5G in the Sky: The Future of High-speed Internet via Unmanned Aerial Vehicles

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ABSTRACT

millimeter-wave (mmWave) technology provides new opportunities to support high throughput wireless applications by utilizing the high-frequency spectrum. However, due to the short wavelength and narrow beamwidth of mmWave signal, mmWave networks are highly susceptible to blockage. Hence, they enable high throughput links only when there is a clear line-of-sight (LOS) path between users and terrestrial base stations. Unfortunately, this requirement has limited the applications of mmWave technology in outdoor scenarios.

In this paper we propose GigSky, a mmWave network which utilizes UAVs as aerial relays to solve the coverage problem of mmWave networks. In contrast to past work which mostly focuses on the idea and the theoretical aspect of using UAVs in wireless networks, this paper targets the practical issues in building an end-to-end system. In particular, it introduces a new design which enables UAVs to passively beamform to users in different areas on the ground without requiring complex and costly phased arrays which are used in traditional systems to create and steer mmWave beams.

CCS CONCEPTS

• **Networks** → **Wireless access points, base stations and infrastructure**; • **Hardware** → **Analysis and design of emerging devices and systems**.

KEYWORDS

5G, millimeter-wave, UAV

ACM Reference Format:
Tianxiang Li, Mohammad H. Mazaheri, and Omid Abari. 2022. 5G in the Sky: The Future of High-speed Internet via Unmanned Aerial Vehicles. In *The 23rd International Workshop on Mobile Computing Systems and Applications (HotMobile '22), March 9–10, 2022, Tempe, AZ, USA.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3508396.3512874

1 INTRODUCTION

In recent years, the growing demand for high data rate and low latency wireless applications such as real-time video streaming, virtual reality (VR), and augmented reality (AR) have facilitated the development of the fifth-generation (5G) wireless technologies.

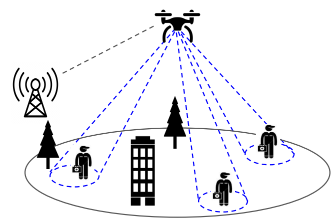


Figure 1: GigSky Example Scenario

The millimeter-wave (mmWave) spectrum is considered one of the key enabling technologies of 5G with its high network capacity at higher frequencies (above 24 GHz). The large bandwidth of mmWave frequency makes it the ideal solution for supporting high throughput applications at high-density areas.

Despite the merits of the mmWave technology, today's mmWave networks have limited coverage which makes them unsuitable for many applications. In particular, due to the high frequency nature of mmWave, these signals experience greater path loss than low frequency signals. Therefore, mmWave radios have to use directional antennas to focus their transmitted power into narrow beams to compensate for that loss. Unfortunately, since these beams can be easily blocked by obstacles such as buildings or human body, mmWave networks require to have a line-of-sight (LOS) path between the transmitter and the receiver to enable high-data-rate links. One potential solution to solve this problem is to use a large number of base stations to guarantee a line-of-sight path between a user and an access point all the time. Unfortunately, this solution is not practical for multiple reasons. First, depending on the distribution of the users, it may be hard to predict the real-time network demand of an event or hotspot beforehand. Second, upgrading the legacy infrastructure is costly and time-consuming. Finally, there is a limited number of places where a terrestrial base station can be deployed. These challenges drive the need for an on-demand, mobile mmWave network, capable of rapid deployment and reconfiguration.

To address this problem and meet the network demands in real-time, we propose GigSky, a wireless network architecture which leverages UAVs (Unmanned Aerial Vehicles) as network relays for future 5G and 6G deployments. Compared to the stationary ground infrastructure, UAV networks provide better LOS links to ground users, and can be deployed dynamically on demand. For example, during concerts and sports events, where a large number of users will gather together, GigSky can be used to provide a high-data-rate link to each user, enabling stadium Augmented Reality (AR) experience. Similarly, in areas where the ground infrastructure is under-developed or damaged such as rural areas or disaster relief scenarios, GigSky can be used to provide high-data-rate wireless links to users, robots and first responders.

HotMobile '22, March 9–10, 2022, Tempe, AZ, USA

ACM ISBN 978-1-4503-9218-1/22/03…$15.00
https://doi.org/10.1145/3508396.3512874

In contrast to past work which mostly focuses on theoretical and general idea of using UAVs for 5G networks [10, 20, 21], this paper focuses on addressing some practical challenges of implementing this vision. In particular, building a UAV relay operating at mmWave frequency is very challenging since UAVs need to maintain backhaul connection to a remote ground base station while providing directional communication links to many ground users, as shown in Figure 1. The main challenge to achieve this goal is to create multiple beams simultaneously while each transmitting a different signal to each user. Although past mmWave work has proposed different approaches and schemes for creating and steering directional beam, they are not practical for UAVs since they rely on phased arrays. Unfortunately, phased arrays which supports many users simultaneously are costly, complex and have high power consumption since they require a large number of antennas and multiple radio chains.

To solve this challenge, GigSky builds on Frequency Scanning Antenna (FSA), used in applications such as imaging [24], and weather measurement [9]. In particular, we develop a passive relay which steers the signal in different directions based on the frequency of the signal. Our design enables the UAV to send each channel of the 5G mmWave spectrum band to a different beam direction, covering different areas on the ground with different beams and different frequency channels. The main advantage of this approach is that it uses only passive components and does not need any phased arrays which are costly and complex.

This paper makes the following contributions:

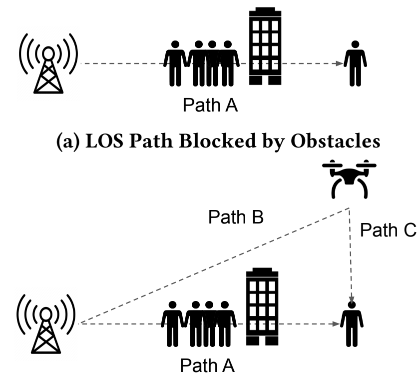
- We introduce GigSky, a UAV mmWave relay system which enables high-data-rate links to a large area of users by solving the blockage problem in outdoor mmWave networks.
- We design a cost-effective passive relay based on FSA to achieve beam steering in the 5G mmWave frequency band of 26.5 GHz to 29.5 GHz.
- Our initial results shows that each GigSky UAV enables throughput of 400 Mbps link to each user when there are up to 30 users. Even when there are 600 users, it can provide each user with a 20 Mbps link which is enough AR 360 degree 4K video [17].

2 RELATED WORK

Previous works on mmWave networks focused on reducing the power consumption of the network [13, 14] and solving the beam alignment problem [2]. In addition, the problem of blockage in mmWave network has been addressed through methods such as using reflection from side walls [1, 13], using a smart surface [4],or through dynamic beam adjustment [19]. However, they focus on indoor scenarios and none of them are practical for large-scale outdoor scenarios. In contrast, this paper focuses on solving the mmWave blockage problem in outdoor scenarios by utilizing UAVs as aerial relays.

In recent years, there is a growing interest in UAV-aided wireless communication [22]. These works utilize the mobility and the LOS communication link provided by the UAV for a variety of application scenarios, such as using UAV as aerial base stations to off-load data traffic from existing infrastructure [11], using UAV as amplify-and-forward relays to increase the network coverage [25] or to overcome link failures [6], as well as using UAVs for data dissemination in Wireless Sensor Networks [23]. However, most of these works focus on the general optimization problems of the UAV network and does not address the challenges of building a mmWave UAV relay.

Finally, there are some works which utilizes UAVs for mmWave communication to provide on-demand high capacity networks [10]. However, most of these works focus on the theoretical analysis. For example, optimizing UAV placement [20] and efficient beamforming [21]. There is a limited number of work which focuses on the implementation and testing of a UAV mmWave system [8, 18]. In these works, the authors use Phased Arrays with complex phase shifters for beam steering, and is tested on a small communication range. Unfortunately, phased arrays which support many users are complex and have high power consumption which is not practical for large scale UAV application. In contrast, we propose a novel design for a mmWave UAV relay which builds on FSA, enabling passive beamforming which significantly reduce the complexity and power consumption.



(a) LOS Path Blocked by Obstacles

(b) NLOS Path through a UAV Relay

Figure 2: Blockage Scenario

3 MMWAVE COVERAGE PROBLEM

One of the main challenges of mmWave technology is signal blockage. As shown in Figure 2a, it is generally hard to guarantee LOS non-blockage communication link directly between the terrestrial base station and the user device. A path with obstacles in between the transmitter and receiver (Path A) can cause significant attenuation to the mmWave signal. For examples, a single wall located between the user and the base station results in penetration loss of 20 to 40 dB [26] at 28 GHz [1]. Similarly, a person standing between the user and the base station, attenuates the signal by 10 to 12 dB [1, 27].

To illustrate the effect of blockage on the throughput, we present a link-budget calculation using a real world example as shown in Figure 2a. We consider a typical terrestrial base station with an Effective Isotropic Radiated Power (EIRP) of 60 dBm [16], and a typical mmWave receiver with 10 dB antenna gain, and noise floor of -89 dBm. The communication frequency is 28 GHz, and the channel bandwidth is 100 MHz. The distance between the user and the base station is 200 meters, which results in around 107 dB free

[1] We will use the 5G NR frequency band of 26.5 GHz to 29.5 GHz and channel bandwidth of 100 MHz in our examples, as this is the spectrum band used by a number of carriers

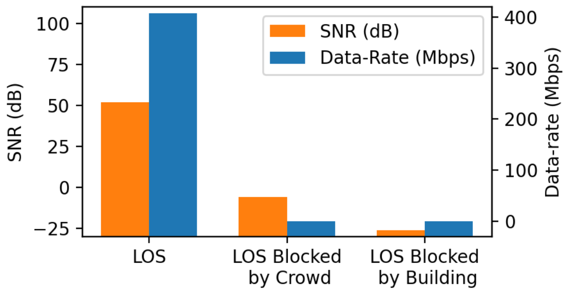


Figure 3: Blockage Impact on SNR and Data Rate of mmWave 5G.

space path loss. For our calculation, we only consider the downlink, where the base station is the transmitter and the user device is the receiver. However, similar link budget calculation can be done for uplink too. We calculate the received signal power P_{rx} based on eq.(1), where P_{tx} is the transmitter EIRP, A_{rx} is the receiver antenna gain, L_{path} is the free-space path loss, and L_{obs} is the penetration loss of the obstacles.

$$P_{\text{rx}} = P_{\text{tx}} + A_{\text{rx}} - L_{\text{path}} - L_{\text{obs}} \quad (1)$$

We then calculate the receiver SNR value based on eq.(2), where P_{nf} is the noise floor value.

$$SNR = P_{\text{rx}} - P_{\text{nf}} \quad (2)$$

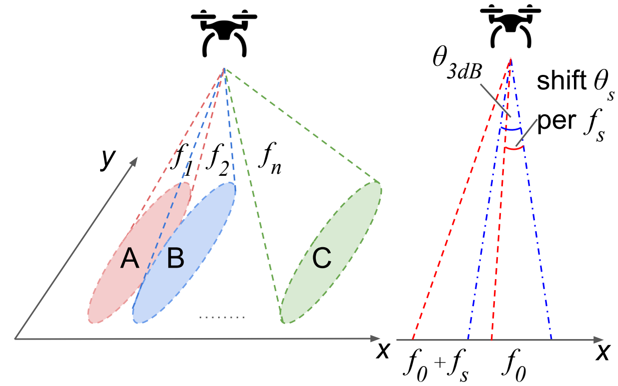
Figure 3 shows the calculated SNR of the received signal and the data rate of a single user in three different scenarios. In the case with LOS path between the base station and the user, the receiver SNR is 52 dB. When there is a crowd of people blocking the path, the SNR decreases to -6 dB. In the case of a building blocking the signal path, the SNR drops to -26 dB. To evaluate the effect of blockage on data rate, we ran simulations with a single base station and a single user using the the ns-3 mmWave simulator [15]. We set up the parameters as mentioned above. The simulation results show that the data rate of a single user in is 408 Mbps when there is no blockage[2]. The user data rate drops to 0 Mbps when a crowd or a building is blocking the signal path. This result shows that blockage of a mmWave signal has significant impact on the throughput.

To solve this blockage problem, we propose GigSky, an aerial relay system for mmWave communications. We introduce the details of our design in the next section.

4 GIGSKY

GigSky is a UAV relay system operating at mmWave frequency, and it provides over-the-air non-blockage communication paths between the transmitter and the receiver, as shown in Figure 2b. To cover all users on the ground and simultaneously provide high-data-rate connectivity to them, GigSky needs to create multiple beams where each is pointing to a user, as shown in Figure 1. Furthermore, to minimize the interference between adjacent users, each beam should operate on a different frequency channel. Based on the data rate result in Section 3, the max channel throughput is 408 Mbps. Given that the required data rate is 5 Mbps for HD video streaming and 20 Mbps for AR 360 degree 4k video, a single channel can

[2]The channel throughput is computed based on single component carrier, single MIMO layer, time division multiplexing, and adaptive modulation and coding [15]



(a) GigSky's Beams Coverage **(b) FSA Frequency Shift**

Figure 4: GigSky's Passive Beam Steering. (a) shows how GigSky divides users on the ground into clusters, where each cluster uses a different frequency channel. Clusters A, B, and C uses frequencies f_1, f_2, f_n respectively. (b) shows how GigSky's beam angle changes with the signal frequency. θ_s is the angle shift of the beam when the signal frequency shifts from f_0 to $f_0 + f_s$. θ_{3dB} is the 3dB beamwidth of FSA.

support up to 81 and 20 users, respectively. This means that GigSky needs to narrow its beams in one axis (x axis) and stretch it in another axis (y axis), as shown in Figure 4a. In particular, GigSky splits users into n different clusters along the x axis, where each cluster uses a different frequency channel. This enables GigSky to use both FDMA (frequency-division multiple access), and TDMA (time-division multiple access) schemes to support many users.

The main question which needs to be answered is how GigSky can steer different signal to different direction. The traditional approach for mmWave beam steering is to use phased arrays, which use phase shifters to alter the phase of the signal on each element of an antenna array to steer the beam in different directions [12]. However, phased arrays require phase shifters and active components which make their design complex and power hungry. Furthermore, since they need to transmit different signals to each beam, they require multiple radio chains. Unfortunately, such a design is complex and have high power consumption which is unsuitable to be deployed on a UAV. Instead, GigSky develops a mmWave Frequency Scanning Antenna (FSA) for beam steering on the UAV. We introduce the principles and design challenges of FSA in the next section.

4.1 Frequency Scanning Antenna (FSA)

FSA is a passive structure which focuses and transmits a signal toward a direction, where the direction depends on the frequency of the input signal, as shown in Figure 5. In particular, when a signal is fed to this structure, the signal gradually leaks into space. Therefore, this structure works similar to an array of emitting elements where the phase shift of the signal at each element is a function of the distance of the element from the signal feed and frequency of the signal. This natural phase shift enables the structure to receive or transmit a signal toward a direction, where the beam direction is a function of signal frequency. In particular, the angle of the beam, θ,

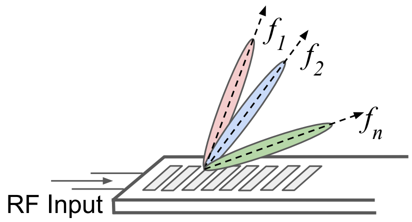


Figure 5: Frequency Scanning Antenna. The input signal leaks into space as it travels through the antenna structure, forming highly directional beams. The beam angle is dependent on the input signal frequency.

can be expressed as:

$$sin(\theta) = \frac{\beta}{k_0}, \tag{3}$$

where β is a parameter of the design, known as the waveguide number and k_0 is the free space wavenumber [7]. Both β and k_0 change with frequency but in a FSA structure, the variation of β is much higher. Therefore, the beam rotates with the change of the frequency.

4.2 FSA versus Phased Arrays

Both FSA and phased arrays are used to focus energy into narrow beams, each approach has its own pros and cons. Therefore, depending on the application one might be more suitable than the other. In this section we look at the differences between these two approaches from different aspects.

Complexity and Cost Phased arrays are more costly and complex compared to FSA. FSA is a passive structure while phased arrays require phase shifters, which care costly. In addition, to properly shape and steer the beam in a phased array, it requires calibration and extensive control over the phase shifters which adds to the complexity of the system.

Energy Consumption Generally the phase shifters are lossy. So in a phased array system, active RF components are required to compensate the loss. As a result, phased array systems are power hungry, while FSA is free of any active RF component and doesn't consume power.

Bandwidth Requirement Phased arrays can steer the beam without changing the frequency of the signal, while FSA requires changing the frequency of the signal to steer the beam. Therefore, FSA requires larger bandwidth than phased arrays to operate. However, this will not be an issue for our application since there is a large bandwidth available in the 5G spectrum resources. Moreover, to achieve the maximum throughput, both FSA and phased arrays need to divide users into different channels of the available spectrum. Thus, the spectrum utilization is the same for both approaches.

Multi-beam Capability FSA can simply be used to generate multi-beam patterns. This is due to the fact that the beam angle of FSA increases with the input signal frequency. Therefore, by feeding different channels to the FSA, it is able to passively generate multiple beams in different directions. In contrast, this process is much more complex in the the phased array. To simultaneously cover multiple users at different angles with a phased array, it requires the same number of independent transmitter and receiver chains. As a result, the required hardware becomes extensively costly and consumes a lot more power compared to FSA.

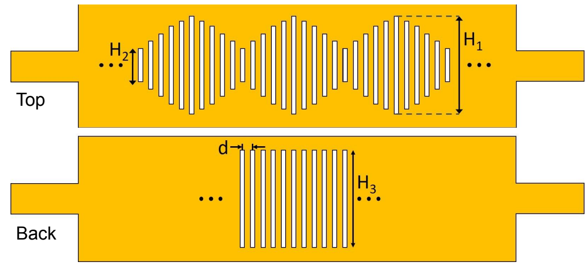


Figure 6: GigSky's Designed FSA Antenna. The top figure shows the top layer of the antenna where periodic modulated slots are placed. The bottom figure shows the bottom layer of the antenna which has equal length periodic slots.

Mobility The beam angle of FSA is determined by the input signal frequency, while the beam angle of phased arrays is controlled electronically by adjusting the phases of the antenna elements. Because the FSA beam direction for each frequency channel is fixed, mobile devices may experience frequent channel switching when moving across different beams of an FSA. In comparison, phased array antenna offers more flexibility in beam steering since it can align the beam of a specific channel with the mobile device when it is moving.

Sidelobes Generally, an FSA antenna has higher sidelobe level compared to a phased array. However, the sidelobe does not create interference for adjacent channels of FSA since each channel operates in a different frequency range.

4.3 Our FSA Design

FSA has been used in a number of fields due to its low complexity in beam steering compared to phased array antenna systems. For example, by feeding swept frequency input signal to orthogonal FSAs, a system can achieve multi-dimensional radar image scanning [24]. By using frequency scanning technique to steer the beam in a certain elevation scan angle, it can also be used to build weather measurement systems with much lower complexity [9]. These works have shown the capability of FSA in creating and steering the beam.

In this work, we build on past work on FSA to design a mmWave FSA antenna for 5G communication using UAVs. In particular, we build an FSA which operates at 5G NR Frequency Band n257 which is being supported by a number of carriers globally. In this standard, the carrier frequency (f_c) is from 26.5 GHz to 29.5 GHz and channel bandwidth is 100 MHz. To maximize the FSA gain, we designed our FSA to achieve 3 dB beamwidth (θ_{3dB}) of 10 degrees or less . Moreover, our FSA design needs to shift the beam by θ_s when the signal frequency changes by the channel bandwidth (i.e. 100 MHz). To avoid any gaps between the beams, we need to make sure θ_s is smaller than θ_{3dB}.

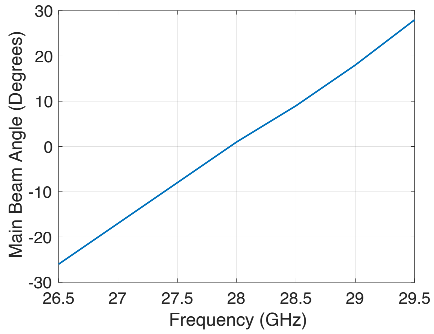


Figure 7: FSA Beam Angle vs the Feed Signal Frequency

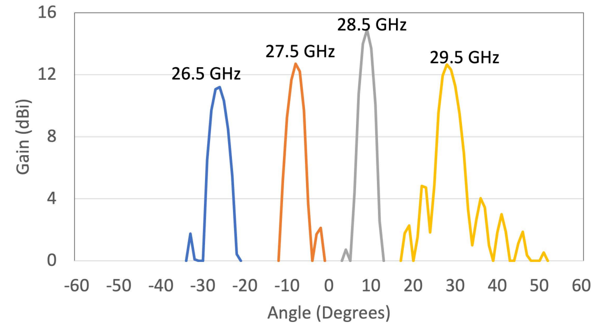


Figure 8: FSA Beam Gain vs Beam Steering Angle for Feed Signal Frequencies of 26.5 GHz, 27.5 GHz, 28.5 GHz, and 29.5 GHz

Current implementations of FSA require a large bandwidth to achieve wide scanning range. Unfortunately, such a large bandwidth is not available in our application. Therefore, we need to design an FSA which requires smaller bandwidth for scanning the whole space. Our approach is to use a slow wave structure by using longitudinal slots along a waveguide. In this kind of structure, the phase of the wave changes much faster with the length of the structure, therefore it can scan the space with much narrower bandwidth. However, the main limitation of such structure is that they are not radiating well. To solve this problem, we use space harmonics techniques [3]. In particular, we use periodic radiating elements (known as slots) where their length is modulated by a sinusoidal function along the antenna length, as shown in Figure 6. The combination of periodicity and length modulation provides high scan rate. This design enables a wide scanning angle within the available frequency range. The design parameters to control the characteristics of the FSA are H_1,H_2, H_3 and d. In addition, by controlling the total number of slots, we could adjust the 3dB beamwidth (θ_{3dB}) of the antenna to less than 10 degrees.

5 EVALUATION

In this section we analyzed and evaluated the performance of GigSky in terms of air to ground communication.We first evaluated the beam steering performance of GigSky using CST Microwave Studio, to show the scan angle we can achieve under 5G NR frequency band, the gain of the FSA beams, as well as the coverage on the ground. We then evaluated the achievable data rate of the user device, when GigSky relays the signal from a terrestrial base station over-the-air to the ground user, based on ns-3 mmWave simulator.

5.1 Beam Steering Performance

Based on our evaluation results, GigSky's FSA has a 3dB beamwidth of 6 degrees in the x axis and 45 degrees in the y axis. This meets our goal of having narrow beam in one dimension (x axis) to avoid interference and wide beam in the other dimension (y axis) to increase the user coverage for each channel. Next, we evaluate the performance of GigSky in steering the beam for different frequencies.

Figure 7 shows the direction of the beam versus the signal frequency for GigSky's FSA. Our design achieves the scan ratio of m = 50 MHz/degree, which means the beam angle of the FSA shifts by 2 degrees for every 100 MHz frequency difference. Thus, the beam angle shift θ_s for adjacent frequency channels is 2 degrees, as shown in Figure 4b. The total scan angle for the 26.5 GHz to 29.5 GHz frequency band is 64 degrees. The beam angle shift θ_s is small enough to guarantee there are no coverage gaps between adjacent channels, and the total scan angle is large enough to ensure a wide area coverage for the UAV.

Finally, Figure 8 shows GigSky's FSA gain for sample frequencies of 26.5, 27.5, 28.5, and 29.5 GHz. The y axis is the gain of the FSA beam in decibels and the x axis is the angle of the beam in degrees. The figure shows that our design sends signals of different frequency bands to different direction while always achieving a gain of more than 10 dB which is sufficient to achieve high SNR at the user.

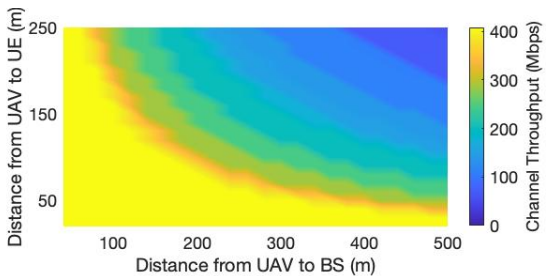
5.2 Coverage Performance

As mentioned in Section 4, our FSA design operates in the 5G NR frequency band of 26.5 GHz to 29.5 GHz, with 30 available 100 MHz channels. This means there are 30 channels aligned along the x axis (n = 30). Assuming the elevation height of the UAV is h, the 3dB beam width of a single channel in the x axis is $2h * tan(\theta_{3dB}/2)$ and the total width of GigSky's coverage in the x axis is $2h * tan((\theta_{3dB} + \theta_s(n-1))/2)$. The length of GigSky's coverage in the y axis is $2h * tan(\theta_{3dB}/2)$. Considering a scenario where the UAV is 100 meters above ground (h = 100) to comply with FAA regulations [5], the width and length of each cluster on the ground is 10.48 m and 82.84 m, respectively. Therefore, the coverage area of a single cluster (i.e. a 100 MHz channel) will be 868.16 m^2. Considering all clusters, the total coverage area of each GigSky's UAV will be $10,353\ m^2$, which is much larger than a football stadium.

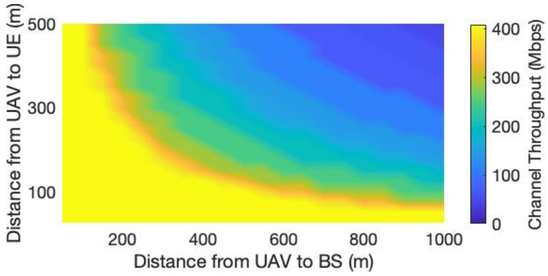
5.3 Data Rate Performance

To calculate the data rate that GigSky provides to each user, we consider a similar setup as illustrated in Figure 2b. We assume the EIRP of the base station is 60 dBm, the receiver gain is 10 dB, and the noise floor is -89 dBm. The UAV has 20 dB receiving antenna gain, 40 dB amplification gain, and 10 dBi antenna gain from the FSA.

We calculate the received signal power P_{rx} based on eq.(4), where P_{tx} is the transmitter EIRP, A_{rx} is the receiver antenna gain, A_{uav} is the total gain on the UAV, L_{path_B} is the path loss between the base station to the UAV, L_{path_C} is the path loss between the UAV



(a) 40 dB amplification gain on the UAV



(b) 50 dB amplification gain on the UAV

Figure 9: Channel Throughput for Different Distances from the UAV to the Base Station (BS) and from the UAV to the User (UE)

and the user.

$$P_{\text{rx}} = P_{\text{tx}} + A_{\text{rx}} + A_{\text{uav}} - L_{path_B} - L_{path_C} \quad (4)$$

Note, the path loss is calculated based on the free space path loss equation:

$$L_{path} = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}(4\pi/c) \quad (5)$$

where f is the signal frequency, d is the distance between the transmitter and the receiver, and c is the speed of light in vacuum. We then calculate the the SNR of the signal at the user using eq.(2). Finally, based on this SNR, we ran simulations on the ns-3 mmWave simulator [15] to generate the data rates for different distances between the UAV to the base station (BS) as well as the distance between the UAV to the user (UE). Figure 9a (a) shows the result of this evaluation. As the figure shows, when the UAV is 100 meters from the user and 150 meters from the base station (BS), GigSky achieves the maximum channel throughput of 408 Mbps. Therefore, each channel can support up to 80 and 20 users while each has 5 and 20 Mbps data rate, respectively. Considering all 30 channels, GigSky can support up to 2400 or 600 users to do live video streaming or 360 degrees 4k AR, respectively. In the extreme case, when the UAV is 250 meters from the user and 500 meters from the base station, GigSky still achieves around 32 Mbps channel throughput. Note, this performance can be further improved by using higher amplification gain at the UAV. For example, if we increase the amplification gain on the UAV by 10 dB, the coverage of the UAV can be significantly increased as shown in Figure 9b. In this case, GigSky achieves the max channel throughput of 408 Mbps even when the UAV is located 100 meters away from the user and 500 meters away from the base station.

6 DISCUSSION AND CONCLUSION

This paper presents GigSky, a system that solves the blockage problem of mmWave networks in outdoor scenarios by using UAVs as mmWave relays. It does so by developing a passive design which enables UAVs to focus and transmit mmWave signals to multiple users simultaneously. The paper also presents initial results that show GigSky 's capability in delivering high-data-rate mmWave wireless connectivity to users in applications such as stadium Augmented Reality (AR). Nevertheless, since mmWave communication have different requirements than traditional wireless communications, in order to enable a full UAV based mmWave network, the following topics require further study:

MIMO Spatial Multiplexing In this paper we proposed the basic design of using FSA to provide high data rate for different channels. As MIMO (Multiple-Input and Multiple-Output) technology is one of the key enablers of 5G high capacity networks, one can also incorporate MIMO into our design, to further increase the number of users GigSky can support in each channel. The UAV can also act as a MIMO relay to perform spatial multiplexing of multiple data streams to users distributed in different areas in each channel. Therefore, integrating MIMO with our FSA design is an interesting research direction.

Dynamic Channel Allocation Since the 3dB beamwidth θ_{3dB} of GigSky's beams is bigger than the steering angle θ_s, a user can be covered by beams from multiple frequency channels. This provides an opportunity to further optimize the channel allocation for users. In particular, which channel is allocated for each user is determined based on both the signal strength of the channel relative to the location of the user and how occupied each channel is. This enables more efficient utilization of the bandwidth of each channel when there are many users located in the same area, and ensures higher data rate for each user. Integrating this idea into GigSky is an interesting research problem.

ACKNOWLEDGMENTS

We thank the shepherd, Prof. Nirupam Roy, and the anonymous reviewers for their valuable feedback on this paper. We thank NSERC, Canada Foundation for Innovation (CFI), and Ontario Research Fund (ORF) for their partial support.

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