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Article

A Spectrum Management Platform Architecture to Enable a Sharing Economy in 6G

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Abstract: We propose a novel vision to trade and allocate wireless spectrum in 6G communication networks inspired by the concept of the sharing economy. We argue that such an approach will help ease the surge in demands for wireless spectrum that will characterise the 6G world. We also introduce HODNET (Heterogeneous on Demand NETwork resource negotiation), an open platform that is able to realise this new spectrum-sharing model. To demonstrate the benefits of spectrum trading and allocation in this new paradigm, we considered the use-case of massive Internet of Things (IoT) on a local scale. We simulated a large IoT deployment and evaluated the spectral efficiency of the system when managed using HODNET compared with a standard 5G deployment. Our experiments show that HODNET can indeed offer better allocation, based on our spectrum sharing model, of spectrum resources compared with standard allocation approaches.

Keywords: Beyond 5G; 6G; spectrum sharing; software-defined network; massive IoT

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1. Introduction

The number of mobile phones and tablets in use has now significantly outgrown fixed phones and wired devices. Besides phones and tablets, billions of other devices are now also wirelessly connected to the Internet, including personal devices, cars, cameras, health devices, garbage bins, traffic lights, and various industrial sensors and actuators. This emergence of the Internet of Things (IoT) has resulted in a surge in data traffic over wireless mediums. According to Cisco [1], this traffic grew by 63% in comparison to 2015, reaching an average of 7.2 exabytes per month. The fifth generation of mobile networks (5G) represents a significant part of the latest development in wireless communications and is expected to support this massive growth in wireless IoT and ultra-high-resolution video streaming. This will fuel wireless data traffic to increase even further, by at least a factor of 5 by 2024 [2].

The telecommunication industry and regulators are facing a major challenge in satisfying these ever-increasing demands for wireless bandwidth. Spectral resources have always been scarce and will become even more so in the future. The current spectrum allocation strategy, which is still based on the static allocation of frequency bands, is considered by many as wasteful. Several contributions have been made to alleviate spectrum congestion using high radiofrequency bands and visible light communications. However, it is widely agreed that carrier frequencies below 6 GHz are mostly needed for wireless communications, including 5G, due to their more suitable propagation properties. Given this usable spectrum, two types of solutions are being discussed. One is to allocate more spectrum to communications, which inevitably means recovering blocks of low and medium frequencies. This solution, often called spectrum reframing or refarming, is too limited when facing such high radio spectrum demands.

The second type of solutions are various forms of spectrum sharing. Spectrum sharing has received a lot of attention over the last few years and is promoted as an alternative to the fixed licence model that has been used for nearly a century. Three spectrum frameworks are commonly discussed regarding 5G [3] and include Citizens Broadband Radio Service (CBRS) approaches, Licensed Shared Access (LSA), and Concurrent Shared Access (CSA), which are discussed in more detail in the next section. The key observation however is that all these models still rely on a major licence holder (an entity or a club of entities) which has primary rights and may allow other parties to use spectrum which the major holder is not using, in an only quasi-dynamic way.

There are frequency bands where allocation (either administrative or market-based) does not apply. Such bands, commonly known as unlicensed frequency bands, are not owned by any entity and can be used freely by stakeholders for a variety of applications [4]. The most well-known frequency band in this class is 2.4 GHz, which is widely used for Wi-Fi, Bluetooth, and many other communication technologies. Here, the spectrum is shared by protocol design but will eventually lead to the complete depletion of the band [5].

In this article, we propose a new way of sharing spectrum, which is completely based on the dynamic matching of offer and demand of network resources. It is based on the principles of the sharing economy paradigm. The remainder of this paper is structured as follows. Section 2 provides a detailed analysis of the state of the art on spectrum sharing and our novel contributions. Then, in Section 3, we build the case for a new form of spectrum sharing, based on the principles of the sharing economy, and in Section 4, we propose the system architecture with which this can be achieved. We illustrate the benefits of this approach with a use case revolving around massive IoT deployment in Section 5. Final conclusions and significant aspects to explore further are given in Section 6.

2. Literature Review

2.1. Traditional Spectrum Allocation and Sharing

Currently, spectrum allocation is still dominated by administrative allocation controlled by national regulators. These regulators also stipulate static conditions on how operators can utilise the allocated spectrum, expressed in offered capacity, coverage, etc. although these conditions do not always reflect the real requirements of wireless users [6].

An alternative approach is to apply the laws of the market to incentivise a fairer and more consumer-oriented allocation of the spectrum resource. Here, the right to operate blocks of radio frequency will be granted to operators who value this spectrum the most, for instance as determined by auctions. This approach has been very successful in the 3G, 4G, and 5G eras. In LSA [7], market-based allocations allow an operator to lease some of its frequencies to a third party, thus introducing more flexibility in the dynamic of spectrum allocation.

A variety of LSA is CSA [3]. Here, multiple operators share access to the same block of the spectrum but in a coordinated and managed way. An example is club licencing: A licence is given to a club of operators. An operator can use the whole block if it is the sole provider in an area. When another club member wants to operate in that area too, it has the right to a fair share of the block. This is a form of dynamic spectrum sharing, but time scales are measured in weeks or months rather than minutes or hours. CBRS has also recently been authorised for use in the United States. Here, a three-tiered spectrum authorisation framework accommodates various commercial models simultaneously for the 3.5 GHz band [8]. The highest tier is Incumbent Access, which reserves a part of the band for radar operation, similar to administrative allocation. In the second tier, Priority Access, sub-bands of 10 MHz are licenced commercially, such as market-oriented allocation. In the General Authorised Access, users are permitted to use any portion of the band not assigned to higher tier users but still need to acquire a temporary low-cost license for use of the spectrum in, e.g., a single building.

A commonality between these spectrum-sharing models is that they rely on spectrum uniquely allocated to a major licence holder which has primary rights to it in a semi-static way, regardless of whether that spectrum is actually used or not. This inevitably leads to spectrum waste, where the demand is low, and spectrum congestion, where the demand is high, and unnecessary costs either way. The only alternative able to address this problem is to use the so-called unlicensed bands. Here, everybody has the fundamental right to access the spectrum anytime and anywhere but must accept possible interference from other users. Most protocols using these bands typically have "listen-before-talk", "clear channel assessment" and "duty-cycle muting" mechanisms included to allow other devices to access the medium too [9–11], but when congestion becomes eminent, they all apply the law of the jungle resulting in only losers [4]. Moreover, works in [12,13] illustrate how multiple systems that coexist in unlicensed bands interfere with each other due to asymmetries and selfish system behaviour. The authors then propose punishment strategies based on game theory which allow for fair and efficient use of the band. However, the solutions are not evaluated in realistic scenarios involving wireless technologies.

2.2. Spectrum Sharing Platforms

Several articles in the literature propose platforms to address the problem of spectrum resource scarcity for next-generation networks. The work in [14] presents a survey on spectrum sharing for next-generation networks discussing how several methods can be implemented in a general architecture. Moreover, the authors discuss techniques for spectrum sensing, network selection, channel allocation, and power optimisation in spectrum sharing together with the corresponding security issues. The authors in [15] present a survey on recent spectrum-sharing solutions for 5G networks and 5G-enabling technologies. Spectrum-sharing methods are presented in terms of network architecture, spectrum allocation, and spectrum access solutions. Furthermore, they provide a survey on cognitive radio (CR) technology for spectrum sharing in 5G networks. Additionally, the work in [16] proposes a solution based on CR in 5G networks. Specifically, it proposes the integration of non-orthogonal multiple access (NOMA) with CR into a holistic system, namely a cognitive NOMA network, for intelligent spectrum sharing. In [17] authors present a survey on spectrum-sharing solutions, interference models, and interference management for IoT technology. Work in [18] presents a green spectrum-sharing framework targeting Beyond 5G networks with the aim to improve spectrum utilisation through a cost-efficiency approach for IoT devices.

Moreover, note that communication networks have recently witnessed a paradigm shift in the way data traffic and spectrum resources are managed. The introduction of novel softwarisation techniques such as Software Defined Networking (SDN) [19] and Network Function Virtualisation (NFV) [20] has enabled more scalable and efficient management of these networks. Although initially limited to wired networks, such techniques are now also used for wireless communications. The rise of Software Defined Wireless Networking (SDWN) [21] represents an extension of SDN specifically in this context. Spectrum programming [22] extends this concept further, from managing data traffic right down to the radio resources themselves. In this context, the Wi-5 spectrum programming architecture in [22] presents a system to manage radio resources for Wi-Fi networks.

2.3. Our Motivations and Novel Contributions

The efficient use of the spectrum will be a crucial problem in 6G and will face further challenges in comparison with current wireless technologies, mainly due to the targeted multi-Gigabit data rates and a broader set of potential spectrum bands and spectrum management strategies. Therefore, 6G will need novel and intelligent spectrum allocation and sharing models [23]. The introduction of virtualisation, softwarisation, and programmability technologies, including Artificial Intelligence (AI), will undoubtedly help address these challenges. This trend has already started in 5G, for example with the introduction of SDN and NFV in the core as we have previously mentioned, which made concepts such as Mobile Edge Computing (MEC) and network slicing possible. In this context, we believe that the spectrum-sharing mechanisms and platforms for 5G illustrated in Sections 2.1 and 2.2 present key limitations that make them unsuitable for upcoming 6G networks. These limitations can be summarised as follows:

- Current spectrum-sharing mechanisms and platforms only acknowledge operators as service providers, thus eliminating other entities that own or manage a wireless network and that could offer wireless spectrum access;
- They lack flexibility as reflected in the architecture of current wireless systems and their radio access and allocation protocols, which are too elementary and do not consider the characteristics of the wireless devices and their data traffic requirements. For instance, an IoT device will always try to connect to its operator's base station although there may be closer Radio Access Nodes (RANs) which could save them energy.

Therefore, in this paper, our aim is to address these limitations by proposing a novel spectrum-sharing model, applicable to 6G networks, which is completely based on the dynamic matching of offer and demand of network resources. It is based on the principles of the sharing economy paradigm. In this model, any entity that owns or manages a wireless device (mobile phones, Wi-Fi Access Points, etc.) can offer wireless spectrum access and hence could contribute to connecting wireless devices.

3. Trading and Allocating Spectrum as Part of a Sharing Economy in 6G

3.1. Principles and Definitions

In this section, we introduce a new way of sharing the spectrum, based on the principles of the sharing economy paradigm, and its foundation in the dynamic and distributed matching of offer and demand of spectrum resources. The sharing economy is defined as creating a business model allowing consumers to be paid for providing a service similar to what they receive. It is currently considered among the most innovative and efficient sharing economic models. The strength of this concept comes from its ability to bypass traditional intermediaries and use Internet platforms to connect consumers to suppliers of goods and services. It has helped to increase the capacity of markets, bring down prices and enhance the reliability of services.

The concept is strongly rooted in the observation that many economic resources are more and more provided by the consumers themselves (hence the popular term "prosumers") instead of by large incumbent operators. We also see such a trend with wireless communications. With the arrival of private picocells and the ability of most Wi-Fi end-user devices to provide hotspot services to other devices, many users not only have a demand for wireless capacity but are also able to offer it to others. Our aim, therefore, is to design a spectrum-trading platform that matches offer and demand locally and dynamically, provides broker deals, and aids business partners in executing, securing, validating, and verifying these deals. Of course, similar wireless spectrum-trading platforms can already be found in the literature [24] and there is an established discussion on so-called 'Spectrum as a Service' approaches [25,26] but our novelty as outlined in the previous section, is the inclusion of any potential connectivity provider in our system and the flexibility to cover a broad range of technologies and use cases.

Our vision is, therefore, to allow any entity that owns or manages a wireless network (which we call an "operator" in the remainder of this paper) to trade its spectrum resource with any user in a range that requires it. A wireless network can be licenced or unlicenced, including both Wi-Fi and IoT deployments and cellular networks. In its extreme, such a trading platform would make the current market-oriented licencing a system of the past and, while this may sound controversial, it is a normal cause of things in economics: after demand is created by rolling out services by government-owned or -regulated monopolistic industry, a deregulated and distributed market can take over. We are currently witnessing this with taxi rides, power generation, public transport, space exploration, etc. As illustrated by the example in Figure 1, our vision is to make radio resources universally available for trading and sharing between any operator and 6G users. Moreover, note that we apply the following definitions:

- Spectrum Trading is the act of voluntary matching of offer and demand of spectral resources between parties acting in a common geographical space in which spectral resources are scarce and contended. The parties are treated as economic actors and trading may or may not result in consensus and a joint agreement. Trading may or may not be galvanised by a broker;

- Spectrum Allocation is the act of allocating spectral resources offered by one or more parties to parties who demand spectral resources. Ideally, the allocation follows from the consensus resulting from the previous step of trading and correctly executes the joint agreement;
- Spectrum Sharing is the most likely result of Spectrum Allocation: parties are sharing the spectral resources as agreed upon. Alternatively, the spectrum is not shared, and one party consumes it all.

While a radio resource management approach that makes our vision possible will be presented in Section 5, in the remainder of this section, we explore the requirements and potential technical approaches to achieve this.

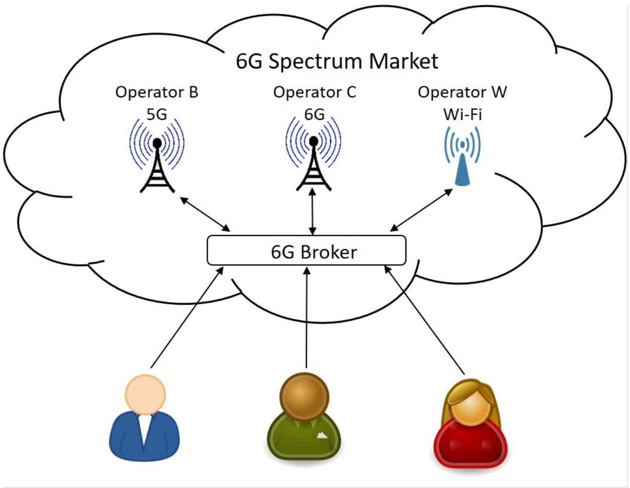


Figure 1. Vision of spectrum trading and allocating as part of a sharing economy in 6G with an online broker.

3.2. Requirements of the Spectrum Trading Platform

Realising this vision requires the functionality of wireless devices and Radio Access Networks (RANs) to be enhanced such that resources become discoverable, sharable, and accessible almost in real time. The key functionality required for a spectrum-sharing economy platform is, therefore:

1. Providing Connectivity. This is the ability to offer connectivity to wireless devices at (at least) the same or (preferably) better quality and efficiency (e.g., energy consumption) than existing radio access schemes. In other words, the platform should be able to connect to every device offering and/or demanding resources and should have access to fine-grained radio- and link-control functionality in order to offer the optimal (i.e., agreed) connectivity;
2. Scalability. The platform needs to support the anticipated scale and density of networks and devices in both current and future deployments, and maximise their capacity based on new and existing Radio Access Technologies (RATs). In other words, dynamic spectrum trading is particularly important when multiple devices vie for resources, and the platform should be able to deal with this, and in near real time: deals may have to be renewed within minutes, with changing offers and demand of devices in range;
3. Heterogeneous Access. This is the ability to offer suitable network access to devices that are heterogeneous in terms of capabilities, requirements, and limitations. Particularly in unlicensed networks, devices sporting different RATs (e.g., Wi-Fi or Bluetooth)

may compete for the same spectral resources. The platform should be able to deal with that.

3.3. Spectrum Trading with Spectrum Programming

As introduced in Section 2, SDN and SDWN are commonly used to enable more scalable and efficient management of wireless networks. In this context, the Wi-5 spectrum programming architecture based on SDWN presented in [22] is a solution to manage radio resources for Wi-Fi networks and we see this platform as a precursor for spectrum sharing and trading as we envision here. The architecture is illustrated in Figure 2. Specifically, we can find the following entities: the Wi-5 Controller (operated by the Wi-5 System Operator) which resides in the control plane, and the Brokering Platform, which is operated by a separate Spectrum Broker. This approach allows having radio parameters programmable through an open Southbound API to the wireless Access Points (APs), and an open Northbound API. Intelligent algorithms can then use these interfaces to obtain certain objectives set by policies that are sent to the Wi-5 Controller by the Brokering Platform. Moreover, the Wi-5 Controller has a Flow and Network Monitoring Module (FNMM), not illustrated in the figure), which performs measurements from the APs, monitors the new flows in the network and communicates this information to the management algorithms.

To our knowledge, this architecture was the first of its kind to treat the wireless spectrum as a resource that can be traded among different service providers [24]. The developers demonstrated the scalability of a single Wi-5 controller in a dense Wi-Fi deployment and explored hierarchical multi-operator/controller approaches which could serve as the basis for req. 2 above. The suitability of the Wi-5 architecture is a key motivation for us to adopt this novel approach for spectrum sharing. However, we need to extend the Wi-5 architecture to support heterogeneous radio access that goes beyond a single RAT (req. 3). Moreover, Wi-5 currently does not address req. 1 as it assumes the Wi-5 controller to be deployed as a physical entity accessible to all devices and service providers.

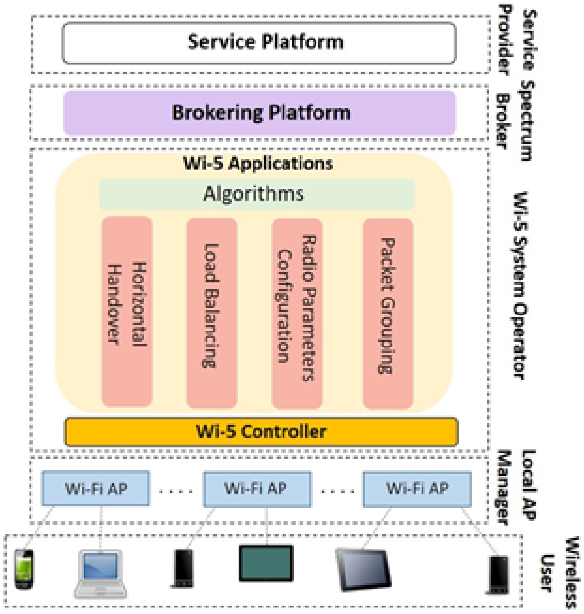
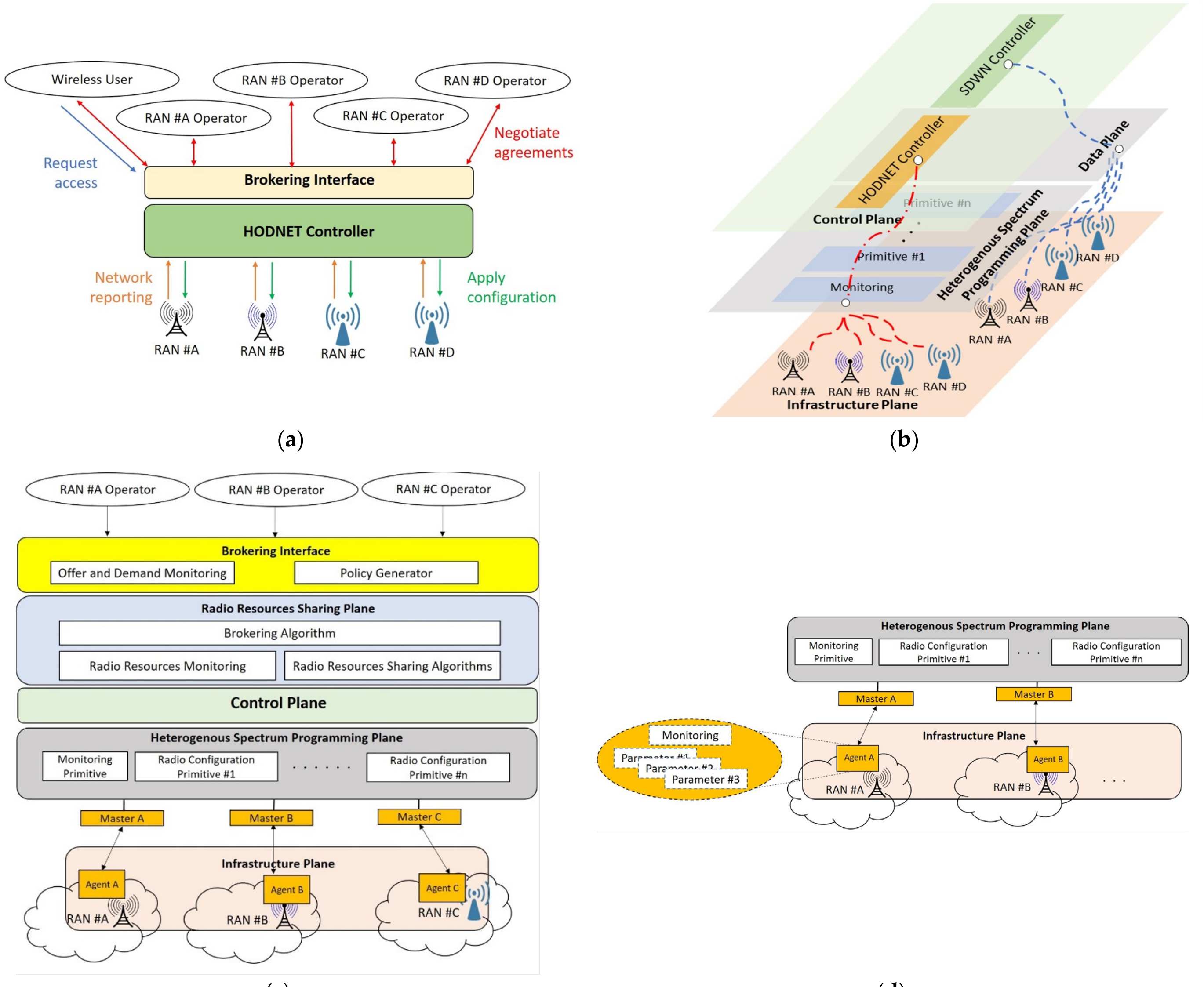


Figure 2. The Wi-5 spectrum programming architecture based on Software-Defined Wireless Networking.

4. HODNET Architecture

Based on the Wi-5 spectrum programming architecture we now propose Heterogeneous On Demand NETwork (HODNET), a spectrum trading architecture for 6G networks. A high-level description of this architecture is presented in Figure 3a. All entities will negotiate through HODNET's Brokering Interface provided. To enforce our concept, operators may dynamically join and leave the system in the same way that drivers in a taxi-sharing service are available at different times as it suits them, and operators can 'charge' more for offering connectivity during busy times but less when demand is low. The Controller is a centralised entity that populates the Brokering Interface with information related to the underlying RANs that have resources on offer in a given area. It also takes the outcome of the negotiation between the entities from the Brokering Interface, i.e., the operators of each RAN, and implements it. To maintain its scalability, HODNET adopts the SDWN model as described above (req. 2) but adopts a heterogeneous spectrum programming approach that allows it to manage multiple radio access networks seamlessly (req. 3).



(**a**) (**b**)

(**c**) (**d**)

Figure 3. Description of HODNET architecture: (**a**) high-level description of HODNET architecture; (**b**) illustration of the difference between HODNET and SDWN control paths; (**c**) planes in HODNET architecture; (**d**) Interaction between Agent and Master in HODNET architecture.

4.1. Description of HODNET Planes

The HODNET architecture defines a set of planes that facilitate the low-level programmability necessary to achieve scalable, logically centralised spectrum trading as depicted in Figure 3c. While Wi-5 only considered a single centralised physical controller for a specific scenario, HODNET can be deployed in a distributed manner, making use of dynamic Edge Computing platforms, and partly being implemented through NFV and Service Function Chaining architectures to facilitate multi-operator deployments. This will further reinforce the scalability aspects of HODNET (req. 2) and address the availability issues discussed above (req. 1). The planes presented in Figure 3c can be described as follows:

- Infrastructure Plane. This plane includes the nodes through which the radio resources of each RAN can be accessed and shared, such as 5G Base Stations (gNBs) or Wi-Fi APs. The nodes each run software agents which expose the parameters to configure these nodes, such as transmission power, transmission and reception channel, coding scheme, and the number of connected devices.
- Heterogeneous Spectrum Programming Plane. This plane defines the primitives that enable access to and configuration of the RAN parameters. The configurations are applied to the nodes via a Master/Agent system which translates them to be specific to the underlying technology (e.g., 802.11 channel and transmission strength) and also includes a monitoring primitive that gathers information related to the radio resources available at each RAN.
- Control Plane. This plane includes the HODNET controller as well as the SDWN controller. The difference between the roles of each controller is depicted in Figure 3b. The SDWN controller is responsible for managing the data path, depicted by a blue dashed line. The HODNET controller is responsible for managing the spectrum path (depicted by a red dashed line), i.e., the radio configuration of the access nodes. The control plane will, for example, coordinate vertical handovers between operators and technologies via the SDWN Controller but manage interference using the HODNET Controller.
- Radio Resources Sharing Plane. This plane implements a variety of Radio Resource Management (RRM) algorithms and monitoring mechanisms, communicating with the available RANs about their resources via the control plane. The algorithms use the collected monitoring information and apply heterogeneous RRM techniques such as cell aggregation. Note that the techniques used to manage the heterogeneous radio resource will be limited to the RATs accessed by the controller through the Heterogeneous Spectrum Programming Plane.
- Brokering Interface. This is the interface between the Radio Resources Sharing Plane and the various operators. It automates the negotiation process, in which the RANs and offers are each represented by agents. The agents then barter a deal, e.g., using a negotiating algorithm as described in [13]. While an in-depth analysis of this functionality is beyond the scope of this paper, an example of what the architecture for such a Brokering Platform could look like has been published in [27].

4.2. Interaction between HODNET Planes

The lower two HODNET planes interact through Master and Agent components. Figure 3d illustrates how an Agent in the Infrastructure Plane exposes all the parameters required to configure the RAN from the Master. It also operates a monitoring function that gathers information related to the RAN such as its status and the quality of the channel. The configuration and monitoring information gathered by the Agent is accessed by the Radio Configuration and Monitoring Primitives in the Heterogeneous Spectrum Programming Plane through the Master. The Master also allows a radio configuration to be applied back to the RAN via the Agent. Note that there will be one Master-Agent pair associated with each RAN. This will enable the controller to configure each node separately and according to the nature and specifics of the RAT it operates on.

The Radio Resource Sharing plane enables the implementation of different algorithms that could be applied to marshal the radio resources necessary to satisfy the requirements of the IoT network. Several approaches have been proposed in the literature to achieve this goal [28,29] depending on the available RATs. These algorithms are implemented here via the northbound API of the HODNET controller, as illustrated in Figure 3c, and can be configured to optimise various aspects of the operation of the managed networks. The controller will execute these algorithms using the primitives exposed by the Heterogeneous Spectrum Programming Plane as described above.

It is worth noting that, as we have mentioned in Section 4, HODNET is based on the Wi-5 architecture which does not introduce significant overhead to real-time operation through the execution of algorithms for spectrum sharing and RAT selection [22]. On the other hand, if HODNET is implemented on limited computing and networking resources, the trading, brokering, and allocation may take some time, and the ambition of "real-time" dynamic sharing may be difficult to achieve. However, it will nevertheless be a significant improvement over the current static mechanisms deployed in 5G.

5. Use Case: Spectrum Access in Massive IoT

To illustrate how significant the benefits can be of deploying spectrum through an architecture such as HODNET, we analyse the following use case of massively deployed wireless IoT devices within a limited area. It is expected that over the next ten years the number of IoT devices will reach densities of several million devices per square kilometre. Current radio access models, including both grant-based and grant-free models have not been designed to guarantee wireless connectivity on this scale. This is because operators cannot currently provide enough spectrum capacity to satisfy the demands of these devices [30]. In this use case, HODNET will act as the platform linking IoT networks to entities offering wireless spectrum and connectivity. We envisage that a RAN operator initially manages its wireless network independently (i.e., in the traditional way), resulting in inadequate spectrum access. By introducing HODNET as a brokering and control entity, other operators could be invited to trade spectrum access and alleviate each other's burden based on the new spectrum-sharing paradigm. HODNET coordinates with the operators to optimise the spectrum usage through the monitoring and sharing functionality in the Radio Resources Sharing Plane and, as such, increases usable capacity.

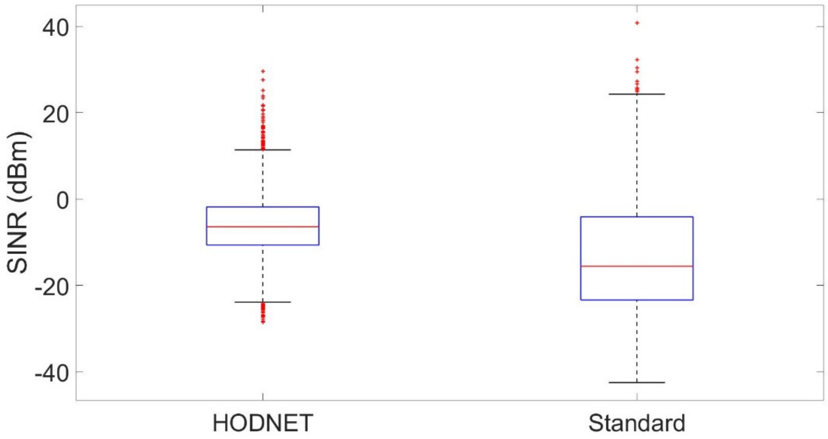
For our analysis, we focus on two performance metrics:

- Signal to Interference plus Noise Ratio (SINR): this is the average SINR experienced by all IoT devices in the network;
- Probability of denying connectivity: this is the percentage of devices that cannot achieve their bit rate requirements.

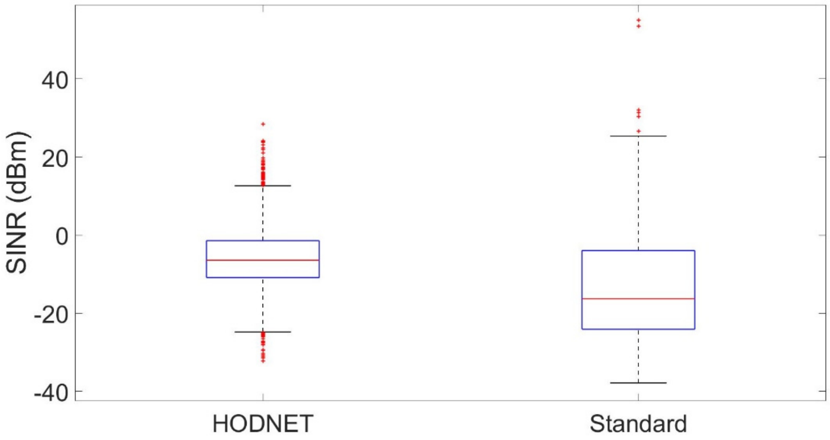
We used MATLAB to simulate a dense deployment of IoT devices served by a set of RANs that belong to different network operators, all deployed in an open-air area of 250 m × 250 m. We then introduce HODNET and assess how both approaches (with and without HODNET) can provide connectivity to IoT devices while optimising network capacity, and how they then perform as the number of devices increases. Each RAN can be either a 5G Base Station (gNB) or a Wi-Fi 802.11ah Access Point (AP). Specifically, the 5G connectivity is provided by 4 gNBs and the Wi-Fi connectivity is offered by 16 802.11ah APs. Furthermore, the 20 nodes belong to 4 different operators, with each one managing 5 nodes. We assume that each node offers a 5 MHz uplink channel operating on the 880–915 MHz and a 4 MHz uplink channel on 900–928 MHz frequency bands in the case of the gNBs and Wi-Fi APs, respectively. We also assume that the IoT devices have transmission power capabilities varying between 1 and 10 dBm and data rates varying between 8 kbps and 128 kbps. The selected settings are representative of a dense environment [31], and follow 3GPP and IEEE specifications. Note that the aim of this implementation is to demonstrate the benefits of our novel spectrum-sharing paradigm that we envision for next-generation 6G networks, through the massive IoT use case involving technologies currently available in the market, i.e., Wi-Fi and 5G. As we will demonstrate in the rest of this section, these results will encourage further investigation to extend our approach into next-generation 6G-based technologies.

Moreover, for the sake of comparison, we consider a simplified version of 5G that connects each IoT device to the closest of its 5 available nodes and does not have access to the connectivity offered by other operators, whereas the HODNET Controller can utilise the whole environment. For this, HODNET implements a Sharing-Economy-based Smart Connectivity algorithm on its Radio Resource Sharing Plane based on information gathered from the Infrastructure Plane. This information includes the Received Signal Strength Indicator (RSSI) monitored by the RANs from each IoT device and the number of devices connected to each RAN. This algorithm connects dynamically each IoT device to the RAN belonging to any RAN operator that has the smallest number of connections, and which provides a sufficient RSSI based on the data rate requirements. This is indeed a very simple trading paradigm, but the following figures show that even such an uncomplicated scheme can produce a significant improvement in resource utilisation.

Figure 4 shows the performance results in terms of SINR for different numbers of IoT devices distributed in the deployed area. The upper and lower edges of the plotted boxes are the 25th and 75th percentile of the values. The median values are indicated by the central red lines. The whiskers extend the SINR values to the most extreme points still not considered an outlier, while the values which we considered as outliers are indicated by red dots. The figure shows that our approach results in better performance in terms of SINR compared with regular 5G operation regardless of how many IoT devices are connected to the network. Specifically, the figure illustrates how: (1) the median value is always higher for our approach; and (2) although the standard method has an extensive range of SINR, most of these values are below the median value achieved by the proposed approach.

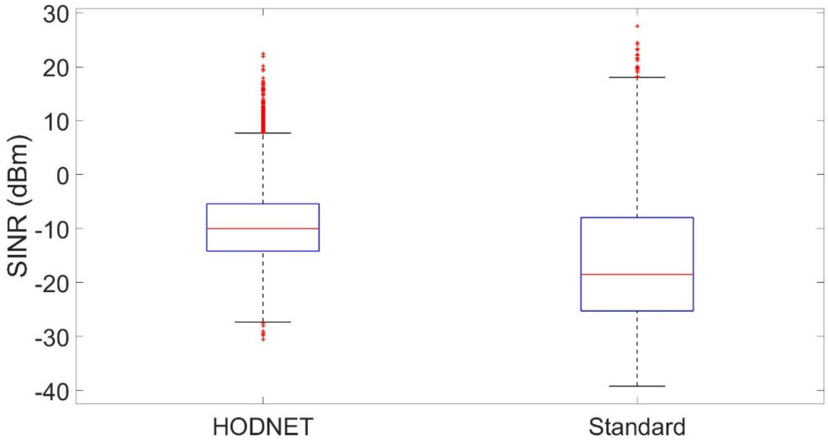


(**a**)



(**b**)

Figure 4. *Cont.*



(**c**)

Figure 4. Measured SINR under both access models for different numbers of IoT devices: (**a**) SINR in case of 1000 IoT devices; (**b**) SINR in case of 2000 IoT devices; (**c**) SINR in case of 3000 IoT devices.

Figure 5 illustrates how this overall increase in SINR leads to improved overall connectivity. It shows that the probability of denying connectivity decreases by 76%, and 16%. and 13%, for 1000, 2000, and 3000 IoT devices, respectively, when HODNET is applied compared with a standard 5G connectivity scenario. However, while with HODNET the blocking probability is always lower than in a standard 5G scenario regardless of the number of devices, it is also clear from Figure 5 that the network is reaching over-saturation when going well above 1000 devices. There is, of course, an absolute maximum to the available capacity and HODNET does not provide extra capacity but instead optimises the effectiveness with which these resources are used by the devices. As such, while this problem may only be solved by the development of more efficient RATs and the addition of usable frequency bands, HODNET can help to maximise the available resources.

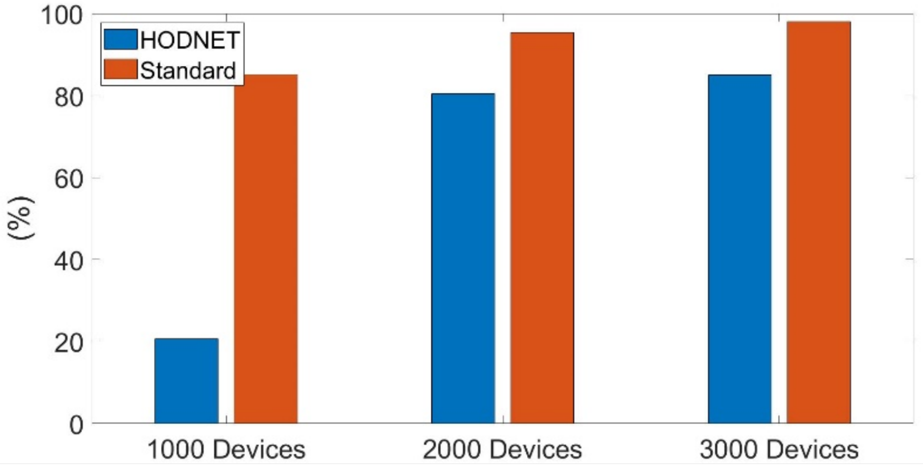


Figure 5. Probability of denying connectivity for different numbers of IoT devices.

6. Conclusions

Current spectrum allocation models for 5G are still based on relatively static frequency band allocation and centralised licencing, with the only alternative provided by unlicensed bands. In either case, unnecessary congestion is observed when the demand is high, due to the suboptimal spectrum management that these models allow for. In this article, we proposed a new vision for spectrum sharing in wireless and mobile networks, based on the recent developments in economic models around sharing of common goods. This vision of trading and allocating spectrum as part of a sharing economy in 6G centres around the ability to automate the matching of locally offered and demanded spectral resources, incentivising stakeholders to share their resources and, therefore, help in easing the demand for this scarce resource.

We also introduced the system architecture of HODNET, an open platform that is capable of realising this new sharing model. HODNET is based on spectrum trading between operators to optimise efficiency and scalability on a high level and builds on the concept of spectrum programming down to the individual radio primitives to enforce fine-grained protocol control.

To demonstrate the benefits of this novel spectrum-sharing paradigm, we considered the use case of massive IoT on a local scale. We simulated a large IoT deployment and evaluated the spectral efficiency of the system when managed using HODNET and compared the results with a standard 5G deployment. We only looked at a very simple trading scheme, in which each IoT device's demand is matched by having it connected to the RAN that has the smallest number of connections, and which provides a sufficient RSSI based on the data rate requirements. Even with such an uncomplicated scheme, a significant improvement in resource utilisation was observed.

Significant aspects to explore further include the wider application of the platform to optimise other metrics, such as efficiency, security, and quality of service. Other important areas to investigate are the upper planes of the platform and the inter-operator spectrum broking system. Key questions include how the good to be traded should be mathematically defined (i.e., the utility function), how dynamic the trading can be executed (we expect in the order of minutes or maybe faster), how deals can be secured, verified, and validated, how the platform can be implemented in a distributed fashion, how participation in the trading can remain voluntary but still effective, and how this concept can be extended to other types of network resources. We, therefore, conclude that the concept of enabling a sharing economy in the 6G spectrum has sufficient merit to warrant further investigation and it represents a fascinating step forward for research in this relatively new area of massive automated heterogeneous spectrum trading and allocation.

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References

1. Cisco Annual Internet Report. 2020. Available online: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html (accessed on 26 October 2022).
2. Ericsson Mobility Report. 2020. Available online: https://www.ericsson.com/en/mobility-report/reports/november-2020 (accessed on 26 October 2022).
3. Spectrum Sharing: GSMA Public Policy Position. 2019. Available online: https://www.gsma.com/spectrum/wp-content/uploads/2019/09/Spectrum-Sharing-PPP.pdf (accessed on 26 October 2022).
4. Bazelon, C. Licensed or unlicensed: The economic considerations in incremental spectrum allocations. *IEEE Commun. Mag.* **2009**, *47*, 110–116. [CrossRef]
5. den Hartog, F.; Raschella, A.; Bouhafs, F.; Kempker, P.; Boltjes, B.; Seyedebrahimi, M. A pathway to solving the Wi-Fi tragedy of the commons in apartment blocks. In Proceedings of the 27th International Telecommunication Networks and Applications Conference (ITNAC), Melbourne, Australia, 22–24 November 2017; pp. 1–6.
6. Anker, P. From spectrum management to spectrum governance. *Telecommun. Policy* **2017**, *41*, 486–497. [CrossRef]
7. Mustonen, M.; Matinmikko, M.; Palola, M.; Yrjölä, S.; Horneman, K. An evolution toward cognitive cellular systems: Licensed shared access for network optimization. *IEEE Commun. Mag.* **2015**, *53*, 68–74. [CrossRef]
8. Grissa, M.; Yavuz, A.A.; Hamdaoui, B.; Tirupathi, C. Anonymous Dynamic Spectrum Access and Sharing Mechanisms for the CBRS Band. *IEEE Access* **2021**, *9*, 33860–33879. [CrossRef]

9. Ali, R.; Kim, B.; Kim, S.; Kim, H.; Ishmanov, F. (ReLBT): A Reinforcement learning-enabled listen before talk mechanism for LTE-LAA and Wi-Fi coexistence in IoT. *Comput. Commun.* **2020**, *150*, 498–505. [CrossRef]
10. Zhang, J.; Liu, S.; Yin, R.; Yu, G.; Jin, X. Coexistence algorithms for LTE and WiFi networks in unlicensed spectrum: Performance optimization and comparison. *Wirel. Netw.* **2021**, *27*, 1875–1885. [CrossRef]
11. Qin, Z.; Li, A.; Wang, H. Modeling and Performance Analysis of LTE Coexisting with Wi-Fi. In Proceedings of the International Conference on Information, Communication and Networks (ICICN), Xi'an, China, 22–25 August 2020.
12. Etkin, R.; Parekh, A.; Tse, D. Spectrum Sharing for Unlicensed Bands. *IEEE J. Sel. Areas Commun.* **2007**, *25*, 517–528. [CrossRef]
13. Van Heesch, M.; Wissink, P.L.J.; Ranji, R.; Nobakht, M.; Den Hartog, F. Combining Cooperative with Non-Cooperative Game Theory to Model Wi-Fi Congestion in Apartment Blocks. *IEEE Access* **2020**, *8*, 64603–64616. [CrossRef]
14. Koura, H.; Jhaa, R.K.; Jain, S. A comprehensive survey on spectrum sharing: Architecture, energy efficiency and security issues. *Elsevier J. Netw. Comput. Appl.* **2018**, *103*, 29–57. [CrossRef]
15. Ahmad, W.S.H.M.W.; Radzi, N.A.M.; Samidi, F.S.; Ismail, A.; Abdullah, F.; Jamaludin, M.Z.; Zakaria, M.N. 5G Technology: Towards Dynamic Spectrum Sharing Using Cognitive Radio Networks. *IEEE Access* **2020**, *8*, 14460–14488. [CrossRef]
16. Lv, L.; Chen, J.; Ni, Q.; Ding, Z.; Jiang, H. Cognitive Non-Orthogonal Multiple Access with Cooperative Relaying: A New Wireless Frontier for 5G Spectrum Sharing. *IEEE Commun. Mag.* **2018**, *56*, 188–195. [CrossRef]
17. Zhang, L.; Liang, Y.-C.; Xiao, M. Spectrum Sharing for Internet of Things: A Survey. *IEEE Wirel. Commun.* **2019**, *26*, 132–139. [CrossRef]
18. Wang, X.; Umehira, M.; Akimoto, M.; Han, B.; Zhou, H. Green spectrum sharing framework in B5G era by exploiting crowdsensing. *IEEE Trans. Green Commun. Netw. Early Access* **2022**, 1. [CrossRef]
19. Bera, S.; Misra, S.; Vasilakos, A.V. Software-Defined Networking for Internet of Things: A Survey. *IEEE Internet Things J.* **2017**, *4*, 1994–2008. [CrossRef]
20. López, L.I.B.; Caraguay, L.V.; Villalba, L.J.G.; López, D. Trends on virtualisation with software defined networking and network function virtualisation. *IET Netw.* **2015**, *4*, 255–263. [CrossRef]
21. Rawat, D.B.; Reddy, S. Recent advances on Software Defined Wireless Networking. In Proceedings of the SoutheastCon 2016, Norfolk, VA, USA, 30 March–3 April 2016; pp. 1–8.
22. Bouhafs, F.; Mackay, M.; Raschella, A.; Shi, Q.; Hartog, F.D.; Saldana, J.; Munilla, R.; Ruiz-Mas, J.; Fernandez-Navajas, J.; Almodovar, J.; et al. Wi-5: A Programming Architecture for Unlicensed Frequency Bands. *IEEE Commun. Mag.* **2018**, *56*, 178–185. [CrossRef]
23. Matinmikko-Blue, M.; Yrjola, S.; Ahokangas, P. Spectrum Management in the 6G Era: The Role of Regulation and Spectrum Sharing. In Proceedings of the 2nd 6G Wireless Summit (6G SUMMIT), Levi, Finland, 17–20 March 2020.
24. Qin, Q.; Choi, N.; Rahman, M.R.; Thottan, M.; Tassiulas, L. Network Slicing in Heterogeneous Software-defined RANs. In Proceedings of the IEEE International Conference on Computer Communications (INFOCOM), Toronto, ON, Canada, 6–9 July 2020.
25. El-Refaey, M.; Magdi, N.; Abd El-Megeed, H. Cloud-assisted spectrum management system with trading engine. In Proceedings of the International Wireless Communications and Mobile Computing Conference (IWCMC), Nicosia, Cyprus, 4–8 August 2014.
26. Teng, F.; Guo, D.; Honig, M.L. Sharing of Unlicensed Spectrum by Strategic Operators. *IEEE J. Sel. Areas Commun.* **2017**, *35*, 668–679. [CrossRef]
27. den Hartog, F.; Bouhafs, F.; Shi, Q. Toward secure trading of unlicensed spectrum in cyber-physical systems. In Proceedings of the 16th IEEE Annual Consumer Communications & Networking Conference (CCNC), Las Vegas, NV, USA, 11–14 January 2019; pp. 1–4.
28. Kan, S.; Chen, H.; Zhu, Y.; Li, W. Aggregation based Cell Selection Methods for multi-RAT HetNet. In Proceedings of the 8th International Conference on Wireless Communications & Signal Processing (WCSP), Yangzhou, China, 13–15 October 2016; pp. 1–5.
29. Peng, M.; Wang, C.; Li, J.; Xiang, H.; Lau, V. Recent advances in underlay heterogeneous networks: Interference control, resource allocation, and self-organization. *IEEE Commun. Surv. Tutor.* **2015**, *17*, 700–729. [CrossRef]
30. Chen, X.; Ng, D.W.K.; Yu, W.; Larsson, E.G.; Al-Dhahir, N.; Schober, R. Massive access for 5G and beyond. *arXiv* **2020**, arXiv:2002.03491. [CrossRef]
31. Bouhafs, F.; Seyedebrahimi, M.; Raschellà, A.; Mackay, M.; Shi, Q. Per-flow radio resource management to mitigate interference in dense IEEE 802.11 wireless LANs. *IEEE Trans. Mob. Comput.* **2019**, *19*, 1170–1183. [CrossRef]