126] and Caballero *et al.* [136] point at security vulnerabilities that might arise from exposing resources in multiple network slices for sharing among different tenants. As Afolabi *et al.* [126] provide a specific focus on VNF sharing, the higher the level of sharing VNFs between tenants, the more likely are the security vulnerabilities [126]. Thus, Afolabi *et al.* bring into focus the service description project [169] that is developed for network slicing, proposing the use of additional quantitative or qualitative parameters to distinguish the levels of security required by individual slices. Although each slice must have independent security mechanisms, and even a more granular approach by enabling security mechanisms on the VNF level, Caballero *et al.* emphasize the importance of a multi-level security framework that defines policies for different slices in multiple administrative domains, in order to prevent unauthorized access to slice resources. The lack of such framework remains a barrier towards adopting multi-tenancy approach in network slicing and sharing [136]. A specific cross-domain focus in security is brought by Taleb *et al.* [138], pointing at opportunities of extending border security protocols among different administrative domains that are orchestrated by multi-domain service management.

Furthermore, although their approach refers to IoT, Silva *et al.* [71] address the general problem related to privacy: privacy must be ensured regardless of the specifics of resource sharing. Facilitating sharing on a proprietary device (IoT or not) brings risks in maintaining privacy. Therefore, in whichever way the resources are shared, the privacy of the users who are involved in sharing must not be compromised. Despite its huge importance as it directly impacts sharing actors, privacy has not been addressed widely and requires more work.

In the last ten years, blockchain technology gained significant attention, since it avoids a single point of failure, and the security bottleneck by storing a copy of database file at the premises of all sharing entities [84]. In particular, given the opportunity to generate and use multiple keys, blockchain allows users to retain and enjoy more privacy by chaining data with hashes and pairs of keys. As Rawat [84] pointed out, trust in blockchain is established due to the group consensus where transactions are authorized by all users in the network. Accordingly, there is a significant potential in blockchain to be leveraged by resource sharing, as it enables sharing copies of transaction records to all parties, i.e., sharing actors maintaining their own instance of the blockchain database.

g) Non-technical challenges: One of the primary goals of national regulators is to ensure competition among network operators (and/or other actors) [44], since it usually motivates operators to strive toward assuring better service quality as well as a pool of plentiful services and applications for the end users. However, such competition is tightly coupled with trust among operators, in particular when dealing with traffic monitoring and management of shared resources [44].

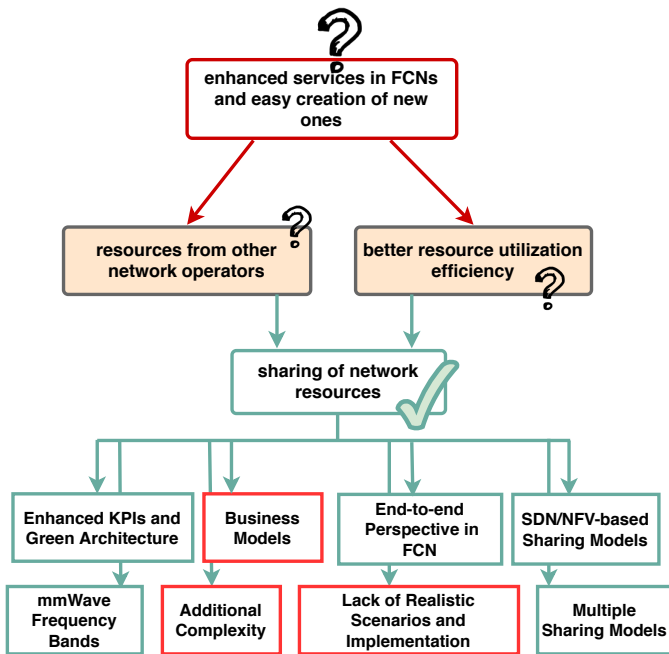


Fig. 9: The idea of sharing network resources in a nutshell; Summarized benefits and open questions

From the perspective of other market players (i.e., in addition to the operators), Silva *et al.* [71] study the competition which emerges from cooperation and sharing between constrained and unconstrained devices. Their work indicates that the instances of devices from the same pool (i.e., unconstrained/constrained) should assist their neighbors and share with them the resources provided by devices from the other pool (i.e., constrained/unconstrained). However, the authors also press to limit this kind of assistance in order to avoid exhausting of available energy of both types of devices. All of the above open issues provide a reason to urgently tackle the need for a new business model tailored to FCNs, which defines fair strategies of sharing and assures benefits for all sharing entities.

VIII. DISCUSSION AND OPEN QUESTIONS

Based on the overview shown in Fig. 9, in this section we summarize the survey and discuss some of the questions that remain to be addressed. In Fig. 9, the green boxes reflect the beneficial nature of resources sharing. Moreover, the red boxes highlight the topics that we think require more considerable study. Due to the dynamic and challenging environments of 5G networks, it is important to enable joint operation across both existing and new services, despite their substantial differences. Thus, FCNs need to enhance existing services, while being capable of properly utilizing the full 5G potential (i.e., enhanced spectral and network efficiency, smart security, self-driving cars, enhanced QoS and QoE). As presented in Fig. 9, there are two recognized paths that network designers and operators can take to achieve such goals and be able to cope with utmost stringent service requirements in FCNs. During the network planning and design phases, none of the operators can fully envision the amount of resources needed for proper service

operation. Given the fluctuating nature of wireless traffic, the previous problem becomes even more severe, leaving the operators with excess or shortage of resources. If not properly shared, a large portion of network resources that belong to a certain network operator would remain unutilized. From the overall elaboration provided in this survey, here we discuss and point at the the topics that either can be used as incentives for sharing or that need to be further addressed.

a) *Enhanced KPIs and green architecture*: The idea of sharing heterogeneous network resources basically means releasing those resources and temporarily leasing them to other entities/actors, e.g., while not in use. There are several challenges, as presented in Section VII, which still undermine the feasibility of resource sharing in real implementation scenarios. Nonetheless, sharing brings huge benefits in terms of enhanced KPIs and *green* network operations. The latter directly refers to the energy efficient FCNs, resulting in lower energy consumption which is particularly important in IoT scenarios, with devices with limited battery life. Some of the attempts to decrease energy consumption and thus increase the energy efficiency are presented in the survey, addressing energy sharing among devices in an IoT ecosystem as well as turning off the BTSs when traffic is low.

According to the various references studied in this survey, sharing of resources can lead to substantial savings if a resource orchestrator manages the sharing process between the slices. On the other hand, enhancing overall resource utilization by reducing the resource wastage potentially increases the possibility to accommodate even more operators in the same network. Therefore, if more operators coexist, it ultimately leads to increase in competition, which can further result in enriched and enhanced set of services for the end users. Focusing on the requirements of operators as well as users, this is beneficial for both, since increased demand for new enriched services also brings higher revenues for operators. However, achieving the optimal level of sharing resources is necessary in order to make a desirable trade-off between QoS/QoE and reduction of costs by decreasing the amount of infrastructure resources, and thus has to be studied more carefully. Furthermore, the government and environmental regulation bodies should enforce resource sharing, as they improve environmental and aesthetic conditions, as a result of lower number of locations occupied for installing network equipment, MBSs, FBSs, etc. This is particularly important for regulating 5G networks, whose high densification will introduce a significantly larger number of small cells and BTSs.

b) *Better interrelation between business and technical models*: Our ability to further elaborate on the coexistence between the business, geographic, and technical models, in Section IV-A, was limited by the lack in the literature of references that tackle them jointly. This might be justified by the fact that traditional business models tend to give operators the roles of owners of all network resources and do not include sharing as an option. Regardless of the opportunities and benefits, the real implementation of any architecture for resource sharing might not be even possible if an adequate business model is not generated in accordance with the regu-

lative framework. Such regulatory issues were recognized long ago but still trigger the need for suitable business models, that do not limit the feasibility of the technical models. Although the formal business models are out of the scope of our work, we want to at least emphasize their importance for the proper implementation of technical models. Based on that, operators should rethink their deep-rooted business models in order to evolve from owning to sharing of resources, and to align it with the actual regulation framework.

c) End-to-end perspective in FCN: Given the fact that 5G networks will be service-oriented, on-demand, and highly heterogeneous, there is a strong requirement to view, design, and optimize the network from an end-to-end perspective. In order to keep the 5G promises and to best serve stringent service requirements, it is essential to have an overview of all resources from wireless, optical, IoT, edge, and cloud domains, thereby spanning RAN, core network, and backhaul.

The idea to observe trends and sharing processes from such broad perspective is triggered throughout recognizing the same or similar trends in all domains, at the same or different period of time.

Although sharing of the core network used to be ambiguous due to the control functions being designed around operator's ownership, some advances are recently brought together by adopting SDN and virtualization. That explains the shortage in attempts to study and approach resource sharing in core networks, particularly around service differentiation and confidentiality, which needs to be kept within one operator's boundaries. In accordance with the SDN paradigm, while the data plane ultimately releases parts of the core network for sharing, at the same time the control plane remains unshared. Sharing the data plane of the core FCN enables service differentiation, while maintaining the operator's confidentiality. To the best of our knowledge, such broad perspective adopted in our survey differs from those in existing literature, which focus on one network domain and only specific types of resources. Thus, our survey aims at facilitating future research across diverse domains, enabling their convergence, where suitable.

d) SDN and virtualization as enablers for future sharing: The recently proposed sharing frameworks based on virtualization and SDN are quite broad and thus widely exploited for sharing resources in different domains. In particular, the main function of such sharing frameworks is to establish multiple virtual network instances, by splitting network elements into logically independent units running over the same physical substrate. These logically independent units can be further shared between different actors. Furthermore, the control architecture of the SDN/NFV framework directly impacts the sharing process and its outcomes, and it was in a greater detail discussed in Section VI. Generally a hierarchical approach is favorable in optimizing the trade-off between complexity of the control entity and QoS/QoE levels. The control entity should consist of low-level and high-level controllers or resource brokers, combining benefits from both centralized and decentralized architectures. Another trade-off that deserves further attention in SDN/NFV enabled sharing is the balance between resource isolation and utilization efficiency in multi-tenant scenarios. Proper resource isolation is challenging, as it

was discussed in the previous section, but rather important for the operators to retain control of the resources, among which are those released for sharing. Such control is inevitable for operators in order to maintain adequate levels of security and privacy.

On the other hand, a complete isolation can imply a negative effect on resource utilization efficiency since it might significantly affect the sharing ability.

e) The potential which lays in mmWave bands: 5G networks are about to open new spectrum bands such as mmWave at frequencies between 30 and 300GHz, which can provide novel opportunities for spectrum sharing. The disadvantage of severe attenuation could be exploited to reuse frequencies within short distance [170], enabling cell densification. At the same time, higher densification will lead to higher sharing, in order to lower cost of network ownership. According to the FCC, the larger bandwidth available at such frequencies could potentially be competitive with fiber optics in the access network, or used jointly with fibre to provide additional resilience. Nevertheless, the deployment of services on such high frequencies has to be studied in depth due to upcoming challenges, such as 5G band selection and the unbalance between wideband spectrum availability and high data rates, the unbalance between UL and DL coverage, new investments in denser cell deployments, etc. More detailed information on the topic can be found in the FCC's proceeding [171].

f) Additional complexity: Regardless of the way in which it is implemented, adding sharing functionality to the control and management plane of the network infrastructure increases its overall complexity. Thus, it is essential to address the trade-off between complexity and KPIs' improvements enabled by sharing. In particular, additional complexity will result in deployment of additional equipment, which can increase costs and thus offset the sharing benefits. Another source of complexity, relative to SDN is the increase in delay and signaling traffic caused by centralized architectures. As it was elaborated in the paper, some researchers proposed solutions consisting in moving client evaluation entities (i.e., command/queries, data aggregation and data fusion algorithms, etc.) closer to the shared resources [95] or else balancing the tasks between the SDN controller and the BTSs. In general, within the scope of FCNs, the scalability issues related to increase in complexity for network sharing requires further study.

g) Lack of realistic scenarios: Within the literature we examined, we found several sharing models and architectures. However, there is a notable lack of realistic scenarios in their implementation, since the vast majority of the sharing models have either only theoretical foundation or their testing and validation results are obtained in a simulated environment. Apparently, the lack of adequate tools motivates researchers to extend the existing simulators or to implement new ones. This might lead to a large number of model-specific tools and software platforms which cannot be used in different environments. Taking into consideration the number of publications that we studied during preparing this survey, we realized that there is a significant lack in realistic approaches. But, there are only few attempts to mimic the real environment for the implementation of sharing resources, and we mention them

here, as they might be useful to understand what can be already tested in a more realistic manner. Despite the theoretical base of their sharing approach, Kouvelas *et al.* [94] examined measurements from 280 households as a part of a large IoT environment. The idea for sharing energy inside the microgrid network was initiated from such real scenario. Furthermore, the cost of designing a full virtual optical mesh network topology was illustrated on a sample Italian network in order to evaluate the sharing mechanism in [28]. Indeed, the only attempt to implement sharing resources known to the authors is provided by Vilalta *et al.* [31]. In that case, the virtual optical network resource broker for EONs is incorporated into resource management algorithms which are evaluated in a corresponding testbed environment. The resource broker was in charge of managing virtual elastic optical resources and deploying virtual optical networks on the shared physical infrastructure. Their experimentation in the testbed confirmed feasibility of the proposed algorithms. Another realistic approach which primarily includes experimenting on testbeds, although here resource sharing is intended in the more general sense of testbed federation, is recently presented by Both *et al.* [172]. Their solution encompasses multiple geographically distributed testbeds, used to orchestrate resources and to automatically scale services across multiple domains (wireless, optical, and cloud) [172].

h) Multiple sharing models: Throughout this paper, we have emphasized how FCNs are envisioned to be strongly heterogeneous in technologies, devices, equipment, operators, etc. Thus, it is essential to find a way to harmonize sharing processes end-to-end and fulfil demands for services in wireless and optical domains, altogether with IoT, edge, and cloud paradigms. All of the studied approaches presented in the literature focus on either only one of the domains, or even more specifically they focus on the particular technology or service.

The aim to achieve harmonized sharing of resources with a single sharing model deployed in the network is too ambitious and highly challenging, and thus it is reasonable to consider the deployment of multiple sharing models operating in a joint manner. In particular, sharing models have to be tailored to the specific wireless and optical technologies, and especially to the IoT, edge, and cloud environments. Since all of the aforementioned areas are characterized by different requirements, single sharing models can be merged into multiple sharing model and deployed under the same software framework. An important and promising approach to support diverse experimental scenarios across multiple domains and testbeds was introduced in the previous paragraph. Namely, Both *et al.* [172] introduced inter-domain and inter-technology Control Framework to bridge the gap between optical, wireless, and cloud domains, enabling orchestration of diverse network resources.

IX. CONCLUSION

Sharing in the domain of communication networks is a paradigm which embraces a set of strategies that enable network operators to use their resources jointly in order to

reach a common goal: to provide and guarantee user services while achieving energy and cost reduction. As 5G networks are expected to be highly heterogeneous with customized services that impose highly specific and stringent QoS requirements, network operators will be forced to provide diverse network resources in order to answer such demands. Without sharing resources, the excessive growth in service requests becomes a heavy technological and economic burden for the operators. All of the aforementioned ultimately require a broad view on sharing of heterogeneous resources toward future communication network from the end-to-end perspective. Thus, our survey presented current and past trends in resource sharing and outlined the joint tendencies to share resources in both wireless and optical domains, with specific insight into IoT, edge, and cloud paradigms. Furthermore, it provided extensive discussion on existing sharing techniques as well as challenges, which have to be studied with more attention in order to meet the expected KPIs. Our taxonomy facilitates understanding all the processes included in the resource sharing, thus providing opportunities to design comprehensive sharing models for FCNs.

Spanning both tangible and intangible resources, from wireless, optical, IoT, edge, and cloud domains, these models will empower the research community to build more efficient next generation communication networks. Thus, our survey paves the way toward bringing more efficiency and flexibility to network architectures, which is a seminal point for future research directions.

X. ANNEX

ACRONYMS

3GPP 3rd Generation Partnership Project
5G NORMA 5G NOvel Radio Multiservice adaptive network Architecture
ACN Avoid Close Neighbors
AI Artificial Intelligence
AP Access Point
B2B Business to Business
B2B2C Business to Business to Consumers
B2C Business to Consumers
BBF Broadband Forum
BBU Baseband Unit
BSC Base Station Controller
BTS Base Transceiver Station
CO Central Office
CPRI Common Public Radio Interface
C-RAN Centralized Radio Access Network
CapEx Capital Expenditure
CR Cognitive Radio
CSA Constant Spectrum Allocation
DAD Dynamic Alternate Direction
DAS Distributed Antenna System
D-RAN Distributed Radio Access Network
D2D Device to Device
DL downlink
DSA Dynamic Spectrum Allocation
EC-RAN Enhanced Cloud RAN

EMC Electromagnetic Compatibility
eMMB enhanced Mobile Broadband
EON Elastic Optical Network
EPC Evolved Packet Core
ETSI European Telecommunications Standards Institute
eUTRAN Evolved Universal Terrestrial RAN
FBS Femto BTS
FCC U.S. Federal Communication Commission
FCN Future Communication Network
FDD Frequency Division Duplex
GGSN Gateway GPRS Support Node
GMSC Gateway Mobile Switching Center
GPP General Purpose Processor
GWCN Gateway Core Network
HLR Home Location Register
HSS Home Subscriber Server
IBFD In-Band Full Duplex
InP Infrastructure Provider
INT Inband Network Telemetry
IoT Internet of Things
IP Internet Protocol
ISP Internet Service Provider
KPI Key Performance Indicator
LAA License Assisted Access
LSA Licensed Shared Access
LTE Long-Term Evolution
LTE-U LTE-Unlicensed
LWA LTE-Wi-Fi Aggregation
M2M Machine-to-Machine
MAC Medium Access Control
MANO Management and Orchestration
MBS Macro BTS
MBSS Middleware Based Server System
MEC Multi-Access Edge Computing
MILP Mixed Integer Linear Programming
MIMO Multiple Input Multiple Output
MME Mobility Management Entity
mMTC massive Machine Type Communication
mmWave millimeter wave
MNO Mobile Network Operator
MOCN Multi-Operator Core Network
MORAN Multi-Operator Radio Access Network
MVNO Mobile Virtual Network Operator
NB-IoT Narrowband Internet of Things
NeBV Network-based Virtualization
NFV Network Function Virtualization
NISP National Industrial Symbiosis Program
NoBV Node-based Virtualization
NOMA Non-Orthogonal Multiple Access
NR New Radio
ODN Optical Distribution Network
OEO Optical-Electrical-Optical
OLT Optical Line Terminal
ONF Optical Networking Foundation
ONU Optical Network Unit
OpEx Operational Expenditure
OTT Over The Top
P2P Point-to-Point

PAYG Pay As You Go
PGW Packet data network Gateway
PKI Public Key Infrastructure
PON Passive Optical Network
QoE Quality of Experience
QoS Quality of Service
QoT Quality of Transmission
RAN Radio Access Network
RF Radio Frequency
RNC Radio Network Controller
ROADM Reconfigurable Optical Add/Drop Multiplexers
ROI Return of Investments
RRH Remote Radio Head
SDN Software Defined Network
SDO Software Defined Optics
SDR Software Defined Radio
SGSN Serving GPRS Support Node
SGW Serving Gateway
SLA Service Level Agreement
SP Service Provider
SWS Sub-Wavelength Sharing
TDD Time Division Duplex
TIP Telecom Infra Project
TVWS TV White Space
UE User Equipment
UL uplink
uRLLC ultra-Reliable Low Latency Communication
VHF Very High Frequency
VLR Visitor Location Register
VNF Virtual Network Function
VNO Virtual Network Operator
VPN Virtual Private Network
WDM Wavelength Division Multiplexing
WSN Wireless Sensor Network

REFERENCES

- [1] D. Appleby, "Shared goods," pp. 128–150. [Online] Available: <https://bit.ly/2Uxy6AN>.
- [2] Y. Al-Yasir, *Fundamentals of 5G mobile networks*. 05 2018. [Online] Available: https://www.researchgate.net/publication/324862482_Fundamentals_of_5G_mobile_networks.
- [3] B. Martucci, "What is the sharing economy – example companies, definition, pros & cons," october 2018. [Online] Available: <https://bit.ly/2k81Vm4>.
- [4] K. McBride, "Sharing cities: a case for truly smart and sustainable cities by Duncan McLaren and Julian Agyeman, Cambridge, MA, MIT Press, 2015, 445 pp., \$32.00 (hardback), 978-0-262-02972-8," *Urban Geography*, 2016. doi: <http://dx.doi.org/10.1080/02723638.2016.1235934>.
- [5] V. Behrends, J. G. Bundy, A. B. Phillimore, T. Bell, D. Lawrence, T. G. Barraclough, and F. Fiegna, "Species Interactions Alter Evolutionary Responses to a Novel Environment," *PLoS Biology*, vol. 10, no. 5, p. e1001330, 2012. doi: <http://dx.doi.org/10.1371/journal.pbio.1001330>.
- [6] J. G. Ojalvo, "Dynamical strategies for resource sharing in bacterial Dynamical strategies for resource sharing in bacteria," 2018. [Online] Available: http://www.solvayinstitutes.be/event/workshop/dynamics_2018/talks/garcia_ojalvo.pdf.
- [7] A. Bousia, E. Kartsakli, A. Antonopoulos, L. Alonso, and C. Verikoukis, "Game-Theoretic infrastructure sharing in multioperator cellular networks," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 3326–3341, 2016. doi: <http://dx.doi.org/10.1109/TVT.2015.2445837>.

- [8] Cisco and I. Cisco Systems, "Cisco Visual Networking Index: Forecast and Trends, 2018-2023," [Online] Available: <https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html>.
- [9] 5G-ACIA, "5G for Connected Industries and Automation (White Paper - Second Edition)," no. November, p. 28, 2018. [Online] Available: <https://bit.ly/2BGSMLA>.
- [10] N. Afraz and M. Ruffini, "A sharing platform for multi-tenant pons," *Journal of Lightwave Technology*, vol. 36, pp. 5413–5423, Dec 2018. doi: <http://dx.doi.org/10.1109/JLT.2018.2875188>.
- [11] J. M. Márquez-Barja, M. Ruffini, N. J. Kaminski, N. Marchetti, L. Doyle, and L. A. DaSilva, "Decoupling resource ownership from service provisioning to enable ephemeral converged networks (ecns)," 2016. [Online] Available: <https://bit.ly/2InwwtL>.
- [12] Roya H. Tehrani, V. Seiamak, T. Dionysia, L. Haeyoung, and M. Klaus, "Licensed Spectrum Sharing Schemes for Mobile Operators : A Survey and Outlook," *IEEE Communications Surveys and Tutorials*, vol. 18, no. 4, pp. 1–33, 2016. doi: <http://dx.doi.org/10.1109/COMST.2016.2583499>.
- [13] G. R. Nair, Y. K. Moorthy, and S. S. Pillai, "A Survey on Dynamic Spectrum Sharing Using Game Theory In Cognitive Radio Networks," *International Journal of Research and Engineering*, vol. 03, no. 08, 2016. [Online] Available: <https://core.ac.uk/download/pdf/154060409.pdf>.
- [14] F. Hu, B. Chen, and K. Zhu, "Full Spectrum Sharing in Cognitive Radio Networks Toward 5G: A Survey," *IEEE Access*, vol. 6, no. c, pp. 15754–15776, 2018. doi: <http://dx.doi.org/10.1109/ACCESS.2018.2802450>.
- [15] L. Zhang, Y. C. Liang, and M. Xiao, "Sharing for Internet of Things: A Survey," *IEEE Wireless Communications*, 2018. doi: <http://dx.doi.org/10.1109/MWC.2018.1800259>.
- [16] A. M. Voicu, L. Simic, and M. Petrova, "Survey of Spectrum Sharing for Inter-Technology Coexistence," *IEEE Communications Surveys and Tutorials*, no. i, pp. 1–33, 2018. doi: <http://dx.doi.org/10.1109/COMST.2018.2882308>.
- [17] L. Zhang, M. Xiao, G. Wu, M. Alam, Y. C. Liang, and S. Li, "A Survey of Advanced Techniques for Spectrum Sharing in 5G Networks," 2017. doi: <http://dx.doi.org/10.1109/MWC.2017.1700069>.
- [18] Y. Ye, D. Wu, Z. Shu, and Y. Qian, "Overview of LTE Spectrum Sharing Technologies," *IEEE Access*, vol. 4, no. c, pp. 8105–8115, 2016. doi: <http://dx.doi.org/10.1109/ACCESS.2016.2626719>.
- [19] S. Talebi, F. Alam, I. Katib, M. Khamis, R. Salama, and G. N. Rouskas, "Spectrum management techniques for elastic optical networks: A survey," *Optical Switching and Networking*, vol. 13, no. 2, pp. 34–48, 2014. doi: <http://dx.doi.org/10.1016/j.osn.2014.02.003>.
- [20] A. Goldsmith, S. A. Jafar, I. Maric, and S. Srinivasa, "Breaking spectrum gridlock with cognitive radios: An information theoretic perspective," *Proceedings of the IEEE*, vol. 97, no. 5, pp. 894–914, 2009. doi: <http://dx.doi.org/10.1109/JPROC.2009.2015717>.
- [21] E. P. Goodman, "Spectrum Rights in the Telecom to Come," *San Diego Law Review*, vol. 41, p. 269, 2004. [Online] Available: <https://bit.ly/2Ho3LMu>.
- [22] T. W. Hazlett and B. Skourp, "Tragedy of the Regulatory Commons: Lightsquared and Missing Spectrum Rights," *Duke Law & Technology Review*, vol. 13, no. January, 2014. [Online] Available: <https://bit.ly/2YypuY0>.
- [23] W. S. H. M. W. Ahmad, N. A. M. Radzi, and F. S. Samidi, "5G technology : towards dynamic spectrum sharing using cognitive radio networks," *IEEE Access*, vol. PP, p. 1, 2020. doi: <http://dx.doi.org/10.1109/ACCESS.2020.2966271>.
- [24] A. Kliks, B. Musznicki, K. Kowalik, and P. Kryszkiewicz, "Perspectives for resource sharing in 5G networks," *Telecommunication Systems*, vol. 68, no. 4, pp. 605–619, 2018. doi: <http://dx.doi.org/10.1007/s11235-017-0411-3>.
- [25] S. Zahoor and R. N. Mir, "Virtualization of and iot resource management: A survey," *International Journal of Computer Networks And Applications*, vol. 5, no. 4, p. 43, 2018. doi: <http://dx.doi.org/10.22247/ijcna/2018/49435>.
- [26] A. P. Bianzino, C. Chaudet, D. Rossi, and J. L. Rougier, "A survey of green networking research," *IEEE Communications Surveys and Tutorials*, vol. 14, no. 1, pp. 3–20, 2012. doi: <http://dx.doi.org/10.1109/SURV.2011.113010.00106>.
- [27] L. Mamushiane, A. A. Lysko, and S. Dlamini, "SDN-enabled Infrastructure Sharing in Emerging Markets: CapEx/OpEx Savings Overview and Quantification," *2018 IST-Africa Week Conference (IST-Africa)*, pp. Page 1 of 10–Page 10 of 10, 2018. [Online] Available: <https://bit.ly/2D9E2oD>.
- [28] M. Ali, "Shareability in optical networks: beyond bandwidth optimization," *IEEE Communications Magazine*, vol. 42, pp. S11–S15, feb 2004. doi: <http://dx.doi.org/10.1109/MCOM.2003.1267096>.
- [29] O. Gerstel, I. , D. Klonidis, I. Tomkos, and E. Palkopoulou, "Dynamic Cooperative Spectrum Sharing and Defragmentation for Elastic Optical Networks," *Journal of Optical Communications and Networking*, vol. 6, no. 3, p. 259, 2014. doi: <http://dx.doi.org/10.1364/jocn.6.000259>.
- [30] D. Zhang, *Virtual Resource-Sharing Mechanisms in Software-Defined and Virtualized Wireless Network*. 2018. [Online] Available: <https://bit.ly/2UJXa6K>.
- [31] R. Vilalta, R. Munoz, R. Casellas, and R. Martinez, "Dynamic deployment of virtual GMPLS-controlled elastic optical networks using a virtual network resource broker on the ADRENALINE testbed," *International Conference on Transparent Optical Networks*, pp. 2–5, 2013. doi: <http://dx.doi.org/10.1109/ICTON.2013.6602843>.
- [32] N. Afraz, A. Elrasad, and M. Ruffini, "Dba capacity auctions to enhance resource sharing across virtual network operators in multi-tenant pons," in *2018 Optical Fiber Communications Conference and Exposition (OFC)*, pp. 1–3, March 2018. [Online] Available: <https://ieeexplore.ieee.org/document/8386208>.
- [33] Y. Shi, M. Sheng, and F. He, "A resource management and control model supporting applications in the internet of things," in *Proceedings - 2011 IEEE International Conferences on Internet of Things and Cyber, Physical and Social Computing, iThings/CPSCOM 2011*, 2011. doi: <http://dx.doi.org/10.1109/iThings/CPSCOM.2011.27>.
- [34] A. M. Akhtar, X. Wang, and L. Hanzo, "Synergistic spectrum sharing in 5G HetNets: A harmonized SDN-enabled approach," *IEEE Communications Magazine*, 2016. doi: <http://dx.doi.org/10.1109/MCOM.2016.7378424>.
- [35] H. Kour, R. K. Jha, and S. Jain, "A comprehensive survey on spectrum sharing: Architecture, energy efficiency and security issues," *Journal of Network and Computer Applications*, vol. 103, no. November, pp. 29–57, 2018. doi: <http://dx.doi.org/10.1016/j.jnca.2017.11.010>.
- [36] Y. Han, E. Ekici, H. Kremo, and O. Altintas, "Spectrum sharing methods for the coexistence of multiple RF systems: A survey," *Ad Hoc Networks*, vol. 53, pp. 53–78, 2016. doi: <http://dx.doi.org/10.1016/j.adhoc.2016.09.009>.
- [37] R. Gould and J. Kelleher, "Frequency Sharing Between the Broadcasting-Satellite Service and Other Radiocommunication Services," *IEEE Journal on Selected Areas in Communications*, vol. 3, no. 1, pp. 25–35, 2008. doi: <http://dx.doi.org/10.1109/jsac.1985.1146190>.
- [38] T. A. Prosch, "A possible frequency planning method and related model calculations for the sharing of vhf band ii (87.5-108 mhz) between fm and dab (digital audio broadcast) systems," 1991. doi: <http://dx.doi.org/10.1109/11.86962>.
- [39] V. K. Varma, H. W. Arnold, D. M. J. Devasirvatham, A. Ranade, and L. G. Sutliff, "Interference, Sensitivity and capacity Analysis for Measurement-Based Wireless Access Spectrum Sharing," *IEEE Transactions on Vehicular Technology*, vol. 43, no. 3, pp. 611–616, 1994. doi: <http://dx.doi.org/10.1109/25.312812>.
- [40] S. Tridandapani and B. Mukherjee, "Multicast traffic in multi-hop lightwave networks: performance analysis and an argument for channel sharing," vol. 15, no. 3, pp. 488–500, 1997. doi: <http://dx.doi.org/10.1109/49.564144>.
- [41] G. J. Foschini, "Sharing of the Optical Band in Local Systems," *IEEE Journal on Selected Areas in Communications*, vol. 6, no. 6, pp. 974–986, 1988. doi: <http://dx.doi.org/10.1109/49.1960>.
- [42] P. Papadimitratos, S. Sankaranarayanan, and A. Mishra, "A Bandwidth Sharing Approach to Improve Licensed Spectrum Utilization," *IEEE Communications Magazine*, vol. 43, no. 12, pp. S10–S14, 2005. doi: <http://dx.doi.org/10.1109/MCOM.2005.1561918>.
- [43] J. M. Peha, "Approaches to spectrum sharing," *IEEE Communications Magazine*, vol. 43, no. 2, 2005. doi: <http://dx.doi.org/10.1109/MCOM.2005.1391490>.
- [44] J. Hultell, K. Johansson, and J. Markendahl, "Business models and resource management for shared wireless networks," no. May, pp. 3393–3397, 2005. doi: <http://dx.doi.org/10.1109/vetecf.2004.1404693>.
- [45] F. C. Commission, "Report and Order and Order on Demand and Further Notice of Proposed Rulemaking," *FCC's proceedings*, 2003. [Online] Available: <https://bit.ly/2Kbmcqn>.
- [46] W. Jones, "Share and share not," *IEEE Spectrum*, vol. 40, no. 4, pp. 19–21, 2003. doi: <http://dx.doi.org/10.1109/mspec.2003.1191779>.
- [47] I. F. Akyildiz, W. Y. Lee, M. C. Vuran, and S. Mohanty, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Computer Networks*, 2006. doi: <http://dx.doi.org/10.1016/j.comnet.2006.05.001>.

- [48] H. Sarvanko, M. Höyhty, M. Katz, and F. H. P. Fitzek, "Distributed resources in wireless networks: Discovery and cooperative uses," *ERCIM eMobility Workshop*, 2010. doi: <http://dx.doi.org/10.1073/pnas.0703993104>.
- [49] M. C. V. S. M. Ian F. Akyildiz, Won-yeol Lee, "A survey on spectrum management in cognitive radio networks," *IEEE Communications Magazine*, vol. 46, no. 4, pp. 40–48, 2008. doi: <http://dx.doi.org/10.1109/MCOM.2008.4481339>.
- [50] J. M. Peha, "Sharing Spectrum Through Spectrum Policy Reform and Cognitive Radio," *Proceedings of the IEEE*, vol. 97, no. 4, pp. 708–719, 2009. doi: <http://dx.doi.org/10.1109/JPROC.2009.2013033>.
- [51] C. M. Sudharman K. Jayaweera, Gonzalo Vazquez-Vilar, "Dynamic Spectrum Leasing: A New Paradigm for Spectrum Sharing in Cognitive Radio Networks," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 5, pp. 2328–2339, 2010. doi: <http://dx.doi.org/10.1109/TVT.2010.2042741>.
- [52] F. R. Y. V. C. M. L. Pengbo Si, Hong Ji, "Optimal Cooperative Internetwork Spectrum Sharing for Cognitive Radio Systems With Spectrum Pooling," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 5, pp. 1760–1768, 2010. doi: <http://dx.doi.org/10.1109/TVT.2010.2041941>.
- [53] K. B. L. Karama Hamdi, Wei Zhang, "Opportunistic spectrum sharing in cognitive MIMO wireless networks," *IEEE Transactions on Wireless Communications*, vol. 8, no. 5, pp. 4098–4109, 2009. doi: <http://dx.doi.org/10.1109/TWC.2009.080528>.
- [54] M. J. Marcus, "Sharing government spectrum with private users: opportunities and challenges," *IEEE Wireless Communications*, vol. 16, no. 3, pp. 4–5, 2009. doi: <http://dx.doi.org/10.1109/MWC.2009.5109457>.
- [55] T. Frisanco, P. Tafertshofer, P. Lurin, and R. Ang, "Infrastructure Sharing for Mobile Network Operators," *Conference proceedings of The International Conference on Information Networking*, pp. 444–448, 2008. doi: <http://dx.doi.org/10.1109/ICOIN.2008.4472768>.
- [56] D. E. Meddour, T. Rasheed, and Y. Gourhant, "On the role of infrastructure sharing for mobile network operators in emerging markets," *Computer Networks*, 2011. doi: <http://dx.doi.org/10.1016/j.comnet.2011.01.023>.
- [57] W. J. D. H. Pedro Javier del Cid, Sam Michiels, "Middleware for resource sharing in multi-purpose Wireless Sensor Networks," 2010. doi: <http://dx.doi.org/10.1109/NESEA.2010.5678061>.
- [58] T. E. Darcie, N. Barakat, P. P. Iannone, and K. C. Reichmann, "Wavelength sharing in WDM passive optical networks," *Optical Transmission, Switching, and Subsystems VI*, vol. 7136, p. 71361I, 2008. doi: <http://dx.doi.org/10.1117/12.806535>.
- [59] J. Kibilda and L. A. Dasilva, "Efficient coverage through inter-operator infrastructure sharing in mobile networks," in *IFIP Wireless Days*, 2013. doi: <http://dx.doi.org/10.1109/WD.2013.6686480>.
- [60] E. Jorswieck, L. Badia, T. Fahldieck, E. Karipidis, and J. Luo, "Spectrum sharing improves the network efficiency for cellular operators," *IEEE Communications Magazine*, 2014. doi: <http://dx.doi.org/10.1109/MCOM.2014.6766097>.
- [61] J. M. Park, J. H. Reed, A. A. Beex, T. C. Clancy, V. Kumar, and B. Bahrak, "Security and enforcement in spectrum sharing," *Proceedings of the IEEE*, 2014. doi: <http://dx.doi.org/10.1109/JPROC.2014.2301972>.
- [62] M. De Leenheer, J. Buysse, C. Develder, and B. Mukherjee, "Isolation and resource efficiency of virtual optical networks," in *2012 International Conference on Computing, Networking and Communications, ICNC'12*, 2012. doi: <http://dx.doi.org/10.1109/ICCNC.2012.6167543>.
- [63] R. Vilalta, R. Muñoz, R. Casellas, and R. Martínez, "Dynamic virtual GMPLS-controlled WSON using a Resource Broker with a VNT Manager on the ADRENALINE testbed," *Optics Express*, 2012. doi: <http://dx.doi.org/10.1364/oe.20.029149>.
- [64] F. A. Khandaker, J. P. Jue, X. Wang, Q. Zhang, Q. She, H. C. Cankaya, P. Palacharla, and M. Sekiya, "Statistical capacity sharing for variable-rate connections in flexible grid optical networks," in *2015 IEEE Global Communications Conference, GLOBECOM 2015*, 2015. doi: <http://dx.doi.org/10.1109/GLOCOM.2014.7417756>.
- [65] F. A. Khandaker, X. Wang, Q. Zhang, H. C. Cankaya, I. Kim, T. Ikeuchi, and J. P. Jue, "Statistical sharing of primary and back-up capacity in survivable elastic optical networks," in *GLOBECOM 2017 - 2017 IEEE Global Communications Conference*, pp. 1–6, 2017. doi: [10.1109/GLOCOM.2017.8254765](http://dx.doi.org/10.1109/GLOCOM.2017.8254765).
- [66] X. Wang, Q. Zhang, I. Kim, P. Palacharla, and M. Sekiya, "Support Statistical Sharing in Circuit Switching WDM Optical Networks," 2013. doi: <http://dx.doi.org/10.1364/ofc.2013.otu3a.1>.
- [67] O. Pedrola, D. Careglio, M. Klinkowski, J. Solé-Pareta, and K. Bergman, "Cost Feasibility Analysis of Translucent Optical Networks With Shared Wavelength Converters," *Journal of Optical Communications and Networking*, 2013. doi: <http://dx.doi.org/10.1364/jocn.5.000104>.
- [68] A. Manolova, I. Cerutti, R. Muñoz, S. Ruepp, A. Giorgetti, N. Andriolli, N. Sambo, P. Castoldi, R. Martínez, and R. Casellas, "Distributed Sharing of Functionalities and Resources in Survivable GMPLS-Controlled WSONs," *Journal of Optical Communications and Networking*, 2012. doi: <http://dx.doi.org/10.1364/jocn.4.000219>.
- [69] E. Palkopoulou, I. Stiakogiannakis, D. Klondis, K. Christodouloupoulos, E. Varvarigos, O. Gerstel, and I. Tomkos, "Dynamic Cooperative Spectrum Sharing in Elastic Networks," 2013. doi: <http://dx.doi.org/10.1364/ofc.2013.otu3a.2>.
- [70] I. Stiakogiannakis, E. Palkopoulou, D. Klondis, O. Gerstel, and I. Tomkos, "Dynamic Cooperative Spectrum Sharing and Defragmentation for Elastic Optical Networks," *Journal of Optical Communications and Networking*, 2014. doi: <http://dx.doi.org/10.1364/jocn.6.000259>.
- [71] R. Silva, J. Sa Silva, and F. Boavida, "A symbiotic resources sharing IoT platform in the smart cities context," *2015 IEEE 10th International Conference on Intelligent Sensors, Sensor Networks and Information Processing, ISSNIP 2015*, no. April, pp. 7–9, 2015. doi: <http://dx.doi.org/10.1109/ISSNIP.2015.7106922>.
- [72] A. Kliem and O. Kao, "The Internet of Things Resource Management Challenge," *Proceedings - 2015 IEEE International Conference on Data Science and Data Intensive Systems; 8th IEEE International Conference Cyber, Physical and Social Computing; 11th IEEE International Conference on Green Computing and Communications and 8th IEEE International Conference on Internet of Things, DSDIS/CPSCOM/GreenCom/iThings 2015*, pp. 483–490, 2015. doi: <http://dx.doi.org/10.1109/DSDIS.2015.21>.
- [73] M. Rebato, M. Mezzavilla, S. Rangan, and M. Zorzi, "The Potential of Resource Sharing in 5G Millimeter-Wave Bands," no. 14, 2016. [Online] Available: <https://bit.ly/1S4Nr2N>.
- [74] A. K. Gupta, J. G. Andrews, and R. W. Heath, "On the Feasibility of Sharing Spectrum Licenses in mmWave Cellular Systems," *IEEE Transactions on Communications*, vol. 64, no. 9, pp. 3981–3995, 2016. doi: <http://dx.doi.org/10.1109/TCOMM.2016.2590467>.
- [75] L. Wan and H. T. Co, "4G / 5G Spectrum Sharing for Enhanced Mobile Broad-Band and IoT Services," *IEEE Vehicular Technology Magazine*, p. 10, 2018. doi: <http://dx.doi.org/10.1109/MVT.2018.2865830>.
- [76] O. Al-Khatib, W. Hardjawana, and B. Vucetic, "Spectrum Sharing in Multi-Tenant 5G Cellular Networks: Modeling and Planning," *IEEE Access*, vol. 7, pp. 1602–1616, 2019. doi: <http://dx.doi.org/10.1109/ACCESS.2018.2886447>.
- [77] S. A. A. Shah, E. Ahmed, M. Imran, and S. Zeadally, "5g for vehicular communications," *IEEE Communications Magazine*, vol. 56, pp. 111–117, Jan 2018. doi: <http://dx.doi.org/10.1109/MCOM.2018.1700467>.
- [78] C. Liang and F. R. Yu, "Wireless Network Virtualization: A Survey, Some Research Issues and Challenges," *IEEE Communications Surveys and Tutorials*, vol. 17, no. 1, pp. 358–380, 2015. doi: <http://dx.doi.org/10.1109/COMST.2014.2352118>.
- [79] B. Blanco, J. Oscar, I. Giannoulakis, E. Kafetzakis, S. Peng, J. Pérez-romero, I. Trajkovska, P. S. Khodashenas, L. Goratti, M. Paolino, E. Sfakianakis, F. Liberal, and G. Xilouris, "Computer Standards & Interfaces Technology pillars in the architecture of future 5G mobile networks : NFV , MEC and SDN," *Computer Standards & Interfaces*, vol. 54, no. January, pp. 216–228, 2017. doi: <http://dx.doi.org/10.1016/j.csi.2016.12.007>.
- [80] A. A. Barakabitze, A. Ahmad, R. Mijumbi, and A. Hines, "5G network slicing using SDN and NFV : A survey of taxonomy , architectures and future challenges," vol. 167, 2020. doi: <http://dx.doi.org/10.1016/j.comnet.2019.106984>.
- [81] H. Zhang, N. Liu, X. Chu, K. Long, A. H. Aghvami, and V. C. Leung, "Network Slicing Based 5G and Future Mobile Networks: Mobility, Resource Management, and Challenges," *IEEE Communications Magazine*, vol. 55, no. 8, pp. 138–145, 2017. doi: <http://dx.doi.org/10.1109/MCOM.2017.1600940>.
- [82] X. Li, M. Samaka, H. A. Chan, D. Bhamare, L. Gupta, C. Guo, and R. Jain, "Network Slicing for 5G: Challenges and Opportunities," *IEEE Internet Computing*, vol. 21, no. 5, pp. 20–27, 2017. doi: <http://dx.doi.org/10.1109/MIC.2017.3481355>.
- [83] K. Han, S. Li, S. Tang, H. Huang, S. Zhao, G. Fu, and Z. Zhu, "Application-Driven End-to-End Slicing: When Wireless Network Virtualization Orchestrates With NFV-Based Mobile Edge Computing," *IEEE Access*, vol. 6, pp. 26567–26577, 2018. doi: <http://dx.doi.org/10.1109/ACCESS.2018.2834623>.

- [84] D. B. Rawat, "Fusion of Software Defined Networking, Edge Computing, and Blockchain Technology for Wireless Network Virtualization," *IEEE Communications Magazine*, vol. 57, no. October, pp. 50–55, 2019. doi: <http://dx.doi.org/10.1109/MCOM.001.1900196>.
- [85] B. Yin, W. Shen, Y. Cheng, L. X. Cai, and Q. Li, "Distributed Resource Sharing in Fog-assisted Big Data Streaming," in *2017 IEEE International Conference on Communications (ICC)*, pp. 1–6, May 2017. doi: <http://dx.doi.org/10.1109/ICC.2017.7996724>.
- [86] A. Elrasad, N. Afraz, and M. Ruffini, "Virtual dynamic bandwidth allocation enabling true pon multi-tenancy," in *2017 Optical Fiber Communications Conference and Exhibition (OFC)*, pp. 1–3, March 2017. Online [Available]: <https://ieeexplore.ieee.org/document/7936877>.
- [87] A. Elrasad and M. Ruffini, "Frame level sharing for dba virtualization in multi-tenant pons," in *2017 International Conference on Optical Network Design and Modeling (ONDM)*, pp. 1–6, May 2017. doi: <http://dx.doi.org/10.23919/ONDM.2017.7958528>.
- [88] M. R. Raza, M. Fiorani, A. Rostami, P. Ohlen, L. Wosinska, and P. Monti, "Demonstration of Dynamic Resource Sharing Benefits in an Optical C-RAN," *Journal of Optical Communications and Networking*, vol. 8, no. 8, p. 621, 2016. doi: <http://dx.doi.org/10.1364/jocn.8.000621>.
- [89] P. M. et. al., "Optical and wireless network convergence in 5G systems - an experimental approach," 2018. doi: <http://dx.doi.org/10.1109/CAMAD.2018.8514972>.
- [90] C. K. Dominicini, C. B. Both, J. A. Wickboldt, R. Nejabati, D. F. Macedo, J. Marquez-Barja, and L. da Silva, "Enabling Experimental Research Through Converged Orchestration of Optical Wireless and Cloud Domains," *European Conference on Networks and Communications (EuCNC)*, no. i, pp. 1–2, 2018. [Online] Available: <https://bit.ly/2wLqsUV>.
- [91] P. Alvarez, F. Slyne, C. Bluemm, J. M. Marquez-Barja, L. A. DaSilva, and M. Ruffini, "Experimental Demonstration of SDN-controlled Variable-rate Fronthaul for Converged LTE-over-PON," 2018. doi: <http://dx.doi.org/10.1364/ofc.2018.th2a.49>.
- [92] F. Slyne, R. Guimaraes, Y. Zhang, M. Martinello, R. Nejabati, M. Ruffini, and L. DaSilva, "Coordinated fibre and wireless spectrum allocation in sdn-controlled wireless-optical-cloud converged architecture," in *2019 European Conference on Optical Communications (ECOC)*, pp. 1–3, September 2019. Online [Available]: <https://www.ecoc2019.org/demo.html>.
- [93] E. Municio, J. Marquez-Barja, S. Latré, and S. Vissicchio, "Whisper: Programmable and flexible control on industrial IoT networks," *Sensors (Switzerland)*, 2018. doi: <http://dx.doi.org/10.3390/s18114048>.
- [94] N. Kouvelas, V. Balasubramanian, A. G. Voyiatzis, R. R. Prasad, and D. Pesch, "On inferring how resources are shared in IoT ecosystems; a graph theoretic approach," *IEEE World Forum on Internet of Things, WF-IoT 2018 - Proceedings*, vol. 2018-January, pp. 760–766, 2018. doi: <http://dx.doi.org/10.1109/WF-IoT.2018.8355137>.
- [95] G. Yildirim and Y. Tatar, "Simplified Agent-Based Resource Sharing Approach for WSN-WSN Interaction in IoT/CPS Projects," *IEEE Access*, vol. 6, no. c, pp. 78077–78091, 2018. doi: <http://dx.doi.org/10.1109/ACCESS.2018.2884741>.
- [96] N. S. Vo, T. Q. Duong, M. Guizani, and A. Kortun, "5G optimized caching and downlink resource sharing for smart cities," *IEEE Access*, vol. 6, pp. 31457–31468, 2018. doi: <http://dx.doi.org/10.1109/ACCESS.2018.2839669>.
- [97] L. Tom, C. Tselios, D. M. Area, and G. Tsolis, "On the deployment of an open-source, 5G-aware evaluation testbed," 2018. doi: <http://dx.doi.org/10.1109/MobileCloud.2018.00016>.
- [98] A. Kostopoulos, G. Agapiou, F. C. Kuo, K. Pentikousis, A. Cipriano, D. Panaitopol, D. Marandin, K. Kowalik, K. Alexandris, C. Y. Chang, N. Nikaen, M. Goldhamer, A. Kliks, R. Steinert, A. Mammela, and T. Chen, "Scenarios for 5G networks: The COHERENT approach," *2016 23rd International Conference on Telecommunications, ICT 2016*, 2016. doi: <http://dx.doi.org/10.1109/ICT.2016.7500421>.
- [99] J. Isnard, "Frequency band sharing: utopia or reality? Towards specification of operational scenarios," *IEEE Aerospace and Electronic Systems Magazine*, vol. 17, no. 5, pp. 4–9, 2002. doi: <http://dx.doi.org/10.1109/62.1001985>.
- [100] S. Satkunarajah, K. Ratnam, and R. G. Ragel, "Pre-configured backup protection with limited resource sharing in elastic optical networks," *2015 IEEE 10th International Conference on Industrial and Information Systems, ICIIIS 2015 - Conference Proceedings*, pp. 513–518, 2016. doi: <http://dx.doi.org/10.1109/ICIINFS.2015.7399065>.
- [101] B. Chen, Y. Zhao, and J. Zhang, "Survivable spectrum-shared ability in flexible bandwidth optical networks with distributed data centers," *Photonic Network Communications*, vol. 33, no. 2, pp. 102–111, 2017. doi: <http://dx.doi.org/10.1007/s11107-016-0642-3>.
- [102] S. N. Khan, L. Goratti, R. Riggio, and S. Hasan, "On active, fine-grained RAN and spectrum sharing in multi-tenant 5G networks," in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC*, 2018. doi: <http://dx.doi.org/10.1109/PIMRC.2017.8292672>.
- [103] F. Fund, S. Shahsavari, S. S. Panwar, E. Erkip, and S. Rangan, "Spectrum and Infrastructure Sharing in Millimeter Wave Cellular Networks: An Economic Perspective," 2016. [Available] Online: <https://bit.ly/2LcBpJ5>.
- [104] P. Luoto, P. Pirinen, M. Bennis, S. Samarakoon, S. Scott, and M. Latva-Aho, "Co-primary multi-operator resource sharing for small cell networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 6, pp. 3120–3130, 2015. doi: <http://dx.doi.org/10.1109/TWC.2015.2402671>.
- [105] M. A. Marotta, N. Kaminski, I. Gomez-Miguelez, L. Z. Granville, J. Rochol, L. DaSilva, and C. B. Both, "Resource sharing in heterogeneous cloud radio access networks," *IEEE Wireless Communications*, vol. 22, no. 3, pp. 74–82, 2015. doi: <http://dx.doi.org/10.1109/MWC.2015.7143329>.
- [106] M. Rebato, M. Mezzavilla, S. Rangan, and M. Zorzi, "Resource sharing in 5G mmWave cellular networks," *Proceedings - IEEE INFOCOM*, vol. 2016-September, no. mmNet, pp. 271–276, 2016. doi: <http://dx.doi.org/10.1109/INFCOMW.2016.7562085>.
- [107] R. Yu, J. Ding, X. Huang, M. T. Zhou, S. Gjessing, and Y. Zhang, "Optimal Resource Sharing in 5G-Enabled Vehicular Networks: A Matrix Game Approach," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 10, pp. 7844–7856, 2016. doi: <http://dx.doi.org/10.1109/TVT.2016.2536441>.
- [108] G. Salami, O. Durowoju, A. Attar, O. Holland, R. Tafazolli, and H. Aghvami, "A comparison between the centralized and distributed approaches for spectrum management," *IEEE Communications Surveys and Tutorials*, vol. 13, no. 2, pp. 274–290, 2011. doi: <http://dx.doi.org/10.1109/SURV.2011.041110.00018>.
- [109] J. M. Batalla, C. X. Mavromoustakis, G. Mastorakis, and K. Sienkiewicz, "Internet of Things (IoT) in 5G Mobile Technologies," vol. 8, pp. 25–36, 2016. doi: <http://dx.doi.org/10.1007/978-3-319-30913-2>.
- [110] Ning-Hai Bao, Le-Min Li, Hong-Bin Luo, Zhi-Zhong Zhang, and Hong-Fang Yu, "On Exploiting Sharable Resources With Resource Contention Resolution for Surviving Double-Link Failures in Optical Mesh Networks," *Journal of Lightwave Technology*, vol. 30, no. 17, pp. 2788–2795, 2012. doi: <http://dx.doi.org/10.1109/jlt.2012.2208178>.
- [111] J. Thangaraj, P. D. Mankar, and R. Datta, "Improved shared resource allocation strategy with SLA for survivability in WDM optical networks," *Journal of Optics*, vol. 39, no. 2, pp. 57–75, 2011. doi: <http://dx.doi.org/10.1007/s12596-010-0022-9>.
- [112] C. Li, W. Guo, W. Wang, W. Hu, and M. Xia, "Bandwidth Resource Sharing on the XG-PON Transmission Convergence Layer in a Multi-operator Scenario," *Journal of Optical Communications and Networking*, vol. 8, no. 11, p. 835, 2016. doi: <http://dx.doi.org/10.1364/jocn.8.000835>.
- [113] C. Beckman and G. Smith, "Accepted from open call - Shared networks: making wireless communication affordable," *IEEE Wireless Communications*, vol. 12, no. 2, pp. 78–85, 2005. doi: <http://dx.doi.org/10.1109/mwc.2005.1421931>.
- [114] A. Pagani and K. Mikhaylov, "Resource sharing between neighboring nodes in heterogeneous wireless sensor networks," pp. 522–527, 2015. doi: <http://dx.doi.org/10.1109/EuCNC.2015.7194130>.
- [115] T. Frisanco, P. Tafertshofer, P. Lurin, and R. Ang, "Infrastructure sharing and shared operations for mobile network operators from a deployment and operations view," in *NOMS 2008 - 2008 IEEE Network Operations and Management Symposium*, pp. 129–136, April 2008. doi: <http://dx.doi.org/10.1109/NOMS.2008.4575126>.
- [116] V. Angelakis, I. Avgouleas, N. Pappas, E. Fitzgerald, and D. Yuan, "Allocation of Heterogeneous Resources of an IoT Device to Flexible Services," *IEEE Internet of Things Journal*, vol. 3, no. 5, pp. 691–700, 2016. doi: <http://dx.doi.org/10.1109/JIOT.2016.2535163>.
- [117] C. Li, W. Guo, W. Wang, W. Hu, and M. Xia, "PON bandwidth resource sharing schemes in a multi-operator scenario," pp. 397–401, 2017. doi: <http://dx.doi.org/10.1109/ICNC.2017.7876161>.
- [118] T. Taleb, S. Member, K. Samdanis, B. Mada, H. Flinck, S. Dutta, and D. Sabella, "On Multi-Access Edge Computing : A Survey of the Emerging 5G Network Edge Cloud Architecture and Orchestration," vol. 19, no. 3, pp. 1657–1681, 2017. doi: <http://dx.doi.org/10.1109/COMST.2017.2705720>.
- [119] M. Ruffini and F. Slyne, "Moving the network to the cloud: The cloud central office revolution and its implications for the optical layer,"

- J. Lightwave Technol.*, vol. 37, pp. 1706–1716, Apr 2019. Online [Available]: <http://jlt.osa.org/abstract.cfm?URI=jlt-37-7-1706>.
- [120] F. Slyne, A. Elrasad, C. Bluemm, and M. Ruffini, “Demonstration of real time vnf implementation of olt with virtual dba for sliceable multi-tenant pons,” in *2018 Optical Fiber Communications Conference and Exposition (OFC)*, pp. 1–3, March 2018. Online [Available]: <https://ieeexplore.ieee.org/document/8385950>.
- [121] N. Afraz and M. Ruffini, “A distributed bilateral resource market mechanism for future telecommunications networks,” in *IEEE GLOBECOM 2019 Workshop on Telecommunications and Blockchain*, Dec. 2019. Online [Available]: <https://www.linkedin.com/pulse/distributed-bilateral-resource-market-mechanism-future-nima-afraz/>.
- [122] X. Foukas, N. Nikaiein, M. M. Kassem, M. K. Marina, and K. Kontovasilis, “Flexran: A flexible and programmable platform for software-defined radio access networks,” in *CoNEXT 2016*, 2016. [Online] Available: <https://dl.acm.org/doi/abs/10.1145/2999572.2999599>.
- [123] P. Shantharama, A. S. Thyagaturu, N. Karakoc, L. Ferrari, M. Reisslein, and A. Scaglione, “Layback: Sdn management of multi-access edge computing (mec) for network access services and radio resource sharing,” *IEEE Access*, vol. 6, pp. 57545–57561, 2018. doi: <http://dx.doi.org/10.1109/ACCESS.2018.2873984>.
- [124] A. Ksentini and N. Nikaiein, “Toward enforcing network slicing on ran: Flexibility and resources abstraction,” *IEEE Communications Magazine*, vol. 55, pp. 102–108, June 2017. doi: <http://dx.doi.org/10.1109/MCOM.2017.1601119>.
- [125] S. Nadas, Z. Turanyi, G.ombos, and S. Laki, “Stateless resource sharing in networks with multi-layer virtualization,” in *ICC 2019 - 2019 IEEE International Conference on Communications (ICC)*, pp. 1–7, May 2019. doi: <http://dx.doi.org/10.1109/ICC.2019.8761720>.
- [126] I. Afolabi, T. Taleb, K. Samdanis, A. Ksentini, and H. Flinck, “Network slicing and softwarization: A survey on principles, enabling technologies, and solutions,” *IEEE Communications Surveys Tutorials*, vol. 20, pp. 2429–2453, thirdquarter 2018. doi: <http://dx.doi.org/10.1109/COMST.2018.2815638>.
- [127] X. Foukas, G. Patounas, A. Elmokashfi, and M. K. Marina, “Network slicing in 5g: Survey and challenges,” *IEEE Communications Magazine*, vol. 55, pp. 94–100, May 2017. doi: <http://dx.doi.org/10.1109/MCOM.2017.1600951>.
- [128] F. Malandrino, C. F. Chiasserini, G. Einziger, and G. Scalosub, “Reducing service deployment cost through vnf sharing,” *IEEE/ACM Transactions on Networking*, vol. 27, pp. 2363–2376, Dec 2019. doi: <http://dx.doi.org/10.1109/TNET.2019.2945127>.
- [129] K. Samdanis, X. Costa-Perez, and V. Sciancalepore, “From network sharing to multi-tenancy: The 5G network slice broker,” 2016. doi: <http://dx.doi.org/10.1109/MCOM.2016.7514161>.
- [130] M. Crippa, P. Arnold, V. Friderikos, B. Gajic, C. Guerrero, O. Holland, I. Labrador, V. Sciancalepore, D. Von Hugo, S. Wong, F. Yousaf, and B. Sayadi, “Resource sharing for a 5G multi-tenant and multi-service architecture,” 2017. [Online] Available: <https://bit.ly/2vhtKyq>.
- [131] J. Gang and V. Friderikos, “Optimal resource sharing in multi-tenant 5G networks,” *IEEE Wireless Communications and Networking Conference, WCNC*, vol. 2018-April, pp. 1–6, 2018. doi: <http://dx.doi.org/10.1109/WCNC.2018.8377326>.
- [132] M. Jiang, D. Xenakis, S. Costanzo, N. Passas, and T. Mahmoodi, “Radio Resource Sharing as a service in 5G: A software-defined networking approach,” *Computer Communications*, vol. 107, pp. 13–29, 2017. doi: <http://dx.doi.org/10.1016/j.comcom.2017.03.006>.
- [133] C. Vlachos, V. Friderikos, and M. Dohler, “Optimal Virtualized Inter-Tenant Resource Sharing for Device-to-Device Communications in 5G Networks,” *Mobile Networks and Applications*, vol. 22, no. 6, pp. 1010–1019, 2017. doi: <http://dx.doi.org/10.1007/s11036-017-0822-0>.
- [134] D. Panaitopol, A. Cipriano, K. Katsalis, N. Nikaiein, C.-Y. Chang, F. Kuo, K. Kowalik, H. Kokkinen, G. Agapiou, and A. Kliks, “Spectrum and RAN sharing in 5G networks - a COHERENT approach,” 06 2017. [Online] Available: <http://www.eurecom.fr/publication/5203>.
- [135] J. Gang and V. Friderikos, “Inter-tenant resource sharing and power allocation in 5g virtual networks,” *IEEE Transactions on Vehicular Technology*, vol. 68, pp. 7931–7943, Aug 2019. doi: <http://dx.doi.org/10.1109/TVT.2019.2917426>.
- [136] P. Caballero, A. Banchs, G. De Veciana, and X. Costa-Pérez, “Network slicing games: Enabling customization in multi-tenant mobile networks,” *IEEE/ACM Transactions on Networking*, vol. 27, pp. 662–675, April 2019. doi: <http://dx.doi.org/10.1109/TNET.2019.2895378>.
- [137] H. Khalili, A. Papageorgiou, S. Siddiqui, C. Colman-Meixner, G. Carozzo, R. Nejabati, and D. Simeonidou, “Network slicing-aware nfv orchestration for 5g service platforms,” in *2019 European Conference on Networks and Communications (EuCNC)*, pp. 25–30, June 2019. doi: <http://dx.doi.org/10.1109/EuCNC.2019.8802048>.
- [138] T. Taleb, I. Afolabi, K. Samdanis, and F. Z. Yousaf, “On multi-domain network slicing orchestration architecture and federated resource control,” *IEEE Network*, vol. 33, pp. 242–252, Sep. 2019. doi: <http://dx.doi.org/10.1109/MNET.2018.1800267>.
- [139] R. Kunst, *A QoS-aware resources sharing architecture for homogeneous and heterogeneous wireless networks*. 2017. [Online] Available: <https://bit.ly/2UPKxb9>.
- [140] P. H. Isolani, N. Cardona, C. Donato, G. A. Pérez, J. M. Marquez-Barja, L. Z. Granville, and S. Latré, “Airtime-based resource allocation modeling for network slicing in ieee 802.11 rans,” *IEEE Communications Letters*, pp. 1–1, 2020. doi: <http://dx.doi.org/10.1109/LCOMM.2020.2977906>.
- [141] P. H. Isolani, J. Haxhibeqiri, I. Moerman, J. Hoebeke, J. M. Marquez-Barja, L. Z. Granville, and S. Latré, “An sdn-based framework for slice orchestration using in-band network telemetry in ieee 802.11,” *IEEE Conference on Network Softwarization (NETSOFT2020)*, pp. 1–3, 2020.
- [142] P. H. Isolani, N. Cardona, C. Donato, J. Marquez-Barja, L. Z. Granville, and S. Latré, “Sdn-based slice orchestration and mac management for qos delivery in ieee 802.11 networks,” in *2019 Sixth International Conference on Software Defined Systems (SDS)*, pp. 260–265, 2019. doi: <http://dx.doi.org/10.1109/SDS.2019.8768642>.
- [143] J. Van De Belt, H. Ahmadi, and L. E. Doyle, “Defining and Surveying Wireless Link Virtualization and Wireless Network Virtualization,” *IEEE Communications Surveys and Tutorials*, vol. 19, no. 3, pp. 1603–1627, 2017. doi: <http://dx.doi.org/10.1109/COMST.2017.2704899>.
- [144] F. Slyne, R. Giller, J. Singh, and M. Ruffini, “Experimental demonstration of dpdk optimised vnf implementation of virtual dba in a multi-tenant pon,” in *2018 European Conference on Optical Communication (ECOC)*, pp. 1–3, Sep. 2018. doi: <http://dx.doi.org/10.1109/ECOC.2018.8535109>.
- [145] J. Costa-Requena, R. Kantola, A. Y. Ding, J. Manner, Y. Liu, and S. Tarkoma, “Software Defined 5G Mobile Backhaul,” 2014. doi: <http://dx.doi.org/10.4108/icst.5gu.2014.258054>.
- [146] J. Costa-Requena, J. L. Santos, and V. F. Guasch, “Mobile backhaul transport streamlined through SDN,” in *International Conference on Transparent Optical Networks*, 2015. doi: <http://dx.doi.org/10.1109/ICTON.2015.7193588>.
- [147] W. Kiess, M. R. Sama, J. Varga, J. Prade, H. J. Morper, and K. Hoffmann, “5G via evolved packet core slices: Costs and technology of early deployments,” *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC*, vol. 2017-October, pp. 1–7, 2018. doi: <http://dx.doi.org/10.1109/PIMRC.2017.8292691>.
- [148] Y. Li, “Virtualization in Wireless Networks,” *Wireless and Mobile Networking*, pp. 1–7, 2009. [Online] Available: <https://www.cse.wustl.edu/~jain/cse574-14/ftp/virwn.pdf>.
- [149] M. Chowdhury and R. Boutaba, “Network virtualization: state of the art and research challenges,” *IEEE Comm Mag*, 2009. doi: <http://dx.doi.org/10.1109/mcom.2009.5183468>.
- [150] A. Framework, “GS NFV 002 - V1.1.1 - Network Functions Virtualisation (NFV); Architectural Framework,” vol. 1, pp. 1–21, 2013. Available [Online]: <https://bit.ly/2LwTxNa>.
- [151] S. Farhat, S. Lahoud, A. E. Samhat, and B. A. Cousin, “Resource Sharing in 5G Multi-Operator Wireless Network,” *International Journal of Digital Information and Wireless Communications*, vol. 8, no. 3, pp. 156–161, 2018. doi: <http://dx.doi.org/10.17781/p002431>.
- [152] G. Fortetsanakis, M. Papadopoulou, G. Karlsson, M. Dramitinos, and E. A. Yavuz, “To subscribe, or not to subscribe: Modeling and analysis of service paradigms in cellular markets,” *2012 IEEE International Symposium on Dynamic Spectrum Access Networks, DYSPAN 2012*, pp. 189–200, 2012. doi: <http://dx.doi.org/10.1109/DYSPAN.2012.6478130>.
- [153] B. Leng, P. Mansourifard, and B. Krishnamachari, “Microeconomic analysis of base-station sharing in green cellular networks,” *Proceedings - IEEE INFOCOM*, pp. 1132–1140, 2014. doi: <http://dx.doi.org/10.1109/INFOCOM.2014.6848044>.
- [154] A. Georgakopoulos, A. Margaritis, K. Tsagkaris, and P. Demestichas, “Resource Sharing in 5G Contexts: Achieving Sustainability with Energy and Resource Efficiency,” *IEEE Vehicular Technology Magazine*, 2016. doi: <http://dx.doi.org/10.1109/MVT.2015.2508319>.
- [155] L. Cano, A. Capone, G. Carello, and M. Cesana, “Evaluating the performance of infrastructure sharing in mobile radio networks,” *IEEE International Conference on Communications*, vol. 2015-Septe, pp. 3222–3227, 2015. doi: <http://dx.doi.org/10.1109/ICC.2015.7248820>.

- [156] J. Lun and D. Grace, "Software defined network for multi-tenancy resource sharing in backhaul networks," in *2015 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, pp. 1–5, March 2015. doi: <http://dx.doi.org/10.1109/WCNCW.2015.7122519>.
- [157] J. Zhang, J. Zhang, Y. Zhao, and X. Wang, "Time-dependent spectrum resource sharing in flexible bandwidth optical networks," *IET Networks*, vol. 1, pp. 189–198, December 2012. doi: <http://dx.doi.org/10.1049/iet-net.2012.0119>.
- [158] F. Marzouk, H. Touati, R. Alheiro, and A. Radwan, "Analysis of Multi-Operator Resource Sharing," in *2019 IEEE 2nd 5G World Forum (5GWF)*, pp. 269–273, Sep. 2019. doi: <http://dx.doi.org/10.1109/5GWF.2019.8911698>.
- [159] A. D. Oliva, X. Li, X. Costa-pérez, C. J. Bernardos, P. Bertin, P. Iovanna, T. Deiss, J. Mangues, A. Mourad, C. Casetti, J. E. Gonzalez, and A. Azcorra, "Slicing and Orchestrating Transport Networks for Industry Verticals," no. August, pp. 78–84, 2018. doi: <http://dx.doi.org/10.1109/MCOM.2018.1700990>.
- [160] P. Popovski, K. F. Trillingsgaard, O. Simeone, and G. Durisi, "5G wireless network slicing for eMBB, URLLC, and mMTC: A communication-theoretic view," *IEEE Access*, vol. 6, no. 648382, pp. 55765–55779, 2018. doi: <http://dx.doi.org/10.1109/ACCESS.2018.2872781>.
- [161] C. Bluemm, Y. Zhang, P. Alvarez, M. Ruffini, and L. A. DaSilva, "Dynamic energy savings in cloud-ran: An experimental assessment and implementation," in *2017 IEEE International Conference on Communications Workshops (ICC Workshops)*, pp. 791–796, May 2017. doi: <http://dx.doi.org/10.1109/ICCW.2017.7962755>.
- [162] R. Shrivastava, S. Costanzo, K. Samdanis, D. Xenakis, D. Grace, and L. Merakos, "An sdn-based framework for elastic resource sharing in integrated fdd/tdd lte-a hetnets," in *2014 IEEE 3rd International Conference on Cloud Networking (CloudNet)*, pp. 126–131, Oct 2014. doi: <http://dx.doi.org/10.1109/CloudNet.2014.6968980>.
- [163] M. Ruffini, D. B. Payne, and L. Doyle, "Protection strategies for long-reach pon," in *36th European Conference and Exhibition on Optical Communication*, pp. 1–3, Sep. 2010. doi: <http://dx.doi.org/10.1109/ECOC.2010.5621156>.
- [164] M. Ruffini, M. Achouche, A. Arbelaez, R. Bonk, A. Di Giglio, N. J. Doran, M. Furdek, R. Jensen, J. Montalvo, N. Parsons, T. Pfeiffer, L. Quesada, C. Raack, H. Rohde, M. Schiano, G. Talli, P. Townsend, R. Wessaly, L. Wosinska, X. Yin, and D. B. Payne, "Access and metro network convergence for flexible end-to-end network design [invited]," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 9, pp. 524–535, June 2017. doi: <http://dx.doi.org/10.1364/JOCN.9.000524>.
- [165] S. McGettrick, D. B. Payne, and M. Ruffini, "Improving hardware protection switching in 10gb/s symmetric long reach pons," in *2013 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC)*, pp. 1–3, March 2013. doi: <http://dx.doi.org/10.1364/OFC.2013.OW3G.2>.
- [166] R. Kokku, R. Mahindra, H. Zhang, and S. Rangarajan, "Cellslice: Cellular wireless resource slicing for active ran sharing," in *2013 Fifth International Conference on Communication Systems and Networks (COMSNETS)*, pp. 1–10, Jan 2013. doi: <http://dx.doi.org/10.1109/COMSNETS.2013.6465548>.
- [167] O. Narmanlioglu and E. Zeydan, "New era in shared c-ran and core network: A case study for efficient rrh usage," in *2017 IEEE International Conference on Communications (ICC)*, pp. 1–7, May 2017. doi: <http://dx.doi.org/10.1109/ICC.2017.7997428>.
- [168] B. Niu, Y. Zhou, H. Shah-Mansouri, and V. W. S. Wong, "A dynamic resource sharing mechanism for cloud radio access networks," *IEEE Transactions on Wireless Communications*, vol. 15, pp. 8325–8338, Dec 2016. doi: <http://dx.doi.org/10.1109/TWC.2016.2613896>.
- [169] V. K. Choyi, A. Abdel-Hamid, Y. Shah, S. Ferdi, and A. Brusilovsky, "Network slice selection, assignment and routing within 5g networks," in *2016 IEEE Conference on Standards for Communications and Networking (CSCN)*, pp. 1–7, Oct 2016. doi: <http://dx.doi.org/10.1109/CSCN.2016.7784887>.
- [170] F. C. Commission, "Millimeter wave 70/80/90 ghz service," march 2019. [Online] Available: <https://bit.ly/30w3u1D>.
- [171] F. C. Commission, "Report and order and further notice of proposed rulemaking," *FCC's proceedings*, 2016. [Online] Available: <https://bit.ly/2YypuY0>.
- [172] C. Both, R. Guimaraes, F. Slyne, J. Wickboldt, M. Martinello, C. Dominicini, R. Martins, Y. Zhang, D. Cardoso, R. Villaca, I. Ceravolo, R. Nejabati, J. Marquez-Barja, M. Ruffini, and L. DaSilva, "FUTEBOL Control Framework: Enabling Experimentation in Convergent Optical, Wireless, and Cloud Infrastructures," *IEEE Communications Magazine*, 2019. doi: <http://dx.doi.org/10.1109/MCOM.001.1900270>.



Nina Slamnik-Kriještorac is a PhD researcher in the field of Applied Engineering Sciences, at the University of Antwerp and the imec research center in Belgium. She obtained Master degree in telecommunications engineering at Faculty of Electrical Engineering, University of Sarajevo, Bosnia & Herzegovina, in July 2016. In the period from 2016 to 2018, she worked as a Teaching Assistant at Faculty of Electrical Engineering, University of Sarajevo. Her current research is mostly based on management and orchestration of next generation

end-to-end network resources and services, aimed at enabling programmable networks for flexible smart cities.



Haris Kremo received the Dipl.Ing. degree from the School of Electrical Engineering, University of Sarajevo, Bosnia and Herzegovina, in 2000, and M.S. and Ph.D. degrees from Rutgers, The State University of New Jersey in 2005 and 2011, respectively. From 2000 to 2002 he was a Research Engineer with ENERGOINVEST dd, Bosnia and Herzegovina. From 2003 to 2010 he was a Graduate Assistant with the Wireless Information Networks Laboratory WINLAB as one of the engineers responsible for design and maintenance of the ORBIT

wireless testbed. After graduation he spent one year as a Postdoctoral Research Associate at the EDGE Lab, Princeton University. From 2011 to 2016 he was a Researcher with Toyota InfoTechnology Center, Tokyo working on dynamic spectrum access, vehicular wireless communications, and automated driving systems. From 2016 to 2018 he worked at the CONNECT Centre, Trinity College Dublin in the field of wireless communications for Internet of Things. Briefly, he was a Senior Researcher with the University of Antwerp IDLab and an Assistant Professor at the International University of Sarajevo, Bosnia and Herzegovina. Currently, he is a Research Scientist with the Chair for Distributed Signal Processing at the RWTH Aachen University.



Marco Ruffini received his M.Eng. in telecommunications in 2002 from Polytechnic University of Marche, Italy. After working as a research scientist for Philips in Germany, he joined Trinity College Dublin in 2005, where he received his Ph.D. in 2007. Since 2010, he has been Assistant Professor (tenured 2014) at TCD. He is Principal Investigator (PI) of both the CONNECT Telecommunications Research Centre at TCD, and the IPIC photonics integration centre headquartered at the national Tyndall institute.

Dr. Ruffini is currently involved in several Science Foundation Ireland (SFI) and H2020 projects, and leads the Optical Network Architecture group at Trinity College Dublin. His main research is in the area of 5G optical networks, where he carries out pioneering work on the convergence of fixed-mobile and access-metro networks, and on the virtualisation of next generation networks, and has been invited to share his vision through several keynote and talks at major international conferences across the world. He has authored over 120 international publications, over 10 patents and contributed to the BroadBand Forum standardisation body.



Johann M. Marquez-Barja currently is an Associate Professor at University of Antwerpen and imec. He is the Head of the Wireless Cluster at imec IDLab UAntwerp. He was and is involved in several European research projects, being Principal and Co-Principal Investigator for many projects. He is an ACM member, and a Senior member of the IEEE Communications Society as well as the IEEE Education Society, where he participates in the Standards Committee. His main research interests are: 5G advanced architectures including edge computing;

flexible and programmable future end-to-end networks; IoT communications and applications. He is also interested in vehicular communications, mobility, and smart cities deployments. Prof. Marquez-Barja is co-leading the Citylab Smart City testbed, part of the City of Things programme, located in Antwerpen, Belgium. He has studied in USA, Bolivia, Cuba, and Spain. He received a personal grant from the EU under the prestigious Alban Programme to pursue a PhD degree. Prof. Marquez-Barja has been given several keynotes and invited talks in different major events. He is serving as Editor and Guest editor for four International Journals, as well as participating in several Technical Programme and Organizing Committees for different worldwide conferences/congresses.