mmSubArray: Enabling Joint Satellite-Terrestrial Networks in Millimeter-wave Bands

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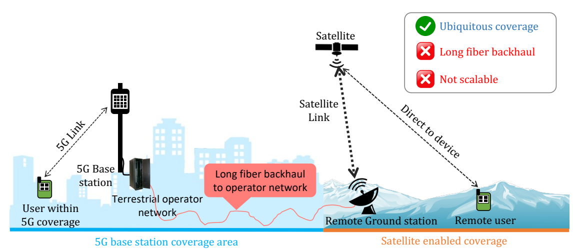
ABSTRACT

The future of global connectivity relies on the seamless integration of satellite and terrestrial networks. Recent advancements have enabled terrestrial devices to connect directly to satellites, while high-speed 5G millimeter-wave links offer a promising solution for backhauling ground station data. This paper introduces the concept of joint satellite and terrestrial networks (*Jointnets*), which necessitates both coexistence and backhaul. In this framework, satellites and ground stations act as relays between terrestrial base stations and devices, removing coverage barriers and providing global connectivity. However, the significant spectrum overlap between 27.5 to 30.0 GHz leads to co-channel interference degrading efficiency or causing complete link failure. Existing approaches only focus on coexistence, resulting in spectrum inefficiency and coverage gaps. We present *mmSubArray: Array of Sub-band Phased Arrays*, a novel solution utilizing commercial off-the-shelf phased arrays to achieve full-spectrum utilization and enable *Jointnets*. Through extensive simulations and real-world measurements, we demonstrate the interference challenges and evaluate the efficacy of our approach. Additionally, we have open-sourced our Python simulator and hardware implementation source codes, providing valuable tools for industrial deployment and future research.

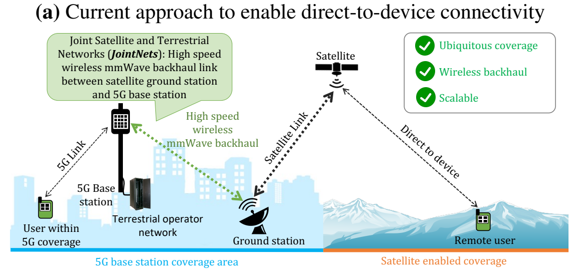
INTRODUCTION

Traditionally, satellite and terrestrial networks operated independently; terrestrial phones connected only to nearby base stations, while satellite phones were necessary for satellite connections. However, recent advancements in Low Earth Orbit (LEO) satellites and the development of more powerful antennas in smartphones have made satellite direct-to-device connectivity a reality [1–3]. This innovation allows terrestrial user devices to connect to nearby terrestrial base stations when within coverage and directly to satellites when outside coverage, necessitating the integration of satellites into the terrestrial (5G and 6G) ecosystem [4].

The current architecture for satellite direct-to-device connectivity involves remote devices connecting to satellites in lower frequency bands, which then route the data to satellite ground stations. As illustrated in Figure 1a, these ground stations use **long fiber cables** to connect to the terrestrial operator network, facilitating data exchange between satellite and terrestrial networks [5,6]. Typically, these ground stations are located in remote areas, far from terrestrial operator networks, and require fiber backhaul connectivity over challenging terrain, leading to high deployment and maintenance costs.



(a) Current approach to enable direct-to-device connectivity



(b) Proposed approach to enable *JointNets*

Figure 1: An illustration of remote devices connecting to terrestrial networks via satellites and ground stations. (a) Shows the current approach for enabling satellite direct-to-device connectivity. (b) Demonstrates the joint satellite and terrestrial networks (*JointNets*) approach, where a high-speed wireless mmWave link provides backhaul between the ground station and the 5G base station.

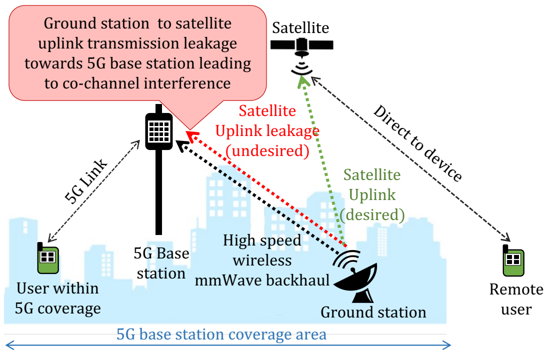


Figure 2: An illustration of satellite ground station interference to a 5G mmWave link: If the ground station and 5G base station are nearby and utilize the same frequency bands, the ground station's active transmission to a satellite can leak towards the 5G base station. This leakage results in co-channel interference to the 5G mmWave link, potentially causing link outages and resource wastage.

Additionally, this approach faces **scalability challenges** as the demand for direct-to-satellite connectivity increases. Thus, the current approach incurs significant operational costs for fiber backhaul, increases latency, and restricts scalability to new ground stations.

To overcome this issue, we argue the need for **joint satellite and terrestrial networks** (*JointNets*). The main problem with the current approach is that satellite and terrestrial networks are disjoint, requiring fiber backhaul to connect them. Instead, *JointNets* proposes deploying ground stations within terrestrial coverage areas and utilizing high-speed millimeter-wave links for data backhaul. This approach eliminates the need for long optical fibers to remote locations, facilitates the deployment of more ground stations as needed, and decreases latency by positioning ground stations closer to the terrestrial operator network. As illustrated in Figure 1b, placing ground stations near 5G base stations and enabling *JointNets* with backhaul using high-speed Millimeter-wave (mmWave) link assists in connecting remote users to 5G/6G base stations, effectively removing barriers and enabling seamless global connectivity. This integration is also financially beneficial for both satellite and terrestrial operators, allowing them to scale operations more effectively, fully utilize the available spectrum, and avoid the high costs associated with fiber backhauls [7].

JointNets has two key requirements: (1) Enabling coexistence of both satellite and terrestrial networks, (2) Enabling backhaul or connectivity between the two networks. While the proximity of satellite ground stations to the 5G base stations enables JointNets, it potentially leads to interference from one network to another due to the overlap in frequencies. The uplink frequencies for satellite ground stations (27.5 to 30.0 GHz [8–13]) and the 5G mmWave frequency bands (27.5 to 28.35 GHz [14]) have a huge spectrum overlap. When both networks have active link transmissions within the same frequency spectrum, it leads to co-channel interference. This interference raises the noise floor, resulting in a degraded signal-to-noise ratio (SNR) and potential link failure. As demonstrated in Figure 2, when a ground station actively transmits to a satellite within 5G frequency bands, it also leaks into the 5G base station direction via side lobes. This leakage can severely degrade the 5G link or entirely cause link failure, depending on the interference strength. Therefore, solutions are needed that address interference due to frequency overlap and enable *JointNets* (coexistence and backhaul).

How do current solutions address these requirements? Most current deployments adhere to distance separation, with 5G base stations installed in urban areas and ground stations in remote locations. However, this approach does not fully integrate both networks or enable *JointNets*. Two other approaches that address interference even when 5G base stations and ground stations are in close proximity are frequency and direction separations.

Frequency Separation: This approach avoids overlapping frequencies, with 5G base stations utilizing only non-overlapping bands to support users. While it can facilitate backhauling in non-overlapping bands, it results in significant spectrum wastage by not utilizing the overlapping bands. In scenarios with complete overlap, this approach leads to 100% *Direction Separation:* This approach uses phased arrays at 5G base stations to suppress interference through beam nulling. It can only enable coexistence but lead to coverage holes by not supporting interference directions.

While these approaches address interference, they often lead to spectrum wastage by avoiding overlapping frequency bands or creating coverage gaps in 5G networks by avoiding specific directions or areas. Moreover, these methods primarily focus on achieving coexistence rather than facilitating the integration of both networks and the effective use of the spectrum. Therefore, we require innovative solutions that address interference issues and enable *JointNets* without compromising spectrum utilization and coverage.

We present **mmSubArray: Array of Sub-band Phased Arrays**, which addresses the interference issue while enabling *JointNets*—coexistence and backhaul. mmSubArray achieves this without sacrificing spectrum or coverage by leveraging a key insight: the overlap between satellite and 5G bands is partial and does not span the entire 5G bandwidth. This presents an opportunity to utilize non-overlapping bands to support interference direction and use overlapping bands to serve

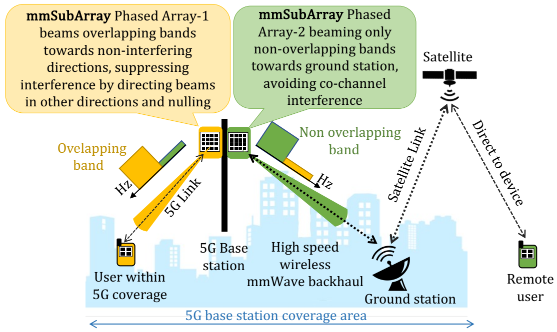


Figure 3: mmSubArray splits the bandwidth into overlapping and non-overlapping sub-bands. This approach avoids co-channel interference in non-overlapping bands and supports ground stations or users in the interference direction. To suppress interference in overlapping bands, we beam in other directions and apply nulling in the interference direction, pushing interference below the noise floor.

users in other directions. Our objective is to build mmSubArray using a commercial off-the-shelf phased array. Traditional phased arrays have a fundamental limitation: they beam the full bandwidth in a single direction and cannot arbitrarily split the bandwidth to beam it in different directions [15]. To overcome this challenge, mmSubArray divides the bandwidth into overlapping and non-overlapping sub-bands and employs different phased arrays to beam each sub-band instead of one phased array beaming the full bandwidth. This *"array of phased arrays"* approach allows serving each sub-band in a different direction, enhancing overall spectral efficiency and coverage.

Enabling backhaul in non-overlapping bands: Through our over-air experiments, we observed that adjacent channel interference does not affect the mmWave link, even in the same location. As shown in Figure 3, mmSubArray enables backhaul by supporting ground stations or users in the interfering directions using non-overlapping bands. This ensures no co-channel interference in non-overlapping bands, thereby establishing a reliable link between the ground station and 5G base station and avoiding coverage holes.

Enabling coexistence in overlapping bands: mmSubArray beams overlapping bands in other non-interfering user directions. The inherent phased array beam pattern reduces interference in the side lobes. Additionally, we employ nulling to fully suppress interference power below the noise floor, nullifying the interference effect and enabling reliable communications in overlapping bands. Therefore, mmSubArray effectively suppresses interference and enables coexistence with full spectrum utilization.

We conducted real-world and simulation-driven measurements to understand the effect of interference on 5G mmWave links. Our hardware experiments provided three key insights: first, how interference degrades the mmWave link and leads to packet detection failure; second, even partial overlap has similar effects as long as the interference power is high; third, the position of overlap does not change the effects of co-channel interference, and phased arrays handle adjacent-channel interference. These insights led us to develop mmSubArray to address the interference problem and enable *JointNets*. Furthermore, we developed a Python simulator to evaluate our approach. Finally, we developed a prototype that demonstrates mmSubArray efficacy using commercial off-the-shelf phased arrays.

To summarize our contributions:

- We proposed mmSubArray: Array of Sub-band Phased Arrays, built using off-the-shelf phased arrays to suppress interference and enable effective spectrum usage, facilitating joint satellite and terrestrial networks (*JointNets*).
- We open-sourced our Python simulator, which helps understand our approach's effectiveness and limitations in various scenarios, such as interference suppression and supporting users simultaneously in multiple directions.
- We developed mmSubArray prototype with off-the-shelf phased arrays. Our complete code base, including hardware implementation and Python simulator, is available at github, webpage

IS INTERFERENCE A PROBLEM?

In this section, we delve into the concepts of co-channel interference and adjacent-channel interference, highlighting their relevance to our study. We aim to evaluate these interferences and highlight the requirements to enable joint satellite and 5G communications in the subsequent discussion.

Co-channel Interference

Co-channel interference occurs when two or more communication systems simultaneously use the same frequency bands. In our scenario, both the satellite uplink from ground stations to satellites and the 5G link from users to base stations operate in the same frequency bands (27.5 to 28.35 GHz), leading to co-channel interference. This interference raises the noise floor, severely degrading the signal-to-noise ratio (SNR), which reduces link capacity, increases error rates, and can potentially cause link failure. For instance, a nearby ground station transmitting in the 27.5 to 28 GHz band will interfere with the entire 5G link's band (27.5 to 28 GHz). Ideally, we aim to avoid

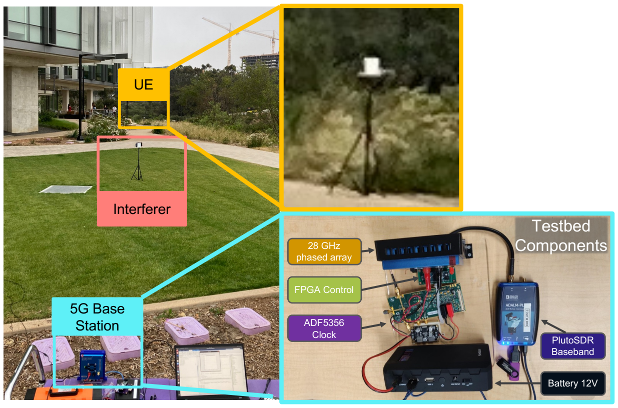


Figure 4: Hardware setup to evaluate the effect of interference on a 5G mmWave link: We used three mmWave setups acting as a 5G base station, an interferer, and user equipment (UE). Each setup consisted of a 28 GHz phased array, a Pluto SDR, an ADF5356 clock, and a 12V battery, as shown in the figure. Throughout the experiments, the base station and user remained fixed while we varied the interferer's gain, bandwidth, and center frequency to understand the impact of interference on a given 5G link.

increasing the noise floor. To achieve this, we must suppress interference below the noise floor. Satellite ground station interference power at a 5G base station is influenced by factors such as distance, beam angles, and the ground station's orientation. Consider an earth station that is located 1km away from the 5G BS, that has an EIRP of 70dBm and supporting a minimum elevation angle of 5°. To suppress interference at 5G BS to below the noise floor for a 100 MHz bandwidth channel, using the 3GPP-RMA model [16,17], a substantial suppression of 40 dB is required.

Adjacent-channel Interference

Adjacent channel interference occurs when there is an active transmission with high power in an adjacent channel. Unlike co-channel interference, it does not directly increase the noise floor but instead raises the dynamic range on the ADC, thereby increasing quantization noise for the desired signal and affecting the SNR. For instance, if the ground station is transmitting to a satellite in the 27.8 to 28 GHz band (200 MHz), it will cause adjacent-channel interference to the 5G base station using the adjacent band, 28 to 28.2 GHz (200 MHz). Given the high propagation and blockage losses in mmWave frequencies (unlike sub-6 GHz frequencies), stringent spectrum masks, and advanced ADCs, adjacent channel interference is unlikely to significantly affect the link in most practical scenarios. Furthermore, we've also observed in our over-the-air experiments that adjacent channel interference does not have any effect on the 5G mmWave link.

INTERFERENCE EVALUATIONS USING OVER-THE-AIR EXPERIMENTS

In this section, we discuss our hardware over-the-air mmWave experiments at 28 GHz to understand the impact of interference on mmWave links.

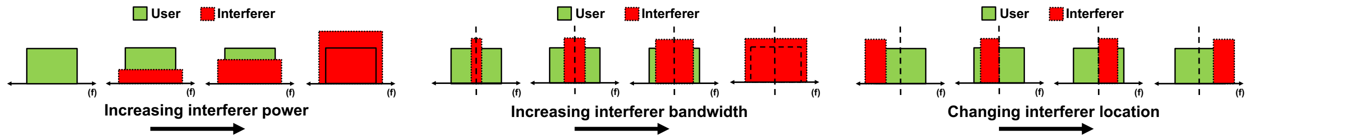
Hardware Setup

To understand the interference effects on mmWave links, we used a simple setup with a 5G base station as the receiver, a user device as the transmitter, and an interferer. As shown in Figure 4, we used three phased array setups for the 5G base station, user device, and interferer. The 5G base station and interferer were configured to have directional beams, while the user device was omnidirectional. Additionally, we used PlutoSDR devices for the user and interferer to transmit 5G specifications-compliant OFDM waveforms in a loop (continuous transmit mode with PlutoSDR). The transmitter and interferer operated with a default bandwidth of 30.72 MHz unless otherwise specified. For more details about the implementation and setup, please refer to mMobile testbed [18].

Evaluation Findings

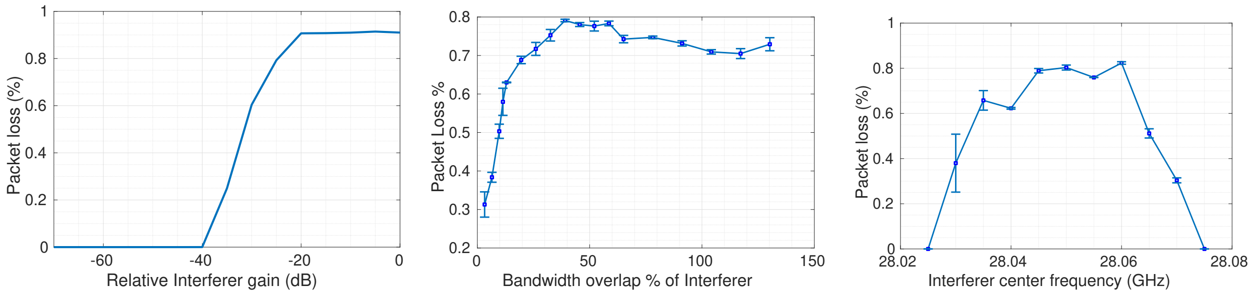
Our objective was to understand how the Signal-to-Interference-plus-Noise Ratio (SINR) and Bit Error Rate (BER) change with varying interference power, the percentage of overlapping frequency bands, and the effects of both co-channel and adjacent-channel interference on mmWave links as shown in Figure 5.

(1) Variations with Interference Power: Our goal is to demonstrate how SINR and BER change as interference power varies. As shown in Figure 5a, we began with the maximum gain of the interference SDR and gradually reduced it by up to 70 dB to analyze its effect on the 5G base station. Our observations align with theoretical expectations: high interference power leads to a link failure or very low SINR, while low interference power does not significantly affect the SINR or SNR of the signal. We found that the 5G base station couldn't detect any OFDM symbols until we reduced the interference by approximately 30 dB, resulting in link failure. As shown in Figure 6a, packet loss is absent when the interference is between -70 and -40 dB, and gradually increases up to -20 dB and then reaches a maximum beyond -20 dB of relative interference power. Similarly, in Figure 7a, between -20 dB and -40 dB reduction, the BER gradually improved from 0.5 (worst) to nearly 0 (best). Beyond a -40 dB reduction, interference no longer affected the user's SNR, as the interference power fell below the noise floor, allowing the noise



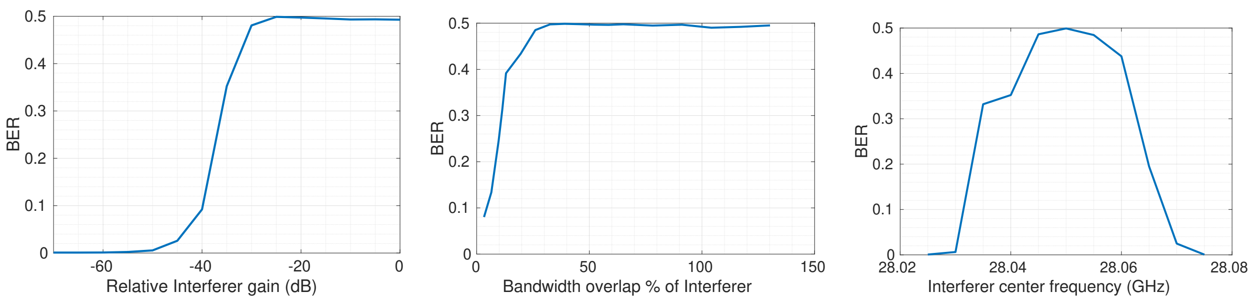
(a) Increasing interference power **(b)** Increasing interference bandwidth **(c)** Changing interference location

Figure 5: Three possible scenarios were tested. Fig-(a) Increasing interference power while user power, user bandwidth, interference bandwidth and location are fixed. Fig-(b) Increasing interference bandwidth while the user power, user bandwidth, interference power and location are constant. Fig-(c) Changing the location of the interference within the bandwidth user consideration, while user and interference power, bandwidth are fixed.



(a) Packet Loss % vs Relative Interference gain **(b)** Packet Loss % vs Interference Bandwidth **(c)** Packet Loss % vs Location of interference

Figure 6: Packet loss for each of the three scenarios. Fig-(a) Packet loss % increases as interference power with respect to the user is increased. Fig-(b) Packet loss % increases as interference bandwidth is increased. Fig-(c) Packet loss % is high when the interferer is present in-band, while there is still some packet loss when the interferer is partially in-band.



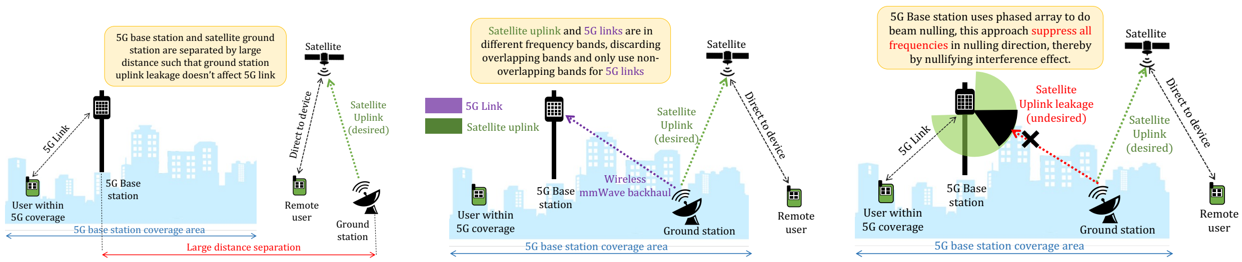
(a) BER vs Relative Interference gain **(b)** BER vs Interference Bandwidth **(c)** BER vs Location of interference

Figure 7: BER for each of the three scenarios. Fig-(a)BER increases as interference power with respect to the user is increased. Fig-(b) BER increases as interference bandwidth is increased. Fig-(c) BER is high when the interferer is present in-band, while there is still some bit-error when the interferer is partially in-band.

floor to dominate. We observe that although packet loss is not a hundred percent, the BER is maximum, as although packets are decodable, the errors are maximum. Hence, we demonstrate that strong interference leads to link failure or degraded BERs and emphasize that suppressing interference power below the noise floor can enable joint communications.

(2) Variations with percentage of frequency overlap: We analyzed the required bandwidth overlap for interference to be effective as shown in Figure 5b. We employed a user setup with a bandwidth of 30.72 MHz and varied the interference bandwidth from 0.5 MHz to 40 MHz, ranging from approximately 1% to beyond 100% bandwidth overlap. The key observation is that as long as the bandwidth overlap exceeds 20% (6 MHz), it consistently has the same effect, leading to near link failure for more than 70% times (Figure 6b). The bit error rate also saturates to 0.5 after 20% overlap, as shown in Figure 7b. As the bandwidth overlap decreases below 20%, the interference effect diminishes. Although this trend is consistent across various iterations of measurements, the exact cutoff point where the interference effect drops and converges to zero may vary slightly. Therefore, this analysis highlights a crucial point: even a strong interferer with a small fraction of bandwidth overlap can still cause link outages and result in the complete wastage of the available bandwidth.

(3) Variations with overlap positions: Co-channel and Adjacent channel interference: In this experiment,



(a) Coverage area avoidance - distance apart **(b)** Frequency avoidance - filtering **(c)** Direction avoidance - beam nulling

Figure 8: Traditional techniques to avoid interference and enable coexistence. Fig-(a) Although distance separation allows full-spectrum usage on both networks, It disjoints both terrestrial and satellite networks. Fig-(b) Filtering mandates different frequency bands for terrestrial and satellite networks, leading to bandwidth/spectrum wastage. Fig-(c) Beam nulling efficiently suppresses interference but cannot serve users in interference directions, leading to coverage gaps and resource wastage.

we aimed to determine whether the overlap position changes the co-channel interference effects on the mmWave link. We set the user setup to 30.72 MHz centered at 28.05 GHz (28.35 to 28.65 GHz) and fixed a 10 MHz bandwidth for the interferer. By varying the interferer's center frequency from 28.25 to 28.75 GHz in 0.05 GHz steps, we covered adjacent-channel overlap, partial adjacent and partial co-channel overlap, and co-channel overlap scenarios. Our observations, as illustrated in Figure 6c and Figure 7c, indicate that the interference effect remains almost consistent regardless of the overlap position (packet loss % is around 0.8 and BER is almost 0.5), provided the overlap percentage is the same. Additionally, adjacent-channel overlap (at 28.25, 28.30, 28.70, and 28.75 GHz) showed no impact on the user link, with a BER of 0. Partial overlaps between 28.35 and 28.65 GHz resulted in interference effects that fell between full-overlap and no-overlap scenarios, aligning with previous results. Therefore, the key takeaways are that the position of co-channel overlap does not change the interference effect as long as the overlap percentage is consistent, and **adjacent-channel interference does not affect the 5G mmWave link**.
Therefore, through our over-the-air hardware experiments, we demonstrate that coexistence and integration of both satellite and terrestrial networks are feasible if we can suppress co-channel interference below the noise floor.

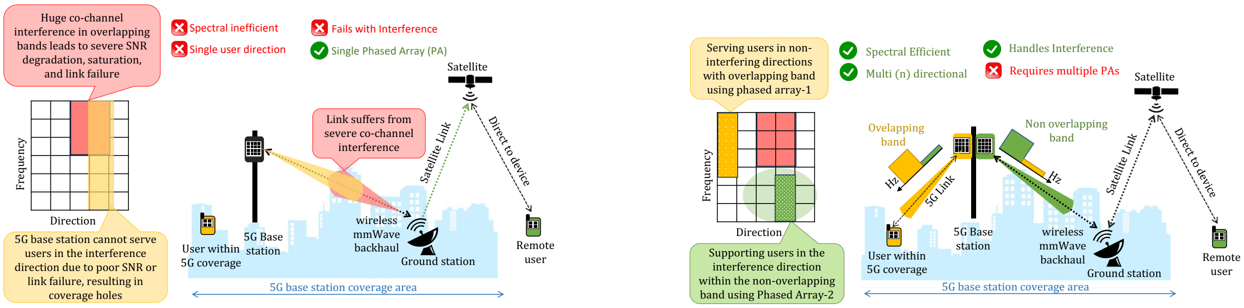
CURRENT SOLUTIONS FOR CO-EXISTENCE

To suppress the interference and enable coexistence, current solutions rely on one or a combination of the following techniques to enable effective spectrum utilization between satellite and terrestrial networks and ensure their coexistence:
(1) Coverage area avoidance - distance separation: This technique involves separating satellite ground stations and 5G base stations sufficiently so that the transmission from the ground station does not reach the 5G base stations or the users they support, as depicted in Fig-8a. In US, Federal Communications Commission (FCC) recommends coexistence through coverage area avoidance. Moreover, it restricts the number of ground stations to two per county and confines their placement to less populated areas, thereby ensuring that 5G networks can cater to more densely populated regions. While this approach facilitates coexistence, it results in coverage gaps by limiting support near ground stations.

(2) Frequency avoidance - filtering: In scenarios where satellite ground stations and 5G base stations are in close proximity, filters are employed to suppress overlapping frequencies. By avoiding overlapping frequencies, as depicted in Fig-8b, filters enable communication with users in the interference direction using non-overlapping bands. While effective for addressing adjacent channel interference, filters pose new challenges for co-channel interference. Firstly, the interference overlap band is variable, making it difficult to dynamically adjust filtering frequency and bandwidth in real time. In addition, filters may block frequencies from all directions, leading to the wastage of the entire overlapping band.

(3) Direction avoidance - beam nulling: This method utilizes an array of antennas at the 5G base station to nullify interference in specific directions. As demonstrated in Fig-8c, while this enables simultaneous communications, it results in coverage gaps by preventing the base station from serving users in the interference direction. Consequently, even if the base station has resources and users awaiting connection in the interference direction, it cannot serve them, leading to resource wastage and reduced capacity.

Therefore, all these solutions create some form of disjoint between satellite and terrestrial networks to enable simultaneous communications, sacrificing



(a) Demonstrating 5G base station functionality with a Single phased array.

(b) An illustration of mmSubArray: Array of Sub-band Phased Arrays

Figure 9: We compare the mmSubArray architecture with a single-phased array setup, highlighting four key features: spectral efficiency, robustness to interference, multi-user direction support, and hardware complexity. Figure (a) illustrates a traditional phased array setup, which requires only one phased array but does not support multiple user directions simultaneously, fails in the presence of interference, and wastes resources by beaming the full bandwidth even if the user does not require it. Figure (b) depicts the mmSubArray system, which supports multiple user directions, effectively handles interference, and is spectrally efficient. However, it requires multiple phased arrays, increasing hardware complexity.

resources such as area, frequency, and direction. We need innovative solutions that enable joint satellite and terrestrial communications while ensuring full-spectrum usage for both networks.

mmSubArray DESIGN

In this section, we discuss our system model. We then explore traditional phased arrays and their limitations in facilitating joint satellite and terrestrial communications. Subsequently, we delve into our proposed mmSubArray design and elucidate how it effectively suppresses interference, thereby enabling seamless integration of satellite and 5G links.

System Model Assumptions:

The system model assumes a ground station located near a 5G base station, with a reliable mmWave link feasible between them without interference. While partial band overlap interference from the ground station is assumed, in the extreme case of full band overlap, the interference can be managed using standard beam nulling techniques. Although there are various methods to detect and localize interference in frequency and angle, this model assumes that the direction and angle of interference are known/calculated beforehand.

Single Phased Array Architecture:

Unlike sub-6 GHz frequencies, the fundamental problem with traditional phased arrays is their inability to beamform specific frequency bands in different directions. As depicted in Fig-11a, the 1-D beamforming pattern is applied uniformly across all radiated frequency bands, directing all frequency resources into a single direction (Fig-10a). This limitation results in spectral inefficiency and restricts communication to a single user direction.

Further, if there is an interference in any part of beamed frequencies, it will lead to co-channel interference and potentially cause complete link failure. As shown in Fig-6b and Fig-7b, even a minimal overlap of 20% can significantly degrade the link. The most common method to address coexistence with traditional phased arrays is beam nulling, which avoids interfering directions and beams only in non-interfering directions. However, this approach does not serve users in the interference direction, leading to spectrum wastage and coverage holes.

Another challenge is the high ADC/DAC requirements due to a single RF chain phased array with a large bandwidth, which needs to support 850 MHz on one RF chain. Therefore, new solutions are required that more practical systems that can efficiently use the full spectrum while enabling satellite ground stations and 5G connectivity.

mmSubArray: Array of Sub-band Phased Arrays

mmSubArray is designed to facilitate joint satellite and 5G communications while ensuring full-spectrum utilization across both networks. The key innovation is the use of multiple phased arrays, each beaming different subbands in various user directions. This approach allows mmSubArray to support multiple user directions simultaneously and significantly reduces ADC/DAC requirements by a factor of $1/n$, where n is the number of antennas.

The key insight behind mmSubArray is that the overlap between satellite and terrestrial networks is typically partial. For example, in most scenarios, the overlap affects only a portion of the total available bandwidth. To capitalize on this, we propose a two-step solution: splitting and nulling.

- **Splitting**: We divide the available bandwidth into overlapping and non-overlapping bands. One or more phased arrays are dedicated to serving the overlapping band in non-interfering directions, while the remaining phased arrays serve the non-overlapping band in interfering directions.
- **Nulling**: Although splitting and directing overlapping bands to other directions reduces the gain in the interfering direction, high suppression is still needed in many scenarios. To achieve this, we employ nulling. Additionally, we use orthogonal projection with multiple null constraints to create a wide null in the interference direction.

This approach avoids resource wastage, allowing the 5G base station to communicate in both interference-prone and interference-free directions, thereby preventing coverage holes. It also effectively suppresses interference and facilitates joint communications. However, this solution does require the use of multiple phased arrays.

For example, if a satellite ground station transmits uplink in the 27.5 to 28.0 GHz band, it could potentially interfere with 5G base stations communicating in the same direction. Suppose there are three users waiting for network access. mmSubArray can split the available spectrum into three sub-bands: band1 (27.5 to 27.75 GHz), band2 (27.75 to 28.0 GHz), and band3 (28.0 to 28.35 GHz). Each sub-band is radiated by a different phased array into different user directions. Band1 and band2, which fall into the overlap region, are directed in non-interference directions with nulling, while band3, the non-overlapping band, is used to bridge the link between the 5G base station and the ground station or users in the ground station direction.

mmSubArray Evaluations

To evaluate mmSubArray and demonstrate its effectiveness in suppressing interference, we utilized both Python simulations to showcase beam patterns and mmSubArray hardware setup to illustrate the end-to-end link's functionality even under high interference conditions. In this section, we will delve into our Python simulator and hardware setup, along with their respective results.

Python Simulator Overview

We developed a Python simulator to visualize the expected beam pattern from the mmSubArray system. Typically, commercially available off-the-shelf phased arrays come with configurations such as 8x4 and 8x8 antenna elements for serving mmWave bands. For our simulations, we considered only a one-dimensional (1x8) linear antenna array. This choice allows us to explain two-dimensional frequency space plots efficiently.

Additionally, we assumed that the total mmWave frequency band available for the base station spans from 27.5 to 28.35 GHz, totaling an 850 MHz bandwidth. We ensured that the total transmitted power of a single-phased array and mmSubArray remained the same to enable a fair comparison.

Furthermore, we have open-sourced this simulator, which serves as a valuable tool for both academic and industry professionals to quickly analyze beam patterns in both frequency and angular domains as initial checkpoints. Moreover, this simulator can be customized to meet specific user requirements.

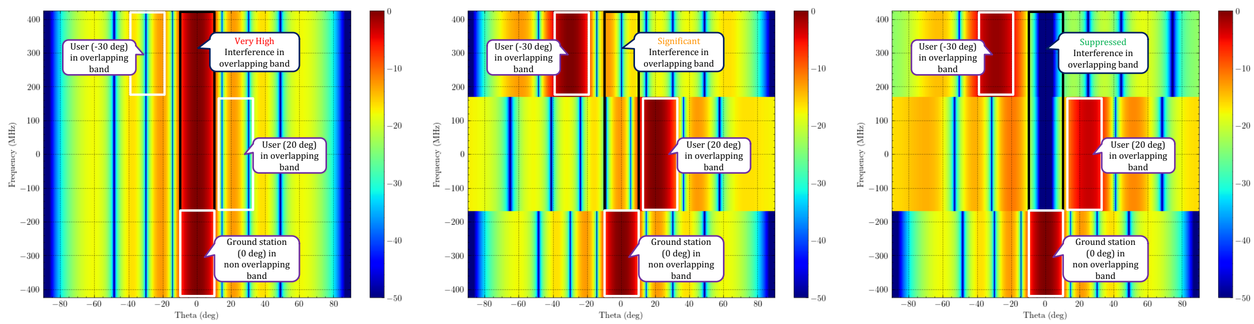
Beam Pattern Simulations

Our objective here is to demonstrate the efficiency of mmSubArray in suppressing interference and its ability to serve users even in interference-prone directions effectively. We assume three users are awaiting connectivity in three different directions, at -30, 0, and 20 degrees in the azimuth direction, with each user requiring only a partial bandwidth. Furthermore, an interferer is positioned at 0 degrees with a 70% overlap, causing co-channel interference to the base station.

Traditionally, phased arrays operate in one domain, as depicted in Fig-11a, distributing the same beam pattern across the total available frequency band. In other words, the one-dimensional beam pattern shown in Fig-11a resembles the two-dimensional frequency space domain represented in Fig-10a. However, this approach presents two main issues. Firstly, if there is a strong interferer, it can cause co-channel interference and potentially lead to link failure. Secondly, if a user does not require the entire bandwidth, this leads to spectrum wastage.

mmSubArray addresses this issue in two steps: bandwidth splitting and beam nulling.

Bandwidth splitting: We divide the available bandwidth into overlapping and non-overlapping bands and serve users to reduce interference. In the given case, we observe that the first 30% of the bandwidth is interference-free (non-overlapping), while the remaining 70% has interference (overlapping band). We direct the first 30% to the ground station or users in the ground station direction, supporting the interference direction (0th degree). Meanwhile, we serve the remaining 70% in other user directions to avoid spectrum wastage. Since the bandwidth is substantial, we further split the overlapping band to support two users in

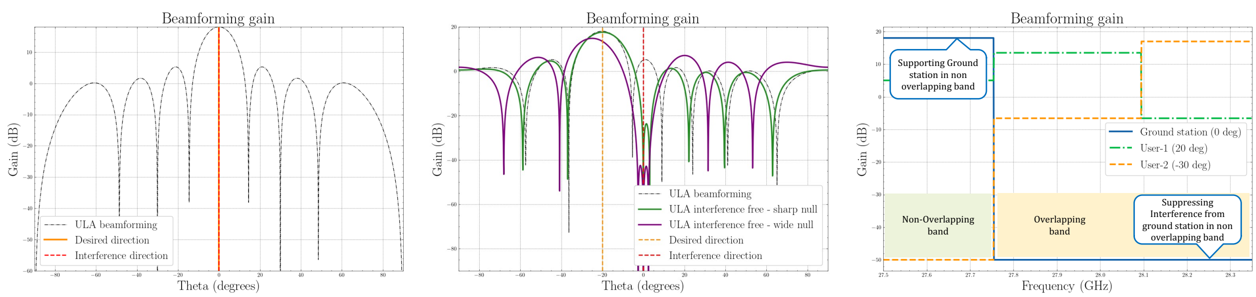


(a) Beam pattern for a single phased array with all frequencies beaming in the one desired direction.

(b) Beam pattern for mmSubArray (Split only) - Splitting bandwidth and beaming in different user directions.

(c) Beam pattern for mmSubArray (Split and Null) - Nulling to further suppress interference power below the noise floor.

Figure 10: An illustration of two-dimensional heatmaps with both frequency and space dimensions. Figure (a) depicts a traditional phased array, beaming all available bandwidth in one direction. Figures (b) and (c) exemplify mmSubArray's ability to beam sub-bands in different directions. As shown in Figure 10c, it further employs nulling in the interference direction to fully suppress the interferer below the noise floor.



(a) Beam pattern in theta domain for single phased array

(b) Beam pattern in theta domain for mmSubArray after splitting and nulling

(c) Gain (dB) in three user directions - showing interference band suppression in 0 deg

Figure 11: This illustration depicts beam patterns or gain in dB for three scenarios. Fig-(a) shows one-dimensional beamforming gain for a phased array beaming at a 0-degree angle. Fig-(b) quantifies the extent to which interference strength can be nullified. In Fig-(c), we demonstrate how splitting can result in three distinct beam directions (0), where we observe high gain in the non-overlapping band and very low gain in other frequencies at 0 degrees.

non-interference directions (-30 and 20 degree angles), thus minimizing spectrum wastage.

Beam nulling: The interference at 0 degrees may still pose a problem for the base station in serving these users. To address this, we implement angle nulling for the two users. As depicted in Fig-10c, phased array 2 beams the main lobe towards the 20-degree angle and creates a null at the 0-degree angle, while phased array-3 beams the main lobe towards the -30-degree angle and nullifies the interference at the 0-degree angle. For instance, as illustrated in Fig-11b, the base station nullifies gain in the interference direction, ensuring it is 60 dB lower than the desired beam, effectively pushing the interference below the noise floor.

As demonstrated in Fig-11c and Fig-11b, the base station effectively serves users in three directions: 0, 20, and -30 degrees. We observe interference from the ground station in the 27.8 to 28.35 GHz range in the 0th degree direction. By serving the non-overlapping first 30% band in the 0th direction and the rest in other user directions while suppressing interference in the 0th direction, we effectively utilize the full spectrum and enable communications in the interference direction.

RELATED WORK

Most studies on coexistence are in 3.8 GHz band [19]. Recent studies model interference in mmWave bands [20–22]. [23] studied the interference caused by Vehicle-mounted earth stations (VMES) on 5G links using theoretical models. [24] proposed a joint carrier, power, and bandwidth-allocation schemes to mitigate the effect of in-band interference, assuming coordination between the satellite terminal and 5G base station. [25] performed analysis by deriving the statistical distributions of the received signal-to-interference ratio and signal-to-noise plus interference ratio at the base station receiver. [26] derived an analytical expression of capacity for link under interference while considering the impact signal attenuation due to rain attenuation in channel-fading distribution. The study in [27] concluded that several kilometers of separation between the ground station and the 5G base station is required for coexistence.

Similarly [28] developed a ray-tracing based analytical tool for understanding cross-interference between terrestrial and non-terrestrial networks. In contrast to these simulation-based studies, we conduct over-the-air experiments using 28 GHz radios with phased arrays and OFDM waveform to understand the impact of interference from ground station to a 5G base station. We also propose a novel method mmSubArray, to mitigate the impact of interference using frequency-selective nulling while maintaining high coverage and performance. As shown in Section , creating a null around 5G base station creates a coverage hole in that region and any 5G devices in this region would be denied any 5G cellular services including the emergency 911 services. Our proposed mmSubArray creates frequency-selective nulls in this region which allows serving users in this region using a sub-set of non-overlapping bands, thus preventing denial of service in this area.

Interference from 5G cellular to satellite in space is modeled in [29–31]. For instance, a recent work, [31] analyzed the co-channel interference and out-of-band (OOB) leakage power from terrestrial networks to satellites using stochastic geometry and proposes to reduce the density of terrestrial deployments to mitigate this interference. However, different from these models, instead of interference at satellite, we consider the interference at 5G base station in uplink. [32] proposes to perform sharp frequency filtering to reduce out-of-band interference.

SUMMARY AND FUTURE DIRECTIONS

This paper proposes joint satellite and terrestrial networks (*JointNets*) enabling coexistence and backhaul for seamless global connectivity. It addresses the issue of spectrum overlap between satellite ground station uplinks and 5G mmWave links, which leads to co-channel interference and reduced efficiency of 5G links. The proposed solution, *mmSubArray: Array of Sub-band Phased Arrays*, utilizes commercial off-the-shelf phased arrays to achieve full-spectrum utilization and seamless operation of both networks. The effectiveness of *mmSubArray* in mitigating interference and enhancing spectrum efficiency is demonstrated through extensive simulations and over-the-air hardware experiments.

Future research will focus on developing a digital twin to replicate real-world deployments of satellite ground stations and 5G base stations. This model will assess interference strength by considering factors such as geographical location, path loss due to various environments, antenna orientations, and deployment density, aiding in optimal placement and configuration. Additionally, new hardware architectures will be explored to enable joint terrestrial and satellite networks, with an emphasis on reducing the energy footprint while maintaining high performance and reliability.

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