Spectrum on Demand: A Competitive Open Market Model for Spectrum Sharing for UAV-assisted Communications

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***Abstract*—Unmanned aerial vehicles (UAVs)-assisted communication has gathered significant interest of the industry, especially with regards to the vision of providing ubiquitous connectivity for beyond 5G (B5G) networks. In this article, we motivate the need for utilizing licensed spectrum for UAV-assisted communication and discuss its advantages such as reliability and security. Moreover, we explore a new dimension to spectrum sharing by proposing a decentralized competitive open market approach-based model, where the different mobile network operators (MNOs) have the opportunity to lease the spectrum to UAV base stations (UAV-BSs), leading to new revenue generation opportunities. The proposed spectrum sharing mechanism is based on the logarithmic utility function and willingness to pay of each UAV-BS. We provide a tradeoff analysis between spectrum sharing and price offered by the MNOs, highlighting the impact of the willingness to pay on the spectrum sharing. The results also highlight the behaviour of price and spectrum shared w.r.t. time, thereby providing an insight into different performance regions until the algorithm converges to it's optimal value. In addition, we also present future directions that could lead to interesting analyses, especially with regards to incentive-based spectrum sharing and security.**

I. Introduction

Ensuring ubiquitous connectivity is one of the major challenges that is being faced by the research community, especially in the context of massive Internet of Things (MIoT), where billions of devices will be connected. It is projected that the number of connected devices will rise exponentially by 2030, triggering the need for developing new solutions to provide ultra-reliable low latency communications (URLLC). Viewing the IoT paradigm and the numerous new applications that are emerging, the need for exploring new and innovative techniques to ensure seamless connectivity seems inevitable. The rising demands would render the current network infrastructure insufficient in terms of providing connectivity to the users. Therefore, the research has been diverted towards finding new solutions to ease the burden on current network infrastructure and introducing new techniques to realize the vision of beyond 5G (B5G) networks. Heterogeneous networks (HetNets) have been envisioned as a panacea for overcoming spectrum congestion, allowing several network tiers to operate simultaneously on different frequency bands. Recently, the unmanned aerial vehicle (UAV)-assisted communication has attracted significant attention of the researchers. UAV-assisted communication adds an extra-terrestrial network tier to a HetNet, which leads to several advantages in terms of network reliability and coverage [1]. A UAV base station (UAV-BS) can add a layer of UAV cells to realize new applications, especially in the scenario where the network demands are not static and there is a need to adapt to changing demands. UAV-assisted communication is being considered as an important aspect of providing ubiquitous connectivity for B5G networks, especially in the context of MIoT. UAVs can act as wireless access points, where a transceiver is mounted on the UAVs to establish communication links with terrestrial users. Flying adhoc networks (FANETs) can also be formed through a batch of UAVs in a particular geographical area, providing broadband wireless communication [2]. A major advantage of UAV-assisted communication is the flexibility to move in a 3D space. The UAV can change its location to improve the link quality based on the service requirements and the quality of service (QoS) constraints. Moreover, the UAVs can establish line-of-sight (LoS) links with the users, thereby leading to high rate and reliable links.

The utilization of UAV-assisted communication in disaster scenarios, where the traditional network infrastructure is partially or fully damaged due to disasters, is another important application of UAVs [3]. Moreover, coverage holes or shadow regions can also be avoided by using UAV-BSs. The flexibility of deployment of UAVs can also allow several commercial applications, especially in the context of hotspots, e.g., a stadium or a concert. Other commercial application include UAV-assisted delivery system, where the users are provided products at their doorstep. UAV-assisted communications introduce a number of governmental and non governmental services such as surveillance, public safety, farming and commercial applications such as Amazon Prime air [4]. In a nutshell, UAV-assisted communication can allow numerous new applications that are not realizable through traditional network infrastructure.

The mobile nature of UAVs highlights the need for intelligent spectrum sharing techniques to meet the QoS requirements. It is pertinent to note that most of the UAV-BSs present in the market today operate on the unlicensed

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spectrum. The utilization of unlicensed spectrum characterized by limited data rate, is vulnerable to interference and provides low reliability, thereby severely restricting the performance of UAV-assisted communication. For example, the spectrum allocation from unlicensed spectrum such as the industrial, scientific and medical (ISM) band has been considered as one of the solutions, however, as mentioned earlier, the unlicensed spectrum comes with its own disadvantages. Therefore, in this article, we motivate a UAV-assisted communication network that leverages the licensed spectrum. One possible solution to deal with the scarcity of licensed spectrum is to share the spectrum with the existing communication systems, such as cellular networks or mobile network operators (MNOs) with licensed spectrum. However, keeping in view the distributed nature of UAV-assisted networks, traditional spectrum sharing approaches such as spectrum sensing or spectrum sharing based on geolocation databases might not be efficient for dynamic UAV-assisted cellular networks. Moreover, the use of unlicensed spectrum may lead to security issues for the users. Utilization of licensed spectrum, on the other hand, can provide several benefits that include security and reliability.

To cope with the above mentioned problems of utilizing traditional spectrum sensing for UAVs networks, few researchers have proposed to use spectrum sharing based on mutual agreements, where a mobile network operator with licensed spectrum shares or leases its licensed spectrum to the UAV-BSs for providing pre-decided services. In future dense network environments, UAV-BS and the ground BS might belong to different network operators. Another use case might be a situation where several UAVs might not belong to the same MNO, i.e., the UAVs enjoy the liberty to share the spectrum with different MNOs, leading to the concept of open market. Moreover, due to the scarce usable bandwidth available at the MNOs, where sharing of spectrum may affect the QoS or bandwidth requirement of the MNO, it would be difficult to convince an MNO to lease its spectrum to UAV-BSs. In this scenario, it is crucial to design an approach with the perspective of mutual benefit for both the MNO and the UAV-BS [5]. The MNO can be provided with some incentives, e.g., in the form of revenue, to persuade it to lease its spectrum to UAV-BS. In this article, motivated by our work in [6] on decentralized power distribution in smart grids, we explore the concept of *open market* and propose an incentive-based spectrum sharing scheme, where an MNO with extra or unused spectrum shares its spectrum with the interested UAVs as shown in Fig. 1.

Our aim is to explore a new dimension with regards to revenue generation, where the UAVs have the option to share the spectrum with different network operators depending on their demands. Specifically:

- We propose a competitive open market approach-based system model for spectrum sharing, where the UAVs have the liberty to share the resources with different MNOs.
- We propose a spectrum sharing algorithm based on the logarithmic utility function and willingness to pay of each UAV, leading to a decenetralized approach to spectrum sharing.
- A unique network scenario involving multiple MNOs and several UAV BSs is analyzed to demonstrate the tradeoff between spectrum sharing and the respective price charged.

In this article, we first motivate the need for UAV-assisted communication in the context of B5G communication networks, with some use cases. Next, we discuss the spectrum sharing in UAV-assisted networks with a focus on open market concept in Section III. In Section IV, we present the proposed system model. A case study follows the aforementioned discussion in Section V, where we present our results to support the idea of decentralized decision making in an open market environment, followed by conclusions and future directions in Section VI.

II. UAV-ASSISTED COMMUNICATION

In this section, we present several aspects of UAV-assisted communication along with its benefits in realizing B5G communications. We also discuss some emerging aspects such as internet-of-UAVs (IoUAVs), UAVs for disaster areas, smart community and other commercial applications. We explore these aspects by keeping in view the need for employing the concept of open market, which forms a part of our proposed system model, which is explained in Section IV.

A. UAVs for hotspot areas

The fact that UAVs are easily programmable and deployable, makes them a suitable candidate for providing coverage in hotspot areas. UAVs can be deployed in hotspot areas, such as a football stadium or a concert, where there is a sudden rise in demand for services. The recent technological advancements, mainly in terms of miniaturization, have allowed the UAV-BSs to possess high computational capacity, thereby allowing it to transmit and receive signals. This is financially viable from the network operators perspective, as they do not have to deploy a permanent terrestrial BS. The UAV-BS can be deployed once the need arises, allowing extra revenue generation for the MNOs. In section III, we discuss how the UAV-BSs can benefit from acting as an agent (AG), i.e., sharing spectrum resources with several MNOs.

B. Internet of UAVs (IoUAVs): Service from the sky

The existing MIoT ecosystem and its integration with the UAVs will lead to several new applications. Building cooperative networks between IoT devices and UAVs can lead to the concept of IoUAVs [7],[8], where along with the IoT devices the UAVs also operate cooperatively to ensure successful transmissions and enhance the coverage. The mobility of UAVs can allow a deployment on demand, creating an interesting interplay between IoT on ground and IoUAVs. UAV-assisted communications will also be integrated with machine type communications (MTC), which is also known as machine-to-machine (M2M) communication. The aforementioned scenarios signify the need for providing reliable and secure connectivity to the users, which can be provided through the utilization of licensed spectrum.

C. UAVs for disaster area networks and smart community

Emergency networks have gathered significant attention recently, mainly for finding ways to minimize the damage or to conduct rescue efforts. In case of an unforeseen event, the disaster relief can be conducted effectively through UAV-assisted communication. In the case of disasters, the traditional network infrastructure is either destroyed or it cannot work at its full capacity. Hence, UAV-assisted communication becomes an economically feasible solution as compared to the terrestrial networks. For example, in case of a failure of one BS, the UAVs can be used to extend the coverage of adjacent BSs to ensure temporary connectivity. Public safety networks can also benefit from UAV-assisted communication. UAVs can help in realizing the concept of *smart community*, where the users are able to establish an ad-hoc local network. The UAV-BS can act as the central BS for all the smart devices in a particular geographical region, allowing the users to stay connected in the event of failure of other network services. This localized approach forms the basis of smart community, where all the entities in a community are able to sustain transmissions in case of any unforeseen events. However, for providing the desired QoS to the users in a smart community, it is important that the UAV-BS has enough resources at its disposal to cater to the demands of the users.

D. Commercial benefits

The UAV-based communication networks have ushered in a new market, that is still untapped. UAVs do not require an allocation of any terrestrial location, thereby saving costs of rent and/or deployment. Moreover, they can be deployed according to the changing demands and other factors depending on the geographical context. For example, in an area which is prone to disasters or other calamities that may destroy the infrastructure leading to several economic losses, the flexibility of deployment of UAVs can greatly help in saving the network operators from losses. UAVs can lead to several applications with regards to IoT [9]. These numerous commercial benefits can only be accrued if we move towards the open market concept discussed in this article, where the UAV-BSs can act as a third party that provides connectivity to the users. In the next section, we provide an overview of the spectrum sharing techniques reported in literature.

III. Spectrum Sharing for UAV-assisted Communications

In this section, we provide a brief review of some of the spectrum sharing techniques that have been used for UAV-assisted communications, where we explain how most of the works in literature have emphasized on scenarios based on single MNO. The works in literature have considered network sharing with single network operators, that can be grouped under the concept of closed market. We motivate the contributions of this work by focusing on the need for open market, leading to a decentralized approach, where the UAVs also play a dynamic role in the spectrum management. Moreover, we also highlight the need for using licensed spectrum that will be a driving force behind the economic benefits of the UAV-assisted communications.

A. Spectrum sharing techniques: A brief review

Several works have appeared in literature, emphasizing on the need for spectrum management for UAV-assisted networks. Spectrum sharing for drone small cells (DSCs) is essential for providing coverage for all users in a geographical location. The spectrum sharing between DSCs and network operators can become challenging with regards to the resources available and the interference issues [10]. When we talk in the context of operating under a standardized regime, the spectrum sharing takes place in the licensed spectrum. The spectrum sharing can also overcome the limitation of under utilization of licensed spectrum. A spectrum sensing mechanism for TV band is presented in [11], where the UAVs can opportunistically access the vacant spectrum resource. However, operating under single network operator will not be practicable with regards to the concept of competitive market. Authors in [12] have discussed a hybrid network architecture, where the UAVs share the spectrum with ground base stations to provide coverage to the cell edge users. The hybrid architecture allows the UAVs to provide coverage to a cellular hotspot area, where it is more feasible to set up a temporary BS instead to spending on permanent infrastructure. It is financially viable for the MNOs to provide 'on demand' services that are required for shorter span of time through UAVs. The network model considered in this work is based on a single cell scenario where one BS is sharing the resources with a single UAV to serve the users. In our proposed model, we motivate the hybrid architecture where several UAVs are operating in an area served by different MNOs. Authors in [13] present a solution for spectrum sharing in UAV-assisted networks, where they discuss the overlapping of resources between UAVs.

B. Benefits of Licensed Spectrum

The utilization of licensed spectrum for UAV-based communication will become inevitable, especially when we talk about massive deployment of UAVs [14]. In B5G communication networks, the quality of experience (QoE) forms one of the important metrics to ascertain the quality of communication links. Unlicensed spectrum will not be able to support the transmissions with regards to ensuring QoE. The utilization of unlicensed spectrum for UAV communication is also marred by security issues, which can dissuade the users from participating in UAV-assisted communications. Therefore, as the deployment of UAV-assisted networks increases, the need for standardizing the overall network architecture would gain ground. In this context, we emphasize that the operation of UAV-assisted communication in the licensed spectrum needs to be explored. Ensuring URLLC is necessary for allowing the UAV-assisted communication to become part of the overall IoT ecosystem. In mission critical applications, the utilization of licensed band would add to the trust on the network, bringing in more users willing to initiate UAV-assisted communications. According to Federal Communications Commission (FCC) in the USA, there is a spectrum crunch with regards to unlicensed bands such as the ISM band [11].

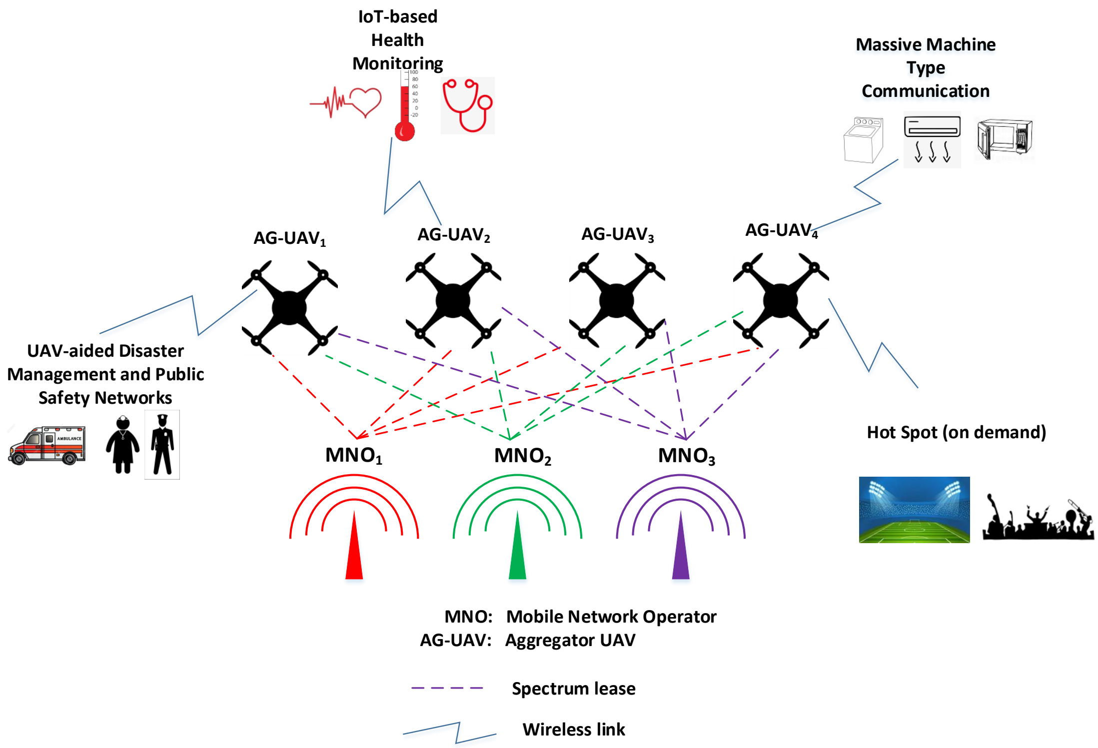

Figure 1: Open market network scenario

IV. Spectrum on demand: System Model

Although several works have appeared in literature that have analyzed the spectrum sharing for UAV-assisted communication but they have focused on a centralized approach of spectrum control, i.e., the decision power lies with the MNO. Centralized approach is not suitable in case of IoT networks, where each device has its own service requirements, especially when we consider B5G networks. Therefore, while operating in the licensed spectrum, it is important to delegate the control from the MNO to the UAV-BS. Most of the previous works have considered the scenario of a single MNO providing coverage to the UAVs. We consider the presence of several MNOs and deviate from the traditional concept of spectrum allocation control by a single MNO. It is pertinent to mention that in our analysis, the UAV-BSs belong to the third party, where the UAV-BSs borrow the licensed spectrum from the MNOs in the vicinity. Thus, our problem takes the form of spectrum sharing problem instead of the traditional resource allocation problem. However, similar analysis can be expanded for the resource allocation in a hybrid architecture where some UAV-BSs belong to third party and some are owned by the MNOs. We consider the concept of open market, where a UAV acts as an agent. The agent is able to choose the spectrum resources from several MNOs. In this article, we refer to such UAVs as agent UAV (AG-UAV). Each network operator can lease the spectrum to the AG-UAVs falling in its range, leading to an open competitive market. In the proposed model, AG-UAVs belong a third party so the MNOs might be unaware of the routes taken by the AG-UAVs and may not be able to pre-allocate the resources. Moreover, the spectrum requirements of AG-UAVs are based on the demands of the ground users, hence the decisions regarding spectrum sharing are taken by the AG-UAVs instead of MNOs, thereby leading to a decentralised approach. In Fig. 1 we show the open market system model.

Due to the presence of several MNOs and many AG-UAVs, a distributed network is formed, where each AG-UAV has access to many MNOs and every MNO has the option to lease spectrum to many independent AG-UAVs. More specifically, this scenario is beneficial when control mechanism is distributed. Due to the diverse services of future networks, the amount of the spectrum that an MNO is willing to lease to the AG-UAVs is time varying, which, for the sake of analysis in this article is referred to as the *time varying capacity*. The proposed algorithm can be summarized as follows: initially each AG-UAV gathers demands of its associated ground users and sets its preference via willingness to pay value according to the nature of services or applications. The AG-UAV declares

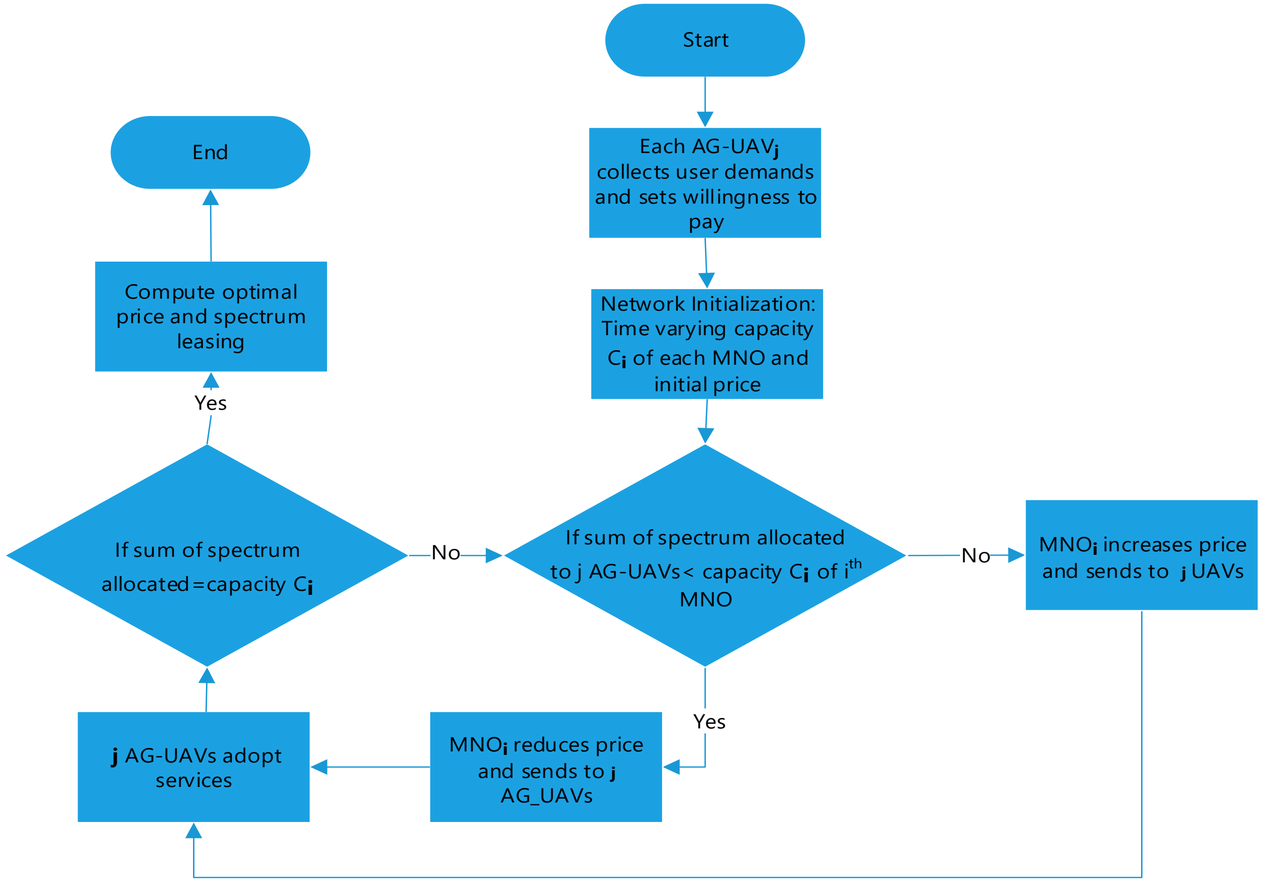

Figure 2: Proposed open market spectrum sharing mechanism

its willingness to pay value to all the MNOs in range. Each MNO has a limited and time varying available spectrum to lease to the UAVs. Upon receiving the willingness to pay information from many AG-UAVs, each MNO checks its own available spectrum that it is willing to lease. Then, the MNO sets the unit price (referred to as price in rest of the paper) for leasing the spectrum. The objective of the MNO is to set its price in such a way that the total spectrum allocation to all the scattered AG-UAVs is less than its available capacity. This price information is broadcasted to all the AG-UAVs, where each AG-UAV responds to the price information by adapting its services to the associated ground users. As a result, AG-UAV sends the preferences to each MNO. This is a recursive process and after some time each AG-UAV adapts its services in such a way that sum of all the spectrum allocated by a particular MNO is less than the capacity of that MNO. At this time instant, price also converges to a constant value which is referred to as *optimal price*. A flow diagram of the aforementioned process is shown in Fig. 2.

The aforementioned spectrum sharing problem is formulated as an optimization problem. The logarithmic utility function is utilized, where the utility function U includes the amount of spectrum and the willingness to pay factor w (AG-UAV's preference) of the AG-UAVs, leading to a weighted logarithmic function. More specifically, we use a utility function that is a weighted logarithmic function of the allocated spectrum, where the weight is the willingness to pay factor. The utility function takes the form of a non decreasing concave function. The objective is to maximize the utility of services at the AG-UAVs, which is conducted by solving the aforementioned utility function at each AG-UAV. It is important to note that the weighted logarithmic approach allows proportional fairness [15]. The willingness to pay factor may depend on the demands of ground users from that AG-UAV or type of service the AG-UAV is providing to the ground users, for example, in critical situations such as a disaster, the AG-UAVs can choose a higher willingness to pay factor as they require priority access to the spectrum to realize transmissions. However, for more delay-tolerant or non-critical applications, they can use a lower willingness to pay factor. This willingness to pay factor is product of the allocated spectrum and the unit price set by MNO and is the characterization of how much total price an AG-UAV is willing to pay. The sum of allocated spectrum to all associated AG-UAVs should be less than the sharable time varying capacity C of the MNO, which is a constraint of the optimization problem. The optimization problem is solved by dual decomposition method, where price is represented by a Lagrange multiplier. In the next section, we present an analysis with results to further strengthen our argument for an open market approach.

V. UAV open market: Results and Analysis

In this section, we present our results and demonstrate how the proposed algorithm converges to optimal price and spectrum sharing for different parameters. We also highlight the impact of change in parameters such as willingness to pay factor w, and how they impact the spectrum sharing. The aim of the simulation model and the results is to exhibit the convergence of the proposed algorithm and analyze its behavior.

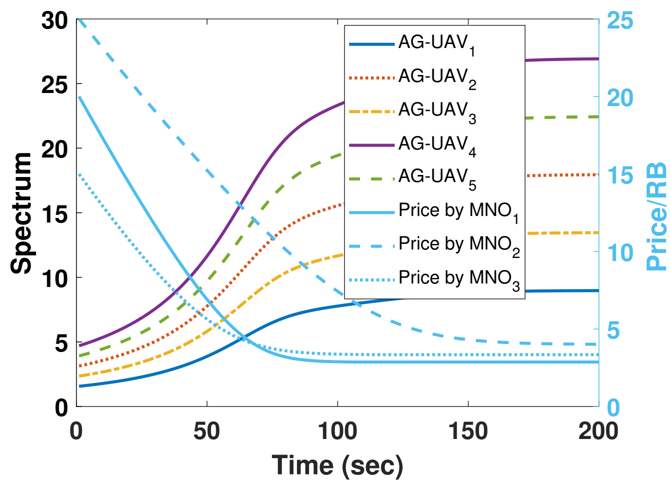

Figure 3: Time versus spectrum sharing and price for 3 MNOs and 5 AG-UAV

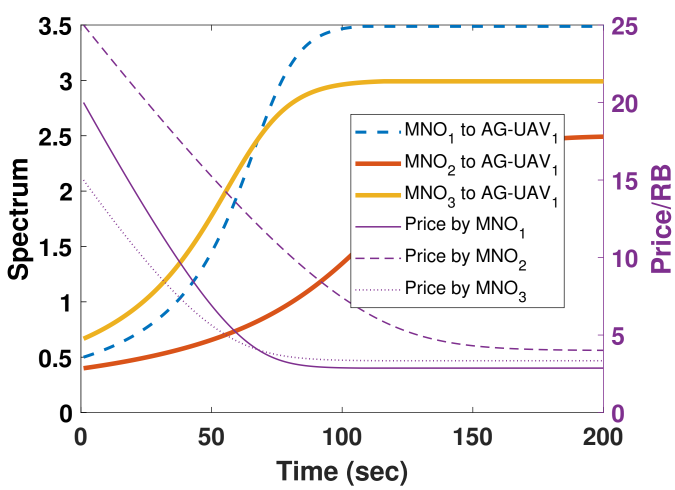

Figure 4: Time versus spectrum sharing and price for 3 MNOs and 1 AG-UAV

The spectrum sharing scenario is considered as shown in Fig. 1 shows the spectrum sharing in a scenario that involves spectrum shared by 3 MNOs with 5 AG-UAVs. We assume that the MNO has an unused spectrum that it is willing to lease, referred to as time varying capacity C resource blocks (RBs). For the sake of analysis, the capacity of MNO_1, MNO_2 and MNO_3 is assumed to be to C_1=35 RBs, C_2=25 RBs and C_3=30 RBs, respectively. It is also pertinent to mention that the algorithm can perform spectrum sharing for other values of capacity C, however to demonstrate the effectiveness of the proposed algorithm we have indicatively considered the abovementioned values of C. It is also assumed that the AG-UAVs are operating in a close vicinity, thereby leading to the competitive nature of spectrum sharing. The willingess to pay factor w for the AG-UAVs is represented by the set $W = \{10, 20, 15, 30, 25\}$, where the cardinality of the set is 5 due to a presence of 5 AG-UAVs. Fig. 3 shows the time versus spectrum sharing and price for this scenario. The plot shows an interplay of the change in demands by the AG-UAVs and the change in price by the MNOs, until the algorithm converges to its stable state, which is signified by the constant value of spectrum sharing and price after a particular time. Once the MNO sets its price to the optimal price, each AG-UAV receives the spectrum according to its demands and willingness to pay. We can also observe that AG-UAV_4 borrows the highest spectrum as its willingness to pay factor is the highest.

In Fig. 4, we show the spectrum shared with a single AG-UAV (for demonstration we selected AG-UAV_1 only) by 3 MNOs. We assume that the AG-UAV_1 is in the range of the MNO_1, MNO_2 and MNO_3, where the MNOs have a capacity of 35, 25 and 30 RBs, respectively. The willingness to pay factor of AG-UAV_1 is set to 20. In this plot, the behaviour of price and the spectrum shared is of particular interest as it shows the impact of change in price on the spectrum demanded. For example, in the initial stages, i.e., at time=0, the price offered by MNO_1 is higher than the price offered by MNO_3. Therefore, AG-UAV_1 borrows a lower spectrum from MNO_1 as compared to MNO_3. But with the passage of time, AG-UAV_1 adjusts its demands and the MNOs adjust their prices. If we observe between time= 60 seconds and t= 200 seconds, we can see that the price offered by MNO_1 decreases as compared to the price offered by MNO_3 at t= 60 seconds, thereby making AG-UAV_1 borrow more spectrum from MNO_1 as compared to MNO_3. Finally, the algorithm converges to its optimal value, which is evident from the constant spectrum sharing and price achieved after a particular time. This plot provides an interesting interplay between the price offered by the MNOs and the spectrum shared by the AG-UAVs.

In Fig. 5, we show the spectrum sharing and price offered by MNO_1 to different AG-UAVs. The capacity of MNO_1 is set to C_1 = 30 RBs. From this plot, we can see that the total spectrum shared by MNO_1 with the 5 AG-UAVs is equal to 30 RBs, proving the accuracy of convergence of the algorithm. Next, we consider the impact of change in the willingness to pay factor set W, where the new set is $W = \{20, 30, 10, 10, 25\}$. Fig. 6 shows the time versus spectrum sharing and price for the MNO_1 to AG-UAVs. If we compare this plot with the plot shown in Fig. 5, we can observe the change in the spectrum sharing. Specifically, if we can observe the spectrum shared with AG-UAV_4, we can observe that when the willingness to pay factor w changes from 30 (which is the maximum among the AG-UAVs) to 10 (which is the lowest among the AG-UAVs), the spectrum shared also changes from highest in the previous case to lowest in the current case.

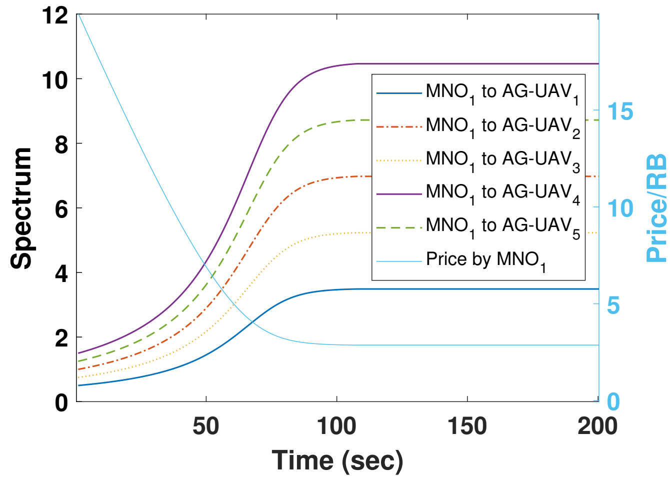

Figure 5: Time versus spectrum sharing and price for 1 MNO and 5 AG-UAVs

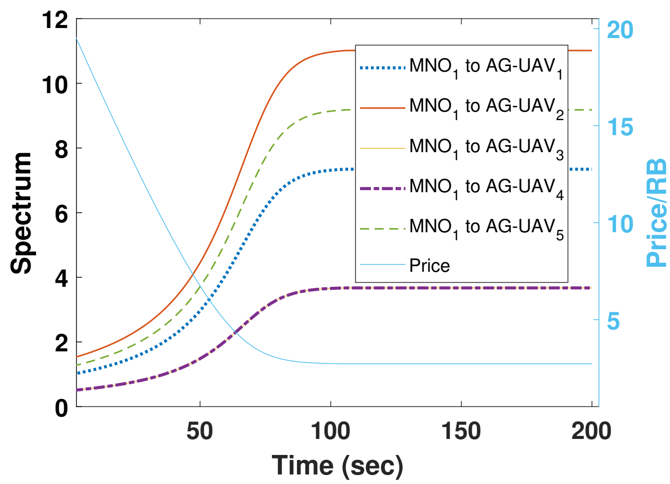

Figure 6: Change in demand by AG-UAVs

VI. Conclusion and Future Works

In this article, we explore a new dimension to spectrum sharing by proposing a decentralized competitive open market approach-based model. The proposed model is based on the UAVs sharing the spectrum with different mobile network operators, thereby leading to new revenue generation opportunities. The main idea behind the proposed algorithm is to consider an approach that is mutually beneficial for both the UAV-BS and the MNOs. The proposed spectrum sharing algorithm is based on the logarithmic utility function and willingness to pay of each UAV, leading to a decentralized approach to spectrum sharing. We present a flow diagram of the proposed algorithm and discuss a case study to analyze the utility of the algorithm. The tradeoff analysis between the price offered by an MNO and the spectrum shared by the AG-UAV is presented to highlight the change in revenue generation based on the demands.

In future, standardization and utilization of licensed spectrum will also allow to avoid sky pollution as the UAVs not authorized will not be allowed to operate. The UAV paths will be defined in order to ensure congestion of air traffic. Moreover, the regulation is also necessary to ensure safety of aviation. For the users, network operators and vendors to mutually benefit from the UAV-based communications, there is a need to standardize. There have been some attempts to standardize the UAV communication. For example, USA FAA has kickstarted standardization activities. National Aeronautics and Space Administration (NASA) is exploring prototype technologies for an UAS traffic management (UTM) system for enabling safe and efficient low-altitude civilian UAV operations. [4].

As a future work, the proposed open market model can be further expanded to a drone cluster based network, where the cluster acts cooperatively to provide services to the users. It would be interesting to observe how the revenue model would behave in cooperative network environment. In this article we considered the case of high-altitude UAVs and assumed that a direct link exists between the users and the UAVs. This analysis can be expanded to the case of low-altitude UAVs where physical blockages might hinder the transmissions. In this case, an extra layer of device-to-device (D2D) network can be added to realize the transmissions. However, viewing the participation of devices, an incentive mechanism for persuading the devices to cooperate needs to be explored. Another interesting direction for future work can be to explore the utilization of blockhain for ensuring a secure network environment. The blockchain-based network can ensure the registration of UAVs and provide an opportunity for trust based smart contracts between the UAVs and the MNOs. It can be interesting to analyse the impact of blockchain-based model on blocking any malicious requests.

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