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Flying Base Station Channel Capacity Limits: Dependent on Stationary Base Station and Independent of Positioning[†]

Sang-Yoon Chang ^{1,*}, Kyungmin Park ², Jonghyun Kim ² and Jinoh Kim ³¹ Computer Science Department, University of Colorado Colorado Springs, Colorado Springs, CO 80918, USA² Electronics and Telecommunications Research Institute, Daejeon 34129, Republic of Korea; kmpark@etri.re.kr (K.P.); jhk@etri.re.kr (J.K.)³ Computer Science Department, Texas A&M University—Commerce, Commerce, TX 75429, USA; jinoh.kim@tamuc.edu

* Correspondence: schang2@uccs.edu

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Abstract: Flying base stations, also known as aerial base stations, provide wireless connectivity to the user and utilize their aerial mobility to improve communication performance. Flying base stations depend on traditional stationary terrestrial base stations for connectivity, as stationary base stations act as the gateway to the backhaul/cloud via a wired connection. We introduce the flying base station channel capacity to build on the Shannon channel capacity, which quantifies the upper-bound limit of the rate at which information can be reliably transmitted using the communication channel regardless of the modulation and coding techniques used. The flying base station's channel capacity assumes aerial mobility and ideal positioning for maximum channel capacity. Therefore, the channel capacity limit holds for any digital and signal processing technique used and for any location or positioning of the flying base station. Because of its inherent reliance on the stationary terrestrial base station, the flying base station channel capacity depends on the stationary base station's parameters, such as its location and SNR performance to the user, in contrast to previous research, which focused on the link between the user and the flying base station without the stationary base station. For example, the beneficial region (where there is a positive flying base station capacity gain) depends on the stationary base station's power and channel SNR in addition to the flying base station's own transmission power and whether it has full duplex vs. half-duplex capability. We jointly study the mobility and the wireless communications of the flying base station to analyze its position, channel capacity, and beneficialness over the stationary terrestrial base station (capacity gain). As communication protocols and implementations for flying base stations undergo development for next-generation wireless networking, we focus on information-theoretical analyses and channel capacity to inform future research and development in flying base station networking.

Keywords: mobile network; 5G; 6G; flying base station; aerial base station; wireless communication; information theory; channel capacity



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1. Introduction

The flying base station, also known as the aerial base station or unmanned aerial vehicle (UAV) base station, represents a new and emerging architecture for next-generation telecommunications networking. While the traditional model in mobile computing has implemented mobility on the user side, flying base stations introduce aerial mobility into the service provider's infrastructure. The flying base station uses its aerial mobility to enhance communication connectivity for the mobile user (the client of the telecommunications service) by approaching the user. This improves the communication link channel and enables a line-of-sight communication path.

While past research and implementations of flying base stations have focused on sporadic and emergency scenarios, e.g., [1–3], future research, development, and standardization efforts are expected to broaden the use of flying base stations in upcoming network architectures, e.g., [4–7]. The improved communication channel resulting from the controlled flying mobility of the flying base station enables the high rate and latency performances expected by upcoming 6G telecommunication applications. The millimeter-wave (mmWave) communications in 6G can particularly benefit from the flying base station, which provides line-of-sight communication between the base station and user equipment. The 3rd Generation Partnership Project (3GPP), which has standardized cellular technologies from 2G to 5G, introduces the concept, objectives, and requirements of the flying base station (termed UxNB base station) for upcoming 6G networking [7,8]. Industries are also developing prototypes, e.g., AT&T’s Flying COW, Google’s SkyBender, Nokia’s F-Cell, and Huawei’s Digital Sky Initiative.

Flying base stations inherently rely on stationary terrestrial base stations, which serve as the bridge gateway to the networking backhaul and cloud via wired networking. Without the stationary terrestrial base station providing the wired connection, flying base stations would not have access to the cloud or the internet. Thus, flying base stations coexist with stationary base stations and their operations are intertwined.

Our work distinguishes itself from previous research by capturing the dependency on the stationary base station (as opposed to just focusing on the communication channel between the user and the flying base station) and by introducing a dedicated flying base station that moves and positions itself for maximum capacity (as opposed to merely controlling and analyzing performance given the relay locations and channels). Section 2 describes the previous research studies and compares them with our work in greater detail.

1.1. Our Contributions

We model the flying base station in relation to the stationary terrestrial base station and jointly study the mobility and RF communications of a flying base station. We introduce and analyze *the flying base station channel capacity*, which is the capacity or the upper-bound limit of the reliable communication rate that the communication channel can achieve, assuming support from physical-layer signal processing and mobility. The flying base station channel capacity builds on the Shannon channel capacity from the Shannon–Hartley Theorem but, because of the flying base station’s mobility capability and purpose, assumes the ideal location and mobility control of the base station. Because the flying base station channel capacity provides the upper bound of the reliable communication rate, it holds true for any digital/signal processing technique and any flying base station position/location (given the locations of the user and the stationary base station). Therefore, we analyze the ideal positioning of the flying base station, which depends on the stationary base station’s relative position to the user’s. To highlight the dependency on the stationary base station, we express the flying base station’s channel capacity with respect to the stationary base station’s parameters; the flying base station’s capacity depends on the stationary base station’s channel and its SNR performance to the user. Furthermore, we analyze the flying base station’s capacity gain over the stationary base station in order to analyze the beneficialness of the flying base station; we identify the flying base station’s transmission power requirement for it to be beneficial over the stationary base station. We analyze the cases when the flying base station supports a full duplex vs. half duplex, the latter of which reduces the bandwidth by half and, thus, requires greater transmission power for the flying base station to be beneficial.

1.2. Paper Organization

The rest of this paper is organized as follows. Section 2 describes the previous related research and identifies the research contributions of this paper. Section 3 describes the system model in cellular communication and defines the parameters and variables used in this paper. Section 4 analyzes the flying base station’s positioning and channel capacity and

Section 5 analyzes the capacity gain beyond the stationary base station. Section 6 presents our simulation results for more concrete numerical analyses. We discuss future directions in Section 7 and conclude the paper in Section 8.

2. Related Work

Previous research studies have focused on the positioning of the flying base station and its interplay and impact on the communication channel to the user. They used the standard path loss model to characterize the channel signal performance with respect to physical distance, e.g., [3,9–12], and the corresponding channel capacity, e.g., [1,3,13–16]. These approaches and metrics are similar to what we used in our work to quantify the channel performances with respect to the flying base station's position. However, this previous research focused on the communication link between the flying base station and the user while disregarding the link between the flying base station and the stationary base station, in contrast to our work.

A relatively small number of studies have focused on the flying base station in relation to the stationary base station. Mach et al. [15] included a stationary base station in their analysis and model, allowing users to connect to the stationary base station instead of a flying base station, similar to our work. However, in contrast to our work, they did not consider the flying base station as a relay to the stationary base station and explored scenarios where the flying base station could operate stand-alone. Madelkhanova et al. [17] captured the reliance of the flying base station on the stationary base station but focused on the flying base station's cell selection (which cell/stationary base station to rely on) and the handover between stationary base stations. They assumed flying base station positioning, which only considered the user's location, not the stationary base station's location, similar to the aforementioned previous research. In contrast, we use the stationary base station's location to control the flying base station's positioning and demonstrate how the flying base station channel capacity depends on the stationary base station's location.

In more general wireless communication, beyond a telecommunications base station, previous studies have focused on relay networking performances, where a relay or multiple relays are introduced to improve communication. The research particularly relevant to our work considered mobility on the relays and included information-theoretic performance analyses, e.g., [18–21]. However, these previous works focused on channel resources, power control, or relay selection, given the relay locations and channels. The relay locations and channels can vary but are given, and previous research works did not consider the relay node's mobility control for positioning. In contrast, our work assumes a flying base station dedicated to the user, thus moving and positioning itself at the ideal location to maximize the flying base station's channel capacity.

3. Our System Model and Primer

This section describes the background/primer and defines the relevant parameters/variables for our research. We model the positions of the base stations relative to the user and analyze how these positions affect channel performances, including the path loss model and channel capacity. Because the flying base station cannot independently serve as the bridge gateway between wired and wireless communications, it functions as a relay and depends on the stationary terrestrial base station to provide connectivity.

3.1. Architecture

The telecommunications service provider infrastructure that provides wireless connectivity to mobile users consists of the flying base station, the stationary terrestrial base station, and the backend core network. Figure 1 shows these entities and the wireless links (dashed arrows) between the user, flying base station, and stationary terrestrial base station. While the user and the base stations communicate locally within one or two channel links, the base stations on the networking edge connect to the core network server through wired communications via routers and switches, as they are geographically far apart. One

core network serves multiple base stations covering different local cells and geographical regions. Our focus is on the wireless channels between the user, the flying base station, and the stationary base station; the wired communications and processing between the stationary base station and the backend are beyond our scope.

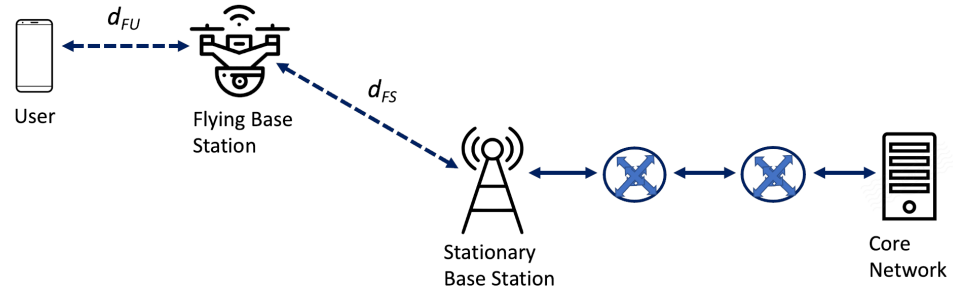


Figure 1. Telecommunications architecture. The wireless links drawn in dashed arrows are between the user (U), the flying base station (F), and the stationary terrestrial base station (S). The flying base station relies on the stationary base station to provide connectivity to the core network and the rest of the network in wired communications, drawn in solid arrows.

Because the flying base station is not directly connected to the wired connections and cannot serve as the bridge gateway, the flying base station serves as a relay to the stationary base station. Both the downlink and uplink communications are conducted wirelessly to support the aerial mobility of the flying base stations. While the stationary base station possesses MIMO and full-duplex capabilities, we consider both scenarios: when the flying base station has full-duplex capability and when it does not, which impacts its connectivity provision performances.

We consider a scenario where the flying base station is added to the stationary base station's existing communication channel to the user (the flying base station cannot operate by itself) and provides another channel option. The flying base station is, thus, *beneficial* if it provides better communication channels and connectivity than the stationary base station.

3.2. Distances and Base Station Moving (d)

The flying base station can control its physical location, and the flying base station location with respect to the user; the stationary base station affects the wireless communication performance. The distance between the user (U) and the flying base station (F) is d_{FU} and the distance between the flying base station (F) and the stationary base station (S) is d_{FS} , as shown in Figure 1. The distance between the user and the stationary base station is d_{SU} . The flying base station—due to its mobility—can control its distance to the user (d_{FU}) and to the stationary base station (d_{FS}).

3.3. Path Loss Model for Channel Attenuation (γ)

As the communication signal propagates in the wireless medium in the air, it attenuates and loses power when reaching the receiver. We use the standard path loss model for channel signal attenuation, which has also been empirically validated [22,23]. In the path loss model, the received power is $P_i \cdot \alpha \cdot d^{-\gamma}$, where P_i is the transmitted power magnitude from the transmitter, i where i is the flying base station or the stationary base station, α is a constant characterizing the channel condition and the antenna gains, d is the distance between the transmitter and receiver, and γ is the path loss exponent. γ typically ranges between 2 and 5, with greater fading and attenuation increasing its value (e.g., the urban environment) [22,23].

3.4. Transmission Power (P, η)

The transmitted power from the stationary terrestrial base station is P_S while that from the flying base station is P_F , where the subscript indicates the transmission source. While the stationary base station generally has a greater overall power transmission power budget

than the flying base station, it also generally serves many more users for the connectivity provision. For example, in the US, as of 2021, there were an estimated 420,000 base stations across the major cellular service providers, serving 208 million data-only users (cellular only, not supporting WiFi) [24], many of which were sensors and smartwatches constantly in use and connectivity. P_S is the transmitted power for a user using the communication link, which is often significantly smaller than the entire transmission power budget of the stationary base station serving multiple users. The stationary base station can also fix its P_S by standard practice because of equity between the users and its fixed cell size.

Because both the stationary and flying base stations serve the same purpose—to serve the user, albeit being physically distinct and located in different hardware and locations—we introduce a system control parameter, η , to define the ratio between the transmission powers, i.e., $\eta = \frac{P_F}{P_S}$, to characterize the power allocations between the base stations. A greater η indicates that the flying base station can allocate more transmission power to the user relative to that of the stationary base station.

3.5. Channel Capacity for Communication Requirements (C , W , SNR)

Because of the signal attenuation, the increase in the channel distance requires greater transmission power so that the received power is sufficient. The required power delivery on the receiver depends on both the channel quality (noise power) and the communication system requirement (data rate). To move away from the specific digital modulation, coding, and signal processing, we use Shannon's channel capacity, which characterizes the theoretical upper bound of the reliable data rate the communication channel can support with respect to the bandwidth (W) and the received signal-to-noise ratio (SNR). SNR is the received signal power divided by the noise power. The communication channel used by the communication system has a noise power spectral density of N_0 , thus making the channel noise power $W \cdot N_0$. The communication system supports the communication rate of R in bps. We do not control these parameters given by the communication system and the channel environment (R , W , N_0 , α , and γ). To meet the reliable bit delivery performance of R , the channel capacity C must be $C \geq R$:

$$C = W \cdot \log_2(1 + SNR) \geq R \quad (1)$$

The channel capacity from the Shannon–Hartley Theorem is highly used in communication theory and captures the reliable communication rate that the channel *can* support, assuming an additive white Gaussian noise channel (AWGN). While independent of physical-layer implementations, including modulation, coding, and the receiver feedback protocol, channel capacity provides a theoretical bound that communication system designers and builders can adhere to when selecting modulation/coding implementation choices and operational constraints.

In addition to enabling performance quantification and analyses in communication theory, the channel capacity limit has provided the upper-bound benchmark for signal processing research and development for decades. Capacity-achieving codes and signal processing research emerged from the 2000s (e.g., [25–27]) to the 2010s (e.g., [28,29]) to the 2020s (e.g., [30,31]).

The theoretical channel capacity is appropriate for our research to study and analyze flying base stations because the development of flying base stations is currently ongoing, and there are no standardized or dominant protocols or algorithms to control the operations of flying base stations. We anticipate the flying base station channel capacity—building on the channel capacity from the Shannon–Hartley Theorem but adding aerial mobility and dependency on the stationary base station—to drive the research and development of the signal and digital/code processing of the flying base station communication.

4. Flying Base Station Channel Capacity and Positioning

We define the *flying base station channel capacity* as the reliable communication rate a flying base station can provide to the user. This definition builds on Shannon's concept of channel capacity, which determines the reliable communication rate a channel can offer. Due to its reliance on the stationary base station (i.e., the flying base station can operate in conjunction with, but not without, a stationary base station), the flying base station channel capacity quantifies the potential channel performance when a flying base station supplements the stationary base station to better serve the user. The flying base station, with the objective of providing connectivity, moves and controls its location with respect to the user and the stationary base station to best serve the user. We, therefore, analyze the ideal positioning of the flying base station with respect to the stationary base station's location in Section 4.1. Assuming the ideal position of the flying base station with respect to the stationary base station, we quantify the flying base station's channel capacity given its power budget (η) and the stationary base station's channel condition in SNR (SNR_{SU}) in Section 4.2.

4.1. Base Station Positioning

4.1.1. Transmission Power Requirement vs. Distance

We derive the minimum transmission power requirement to support the R reliable-bit-rate performance from Equation (1) and use linear algebra and $\text{SNR} = \frac{P\alpha d^{-\gamma}}{W \cdot N_0}$, where the numerator above the fraction is the received power after the attenuation/path loss. Because they are the given environmental or system parameters, we introduce a constant $\beta = \frac{1}{\alpha} W N_0 (2^{\frac{R}{W}} - 1)$. The reliable communication requires the flying base station's power transmission to satisfy the following: $C = W \cdot \log_2(1 + \text{SNR}) \geq R$. This is equivalent to the following:

$$\begin{aligned} C = W \cdot \log_2(1 + \text{SNR}) &\geq R \\ P &\geq \frac{d^\gamma}{\alpha} W N_0 (2^{\frac{R}{W}} - 1) \\ P &\geq \beta d^\gamma \end{aligned} \quad (2)$$

where $\beta = \frac{1}{\alpha} W N_0 (2^{\frac{R}{W}} - 1)$ is given from the channel environment.

Since we prioritize power efficiency, we use the minimum possible transmission power, which is a function of d , as follows:

$$P(d) = \beta d^\gamma \quad (3)$$

4.1.2. The Optimal Location for Transmission

Our scheme is adaptive to the user's location. However, in contrast to the previous research, which focused only on the link between the user and the flying base station (Section 2), the flying base station location also depends on that of the stationary base station. We define the *transmission-optimal location* to be the flying base station location, which yields the least power consumption for communication signal transmissions. Any leftover transmission power beyond the requirement from what is required can be used to improve the SNR performance.

Theorem 1. *The transmission-optimal location is halfway between the user and the stationary base station, so that $d_{FU} = d_{FS} = 0.5 d_{SU}$.*

Proof. Equation (3) when $\gamma \geq 2$ (for practical wireless channels, as discussed in Section 3.3) yields that the required transmission power P (or P_F for the flying base station) is convex with respect to the distance d , i.e., for any distances d_1 , d_2 , and θ , where $0 \leq \theta \leq 1$, $P(\theta d_1 + (1 - \theta)d_2) \leq \theta P(d_1) + (1 - \theta)P(d_2)$. (Alternatively, P is a power function with respect to d , where the exponent is the fixed γ , i.e., $P = \beta d^\gamma$. A power function is convex

in the positive domain if the exponent is greater than one, for example, $\gamma = 2$ yields a quadratic function with d , where the non-dominant linear and constant terms are zero; $\gamma = 2$ yields cubic; and $\gamma = 2$ yields quartic. Thus, if $\gamma > 2$, then P is strictly convex with positive d). From Jensen's inequality, the transmission power consumption of the expected value of the distances d is less than or equal to the expected value of the transmission powers across distances, i.e., $E[P_F(d)] \leq P_F(E[d])$. If $d_{FU} \neq d_{FS}$, then $P_F(\frac{d_{FU}+d_{FS}}{2}) \leq \frac{1}{2}P_F(d_{FU}) + \frac{1}{2}P_F(d_{FS})$. Because the flying base station relays the communication in both directions (to the user and the stationary base station), $d_{FU} = d_{FS} = \frac{d_{FU}+d_{FS}}{2} = \frac{d_{SU}}{2}$ yields the minimum power required for P_F and the transmission-optimal location. $\square$

4.2. Flying Base Station Channel Capacity

The flying base station channel capacity builds on the Shannon channel capacity, as described in Section 3.5. However, the flying base station channel capacity differs from the more traditional Shannon channel capacity due to the flying base station's aerial mobility and the resulting capability to position itself to improve communication performance. The flying base station is dedicated to serving the user for connectivity and, therefore, positions itself in the transmission-optimal location, as analyzed in Section 4.1. Because the transmission-optimal location depends on the relative location of the user and the stationary base station, i.e., halfway, the flying base station's channel capacity depends on its own channel and power capability as well as the channel between the user and the stationary base station, including its SNR and the transmission power of the stationary base station. We analyze the flying base station channel capacity when the base station has full-duplex capability vs. half-duplex capability.

The channel capacity of the stationary base station depends on the SNR of the communication link between the stationary base station, as shown in Equation (1). The stationary base station's SNR to the user is the received power divided by the noise power. Building on Section 3.3 for the received power, $\text{SNR}_{SU} = \frac{P_S \alpha (d_{SU})^{-\gamma}}{W \cdot N_0}$. Then, the channel capacity for the channel link between the stationary base station and user, denoted by C_{SU} , is as follows:

$$C_{SU} = W \log_2 \left(1 + \frac{P_S \cdot \alpha \cdot d_{SU}^{-\gamma}}{W \cdot N_0} \right) = W \log_2(1 + \text{SNR}_{SU}) \quad (4)$$

The channel capacity between the flying base station and the user, denoted by C_{FU} , is as follows:

$$C_{FU} = W' \cdot \log_2 \left(1 + \frac{P_F \cdot \alpha \cdot d_{FU}^{-\gamma}}{W \cdot N_0} \right) \quad (5)$$

where W' depends not only on the available channel bandwidth, W , but also whether the flying base station supports full duplex or not (in the latter case with half-duplex, $W' = 0.5W$).

4.2.1. Full-Duplex Case

The flying base station relays the communication between the stationary base station and the user. If the flying base station has full-duplex capability, it can fully utilize the channel bandwidth for communication (both ways simultaneously and $W' = W$).

Theorem 2. *If the flying base station has full-duplex capability, then the flying base station channel capacity is as follows:*

$$C_{FU} = W \cdot \log_2(1 + \eta \cdot 2^\gamma \text{SNR}_{SU}) \quad (6)$$

Proof. Use Equation (5) with $W' = W$, $P_F = \eta \cdot P_S$, and $d_{FU} = 0.5 \cdot d_{SU}$ from Theorem 1. The algebraic steps and derivations are omitted in this paper. $\square$

4.2.2. Half-Duplex Case

If the flying base station does not have full-duplex capability and can only either transmit or receive (half-duplex), e.g., such as when there are not enough antennas on-board, it must alternate between communicating with the user and the stationary base station. Therefore, the transmission data bandwidth is halved from the channel bandwidth, i.e., $W' = 0.5 W$.

Theorem 3. *If the flying base station has half-duplex capability, then the flying base station channel capacity is as follows:*

$$C_{FU} = 0.5 \cdot W \cdot \log_2(1 + \eta \cdot 2^\gamma \text{SNR}_{SU}) \quad (7)$$

Proof. Use Equation (5) with $W' = 0.5 W$, $P_F = \eta \cdot P_S$, and $d_{FU} = 0.5 \cdot d_{SU}$ from Theorem 1. The algebraic steps and derivations are omitted in this paper. $\square$

5. Flying Base Station Capacity Gain Benefit

We study the capacity benefit of utilizing a flying base station. The flying base station, while amplifying the coverage and communication performances, operates in addition to the stationary base station and cannot replace it. The stationary base station is required even if the user's direct communication link is from/to the flying base station, as the flying base station relays to the stationary base station for backend/internet access. The user can receive the connectivity from the stationary base station or the flying base station. We study if/when the flying base station is beneficial to use over the stationary base station by providing greater channel performance.

5.1. Defining Beneficial and Capacity Gain

We analyze when the flying base station can be beneficial and quantify the benefit of using a flying base station in capacity gain. The flying base station is *beneficial* if its channel capacity to the user is greater than the stationary base station's channel capacity to the user, i.e., $C_{FU} > C_{SU}$. We quantify the benefit of using a flying base station in *capacity gain* $\mathcal{G}$, which is the difference between the channel capacities, i.e., $\mathcal{G} = C_{FU} - C_{SU}$. The flying base station is beneficial and adds benefits over the existing stationary base station if $\mathcal{G} > 0$; otherwise, the user would opt to use the stationary base station.

5.2. Capacity Gain in Full-Duplex Case

If the capacity gains $\mathcal{G} > 0$, i.e., $C_{FU} - C_{SU} > 0$, then the flying base station is beneficial to use in channel capacity.

Theorem 4. *If the flying base station has full-duplex capability, it can be beneficial and provide greater capacity if*

$$P_F > P_S \cdot 2^{-\gamma} \quad (8)$$

Proof. $C_{FU} > C_{SU}$ using Equations (4) and (6) and $d_{FU} = 0.5d_{SU}$ yields $\eta > 2^{-\gamma}$, which is equivalent to $P_F > P_S \cdot 2^{-\gamma}$. Appendix A shows the full proof including the algebraic steps and derivations. $\square$

Theorem 4 states that if the flying base station's transmission power is greater than $2^{-\gamma}$ times the stationary base station's transmission power, then the flying base station is beneficial and can increase the capacity and the reliable communication rate in bits-per-second (bps). Otherwise, if the stationary base station transmission power is greater than $2^{-\gamma}$ times the flying base station's transmission power, then utilizing the flying base station does not provide a capacity benefit. In communications practice, γ is typically 2 to 4, so that the factor $2^{-\gamma}$ ranges from $\frac{1}{4}$ to $\frac{1}{16}$, as discussed in Section 3.3.

5.3. Capacity Gain in Half-Duplex Case

If the flying base station does not have full-duplex capability and either transmits or receives at a time, the transmission bandwidth is halved from the channel bandwidth, as described in Section 4.2.2.

Theorem 5. *If the flying base station has half-duplex capability, it can be beneficial and provide greater capacity if*

$$P_F > P_S \cdot 2^{-\gamma}(\text{SNR}_{SU} + 2) \quad (9)$$

Proof. $C_{FU} > C_{SU}$ using Equations (6) and (4) and $d_{FU} = 0.5d_{SU}$ yields $\eta > 2^{-\gamma}(\text{SNR}_{SU} + 2)$, which is equivalent to $P_F > P_S \cdot 2^{-\gamma}(\text{SNR}_{SU} + 2)$. We do not include the algebraic steps and derivations in this proof. $\square$

Corollary 1. *If the flying base station has half-duplex capability, then the flying base station is beneficial and provides greater capacity if the stationary base station's SNR is less than $2^\gamma \cdot \eta - 2$, i.e.,*

$$\text{SNR}_{SU} = \frac{P_S \propto (d_{SU})^{-\gamma}}{W \cdot N_0} < 2^\gamma \cdot \eta - 2 \quad (10)$$

Corollary 1 defines the received SNR threshold of the stationary base station, given that the flying base station transmission power is fixed relative to the stationary base station's. The left-hand side of Equation (10) is the received SNR when the stationary base station transmits to the user, and the right-hand side is the threshold increasing with the channel condition γ and with the power ratio η . As the user moves away from the stationary base station, the flying base station becomes more beneficial. Such a received SNR-based approach is analogous to the handover across stationary base stations and cells. Similar to a mobile user moving from one stationary base station to another, we can implement a handover from a stationary base station to the flying base station, although the concrete handover protocol between the stationary and flying base stations is left for future research.

6. Simulation Analyses

We present simulations analyses to provide concrete numerical analyses and characterize the dependency between the flying base station channel capacity (C_{FU}), the base station's power ratio (η), the stationary base station's channel condition in SNR (SNR_{SU}), and the channel condition in the path loss exponent (γ). We also analyze the beneficial region and identify the conditions for which the flying base station is beneficial and provides greater channel capacity than the stationary base station.

We vary the power ratio (η), the stationary base station's channel performance in SNR (SNR_{SU}), and the channel condition in the path attenuation exponent (γ) to simulate different communication environments. We vary η , which is the transmission power budget of the flying base station relative to that of the stationary base station, where the base station's power budget is per user, as discussed in Section 3.4. η varies from 0.1 (the flying base station's transmission power for that user is smaller than the stationary base station's) to 20 (greater transmission power). The signal-to-noise-ratio of the stationary base station's channel to the user, SNR_{SU} varies from 0 dB (1) to 20 dB (100). Furthermore, to simulate different wireless channel conditions, we vary the path-loss/attenuation exponent, γ . $\gamma = 2$ simulates the free-space and line-of-sight-dominant channel and increasing γ (to $\gamma = 3$ and then to $\gamma = 4$) simulates wireless channels with stronger non-line-of-sight paths and greater attenuation, as described in Section 3.3. While we analyze how the channel capacity and the beneficial region behave while varying γ , we focus on $\gamma = 2$ when presenting our results in this paper. We focus on $\gamma = 2$, because the flying base station can enable

the line-of-sight communication link (which would be especially important for mmWave communications in 6G), and $\gamma = 2$ is the best to model such communication channel.

6.1. Flying Base Station Channel Capacity: η and SNR_{SU}

We analyze the flying base station channel capacity per bandwidth or $\frac{C_{FU}}{W}$ in bits-per-second over Hz (bps/Hz), because the channel capacity increases proportionally with the transmission bandwidth; as shown in Equation (1), given the bandwidth resource allocated for the channel (W), the channel capacity is the product between W and $\frac{C_{FU}}{W}$.

Figure 2 varies η (the flying base station's power relative to the stationary base station's) and plots the channel capacity given $\text{SNR}_{SU} = 10$ dB and the ideal positioning. The flying base station channel capacity increases as η increases (more transmission power by the flying base station). Figure 2a corresponds to the case when the flying base station has the half-duplex communication capability. When the line-of-sight path dominates ($\gamma = 2$), C_{FU} per bandwidth ranges from 1.16 bps/Hz to 4.82 bps/Hz. For example, if $\eta = 1$, $\frac{C_{FU}}{W} = 2.68$ bps/Hz and if $\eta = 10$, $\frac{C_{FU}}{W} = 4.32$ bps/Hz. Furthermore, the flying base station channel capacity increases as γ increases (i.e., channel greater attenuation) given fixed η ; the flying base station is even more relevant providing greater channel capacity when the channel experiences greater path attenuation loss. Figure 2b corresponds to the case when the flying base station has full-duplex communication capability. The capacity performance doubles the capacity performance from the half-duplex case in Figure 2a because the flying base station does not need to interleave its transmission and receiving if it has the full-duplex capability.

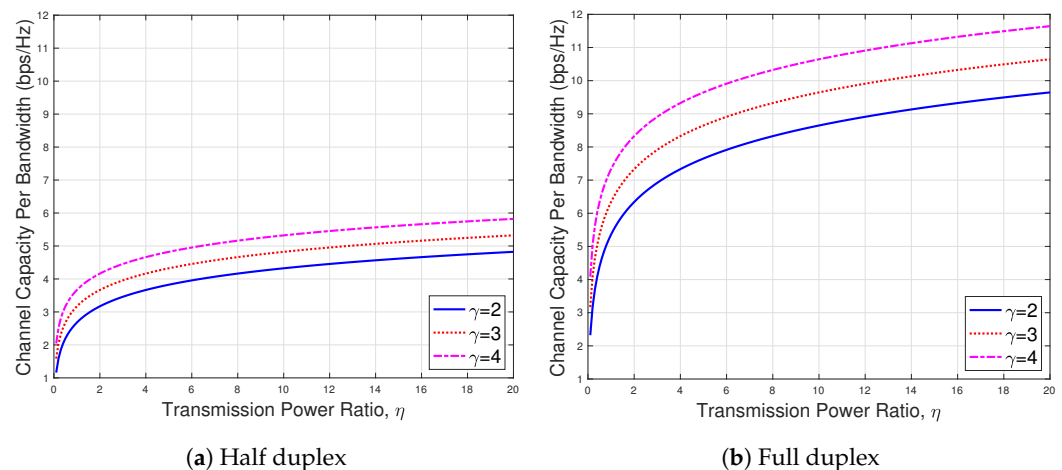


Figure 2. Flying base station channel capacity per bandwidth with respect to the transmission power ratio η .

When varying the stationary base station's SNR given $\eta = 1$ and half-duplex capability, the flying base station channel capacity increases, as shown in Figure 3, because the flying base station acts as a relay between the user and the stationary base station and its channel performance depends on the stationary base station's. The full-duplex capability (Figure 3b) yields twice as much flying base station channel capacity performance as the half-duplex case (Figure 3a).

In both analyses varying η (Figure 2) and varying SNR_{SU} (Figure 3), the flying base station channel capacity increases as γ increases (less dominant line-of-sight path and more fading). While greater γ attenuates the signal quicker as the signal propagates in distance, the flying base station channel increases because the stationary base station's SNR is given (i.e., SNR varies in the x-axis in Figure 3). The SNR itself decreases as γ increases (and thus the stationary base station's channel capacity decreases as expressed in Equation (4)) so greater γ requires either greater transmission power from the stationary base station or greater proximity to the user to achieve the same SNR.

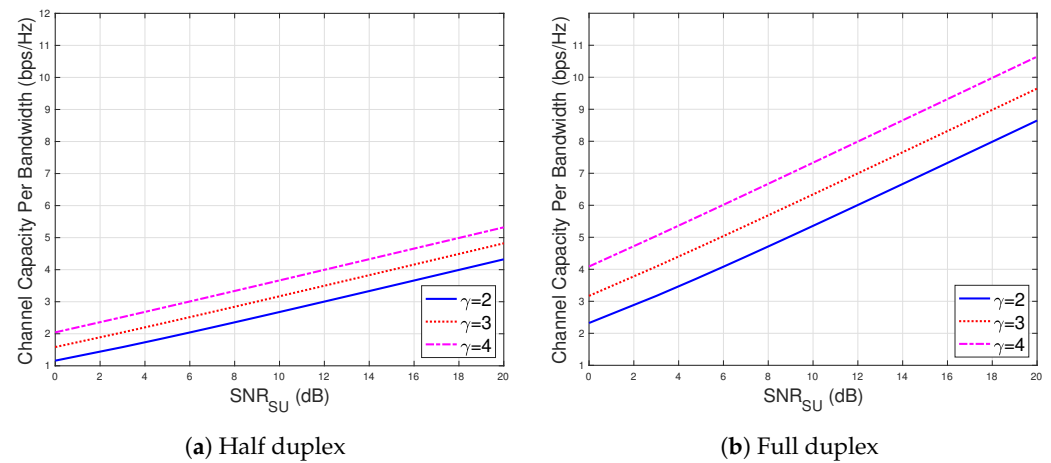


Figure 3. Flying base station channel capacity per bandwidth with respect to the stationary base station's SNR, SNR_{SU} .

6.2. Flying Base Station Channel Capacity: γ

The flying base station channel capacity increases with greater path loss exponent γ . As the wireless communication channel experiences greater attenuation with distance (greater γ) and with the $\text{SNR}_{\text{SU}} = 10$ dB fixed, flying base station channel capacity increases as shown in Figure 4. When the channel performance between the stationary base station and the user is fixed (i.e., $\text{SNR}_{\text{SU}} = 10$ dB), the flying base station introduction increases the channel capacity even more with harsher channel conditions with greater attenuation (greater γ). While γ is usually known to reduce the channel performance because of the greater signal attenuation in communication, the flying base station serving as a relay between the stationary base station and the user provides greater channel capacity. As γ increases from 2 (closer to line-of-sight with no barrier) to 5 (many barriers with higher fading and attenuation), the flying base station channel capacity increases by 55.4%. Comparing the full-duplex (upper curve) and the half-duplex (below curve) in Figure 4, full-duplex capability increases the channel capacity by double, which is consistent with our analyses when the transmission power varies with η in Section 6.1. As γ increases from 2 to 5, the flying base station increase from 5.358 bps/Hz to 8.326 bps/Hz in full-duplex case and from 2.679 bps/Hz to 4.163 bps/Hz in half-duplex case.

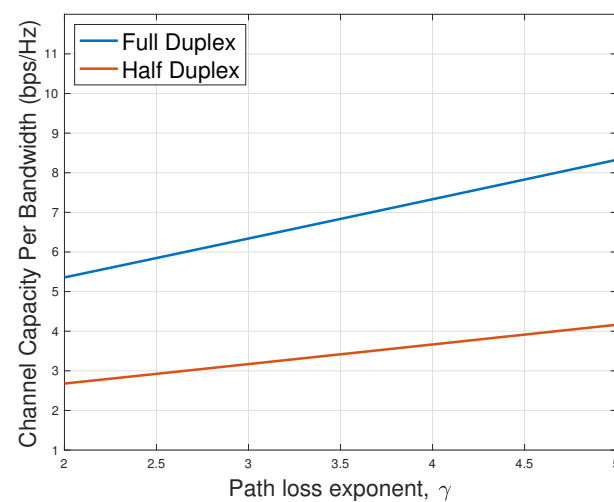


Figure 4. Flying base station channel capacity per bandwidth with respect to path loss exponent γ .

6.3. Beneficial Region and Transmission Power Requirement

We study the conditions when the flying base station becomes beneficial over the stationary base station, i.e., $\mathcal{G} > 0$, and call it the *beneficial region* when such conditions are met.

The flying base station's transmission power affects the communication channel performance and determines if the flying base station is operating within the beneficial region, in which the cellular service operator would want to deploy the flying base station (in addition to the existing stationary base station) so that the user can connect to the flying base station over the stationary base station. We, therefore, analyze the η dependency for the beneficial region while varying the stationary base station's channel condition in SNR, SNR_{SU} .

Figure 5 plots the beneficial region threshold so that the flying base station is beneficial if its transmission power capability η exceeds the threshold and η is above the plotted curve. Figure 5a provide the results of many simulation scenarios varying, SNR_{SU} , γ , and whether the flying base station is full-duplex capable or not. Figure 5b focuses on one of those cases when $\gamma = 2$ and when the flying base station does not support full-duplex capability (i.e., half-duplex capable) and corresponds to the "Half Duplex ($\gamma = 2$)" in Figure 5a. Although Figure 5b provides the threshold behaviors for fewer scenarios, it provides an alternative visualization of the beneficial region by coloring the beneficial region; if (SNR_{SU}, η) falls under the colored beneficial region, then the half-duplex flying base station provides capacity gain over the stationary base station.

The beneficial region threshold behavior is drastically different for the two cases when the flying base station has full-duplex capability or not/half-duplex. The beneficial region threshold behaves much differently when comparing full-duplex vs. half-duplex from the previous capacity performance analyses in Sections 6.1 and 6.2 where the full-duplex simply doubles the capacity performances of the half-duplex. If the flying base station has full-duplex capability, then it is beneficial as long as η is greater than a fixed threshold independent of the stationary base station's SNR. These correspond to the horizontal lines in Figure 5a. If $\gamma = 2$, the flying base station is beneficial as long as $\eta > 0.25$ or the flying base station's transmission power is at least as great as 0.25 times the stationary base station's transmission power. If $\gamma = 3$ and $\gamma = 4$, respectively, the flying base station is beneficial if $\eta > 0.125$ and $\eta > 0.0625$. Thus, if flying base station power per user is greater than a quarter ($0.25\times$) of the transmission power of the stationary base station per user, i.e., $\eta = 1$, then flying base station is beneficial for wireless communications which typically have $\gamma > 2$. In urban environment with greater path attenuation (e.g., physical barriers), γ increases and can reach or exceed 4, and the η threshold for beneficial region decreases, requiring smaller transmission power on the flying base station compared to that of the stationary base station.

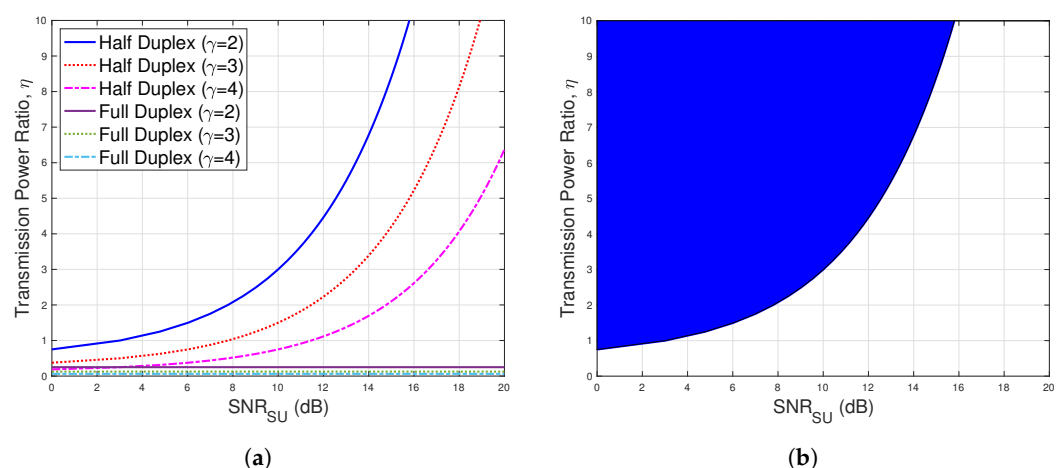


Figure 5. Beneficial region showing the η threshold with respect to SNR_{SU} . (a) Beneficial region varying SNR_{SU} and γ . If η is greater than the threshold (the line in the plot), the flying base station is beneficial. (b) Beneficial region varying SNR_{SU} given half-duplex capability and $\gamma = 2$. The colored region corresponds to the beneficial region.

In the half-duplex case, the η requirement for the beneficial region depends on and varies with SNR_{SU} , as shown in Figure 5a. The greater the SNR between the stationary

base station and the user (SNR_{SU}) the greater the flying base station transmission power requirement (η). For example, if $\gamma = 2$ (Figure 5b), the flying base station is beneficial if its transmission power meets the following requirements dependent on SNR_{SU} : $\eta > 0.75$ when $\text{SNR}_{SU} = 0$ dB; $\eta > 13$ when $\text{SNR}_{SU} = 10$ dB; $\eta > 25.5$ when $\text{SNR}_{SU} = 20$ dB. Greater γ , (i.e., greater attenuation) also decreases the η requirement (i.e., smaller transmission power ratio requirement on the flying base station) for the beneficial region, which is also seen in the full-duplex case.

7. Discussions and Future Directions

We take an information-theoretic approach to study the flying base station positioning, channel performances, beneficialness/utility, and dependence on the stationary base station. Our work provides the fundamental results about flying base stations, which are generally applicable across communication processing and mobility control operations, to guide future research and development in flying base stations for wireless networking. While adding mobility on the base station through the flying base station can provide significant benefits to meet the performance and coverage demands/requirements of future communications, to actualize it to reap such benefits requires further research and development to advance the technology and address the limitations and challenges. This section describes some of those future directions, and we call for greater R&D to actualize and advance flying base station.

7.1. Beyond Communication and Information Theory

Flying base station channel capacity builds on Shannon channel capacity but adds the mobility control assuming cellular-provision-dedicated flying base station, i.e., its mobility control is to maximize the channel capacity performance. Such information-theoretic analyses have historically driven and informed the research and development in wireless communication and its signal processing, as there is currently no standardized or dominant protocol or algorithm to control the operations of the flying base stations. For example, there have been decades of research adapting and controlling the physical-layer signal processing and coding to approach the Shannon channel capacity, including works from the 2000s (e.g., [25–27]), 2010s (e.g., [28,29]), and 2020s (e.g., [30,31]). However, a hands-on implementation using a software-defined radio (for control, adaptation, and implementation of the base station communication functions) and a UAV drone (for mobility control) will provide proof-of-concept validation and facilitate practicality.

7.2. Mobility Challenge

We assume the mobility control and implementation in our work but rather focus on the ideal location identification given the locations of the user and the stationary base station. Because the ideal location for the communication performance provides us with the flying base channel capacity limit which holds true regardless of the flying base station's location, we analyze and identify the ideal positioning/location. However, the mobility implementation incurs real-time costs of energy and time, i.e., moving requires time and energy consumption. Future research is needed to study such factors, costs, constraints, and the trade-off between moving vs. transmitting with greater power. The flying base station's mobility requirement also results in the limitations in energy resource (battery-operated as opposed to having a stable and constant power supply), which in turn requires energy-efficient designs, such as those for controlling sleeping/idle state [32], charging station assignments [33], and positioning [16,34,35].

7.3. Distributed Computing and Edge Intelligence and Control

The flying base station adds greater computing, intelligence, and control on the telecommunication network edge due to its aerial mobility and its location close to the user/recipient of the connectivity provision. In fact, the flying base station provides the first-hop, last-mile wireless link to the user, located between the user and the stationary

base station. Edge sensing and computing enable the autonomous and ad-hoc operations of such flying base stations, as opposed to merely relying on the stationary base station's control communication command transmissions. Edge sensing on the flying base station of the channel state information (CSI), spectrum access, and location can provide richer information to the telecommunication infrastructure (including both types of base stations) to better serve the user. The edge computing on the flying base station can provide greater flexibility and coverage scope across multiple cells/stationary base stations and even connect via another flying base station. Blockchain, a.k.a. distributed ledger technology has synergy with edge computing because it introduces greater computing and intelligence to the distributed nodes, including those on the networking edge. Blockchain, in addition to distributed computing on a distributed set of nodes, introduces the information storage to replace the centralized server providing information access via the query-response model involving remote networking. Blockchain can enable critical edge functionalities including enabling security and distributed control communications to control and set up the operations (e.g., [36,37]) or to provide the root of trust in mobile/vehicular networking from which the other functionalities can be implemented (e.g., [38–40]).

7.4. Securing Flying Base Station

The base station is part of the telecommunications and wireless network provider infrastructure. Securing the base station's availability and integrity is critical because of the user's reliance on the base station for connectivity and because of our reliance on connectivity and remote access in our everyday lives. The previous research implementing security on the base station, such as a security access gateway for edge-based defense [41] or physical-layer security for confidential communication [42], but these assume stationary terrestrial base station which can afford larger and more processing-powerful computing with stable power supply. Flying base stations provide unique challenges, which we have not seen in the past with the traditional stationary base station. Such challenges include the limited resources in computing and hardware size (which can limit the resource budget for security implementations), battery energy/power availability (e.g., [12,43,44]), positioning integrity and reliability (e.g., [12,45–49]), and fake/malicious base station (e.g., [50–52]) in both flying and stationary base station. The security vulnerabilities can arise from the new functionalities or advances in the flying base station (some of which are described in the other subsections in this section). The ongoing 6G research, development, and standardization (before the 6G implementations for practice) can provide opportunities to practice security-by-design to reduce the security costs or enable security objectives, which could have been prohibitive if the security is an afterthought and is added after given the existing protocols/algorithms/designs.

7.5. Facilitating Practice and Standardization for 6G and Beyond-5G

Telecommunications networking research and development often transition to practice via standardization. While 3GPP introduces the notion, objectives, and requirements of the flying base station (called UxNB base station) for the upcoming 6G networking [7,8], further standardization effort enabled by research and development in flying base station will facilitate practice and deployment of flying base station. The flying base station can also be particularly useful for 6G and beyond-5G to provide line-of-sight communication using its mobility, as the mmWave communication signal cannot propagate through physical barriers, unlike the signals we currently use which are in lower frequency bands.

8. Conclusions

The flying base station relies on the stationary terrestrial base station to bridge to the wired communications and connect to the cloud and Internet. Given a stationary base station's channel to the user and its SNR performance, we study the flying base station channel performance in channel capacity. The flying base station channel capacity builds on the Shannon capacity to quantify how much reliable bit transfer the channel *can* support.

However, in contrast to the traditional capacity analyses, the flying base station channel capacity considers both the stationary base station's channel and the mobility of the base station and assumes the ideal positioning of the flying base station. We, thus, analyze the flying base station's ideal position depending on the relative position of the stationary base station and the user. We also analyze the beneficial region and study the flying base station's transmission power requirement to become beneficial over the existing stationary base station's connectivity provision. According to our analyses, the flying base station provides multiplicative gains for the effective SNR on the user for the channel capacity where the gains are from reducing the transmission distance by half (2^γ) and the transmission power ratio (η). However, if the flying base station is not capable of full-duplex communication (i.e., half-duplex and cannot simultaneously transmit and receive communications), then there is a capacity decrease due to the bandwidth reduction to half. Thus, the flying base station's beneficialness over the stationary base station depends on both the stationary base station's SNR (SNR_{SU}) and the transmission power ratio (η) if the flying base station does not have the full duplex capability, while it will be beneficial independent of the stationary base stations' SNR (SNR_{SU}) if full-duplex capable. We introduce and analyze the flying base station's channel performance bound limit (flying base station channel capacity) to inform the flying base station R&D in the next-generation 6G and beyond-5G networking and include discussions for future directions.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Proof of Capacity Gain in the Full-Duplex Case

We revisit Theorem 4 in Section 5.2 and provide full proof, including the algebraic steps and derivations in this appendix.

Theorem A1. *If the flying base station has full-duplex capability, it can be beneficial and provide greater capacity if*

$$P_F > P_S \cdot 2^{-\gamma} \quad (\text{A1})$$

Proof. $C_{FU} > C_{SU}$ using Equations (4) and (6), and $d_{FU} = 0.5d_{SU}$ yields $P_F > P_S \cdot 2^{-\gamma}$.

$$\begin{aligned}
 C_{FU} &> C_{SU} \\
 W \log_2(1 + \eta 2^\gamma \text{SNR}_{SU}) &> W \log_2(1 + \text{SNR}_{SU}) \\
 1 + \eta 2^\gamma \text{SNR}_{SU} &> 1 + \text{SNR}_{SU} \\
 \eta 2^\gamma &> 1 \\
 \eta &> 2^{-\gamma} \\
 P_F &> P_S \cdot 2^{-\gamma}
 \end{aligned}$$

The last inequality is from $\eta = \frac{P_F}{P_S}$ by definition of the transmitted power ratio, η . $\square$

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