

Context-Aware Spectrum Coexistence of Terrestrial Beyond 5G Networks in Satellite Bands

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Abstract—Spectrum sharing between terrestrial 5G and incumbent networks in the satellite bands presents a promising avenue to satisfy the ever-increasing bandwidth demand of the next-generation wireless networks. However, protecting incumbent operations from harmful interference poses a fundamental challenge in accommodating terrestrial broadband cellular networks in the satellite bands. State-of-the-art spectrum sharing policies usually consider several worst-case assumptions and ignore site-specific contextual factors in making spectrum sharing decisions, and thus, often results in under-utilization of the shared band for the secondary licensees. To address such limitations, this paper introduces **CAT3S** (Context-Aware Terrestrial-Satellite Spectrum Sharing) framework that empowers the coexisting terrestrial 5G network to maximize utilization of the shared satellite band without creating harmful interference to the incumbent links by exploiting the contextual factors. **CAT3S** consists of the following two components: (i) *context-acquisition unit* to collect and process essential contextual information for spectrum sharing and (ii) *context-aware base station (BS) control unit* to optimize the set of operational BSs and their operation parameters (i.e., transmit power and active beams per sector). To evaluate the performance of the **CAT3S**, a realistic spectrum coexistence case study over the 12 GHz band is considered. Experiment results demonstrate that the proposed **CAT3S** achieves notably higher spectrum utilization than state-of-the-art spectrum sharing policies in different weather contexts.

I. INTRODUCTION

The availability of sufficient spectrum is of paramount importance in enabling a diverse range of futuristic services, including connected cars, smart healthcare, remote surveillance, disaster management, environmental monitoring, and holographic communications, in the beyond 5G (B5G) cellular networks [1]. However, the spectrum allocated to commercial 5G cellular networks is either overly congested, as in the FR1 band with sub-6 GHz frequency, or inherently limited in coverage, as in the FR2 band with 24 GHz or higher frequency [2]. In this context, sharing the bands primarily allocated to various non-terrestrial (i.e., satellite) communications presents a promising approach to alleviate the extensive spectrum demand of the B5G cellular networks. The wireless research community has recently shown interest in utilizing the mid-band spectrum for the B5G cellular networks, thanks to this band's ability to support long-range communication with high capacity [3]. More specifically, the upper mid-band spectrum (7-24 GHz) is considered as the most vital band for deploying B5G networks by both regulators and standardization

committee [4], [5]. However, in various countries, including USA and Canada, such mid-band spectrum is primarily licensed to various non-mobile broadband communications (e.g., fixed satellite services (FSS)), government operations (radio-location), and scientific missions (e.g., weather satellite) [6]. These incumbent operations are critical and sensitive, and relocating these incumbents to alternative bands is challenging, expensive, and time-consuming. Thus, a *fundamental challenge of sharing (upper) mid-band spectrum with the B5G networks is to safeguard the incumbent operations from harmful interference while maximizing the utilization of shared spectrum for the coexisting cellular networks*.

State-of-the-art spectrum sharing policies typically use the worst-case assumption-based approaches to protect incumbents from harmful interference. For instance, the standard citizen broadband radio service (CBRS) in the USA over the 3.5 GHz band defines a predefined exclusion zone around the incumbents (i.e., navy radars) and deterministically turns off all the active radio links of secondary licenses within the predefined exclusion zone [7]. Such a deterministic policy does not consider any contextual factors and thus, usually results in highly conservative spectrum utilization for the coexisting cellular networks. We emphasize that several contextual factors, such as environment (e.g., weather), network deployments (e.g., building and terrain profiles), base stations' (BSs') capabilities (e.g., beamforming and beam-nulling), satellite trajectory, incumbent receiver's location, and antenna pointing angle, strongly influence the resultant cellular-to-incumbent co-channel interference in spectrum sharing networks. By appropriately exploiting these contextual factors, utilization of shared spectrum in the coexisting cellular networks can be enhanced without creating harmful inference at the incumbent links [8]. For instance, we have recently developed a realistic simulation-based spectrum coexistence study between the terrestrial 5G and non-geostationary satellite orbit (NGSO) FSS links over the 12 GHz (12.2-12.7 GHz) band [9]. Such a study shows that by exploiting deployment contexts in activating cellular BSs, the utilization of the 12 GHz band for the coexisting terrestrial 5G networks is improved by 2.63 times. Accordingly, to facilitate the sharing of the satellite bands with the B5G cellular networks, *context-awareness is of pivotal*

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importance for the spectrum sharing policies.

For context-aware terrestrial-satellite spectrum sharing, a framework is required to (i) collect and process contextual information and (ii) optimize the available degrees of freedom according to these contexts. In various mid-band spectrums, the inherent directionality of terrestrial 5G BSs and incumbent receivers provides several degrees of freedom to optimize. For example, instead of completely turning off a BS, one can reduce its transmit power or deactivate a single sector. Similarly, different beams can be switched on/off at the BS(s) based on the incumbent antenna's pointing angle towards the satellite transmitter. In this work, we develop a spectrum-sharing framework to dynamically control the BSs' transmission parameters according to the networking contexts so that both co-channel interference is mitigated and spectrum utilization is improved. Note that our proposed framework is generic and, with no/little modifications, can apply to a wide range of satellite bands, including 3.1–4.2 GHz, 4.4–5 GHz, 7.125–8.5 GHz, and 12.7–13.25 GHz band.

Contributions: The specific contributions of this paper are summarized as follows.

- A novel context-aware spectrum sharing framework **CAT3S** is developed for enabling spectrum coexistence of 5G broadband in satellite bands. **CAT3S** comprises two key components –(i) a *context-acquisition unit* to capture critical contexts for spectrum sharing, and (ii) *context-aware BS control unit* that determines whether a particular BS is on/off, and if on, the optimal transmitter power and operational beam at each BS sector, such that the network throughput of the 5G network is maximized while maintaining the overall interference below an acceptable threshold at the incumbent receiver(s).
- We model *Context-aware BS control* as a resource optimization problem aimed at dynamically optimizing three key RF parameters of the coexisting 5G networks (i) set of operational 5G BSs in the shared satellite band, (ii) the active set of beams for each operation BS, and (iii) the operational transmit power of each operation BS. Such an optimization is provably NP-hard, and thus, a well-designed heuristic algorithm is proposed to obtain a sub-optimal yet computationally efficient solution.
- For the case study, we consider spectrum sharing between downlinks of terrestrial 5G and NGSO FSS over the 12 GHz band in a semi-urban deployment scenario of Blacksburg, VA, and evaluate the **CAT3S**'s performance in different weather contexts. Notably, no real-world 5G deployments exist in the 12 GHz band. Accordingly, we leverage and extend our recently developed 12 GHz interference analysis tool [9] to simulate the network environment and evaluate the **CAT3S**'s performance. Experimental results show that **CAT3S** simultaneously achieves a lower aggregate I/N ratio at the FSS receiver and higher downlink capacity and number of operational BSs compared to context-unaware spectrum sharing policies at all weather conditions.

II. RELATED WORKS

Resource management is crucial in managing interference and improving spectrum utilization in the terrestrial-satellite

spectrum-sharing networks [10]. In [11], a detailed analysis of the interference resulting from the coexistence between 5G terrestrial and FSS networks over C-band (3.7-4.2 GHz) was presented, and interference mitigation strategies using switching on/off and backing-off transmit power of high-interference BS were proposed. Interference over the C-band can also be reduced by adjusting the exclusion zone's radius around the FSS receiver, transmission power, and beamforming pattern of the transmitting antenna [12]. However, both [11] and [12] relied on heuristic mechanisms to control the networking parameters for interference mitigation. Concerning spectrum sharing over the S-band (3.55-3.65 GHz), a multi-tier dynamic protection zone was developed to protect primary incumbent users from interference and improve secondary users' performance in the CBRs system [13]. Furthermore, a centralized channel allocation scheme was also developed to allocate channels among the paid and unlicensed users in the CBRs system while considering interference protection for incumbent and paid users [14]. However, the studies mentioned above primarily considered static optimization and ignored dynamic variations of the channel and other parameters (e.g., user mobility) in the system. Dynamic resource optimization was investigated in the terrestrial-satellite integrated networks (TSINs), where both terrestrial and satellite users share the spectrum on a co-primary basis. In [15], spectrum sharing between uplink terrestrial and satellite users were studied, and a dynamic optimization for user-access point association, access link's bandwidth allocation, and users' transmit power allocation was developed. A delay quality-of-service aware transmit power allocation was proposed to maximize cognitive satellite network's downlink energy efficiency while keeping interference at the terrestrial networks smaller than a threshold [16]. Considering the Ka-band sharing between satellite and terrestrial networks' downlink operations, hybrid beamforming, user scheduling, and power allocation were proposed to jointly maximize the sum throughput of the terrestrial and satellite networks [17]. Recently, an open radio access network (O-RAN)-empowered framework was proposed to share spectrum between terrestrial cellular networks and government satellite systems, and a dynamic physical resource block (PRB) blanking scheme was developed to mitigate the interference from the terrestrial to satellite networks [18]. However, context-aware resource optimizations are ignored in all these studies. Note that, unlike S and C bands, context-awareness is critically important for sharing upper mid-band spectrum between terrestrial cellular and incumbent networks¹. Essentially, the existing static and dynamic resource optimization schemes [11]–[18] are sub-optimal for upper mid-band spectrum sharing systems.

In the context of USA, there is a significant interest from different stakeholders in opening the 12.2-12.7 GHz mid-band spectrum, commonly known as the 12 GHz band, for 5G terrestrial networks, thanks to the band's favorable propagation

¹Please refer to [8, Table 2] for a detailed list of contexts that impact sharing performance of the upper mid-band spectrum.

characteristics and contiguous 500 MHz bandwidth for both downlink and uplink communications [19]. In the USA, the 12 GHz band is primarily licensed to direct broadcast satellite (DBS) and NGSO FSS services, and because of their ubiquitous deployments, interference protection for such incumbent receivers is a key challenge in sharing the 12 GHz band. Some industry-specific studies investigated the interference between terrestrial 5G and incumbents in the 12 GHz band. For instance, [20] studied interference between terrestrial 5G and DBS networks, while [21], [22] studied interference between terrestrial 5G and NGSO FSS networks. However, these studies adopted a probabilistic approach to interference evaluation and did not present any 5G network optimization schemes to mitigate interference. In [9], we presented a realistic simulation-based interference analysis in the 12 GHz band and proposed heuristic schemes to select operational BSs to keep interference at the FSS receiver smaller than a threshold. However, such a study did not consider improving spectrum utilization for the coexisting 5G cellular networks.

Uniqueness of the Current Work: 5G multi-antenna BSs have the unique capability of creating beams in the desired directions and nulls elsewhere. Such a capability is instrumental in improving spectrum utilization of cellular networks and mitigating interference towards incumbent systems [4]. Our current work develops a resource optimization framework to exploit 5G BSs' beamforming capability for activating a maximum number of BSs in a spectrum-sharing environment. More specifically, our proposed framework validates the suitability of the decision variables using a realistic interference evaluation framework, thereby taking different contextual factors in the BS's parameter optimization. Such context-awareness enables our proposed framework to activate more BSs and beams per BS's sectors compared to the existing approaches without harming the incumbent receivers. Consequently, our current work is unique compared to the state-of-the-art literature.

III. SYSTEM MODEL

A. System Overview and Assumptions

Fig. 1 shows a terrestrial-satellite spectrum sharing scenario. We assume that a total of K 5G BSs are in the considered region, and $\mathcal{K} = \{1, 2, \dots, K\}$ is the set of all BSs. Each BS has three sectors, each covering a 120° angular area. Each sector has a total of M number of sub-arrays, each being fed with an RF chain, and there are a total of N unique codebook vectors for each sub-array, each representing a unique 3D beam direction. The sets of sub-arrays and codebook vectors per sub-array are denoted by $\mathcal{M}$ and $\mathcal{N}$. Emissions from each sub-array propagate with path loss according to the deterministic path loss model, described in Section III.B.3. This model includes clutter and building information as well as rain attenuation. Interference from each active sub-array aggregates at the incumbent receiver, with the relative contribution from each sub-array affected by the antenna pattern and pointing angle of the sub-array, cellular BS's transmit power, path loss, and the antenna pattern and pointing angle of the FSS receiver. Detailed analysis of the interference

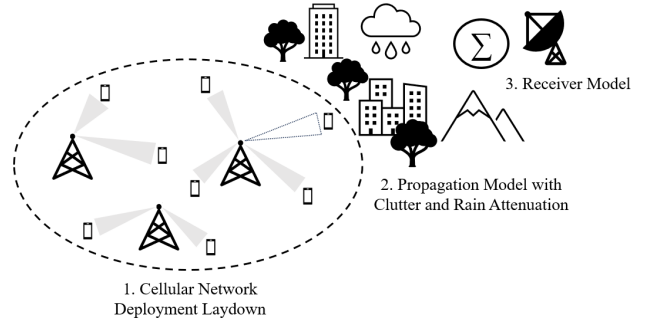


Fig. 1: Overview of the proposed spectrum sharing scenario.

generated from an active sub-array at the incumbent receiver is provided in the following sub-section. All the BSs are assumed to be connected with a centralized control center via a wired feedback line, and the centralized control center hosts a context-aware BS control unit of the CAT3S framework, depicted in Fig. 2, to dynamically adapt the set of active BSs and their RF parameters.

For the tractability of the ensuing analysis, we make the following assumptions. **A1:** The incumbent receiver's location and antenna pointing angle information are available. **A2:** Channel hardening is achieved by the antenna arrays deployed at the cellular BSs. As such, the short-term channel fading is ignored, and only long-term channel impairments (i.e., path loss and shadow fading) are considered for both interference and access links. **A3:** Inter-cell interference in the access links are ignored since the cellular BSs typically optimize their electric down-tilt angles to minimize the inter-cell interference. At the same time, the intra-cell interference between two concurrently active beams at different sectors of a cellular BS is also considered negligible. **A4:** The interference signal received from each sub-array sums constructively at the incumbent receiver. **A5:** In each cellular BS, only one beam per sector can be operational using the best possible transmit power and beam codebook, as obtained from the context-aware BS control unit of CAT3S framework.

B. Analysis of Cellular-to-Incumbent Interference

We develop an enhanced cellular-to-incumbent interference analysis tool by incorporating weather contexts and 5G-compliant codebook-based beamforming capability at the BSs into our previously developed interference analysis tool [9]. The components of the enhanced interference analysis tool are described in Section III.B.1-III.B.4, and the evaluation of interference from an active cellular BS to the incumbent receiver using this tool is provided in Section III.B.5.

1) Transmitter Antenna Pattern of 5G BS: 5G BSs use a $M \times L$ Planar Array antenna for the codebook-based beamforming towards the UEs in each sector within its coverage area, where M and L are the numbers of rows and columns of the antenna element's array. The spacing between two consecutive antenna elements along the x and y axes is denoted as d_x and d_y , respectively, and it is specified as $\lambda/2$ (where λ is the wavelength). Progressive phase shifts are introduced as β_x and β_y the x and y axes, respectively. Each sector of a BS consists of 4 antenna sub-arrays; thus, each BS contains

a total of 12 sub-arrays for all the 3 sectors. Each sub-array is equipped with a total of 64 predefined beam codebooks. For shaping the beams by taking into account the antenna array configuration, antenna elements spacing, and antenna array size, we leverage the planner antenna array factor [23]. For the given azimuth and elevation angles $\theta \in [0, \pi]$ and $\phi \in [-\pi, \pi]$, such an array factor is defined as

$$AF(\theta, \phi) = \left(\frac{1}{M} \frac{\sin^2(\frac{M}{2}\psi_x)}{\sin^2(\frac{\psi_x}{2})} \right) \left(\frac{1}{L} \frac{\sin^2(\frac{L}{2}\psi_y)}{\sin^2(\frac{\psi_y}{2})} \right) \quad (1)$$

Here, the phase differences ψ_x and ψ_y for the k -th wave number are expressed as $\psi_x = kd_x \sin \theta \cos \phi + \beta_x$ and $\psi_y = kd_y \sin \theta \cos \phi + \beta_y$, respectively. The overall antenna gain of i -th beam (in dBi) transmitted from the m -th sub-array of the k -th BS at (θ, ϕ) angle is obtained as

$$G_{5G}^{(i)}(\theta, \phi) = 10 \log_{10}[AF(\theta, \phi)]. \quad (2)$$

2) *Receiver Antenna Pattern of Incumbent:* The Class B wide band earth stations (WBES) antenna pattern, standardized by ETSI, is considered for the incumbent receiver. In particular, for the 12 GHz case study in Section VI, antenna gain for the incumbent (FSS) receiver at ϕ angle relative to the boresight direction is computed using [9, eq. (8)].

3) *Path Loss Model:* Unlike the probabilistic method of computing path loss [27, Table 7.4.2], we develop a deterministic path loss model by accurately determining line-of-sight (LOS) and non-LOS (NLOS) propagation paths between the cellular BSs and incumbent receivers. This model considers various site-specific contextual factors, including geographic locations of the BSs and incumbent receivers, signal obstruction caused by buildings, and weather-induced signal attenuation. We first incorporate the required building information, including buildings' heights, geographical coordinates, and shapes, obtained from the OpenStreetMap database [24] within the considered region. Subsequently, we determine whether any building polygons intersect the interference axis between a cellular BS and an incumbent receiver. The link between a cellular BS and incumbent receiver is classified as NLOS and LOS, respectively, if there are one/more and no intersections. Considering the distance between the cellular BS and FSS receiver is d_k (in km), the path loss is computed by [9].

$$\begin{aligned} PL(d_k) &= \mathbf{1}_{(\beta=0)} (PL_{\text{NLOS}}(d_k) + X(\sigma_{\text{NLOS}})) \\ &+ \mathbf{1}_{(\beta=1)} (PL_{\text{LOS}}(d_k) + X(\sigma_{\text{LOS}})) \end{aligned} \quad (3)$$

where $\mathbf{1}_{(\cdot)}$ is an indicator function; $\beta = 0$ and $\beta = 1$ indicate the existence of NLOS and LOS signal propagation paths, respectively; $X(\sigma_b)$ indicates shadow fading losses (in dB) with σ_b as the standard deviation for $b \in \{\text{LOS}, \text{NLOS}\}$; $PL_{\text{LOS}}(\cdot)$ and $PL_{\text{NLOS}}(\cdot)$ indicate path loss (in dB) over LOS and NLOS propagation paths, respectively. Without loss of generality, we leverage the 3GPP path loss models, [27, Table 7.4.1] for path losses over LOS and NLOS links.

Eq. (3) provides exact path loss in the clear (i.e., sunny) weather conditions. Note that the satellite signals of the

upper mid-band spectrum exhibit several attenuation in rainy weather. To account for that, inspired from [28], we incorporate an additional attenuation factor in the (3). Accordingly, the path loss in the rainy weather condition is obtained as

$$PL(d_k)_{(\text{Rainy})} = PL(d_k) + A_{\text{Rain}} \times d_k \quad (4)$$

where A_{Rain} is the rain-induced attenuation factor in dB/km unit. Using a mathematical model on Rain Wave Attenuation due to Rain (RWAR) [28], which is valid for both vertical and horizontal polarization for 10-100 GHz of the frequency range, the rain-induced attenuation factor is expressed as

$$A_{\text{Rain}} = af^3 + bf^2 + cf + d \quad (5)$$

where a , b , c , and d are rain rate-dependent constants. Leveraging a curve fitting algorithm for vertical polarization [28] and extracting rain rate in mm/h unit (denoted by x) from the OpenWeatherMap API [26]², these constants are expressed as

$$a = -5.520 \times 10^{-12}x^3 + 3.26 \times 10^{-9}x^2 - 1.21x \times 10^{-7} - 6 \times 10^{-6}, \quad (6)$$

$$b = 8 \times 10^{-10}x^3 - 4.522 \times 10^{-7}x^2 - 3.03x \times 10^{-5} + 0.001, \quad (7)$$

$$c = -5.71 \times 10^{-9}x^3 + 6 \times 10^{-7}x^2 + 8.707x \times 10^{-3} - 0.018, \quad (8)$$

and

$$d = -1.073 \times 10^{-7}x^3 + 1.068 \times 10^{-4}x^2 - 0.0598x \times 10^{-3} + 0.0442. \quad (9)$$

4) *Impact of the Incumbent's and Secondary Link's Channel Usage:* The shared band usually has multiple channels. As a result, a beam transmitted from a cellular BS interferes with the incumbent receiver if and only if such a beam is operational in a channel that is under use at the incumbent. To determine whether a beam will interfere with the incumbent link or not, we introduce a binary indicator $\sigma_{k,j} \in (0, 1)$ for the j -th sector ($j \in \{1, 2, 3\}$) of the k -th BS, where $\sigma_{k,j} = 1$ implies that the beam transmitted in the j -th sector of the k -th cellular BS interferes with the incumbent and $\sigma_{k,j} = 0$ otherwise. This variable can be directly determined from the real-time channel-usage and user scheduling information at the incumbent receiver and cellular BSs, respectively. More precisely, $\sigma_{k,j} = 1$ if some users in the j -th sector of the k -th cellular BS are scheduled to the channel used by incumbent and $\sigma_{k,j} = 0$ otherwise.

5) *Evaluation of Cellular-to-Incumbent Interference:* Here, we compute the interference received from the k -th cellular BS to the incumbent receiver. Without loss of generality, we consider that at the j -th sector of the k -th BS, where $j \in \{1, 2, 3\}$, the n_j -th directional beam is transmitted from the m_j -th sub-array, and the total transmit power of the k -th BS is equally divided among the sectors. Accordingly, the

²OpenWeather API provides weather information of a specific day for a certain geolocation or city

co-channel interference (in dB) introduced at the incumbent receiver by the j -th sector of the k -th BS is expressed as

$$I_{k,m_j,n_j}^{(j)} = 10 \log_{10}(P_k) + G_{5G}^{(k)}(\theta_{n_j,int}, \phi_{n_j,int}) + G_{SAT}(\phi_{k,SAT}) - PL(d_{k,SAT}) - 10 \log_{10}(3) \quad (10)$$

where P_k is the transmit power of the k -th cellular BS; $\theta_{n_j,int}$ and $\phi_{n_j,int}$ are the azimuth and elevation angles between the interference axis (from the k -th BS to the incumbent receiver) and the n_j -th beam, respectively; $\phi_{k,SAT}$ is the angle between incumbent receiver's boresight direction and interference axis from the k -th BS; $d_{k,SAT}$ is the distance between the k -th BS and incumbent receiver. Thus, the total interference received from the k -th BS to the incumbent receiver is expressed as

$$I_k = \sum_{j=1}^3 \sigma_{k,j} 10^{\frac{I_{k,m_j,n_j}^{(j)}}{10}}. \quad (11)$$

IV. CAT3S FRAMEWORK

Figure 2 comprehensively depicts the CAT3S framework with all the essential units. CAT3S comprises of the following three key components.

- **Context-acquisition unit:** This unit gathers critical context information for spectrum sharing, such as weather data (e.g., rain data), interference thresholds for different weather conditions, exclusion zone radii, and different transmitting power levels of BSs, from the external/internal context information providers.

- **Context-aware BS Control Unit:** This unit implements Algorithm 1, detailed in the Section IV. B, to dynamically select the following parameters of the coexisting cellular network, namely, (i) the set of operational 5G BSs in the shared satellite band, (ii) the active set of beams for each operational BS, and (iii) the operating transmit power of each operational BS.

- **Environment:** It refers to the terrestrial 5G-satellite spectrum sharing network. Due to the lack of real-world 5G deployments in the satellite band, we exploit our developed interference analysis tool to mimic the spectrum sharing environment. Note that this tool integrates information on the realistic 5G BSs deployments, satellite receiver's positions and antenna pointing angles, detailed 3D building information (geo-locations, heights, footprints, and polygon shapes), and user locations. As a result, this tool helps to infer site-specific path losses and interference caused by a set of BS parameters.

CAT3S implements the following three steps. In Step I, the context-acquisition unit and environment provide feedback on the acquired contexts and received interference from the coexisting cellular network, respectively. In Step II, the context-aware BS control unit executes Algorithm 1 while considering such received information. In Step III, the final output parameters obtained from the context-aware BS control unit are provided to the BSs over reliable feedback channels, and BSs perform downlink data transmission using these parameters such that the total downlink capacity is increased without creating harmful interference to the incumbent link.

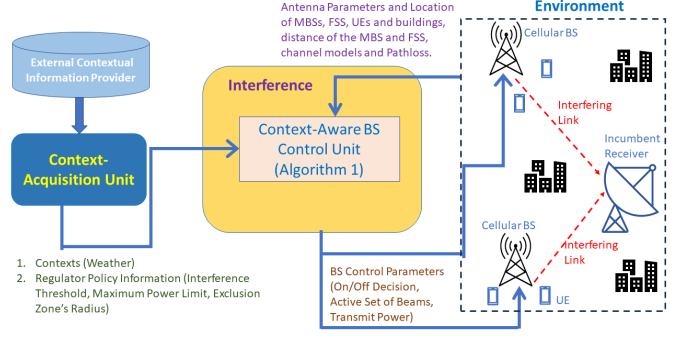


Fig. 2: Overview of CAT3S framework

V. CONTEXT-AWARE BS CONTROL PROBLEM FORMULATION AND ALGORITHM DEVELOPMENT

In this section, we develop an optimization problem to dynamically control BS's parameters (Section V. A) and an algorithm to solve such a problem (Section V. B).

A. Optimization Problem Formulation

We first introduce the optimization variables. Let $\nu_k \in \{0, 1\}$ be the BS activation indicator where $\nu_k = 1$ implies that the k -th BS is operational in the shared satellite band, and otherwise, $\nu_k = 0$. We also introduce another binary variable $z_{k,m,n}^{(j)} \in \{0, 1\}$ where $z_{k,m,n}^{(j)} = 1$ implies that the n -th codebook vector is loaded to the m -th sub-array at the j -th sector of the k -th BS and otherwise, $z_{k,m,n}^{(j)} = 0$. Let $F_{k,m,n}^{(j)}$ be the total number of UEs supported by the beam created by loading the n -th codebook vector to the m -th sub-array at the j -th sector of the k -th BS. The received signal-to-noise-ratio (SNR) at the u -th UE, $\forall u \in \{1, 2, \dots, F_{k,m,n}^{(j)}\}$, is expressed as

$$\text{SNR}_{k,m,n}^{(u,j)} = 10 \log_{10}(P_k) + H^{(m,n)}(\Theta_n, \Theta_u) - PL(d_{k,u}) - 10 \log_{10}(NP) - 10 \log_{10}(3) \quad (12)$$

where $H^{(m,n)}(\Theta_n, \Theta_u)$ is the overall antenna gain (in dBi) from the n -th beam towards the u -th UE with Θ_n and Θ_u as the angle-of-departure and angle-of-arrival, respectively; $PL(d_{k,u})$ is the path loss (in dB) with $d_{k,u}$ as the distance between the k -th BS and u -th UE; and NP is the noise power in Watt. The achievable downlink capacity (in bps/Hz unit) at the u -th UE is obtained as $C_{k,m,n}^{(u,j)} = \log_2(1 + 10^{\text{SNR}_{k,m,n}^{(u,j)}/10})$. Therefore, the total achievable downlink capacity of the k -th BS is obtained as

$$C_k = \sum_{j=1}^3 \sum_{m=1}^M \sum_{n=1}^N \sum_{u=1}^{F_{k,m,n}^{(j)}} z_{k,m,n}^{(j)} C_{k,m,n}^{(u,j)}. \quad (13)$$

A resource optimization problem to maximize the utilization of the satellite band for the coexisting 5G cellular network while ensuring interference protection for incumbent satellite receivers is formulated as P0 at the top of the next page. In P0, the objective function maximizes a weighted sum of the achievable downlink capacity of the 5G cellular network and the number of UEs it supports. Here, $w \in (0, 1)$ is a

$$\begin{aligned}
\text{P0: } & \max_{\substack{\nu \in \{0,1\}, \\ \mathbf{z} \in \{0,1\}, \mathbf{P}}} (1-w) \sum_{k=1}^K \nu_k C_k + w \sum_{k=1}^K \sum_{j=1}^3 \sum_{m=1}^M \sum_{n=1}^N \nu_k z_{k,m,n}^{(j)} F_{k,m,n}^{(j)} \\
\text{s.t. } & \begin{cases} \text{C1: } \sum_{k=1}^K \sum_{j=1}^3 \sum_{m=1}^M \sum_{n=1}^N \nu_k z_{k,m,n}^{(j)} 10^{\frac{I_{k,m,n}^{(j)}}{10}} \leq I_{th} \\ \text{C2: } \min_{u \in \mathcal{U}_{k,j}} \sum_{m=1}^M \sum_{n=1}^N z_{k,m,n}^{(j)} C_{k,m,n}^{(u,j)} \geq R_{th}, \forall j \in \{1, 2, 3\}, k \in \mathcal{K} \\ \text{C3: } P_k \leq P_{max}, \forall k \in \mathcal{K} \\ \text{C4: } \sum_{m=1}^M \sum_{n=1}^N z_{k,m,n}^{(j)} = 1, \forall j, k. \end{cases}
\end{aligned} \tag{14}$$

predefined weight factor. The considered objective function maximizes the utilization of the shared satellite band for the coexisting 5G cellular network while ensuring fairness. In P0, constraint C1 implies that the total interference introduced by the coexisting 5G cellular network to the incumbent receiver must be smaller than a predefined threshold I_{th} ; constraint C2 implies a rate quality-of-service (QoS) constraint for the coexisting cellular networks' UEs with C_{th} as the minimum required downlink data rate and $\mathcal{U}_{k,j}$ as the set of all UEs in the j -th sector of the k -th BS; constraint C3 implies that the transmitted power from each BS must be smaller than a regulator defined maximum transmit power limit, P_{max} , over the shared satellite band; constraint C4 implies that a pair of one codebook vector and one sub-array are selected at each sector of a given BS, i.e., at most one beam can be operational in each sector of a given BS.

Proposition 1: P0 is an NP-hard optimization problem.

Proof: It can be shown by reducing PO to a 0-1 Knapsack problem, a classic NP-hard problem. The proof is omitted due to space limitations.

Since P0 is an NP-hard optimization problem, it cannot be solved in polynomial time. In the next sub-section, we propose a sub-optimal yet computationally efficient algorithm to solve P0 in polynomial time.

B. Proposed BS Control Algorithm

We propose a context-aware BS control algorithm, summarized as Algorithm 1, to efficiently solve P0. Algorithm 1 iteratively optimizes the beam-domain and power-domain control tasks in the inner and outer loops, respectively. More specifically, the beam-domain control selects the active BSs and suitable beams in the active sectors for the given transmit power. Meanwhile, the power-domain control searches for suitable transmit power of the BSs within a feasible range. In the first iteration, the inner loop activates a set of BSs and selects beams in their sectors assuming that all BSs operate at the minimum possible transmit power. The primary objective here is to activate the maximum number of BSs within the shared band without violating interference constraint C1. However, this approach still results in a conservative spectrum sharing scenario because each active BS is allowed to use only the minimum power level. In practice, depending on contextual factors such as weather and deployment scenarios, some BSs can transmit at high power levels without causing harmful interference to incumbent satellite receivers while selecting suitable beam directions. Thus, in the subsequent

Algorithm 1 Context-Aware BS Control Algorithm

- 1: **Input:** Contextual factors, including weather, RF propagation model, 5G deployment information (location and heights of BSs and buildings in the environment), incumbent receiver's location and pointing angle; interference threshold I_{th} .
- 2: Determine the minimum transmit power $P_{min}^{(k)}$ for the k -th BS to satisfy the constraint C2, $\forall k \in \mathcal{K}$, and set $P_{min} = \max_{k \in \mathcal{K}} P_{min}^{(k)}$.
- 3: Determine the set of non-operational BSs $\mathcal{K}_{off} = \{k \in \mathcal{K} | P_{min}^{(k)} > P_{max}\}$. Assign $\nu_k^* = 0$, $z_{k,m,n}^{(j)*} = 0$, and $P_k^* = 0$, $\forall k \in \mathcal{K}_{off}$, $j \in \{1, 2, 3\}$, $m \in \mathcal{M}$, $n \in \mathcal{N}$.
- 4: **Initialize:** The set of operational BSs $\mathcal{K}_o = \mathcal{K} \setminus \mathcal{K}_{off}$; $\nu_k^* = 0$, $z_{k,m,n}^{(j)*} = 0$, and $P_k^* = 0$, $\forall k \in \mathcal{K}_o$, $j \in \{1, 2, 3\}$, $m \in \mathcal{M}$, $n \in \mathcal{N}$; $I_{agg} = 0$; Outer_Iteration_Index=1; Number_of_BS_Power_Change = 0.
- 5: **for** $P \in [P_{min}, P_{max}]$ **do** (**outer loop**)
- 6: **Initialize:** $\mathbf{U}_{BS} = \mathcal{K}_o$, $\mathbf{U}_{sector}^{(k)} = \{1, 2, 3\}$, $P_k = P$, $\forall k \in \mathbf{U}_{BS}$;
- 7: Calculate the following score:

$$\rho_{k,m,n}^{(j)} = \frac{(1-w) \sum_{u=1}^F C_{k,m,n}^{(u,j)} + w F_{k,m,n}^{(j)}}{10^{\frac{I_{k,m,n}^{(j)}}{10}}}$$

- 8: $\forall k \in \mathbf{U}_{BS}, j \in \mathbf{U}_{sector}^{(k)}, m \in \mathcal{M}, n \in \mathcal{N}$.
- 9: **while** $\mathbf{U}_{BS} \neq \emptyset$ **do** (**inner loop**)
- 10: Find $(k^*, j^*, m^*, n^*) = \arg \max_{\substack{k \in \mathbf{U}_{BS}, j \in \mathbf{U}_{sector}^{(k)}, \\ m \in \mathcal{M}, n \in \mathcal{N}}} \rho_{k,m,n}^{(j)}$.
- 11: Calculate $I_{agg}^{Temp} = I_{agg} + 10^{\frac{I_{k^*,m^*,n^*}^{(j^*)}}{10}}$.
- 12: **if** $I_{agg}^{Temp} > I_{th}$ **then**
- 13: **Break;**
- 14: **else**
- 15: **if** Outer_Iteration_Index == 1 **then**
- 16: Assign $\mathbb{B}_{op} \leftarrow \mathbb{B}_{op} \cup (k^*, j^*, m^*, n^*)$; Update $\mathbf{U}_{sector}^{(k^*)} \leftarrow \mathbf{U}_{sector}^{(k^*)} \setminus \{j^*\}$ and $\mathbf{U}_{BS} \leftarrow \{k \in \mathbf{U}_{BS} | |\mathbf{U}_{sector}^{(k)}| \geq 1\}$.
- 17: Assign $z_{k^*,m^*,n^*}^{(j^*)} = 1$, $\nu_{k^*}^* = 1$, $P_{k^*}^* = P$, and $I_{agg} \leftarrow I_{agg}^{Temp}$.
- 18: Update Number_of_BS_Power_Change++
- 19: **else**
- 20: **if** $\mathbb{B}_{op}$ is empty **then**
- 21: Update $\mathbb{B}_{op} \leftarrow \mathbb{B}_{op} \cup (k^*, j^*, m^*, n^*)$.
- 22: **else**
- 23: Replace current indices of the sector, sub-array, and codebook of the k^* -th BS with the indices computed in the Step 9.
- 24: **end if**
- 25: Update $\mathbf{U}_{sector}^{(k^*)} \leftarrow \mathbf{U}_{sector}^{(k^*)} \setminus \{j^*\}$ and $\mathbf{U}_{BS} \leftarrow \{k \in \mathbf{U}_{BS} | |\mathbf{U}_{sector}^{(k)}| \geq 1\}$.
- 26: Assign $z_{k^*,m^*,n^*}^{(j^*)} = 1$, $P_{k^*}^* = P$, and $I_{agg} \leftarrow I_{agg}^{Temp}$.
- 27: Update Number_of_BS_Power_Change++
- 28: **end if**
- 29: **end while**
- 30: Update $\mathcal{K}_o = \{k \in \mathcal{K}_o | \nu_k^* = 1\}$.
- 31: **if** Number_of_BS_Power_Change is not changed **then**
- 32: **Break;**
- 33: **end if**
- 34: **end for**
- 35: **Output:** $\{\nu_k^*\}$, $\{z_{k,m,n}^{(j)*}\}$, $\{P_k^*\}$.

iterations, the outer loop gradually increases transmit power, while the inner loop further optimizes beam steering for the active BSs for the selected power. This allows some BSs to operate using high transmit powers in the shared band while keeping the aggregated interference at the incumbent below a tolerable threshold. It's worth noting that the set of active BSs remains unchanged after the first iteration; the only variables that change are the active BSs' transmit powers and the beams within their sectors.

The key steps of Algorithm 1 are explained as follows. Step 2 determines the minimum value of the transmit power for all the BSs. Step 3 determines the set of BSs that cannot be operational in the shared band with the given transmit power range. Step 4 determines the sets of BSs eligible to be operated in the shared band. In Step 6, for a given transmit power, we first define the following two sets, namely, $\mathbf{U}_{BS}$ and $\mathbf{U}_{sector}^{(k)}$ providing the sets of BSs and sectors to be activated. In Step 7, a score is computed for each combination of the BSs and sectors in the $\mathbf{U}_{BS}$ and $\mathbf{U}_{sector}^{(k)}$ sets, respectively, sub-array, and beam codebook. This score provides a ratio of the overall band utilization to the (anticipated) interference (computed using the interference tool), and accordingly, a high score implies a high priority of activating a particular combination of BS, sector, sub-array, and beam codebook. In Steps 9 and 10, the combination of BS, sector, sub-array, and beam codebook with the highest priority score is selected, and the new value of interference is anticipated, respectively. If the anticipated interference exceeds the tolerable threshold, it implies that no more BS/sector can be activated with the current power, and hence, the inner loop is terminated (Steps 11-12). Otherwise, the best combination of BS, sector, sub-array, beam codebook, and transmit power are sequentially activated (Steps 14-29). At the end of each activation, both $\mathbf{U}_{BS}$ and $\mathbf{U}_{sector}^{(k)}$ sets are updated (Steps 15 and 24). The inner loop is continued until the $\mathbf{U}_{BS}$ set becomes empty. Meanwhile, the outer loop keeps track of the number of BSs whose transmit powers are changed in sequential outer loop iterations (Steps 17 and 26). The outer loop is terminated when all the possible transmit power values are visited or the active BSs' transmit powers can no longer be updated in consecutive iterations (Steps 31-34).

Proposition 2: The worst-case time complexity of Algorithm 1 is $\mathcal{O}(\Delta MNK^2)$ where Δ is the total number of discrete transmit power levels in the $[P_{min}, P_{max}]$ range.

Proof: The proof is omitted due to space limitations.

VI. PERFORMANCE EVALUATION

A. Descriptions of Experimental Setup and Baseline Schemes

For performance evaluation of the CAT3S framework, we consider spectrum coexistence between 5G terrestrial and NGSO FSS networks over the 12 GHz band. Specifically, we exploit a real-world sub-urban deployment scenario at Blacksburg City, Virginia, from our prior study [9]. In the considered deployment scenario, an FSS receiver is located at 1770 Forecast Drive in Blacksburg (37° 12' 9" North latitude and 80° 26' 4" West longitude). In addition, we

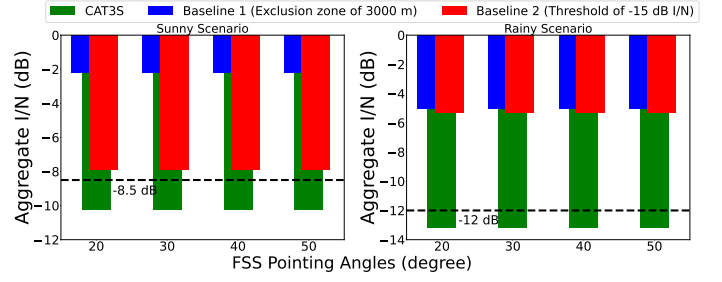


Fig. 3: Aggregate I/N ratio vs FSS's pointing angles.

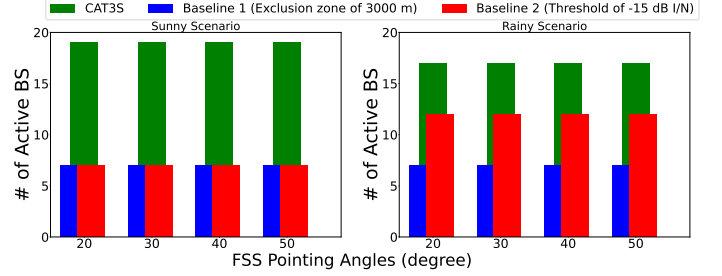


Fig. 4: Number of active BSs vs FSS's elevation angles.

incorporate actual geolocations of 33 macro BS (MBSs) from the OpenCellID database [25] within the 5000m radius of the FSS. The heights of MBS are set to 25 meters for the sub-urban scenario according to 3GPP specifications. Each MBS operates on a 1000m cellular coverage area divided into three sectors (120° each), accommodating 10 randomly located UEs and a total of 12 subarrays. For an accurate and site-specific path loss analysis as discussed in Section IV, information such as heights (10m to 40m), sizes, polygons, and locations of 8664 buildings is incorporated from the OpenStreetMap via overpass-turbo [24]. Furthermore, for the beamforming capabilities in Section IV, we consider 4×4 directional planner antenna array with 0.5λ element spacing and 64 predefined beams in each subarray. As per 3GPP, the specified nominal transmit power for an MBS is set at -38 dBm, and for controlling the MBS's transmit power using Algorithm 1, we explore a power range from -2 dBm to $+2$ dBm relative to this nominal value. Additionally, we consider various FSS pointing angles (20°, 30°, 40°, and 50°) and a down-tilt angle of 10° for the MBSs, as suggested by [21]. We consider weather as the specific context since the 12 GHz band's propagation characteristics vary in different weather conditions. We consider sunny and rainy weather, and these scenarios are determined based on data (e.g., the daily rain rate of a particular city) obtained from OpenWeatherMap [26]. Following [21], the tolerable I/N threshold at the FSS receiver during the sunny weather is set as -8.5 dB. Meanwhile, due to the extensive rain fade, the received signal strength at the FSS receiver is reduced during rainy weather, and consequently, the FSS receiver requires more interference protection in rainy weather. Considering such a fact, the tolerable interference threshold at the FSS receiver during rainy weather is set as -12 dB.

For performance comparison, we consider the following two baseline approaches.

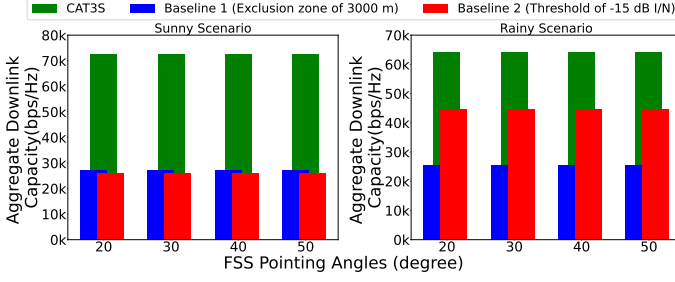


Fig. 5: Achievable downlink capacity vs. FSS pointing angles.

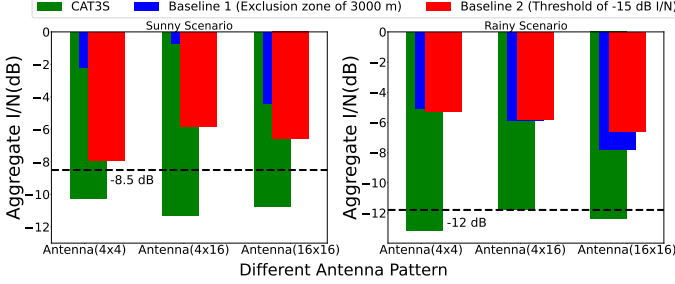


Fig. 6: Aggregate I/N ratio vs. antenna element sizes.

- **Baseline 1:** A deterministic exclusion zone of 3000m around the FSS receiver is considered. All the MBSs that are inside the exclusion zone and that are outside the exclusion zone but generate a higher I/N ratio than the tolerable threshold (i.e., -8.5 dB and -12 dB for the sunny and rainy weather conditions, respectively) are turned off. The selected BSs transmit using the nominal transmit power, and the active beams of these MBSs are selected using the conventional codebook-based beamforming algorithm.
- **Baseline 2:** In this scheme, the I/N ratio from each MBS is evaluated using our realistic interference evaluation framework, and only the MBSs generating I/N ratio smaller than a threshold remain active. Inspired by our prior study [9], we consider -15 dBm as the I/N threshold for activating MBSs in the Baseline 2 scheme. The selected BSs transmit using their nominal transmit power, and the active beams of these BSs are selected using the conventional codebook-based beamforming algorithm.

B. Experiment Results

1) *Performance for FSS Receiver's Various Pointing Angles:* Figs. 3, 4, and 5 illustrate the aggregate I/N ratio received at the FSS receiver, the count of operational MBSs, and the aggregate downlink throughput for all the operational MBSs, respectively. All these performance metrics are evaluated for different FSS pointing angles in sunny (left) and rainy (right) atmospheric conditions for the CAT3S and baseline schemes. For sunny and rainy weather conditions, CAT3S achieves a notably smaller aggregate I/N ratio compared to both baseline schemes. For example, for 30° pointing angle and sunny weather conditions, the CAT3S, Baseline 1, and Baseline 2 schemes achieve -10 dBm, -2 dBm, and -8 dBm, aggregate I/N ratios, respectively. Similarly, for 30° pointing angle and rainy weather conditions, the CAT3S, Baseline 1 and Baseline 2 schemes achieve -12 dBm, -4 dBm, and -4

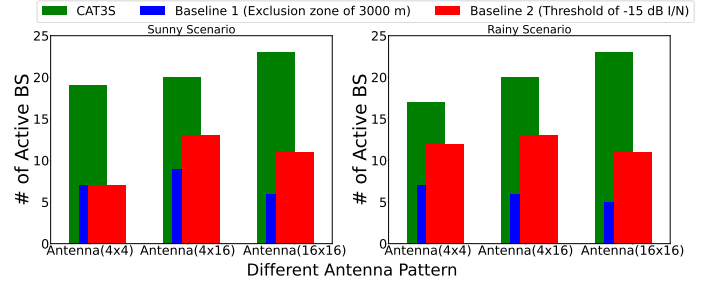


Fig. 7: Number of active MBSs vs. antenna element sizes.

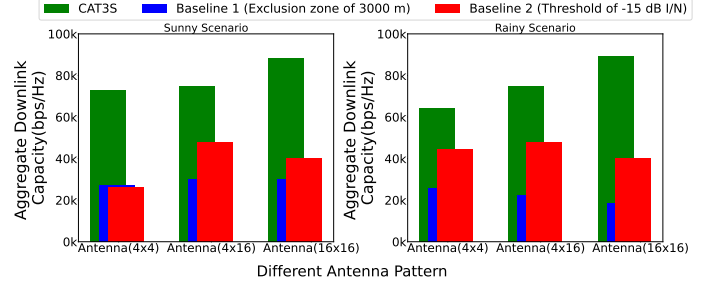


Fig. 8: Achievable downlink capacity vs. antenna element sizes.

dBm aggregate I/N ratios, respectively. At the same time, Figs. 4 depict that the CAT3S keeps more MBSs operational in the shared band compared to both baseline schemes. For example, the CAT3S activates 19 and 17 MBSs in sunny and clear weather conditions, respectively. In contrast, both baseline schemes activate 7 MBSs in sunny weather, and for rainy weather, Baseline 1 and 2 schemes activate 7 and 12 MBSs, respectively. Intuitively, the increased number of operational MBSs significantly enhances the overall achievable downlink throughput of the CAT3S framework. Fig. 5 depicts that the overall achievable downlink throughput of CAT3S reaches $75k$ bps/Hz and $65k$ bps/Hz during sunny and rainy weather, respectively. In contrast, both baseline schemes achieve $\sim 25k$ bps/Hz downlink sum capacity during the sunny weather, and during the rainy weather, Baseline 1 and Baseline 2 schemes achieve $\sim 25k$ and $\sim 45k$ bps/Hz downlink sum capacity, respectively. The aforementioned results depict the efficacy of our CAT3S framework in maximizing shared band utilization for cellular networks without harming incumbent operations in different weather conditions. We also emphasize that considered performance metrics remain the same for a wide range of FSS receiver's pointing angles. Thus, CAT3S's performance is not significantly impacted by the pointing angle selected by the FSS receiver, allowing the FSS receiver to choose the best pointing angles for its use cases.

2) *Performance for MBS's Different Antenna Array Configurations:* Figs. 6, 7, and 8 depict the variations in the aggregate I/N ratios at the FSS receiver, number of operational MBSs, and achievable aggregate downlink for different antenna array configurations at the MBSs (4x4, 4x16, and 16x16 in both the horizontal and vertical directions) under sunny (left) and rainy (right) weather conditions. These figures indicate that for all the antenna array configurations, our CAT3S consistently surpasses the baseline methods by achieving a

lower aggregate I/N ratio, activating more operational 5G MBSs, and enhancing system capacity. Moreover, CAT3S ensures that the aggregate I/N maintains the threshold for both weather conditions. We emphasize that the CAT3S selects the best set of MBSs with the combination of the optimal transmit power and the most suitable set of beams in all three sectors per MBS. Such a capability makes the CAT3S more efficient than the baseline schemes.

We also observe from Figs. 6-8 that the aggregate I/N ratio of the CAT3S does not significantly vary with the antenna array configurations. However, as the antenna array size increases, the number of operation MBSs and downlink sum capacity of the CAT3S increases. This is because, with the increasing number of antenna sizes, relatively sharper and highly directional beams are obtained, which enhances the SNR and, eventually, the total system capacity. However, it is found that both baseline schemes achieve better performance for the 4×16 antenna array configuration than the 16×16 antenna array configuration. The potential reason is as follows. For both baselines, the suitable beams per sector and MBS are selected to maximize the downlink cellular user's performance without considering how much interference this beam could introduce at the FSS. Our experiments found that more MBSs with the 16×16 antenna array generate higher than threshold interference levels at the FSS receiver than the MBSs with the 4×16 antenna array configuration. As a result, to meet the interference threshold at the FSS receiver, for both baseline schemes, fewer MBS are operational with the 16×16 antenna array configuration, and such a fact also reduces the achievable downlink sum capacity of both baseline schemes.

VII. CONCLUSION

A context-aware dynamic spectrum sharing framework by exploiting the beamforming capability of multi-antenna terrestrial 5G MBSs, called CAT3S, was proposed to enable spectrum coexistence between the terrestrial cellular and incumbent networks over the satellite bands. CAT3S acquires and analyzes contexts using a context-acquisition unit and dynamically optimizes the multi-antenna MBSs' parameters using a polynomial complexity MBS control algorithm. Such a capability enables the coexisting cellular network to activate more MBSs in the shared band without creating harmful interference at the incumbent receiver(s). For a proof-of-concept, we evaluated the CAT3S framework's performance using a realistic terrestrial-FSS spectrum sharing simulator over the 12 GHz band for sub-urban deployment in Blacksburg, VA while considering weather as the context variable. Our experimental results show that in both sunny and rainy weather conditions CAT3S (1) keeps the aggregate I/N ratio at the FSS receiver smaller than the tolerable thresholds and (2) achieves higher spectrum utilization for the terrestrial cellular networks than the state-of-the-art spectrum sharing approaches.

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