Bioinspired Dynamic Spectrum Management in 3D Networks

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***Abstract*—In this paper, the challenge of dynamic spectrum management is treated following an economic-based perspective. In particular, a novel bioinspired spectrum allocation from the Network Service Providers (NSPs) to the users is introduced, exploiting the theory of symbiosis under the free competition. The overall objective is to determine the NSPs optimal bandwidth prices to maximize their profit, while satisfying the users bandwidth needs. The aforementioned spectrum management framework is analyzed while exploiting a novel 3D network architecture consisting of High Altitude Platforms (HAPs), Unmanned Aerial Vehicles (UAVs), and ground gNBs NSPs, each one of them presenting different operational characteristics and capabilities in terms of coverage. Specifically, various NSPs owning the ground gNBs, UAVs, HAPs, respectively, engage in a symbiotic relationship with the users, by offering licensed and unlicensed spectrum bands and receiving payment from them in return. The Nash equilibrium is determined for the free market modeling, where the optimal unlicensed bandwidth slices' prices for each NSP are derived. The performance evaluation of the proposed approach is achieved via modeling and simulation.**

***Index Terms*—Dynamic Spectrum Management, 3D Network, Network Economics.**

I. INTRODUCTION

The heterogeneous wireless networks have provided a flexible solution to support the reusability of the scarce spectrum resource and/or the use of different spectrum bands, i.e., licensed and unlicensed spectrum bands [1]. To cope with the growing spectrum demand, this present work introduces a bioinspired modeling approach to the problem. A novel 3D network architecture is designed consisting of ground NextG nodes (gNBs), Unmanned Aerial Vehicles (UAVs) gNBs, and High Altitude Platforms (HAPs) gNBs, driven by the need for efficient spectrum utilization of licensed and unlicensed spectrum bands. In such a setting, a bioinspired dynamic spectrum management framework is introduced based on the theory of symbiosis under the prism of free competition modeling to determine the efficient spectrum allocation and pricing in order to accommodate the users' QoS prerequisites.

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A. Related Work

Dynamic spectrum management based on pricing mechanisms has been investigated in the recent literature as a promising approach of efficiently handling the scarce spectrum resource, under different settings and topologies. For instance, the authors in [2] design a Hotelling game model among the primary (PUs) and secondary users (SUs) of a cognitive radio communication system based on the spectrum quality diversity to provide pricing-based spectrum access to the users. A similar communication setup is considered in [3], where the PUs participate in a market-based spectrum allocation, determining the optimal price of their unused bandwidth, which is purchased by the SUs.

Apart from the cognitive radio communication systems, market-based mechanisms have been applied in NextG cellular networks to deal with the problems of dynamic spectrum management. The authors in [4] design a Stackelberg game among the NSP and the users to determine the optimal bandwidth price and the optimal amount of purchased bandwidth to maximize its profit and their energy efficiency, respectively. A similar modeling is considered in [5] among a spectrum provider (leader) and the base stations (followers), which purchase bandwidth in a dynamic manner in order to push on-demand services stemming from the users. The authors in [6] present an auction-based dynamic spectrum management framework that satisfies the properties of incentive compatibility, revenue maximization, individual rationality, efficiency, computational manageability, and fairness. A similar approach is discussed in [7] where the auction is performed among the NSP and the relays in order to maximize the bandwidth usage.

However, dynamic spectrum management by itself cannot support the exponential growth of spectrum needs by the connected devices. Thus, novel 3D wireless networking architectures have been recently introduced as a promising communication paradigm and solution, exploiting ground and aerial gNBs to create a hierarchical multi-cell communication environment of increased capacity in terms of the number of served users [8]. In [9], the network's utility maximization problem is formulated as a joint 3D UAV placement, user scheduling and association, and spectrum allocation optimization problem, and solved based on a distributed alternating maximization iterative algorithm.

B. Contributions & Outline

The current literature that deals with the problem of dynamic spectrum management in 3D networks, mainly considers simple UAV-assisted networks, without revealing and exploiting the full potential of a real 3D network architecture. This article aims at addressing these exact open research challenges by introducing a novel bio-inspired dynamic spectrum management model in a fully 3D-deployed network architecture, in order to jointly satisfy the users' bandwidth demand, optimize the Network Service Providers (NSPs) revenue, while simultaneously exploiting the licensed and unlicensed spectrum band. The following points highlight the main technical contributions of this research work.

1) A novel 3D networks architecture is introduced consisting of ground gNBs, Unmanned Aerial Vehicles (UAVs) gNBs, and High Altitude Platforms (HAPs) gNBs, which can provide licensed and unlicensed spectrum to the end users in order to support their bandwidth needs to facilitate their communication.
2) An innovative bio-inspired dynamic spectrum management framework is designed following the principles of evolution in biological ecosystems under the prism of symbiosis. Specifically, various NSPs owning the ground gNBs, UAVs, HAPs, respectively, engage in an obligate symbiosis with the users by offering licensed and unlicensed spectrum bands and receiving a corresponding payment from the users in return. Each symbiotic partner, i.e., users and NSPs, aims to maximize its benefit, i.e., utility and profit, and they cannot achieve their goals without the one relying on another.
3) Based on the proposed symbiotic dynamic spectrum management model, a realistic market-based pricing mechanism is introduced by exploiting the symbiotic partners relationship in order to determine the NSPs' optimal bandwidth prices to maximize their profit, while satisfying the users' bandwidth needs. Specifically, the free competition market model is studied, where all the NSPs compete among each other to determine their optimal bandwidth prices and get a share of the users' market. The free competition market model is formulated as a non-cooperative game among the NSPs and the Nash Equilibrium is determined.
4) Essential analysis and discussion, following a detailed simulation-based evaluation are provided. The provided network economics-based analysis is performed in order to highlight the benefits of the free competition pricing model in the symbiotic dynamic spectrum management in 3D networks.

The rest of this paper is structured as follows: Section II describes the bio-inspired dynamic spectrum management model and the symbiotic partners' characteristics. The analysis of the free competition model is presented in Section III. Section IV presents the numerical results and evaluation.

II. Bio-inspired Dynamic Spectrum Management

A. A Bio-inspired Modeling

The proposed symbiotic dynamic spectrum management model is inspired by the evolution of biological ecosystems that relies on mutualistic relationships established among different biological organisms, who benefit from the relationship. The involved dissimilar organisms receive different benefits from the symbiotic relationship, but the goal is common; to survive. In this case, symbiosis is obligatory, which means that the symbiotic partners, otherwise called symbionts, depend on each other for survival. In a symbiotic relationship, the symbiotic partners can exchange resources or services or a combination of them among each other in order to mutually benefit out of this exchange.

Inspired by this symbiotic analogy from the biological ecosystems, the NSPs owning the ground, UAVs, and HAPs gNBs provide their licensed and unlicensed bandwidth to the users, i.e., acting as the corals who provide shelter to the fish, while the users provide payment for the received service, i.e., acting as the fish who eat the seaweed to enable the corals' survival. The NSPs and the users are symbiotic partners and no one can survive without the other. Indeed, the users need to purchase bandwidth from the NSPs in order to be able to communicate, and the NSPs depend on the users' payment for the provided bandwidth in order to stay in business. However, how those different entities, i.e., NSPs and users with competing interests can establish a symbiotic relationship? The answer to this challenging question is provided in Sections III by introducing a free competition model.

B. System Model

We consider a 3D network architecture consisting of ground, UAVs, and HAPs gNBs owned by different NSPs. Let us denote by $I = \{G, U, H\}$ the set of the three different NSPs based on their corresponding deployed ground, UAVs, and HAPs gNBs, respectively. The set of users served by the NSPs is denoted as $\mathcal{N} = \{1, \ldots, n, \ldots, N\}$. The NSPs can provide licensed and unlicensed spectrum bands to the users to support their communication. Also, each NSP can support different geographical areas given the coverage characteristics and capabilities of the ground, UAVs, and HAPs gNBs. The overall set of areas is denoted as $\mathcal{A} = \{1, \ldots, a, \ldots, A\}$ and the set of areas that each NSP serves as $A_i, \forall i \in I = \{G, U, H\}$. For example, we consider $A_H = \{1, 2, \ldots, 7\}$ for the HAPs gNBs, $A_U = \{2, 3, \ldots, 7\}$ for the UAVs gNBs, and $A_G = \{3, 5, 7\}$ for the ground gNBs. The set of users residing in an area a is denoted as $\mathcal{N}_a \subseteq \mathcal{N}$.

The provided licensed spectrum is considered as a safe resource, as the users exclusively use their purchased bandwidth slice [10]. We denote the licensed bandwidth slice as $b^l_{n,i}$[Hz] that user n purchases from NSP i. A typical licensed spectrum band that the NSPs use is the 1850-1990MHz broadband personal communications service spectrum band [11]. Given the exclusive use of the licensed bandwidth slice, the users pay a higher (than the unlicensed bandwidth slice) and fixed price $P_i^{safe}[\frac{\$}{\text{licensed bandwidth slice}}]$. On the other hand, the unlicensed spectrum offered by the NSPs is characterized as a Common Pool of Resources (CPR) and its price $P_{i,a}^{CPR}[\frac{\$}{\text{unlicensed bandwidth slice}}]$ is variable per NSP i per serving area a, depending on the users' demand. The NSPs price vector for the CPR unlicensed bandwidth is $\mathbf{P} = [\mathbf{P}_G^{CPR}, \mathbf{P}_U^{CPR}, \mathbf{P}_H^{CPR}]$, where, $\mathbf{P}_G^{CPR} = [P_{G,3}^{CPR}, P_{G,5}^{CPR}, P_{G,7}^{CPR}]$, $\mathbf{P}_U^{CPR} = [P_{U,2}^{CPR}, \ldots, P_{U,7}^{CPR}]$, $\mathbf{P}_H^{CPR} = [P_{H,1}^{CPR}, \ldots, P_{H,7}^{CPR}]$. Obviously, the price $P_{i,a}^{CPR}$ of the CPR unlicensed spectrum is lower than the price P_i^{safe} due to the risky nature of the resource, which can be overexploited by the users and in this case provide lower QoS guarantee given the increased interference levels.

In the following analysis, we consider that the NSPs, who own the ground, UAVs, and HAPs gNBs are independent of each other and each one aims at maximizing its profit by selling licensed and unlicensed bandwidth slices to the users and determining their optimal selling prices. On the other hand, the users are requesting elastic and inelastic services, which are characterized by strict and relaxed QoS prerequisites, respectively. For their elastic services, the users purchase unlicensed bandwidth slices, given their relaxed QoS constraints which are aligned with the risky nature of the CPR unlicensed spectrum. The exact opposite holds true for inelastic services, where the users purchase licensed bandwidth slices to guarantee the satisfaction of their QoS prerequisites.

C. Symbiotic Partners Characteristics

In this section, we discuss the characteristics of the symbiotic partners, i.e., NSPs and users, otherwise called symbionts. The goal of the users is to maximize their CPR resource utilization profit which consists of the pure CPR resource utilization utility $\mathcal{U}_n(\mathbf{P})$ minus the cost of purchasing CPR unlicensed spectrum. It is highlighted that the user's cost of purchasing licensed spectrum to satisfy its inelastic services is not considered in the optimization of the user's payoff, as this cost is fixed, non-avoidable and depends on the user's inelastic services demand, which regardless of the price, the user has a strict need to satisfy. The corresponding optimization problem for each user is formulated as follows:

$$\textbf{P1:} \quad \max_{b_{n,i}} [\mathcal{U}_n(\mathbf{P}) - \sum_{\forall i \in I} P_{i,a}^{CPR} \cdot b_{n,i}^{unl}] \tag{1a}$$

$$\text{s.t.} \quad P_{i,a}^{CPR} \geqslant 0, \forall i \in I, \forall a \in A_i \tag{1b}$$

$$b_{n,i}^{unl} \geqslant 0 \tag{1c}$$

where $b_{n,i}^{unl}$[Hz] denotes the unlicensed bandwidth slice allocated to user n by the NSP i. It is highlighted that each user can purchase unlicensed bandwidth slices from multiple NSPs serving the area a that the user resides in. Also, the NSPs can use different unlicensed spectrum bands given their communication distance and coverage characteristics. For example, the ground gNBs, which are characterized by high traffic demand can use the 5.725–5.850GHz band (i.e., Unlicensed National Informational Infrastructure or UNII-3 band), which is much less prone to congestion and interference but results in a small coverage area [11]. The UAVs gNBs can use the 5.150–5.250GHz UNII-1 band, which is characterized by a higher coverage area, and the HAPs gNBs can use the 2.412–2.484GHz unlicensed spectrum band, which provides even higher coverage range, with the drawback that it is the most heavily congested unlicensed spectrum band. The users' pure CPR resource utilization utility $\mathcal{U}_n(\mathbf{P})$ can be defined as a quadratic and strictly concave function, where the corresponding CPR unlicensed bandwidth slices demand is linear, by extending the Sigh and Vives model [12], as follows:

$$\begin{aligned}\mathcal{U}_n(b_{n,i}^{unl}, b_{n,j}^{unl}, b_{n,k}^{unl}) &= \alpha_i b_{n,i}^{unl} + \alpha_j b_{n,j}^{unl} + \alpha_k b_{n,k}^{unl} \\ &- \frac{\beta_i {b_{n,i}^{unl}}^2 + \beta_j {b_{n,j}^{unl}}^2 + \beta_k {b_{n,k}^{unl}}^2 + 2\gamma b_{n,i}^{unl} b_{n,j}^{unl}}{2} \\ &- \frac{2\epsilon b_{n,j}^{unl} b_{n,k}^{unl} + 2\zeta b_{n,i}^{unl} b_{n,k}^{unl}}{2}\end{aligned} \tag{2}$$

where α_i, α_j, α_k, β_i. β_j, β_k, γ, ϵ, $\zeta \in \mathbb{R}$ and their values can be determined by following the analysis presented below. Also, $i, j, k \in I = \{G, U, H\}$ with $i \neq j \neq k$.

The optimization problem (1a) – (1c) can be solved by creating the set of linear equations that are derived from $\frac{\partial}{\partial b_{n,i}^{unl}}[\mathcal{U}_n(b_{n,i}^{unl}, b_{n,j}^{unl}, b_{n,k}^{unl}) - \sum_{\forall i \in I} P_{i,a}^{CPR} b_{n,i}^{unl}] = 0, \forall i \in I$ and solving it. The relative values of the coefficients included in Eq. 2 can be determined by calculating the determinants $D_{b_{n,i}^{unl}}$, $D_{b_{n,j}^{unl}}$, $D_{b_{n,k}^{unl}}$, and solving the system of inequalities $D_{b_{n,i}^{unl}} > 0$, $D_{b_{n,j}^{unl}} > 0$, $D_{b_{n,k}^{unl}} > 0$, $D > 0$. By performing the linear algebraic calculations, we can determine the optimal amount of unlicensed bandwidth slices of user n from NSP $i, \forall i \in I$ as follows:

$$b_{n,i}^{CPR}(\mathbf{P}) = B_{n,i}^{CPR} - \mu_i^n P_{i,a}^{CPR} + \mu_{i,k}^n P_{k,a}^{CPR} + \mu_{i,j}^n P_{j,a}^{CPR} \tag{3}$$

where $\mu_i^n = \frac{\beta_k \beta_j - \lambda_{k,j}^2}{D}$, $\mu_{i,k}^n = \frac{\lambda_{k,j}\lambda_{k,i} - \lambda_{j,i}\beta_k}{D}$, $\mu_{i,j}^n = \frac{\lambda_{j,i}\lambda_{k,j} - \lambda_{k,i}\beta_j}{D}$, $D = -\beta_i(\beta_j\beta_k - \lambda_{j,k}^2) + \lambda_{i,j}(\lambda_{i,j}\beta_k - \lambda_{j,k}\lambda_{i,k}) - \lambda_{i,k}(\lambda_{j,k}\lambda_{i,j} - \beta_j\lambda_{i,k})$, $\lambda_{i,j} = \gamma$, $\lambda_{j,k} = \epsilon$, $\lambda_{i,k} = \zeta$, and $B_{n,i}^{CPR} = \frac{\beta_j\beta_k\alpha_i + \lambda_{j,k}^2\alpha_i + \lambda_{j,i}\beta_k\alpha_j - \lambda_{k,j}\lambda_{k,i}\alpha_j}{D} + \frac{-\lambda_{j,i}\lambda_{k,j}\alpha_k + \lambda_{k,i}\alpha_k\beta_j}{D}$ and applying the index rotation for the general case.

Based on the above analysis, the users' CPR unlicensed spectrum demand in an area a can be calculated as $D_{i,a}^{CPR}(\mathbf{P}) = \sum_{\forall n \in \mathcal{N}_a} b_{n,i}^{CPR}(\mathbf{P})$, and for notation convenience, it can be written as follows:

$$D_{i,a}^{CPR}(\mathbf{P}) = B_{i,a}^{CPR} - \kappa_i^a P_{i,a}^{CPR} + \kappa_{i,k}^a P_{k,a}^{CPR} + \kappa_{i,j}^a P_{j,a}^{CPR} \tag{4}$$

where $B_{i,a}^{CPR}$[Hz] denotes the users CPR unlicensed bandwidth demand in area a from the NSP $i \in I$. The coefficient κ_i^a expresses the sensitivity of the users' CPR unlicensed bandwidth demand to the change of the NSP's price, while the coefficients $\kappa_{i,k}^a$ and $\kappa_{i,j}^a$ capture the portion of the CPR unlicensed bandwidth demand that flows from the NSP k and j to the NSP i for an announced price $P_{k,a}^{CPR}$ and $P_{j,a}^{CPR}$, respectively.

The NSPs profit in each area a from selling the licensed and unlicensed bandwidth slices is given below.

$$\mathcal{P}_{i,a}(P_{i,a}^{CPR}, \mathbf{P}_{-i,a}^{CPR}) = D_{i,a}^{CPR} P_{i,a}^{CPR} + \sum_{\forall n \in \mathcal{N}_a} b_{n,i}^{l} P_i^{safe} - \sum_{\forall n \in \mathcal{N}_a} b_{n,i}^{l} \cdot d_i [B_i^l - \frac{B_{i,a}^{CPR} - D_{i,a}^{CPR}}{\sum_{\forall n \in \mathcal{N}_a} b_{n,i}^{l}}]^2 \quad (5)$$

The revenue of the NSP i by selling CPR unlicensed bandwidth slices to cover the users' demand $D_{i,a}^{CPR}$ at a price $P_{i,a}^{CPR}$ is given by the first term of Eq. 5. The NSP's revenue from selling licensed bandwidth slices to the users, i.e., $\sum_{\forall n \in \mathcal{N}_a} b_{n,i}^{l}$, at a fixed price P_i^{safe} is given by the second term of Eq. 5. The third term of Eq. 5 captures the discount offered by the NSP i to the users who purchased licensed bandwidth slices, in the case that the NSP cannot satisfy the users' licensed spectrum demand, for which they have already paid a fixed price P_i^{safe}. The users' minimum licensed spectrum, demand from NSP i is denoted as B_i^l[Hz] and the NSP's discount factor is d_i % of the price P_i^{safe}. Each NSP's overall profit in all its serving areas is given as follows.

$$\mathcal{P}_i(\mathbf{P}_i^{CPR}, \mathbf{P}_{-i}^{CPR}) = \sum_{\forall a \in A_i} \mathcal{P}_{i,a}(P_{i,a}^{CPR}, \mathbf{P}_{-i,a}^{CPR}) \quad (6)$$

III. Free Competition Market Model

Based on the proposed symbiotic dynamic spectrum management environment introduced in Section II, we study the scenario where all the NSPs symbionts compete among each other in a free competition market model in order to determine the optimal price of the CPR unlicensed bandwidth slices. The goal of each NSP is to maximize its profit, thus, the optimization problem can be formulated as follows.

$$\textbf{P2:} \quad \max_{\{P_{i,a}^{CPR}\}_{\forall a \in A_i}} \mathcal{P}_i(\mathbf{P}_i^{CPR}, \mathbf{P}_{-i}^{CPR}) \quad (7a)$$

$$\text{s.t.} \quad P_{i,a}^{CPR} \geqslant 0, \forall a \in A_i \quad (7b)$$

Towards solving the optimization problem (7a) – (7b), we formulate it as a non-cooperative game among the NSPs, $G = [I, \{\mathcal{S}_i\}_{\forall i \in I}, \{\mathcal{P}_i\}_{\forall i \in I}]$, where $I = \{G, U, H\}$ is the set of players, i.e., NSPs, $\mathcal{S}_i$ is their strategy set of unlicensed bandwidth slices' prices, and $\mathcal{P}_i$ is their payoff function, i.e., profit. To determine the optimal prices of the NSPs' CPR unlicensed bandwidth slices in the optimization problem (7a)–(7b), the concept of Nash Equilibrium is adopted.

Definition 1. ***(Nash Equilibrium):*** *The non-cooperative game* $G = [I, \{\mathcal{S}_i\}_{\forall i \in I}, \{\mathcal{P}_i\}_{\forall i \in I}]$ *has at least one Nash Equilibrium price vector* $\mathbf{P}^* = [\mathbf{P}_G^{CPR*}, \mathbf{P}_U^{CPR*}, \mathbf{P}_H^{CPR*}]$*, where* $\mathcal{P}_i(\mathbf{P}_i^{CPR*}, \mathbf{P}_{-i}{}^{CPR*}) \geqslant \mathcal{P}_i(\mathbf{P}_i^{CPR}, \mathbf{P}_{-i}^{CPR*}), \forall \mathbf{P}_i^{CPR} \in \mathcal{S}_i$.

The existence of the Nash Equilibrium for the non-cooperative G can be easily shown given the concavity of the profit function with respect to the NSP's price and that the strategy space $\mathcal{S}_i$ is a continuous compact set. The best response function of each NSP is given as follows:

$$\mathcal{B}_i(\mathbf{P}_i^{CPR}, \mathbf{P}_{-i}^{CPR}) = \arg \max_{\mathbf{P}_i^{CPR}} \mathcal{P}_i(\mathbf{P}_i^{CPR}, \mathbf{P}_{-i}^{CPR}) \quad (8)$$

Based on Eq. 5 and Eq. 6, we can easily show that the following properties hold true for each NSP's best response function: (i) positivity: $\mathcal{B}_i(\mathbf{P}_i^{CPR}, \mathbf{P}_{-i}^{CPR}) > 0, \forall \mathbf{P}_i^{CPR} > 0$, (ii) monotonicity: if $\mathbf{P}_i^{CPR} > \mathbf{P}_i^{CPR\prime}$, then $\mathcal{B}_i(\mathbf{P}_i^{CPR}, \mathbf{P}_{-i}^{CPR}) > \mathcal{B}_i(\mathbf{P}_i^{CPR\prime}, \mathbf{P}_{-i}^{CPR})$, and (iii) scalability: for all $\omega > 1$, it holds true that $\omega \mathcal{B}_i(\mathbf{P}_i^{CPR}, \mathbf{P}_{-i}^{CPR}) \geqslant \mathcal{B}_i(\omega \mathbf{P}_i^{CPR}, \mathbf{P}_{-i}^{CPR})$. Thus, we conclude that the best response function in Eq. 8 is a standard function on [13], and the non-cooperative game G converges to a Nash Equilibrium following a typical best response dynamics algorithm. For simplicity, the Nash Equilibrium can be determined by solving the set of linear equations $\frac{\partial \mathcal{P}_i(\mathbf{P}_i^{CPR}, \mathbf{P}_{-i}^{CPR})}{\partial P_{i,a}^{CPR}} = 0$, following any existing low complexity numerical method, such as the gradient method. Given the existence of Nash Equilibrium, each NSP i can determine the optimal prices of the CPR unlicensed bandwidth slices at each serving area a, i.e., $P_{i,a}^{CPR}, \forall i \in I, \forall a \in A$, and the users can determine the corresponding optimal amount of the purchased slices $b_{n,i}^{unl}$ based on the optimization problem (1a) – (1c).

IV. Evaluation & Results

In this section, a detailed numerical evaluation is presented via modeling and simulation, in order to demonstrate the operational characteristics of the proposed bio-inspired dynamic spectrum management framework under the free competition model. Specifically, the pure operation of the market model is presented in Section IV-A, while a scalability analysis is demonstrated in Section IV-B. Unless otherwise explicitly stated, the following values of the parameters are considered throughout the numerical evaluation: $P_i^{safe} = [800, 900, 1000]$, α_i=α_j=α_k=1300, $\beta_i = -50.23$. $\beta_j = -67.09$, $\beta_k = -91.44$, $\gamma = 2.85$, $\epsilon = 4.7$, $\zeta = 3$, $\mu_{i,k}^n = 7 \times 10^{-3}$, $\mu_{i,j}^n = 9 \times 10^{-3}$, $\mu_{j,k}^n = 8 \times 10^{-3}$, $\mu_i^n = 0.02$, $\mu_j^n = 0.015$, $\mu_k^n = 0.011$, $\kappa_i^a \in [0.2, 0.8]$, $\kappa_j^a \in [0.15, 0.6]$, $\kappa_k^a \in [0.11, 0.44]$ $\kappa_{i,k}^a \in [7 \times 10^{-2}, 2.8 \times 10^{-1}]$, $\kappa_{j,k}^a \in [8 \times 10^{-2}, 3.2 \times 10^{-1}]$, $\kappa_{i,j}^a \in [9 \times 10^{-2}, 3.6 \times 10^{-1}]$, $b_{n,i}^l = 5$, $d_i = [20\%, 15\%, 10\%]$.

A. Pure Operation & Performance

In this section, a detailed evaluation of the proposed bio-inspired dynamic spectrum management framework is presented in order to demonstrate its pure operational characteristics, as well as its performance considering the novel 3D networks architecture proposed in this paper. Specifically, Fig. 1a-1b present the price of the unlicensed bandwidth slice, i.e., unit price, and the corresponding total users' demand of unlicensed bandwidth slices $D_{i,a}^{CPR}(\mathbf{P})$ in three representative areas, i.e., areas 3, 5, 7, where all the NSPs compete among each for the market share under the free market model, respectively. It is noted that the higher the area's ID, the

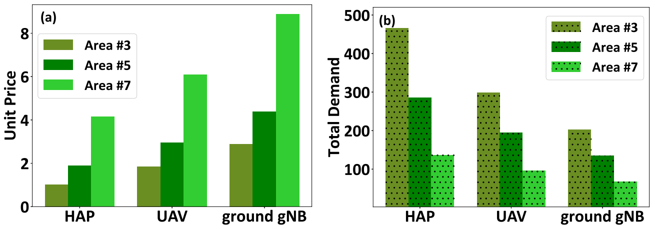

Fig. 1: Unlicensed bandwidth slice unit price and users' total demand in unlicensed bandwidth slices under the free market modeling in three representative serving areas.

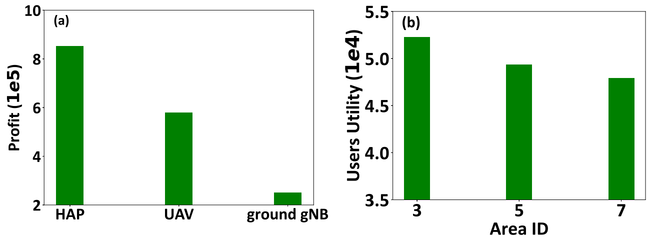

Fig. 2: Network Service Providers (NSPs) profit and users' utility under the free market modeling.

less the initial demand of the users in terms of unlicensed bandwidth slices $b_{n,i}^{CPR}$.

The results demonstrate that the higher the area's ID, the higher the price announced by all the NSPs under the market-based mechanism, i.e., free market (Fig. 1a), given the less initial demand of the users in terms of utilizing unlicensed bandwidth slices. Evidently, given the higher announced price in the areas with higher ID, the less the resulting total demand of the users in terms of utilizing unlicensed bandwidth slices in the free market model (Fig. 1b). The derived higher unit price of the ground gNBs drives the users to purchase a smaller amount of unlicensed bandwidth slices, as shown in Fig. 1b.

Fig. 2a-2b present the NSPs' profit (Eq. 6) and the users' utility (Eq. 2) under the free market model. The results show that the HAPs NSP, who can serve larger coverage areas by providing lower prices for its unlicensed bandwidth slices, dominates the market in terms of market-share profit, being followed by the UAVs NSP. The ground gNBs NSP achieves the smallest profit given that its provided unlicensed bandwidth slices are more expensive due to the fact that the ground gNBs unlicensed spectrum is less prone to congestion and interference.

B. Scalability Analysis

In this section, a scalability analysis is presented in order to show the efficiency and robustness of the proposed bio-inspired dynamic spectrum management framework. Fig. 3a-3b present the NSPs' profit and the users' utility, respectively, for an increasing number of users per area. Specifically, the baseline scenario that is considered is $\mathcal{N} = [40, 30, 30, 20, 20, 10, 10]$, while a step-wise percentage increase of the number of users per area is followed in the scalability analysis. Furthermore, in Fig. 3b, the red line presents the users' average utility and the lower and upper edge of each box quantify the 25 and 75 percentile of the

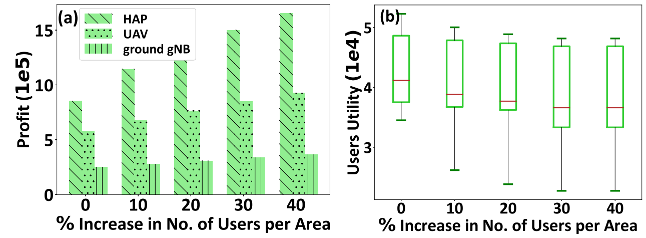

Fig. 3: Scalability analysis with respect to the NSPs' profit and the users' average utility.

users' average utility. The results show that as the number of users increases the profit of the NSPs also increases, while the HAPs NSP achieves higher profit compared to the UAVs NSP and respectively compared to the ground gNBs NSP. Also, by taking a closer look into the numerical results (Fig. 3a), we observe that the profit-making trend of all the NSPs increases at a slower rate compared to the percentage increase of the number of users per area. Focusing on the users average utility (Fig. 3b), we observe that as the number of users per area increases, the users' average utility decreases given that the users share a common pool of resources regarding the unlicensed bandwidth slices.

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