Outage Analysis of Aerial Semi-Grant-Free NOMA Systems
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Abstract—In this paper, we analyze the outage performance of Unmanned Aerial Vehicles (UAVs)-enabled downlink Non-Orthogonal Multiple Access (NOMA) communication systems with the Semi-Grant-Free (SGF) transmission scheme. A UAV provides coverage services for a Grant-Based (GB) user and one Grant-Free (GF) user is allowed to utilize the same channel resource opportunistically. The analytical expressions for the exact and asymptotic Outage Probability (OP) of the GF user are derived. The results demonstrate that no-zero diversity order can be achieved only under stringent conditions on users’ quality of service requirements. Subsequently, an efficient Dynamic Power Allocation (DPA) scheme is proposed to relax such data rate constraints. The analytical expressions for the exact and asymptotic OP of the GF user with the DPA scheme are derived. Finally, Monte Carlo simulation results are presented to validate the correctness of the derived analytical expressions and demonstrate the effects of the UAV’s location and altitude on the OP of the GF user.

Index Terms—Unmanned aerial vehicle, non-orthogonal multiple access, semi-grant-free, outage probability.

I. INTRODUCTION
A. Background and related works

In recent years, Unmanned Aerial Vehicles (UAVs) have been envisioned to play an essential role in space-air-ground integrated networks due to the flexibility of deployment, controllable mobility, and low costs [1]. Multiple access techniques are essential to integrate UAVs into 5G networks and beyond. Non-Orthogonal Multiple Access (NOMA) is regarded as a profitable candidate for 5G networks because of its merit in providing higher Spectral Efficiency (SE) and supporting massive connectivity [2]. Multiple users are served simultaneously in non-orthogonal channel resources by isolating the users in the power domain [3]. Using NOMA technology, UAVs can provide services for multiple users over the same resource block. Quite a few current investigations have considered using NOMA to improve the performance of UAV-enabled communication systems. Hou et al. focused on addressing the spatial distribution problem of NOMA-enhanced UAV network by utilizing stochastic geometry tools [4]-[7]. In [4], a new 3D UAV framework for downlink wireless service to randomly roaming NOMA users was proposed. Analytical expressions for the Outage Probability (OP) and Ergodic Capacity (EC) of Multiple-Input-Multiple-Output (MIMO)-NOMA-enhanced UAV networks were derived. In [5], the NOMA-enhanced UAV-to-everything networks were investigated. The closed-form expressions for the OP and EC of the paired NOMA receivers were derived. In [6], the UAV-centric strategy for offloading actions and the user-centric strategy for providing emergency network were considered, and the analytical expressions of the Coverage Probability (CP) for both scenarios with imperfect Successive Interference Cancelation (SIC) were derived.

NOMA-enhanced terrestrial Internet of Things (IoT) networks and NOMA-enhanced aerial IoT networks were investigated in [7], and new channel statistics were derived for both terrestrial and aerial users. Then, the analytical expressions for the exact and the asymptotic coverage probability were derived. To maximize the sum capacity of NOMA-enabled backscatter communication systems, the transmit power of IoT users at BS and the reflection coefficient of backscatter tag were jointly optimized in [8]. The convex optimization problems were solved by Karush-Kuhn-Tucker conditions.

Performance optimization of NOMA-aided UAV systems has been well-researched in many works. In [9], a UAV-assisted NOMA system was studied where the UAV assisted the Base Station (BS) in providing services to the ground users. The sum rate was maximized by optimizing the UAV trajectory and the NOMA precoding. In [10], an aerial Decode-and-Forward (DF) cooperative NOMA network was jointly optimized concerning UAV height, channel allocation, and power allocation to maximize the data rate. Ref. [11] considered the Energy Efficiency (EE) of the UAV’s communication with imperfect channel state information where the EE was maximized by designing user scheduling and power allocation.

Authors in [12] proposed a time-efficient data collection scheme where multiple ground devices upload their data to the UAV via uplink NOMA. The duration of each time slot was minimized by jointly optimizing the trajectory, device scheduling, and transmit power. In [13], the location of the UAV and power allocation were jointly optimized to enhance
the EE and SE of NOMA-aided UAV systems.

Conventional wireless communication systems operate on Grant-Based (GB) protocols [14]. Each device first transmits a scheduling request to BS and then sends a grant back for resource allocation. The lengthy handshaking process of requesting a grant will be prohibitively costly for the signaling overhead and unacceptable for the resulting latency in massive IoT data transmissions [15]. Ding et al. proposed NOMA-aided Semi-Grant-Free (SGF) transmission schemes and two contention control mechanisms have been presented to ensure that the number of users admitted to the same channel was carefully controlled in [16]. And then, a new SGF transmission scheme combining the flexibility in choosing the decoding order in NOMA was proposed. The closed-form expressions for the exact and asymptotic OP were derived. The results show that the NOMA-aided SGF transmission scheme effectively addresses the problem of the aforementioned request-grant process and the spectrum reserved. Based on [16], a new Power Control (PC) strategy was proposed to guarantee no OP floor entirely by adjusting the transmit power of Grant-Free (GF) user to control the decoding order of SIC at the base station in [17]. In [18], an adaptive power allocation strategy was proposed founded on the relationship between the target date rate of GB users and channel conditions of both GB and GF users. Authors in [19] considered a NOMA system with multiple randomly distributed GF users. The analytical expressions for the OP for with fixed transmit power and dynamic power control strategy were derived, and the small-scale fading, path loss, and random user locations were considered. Furthermore, the outage performance of GF users was analyzed under the best user scheduling scheme and Cumulative Distribution Function (CDF)-based scheduling scheme. In [20], an uplink SGF NOMA system with multiple randomly deployed GF users was studied by utilizing stochastic geometry techniques. A dynamic protocol was proposed to interpret part of the GF users that are paired to NOMA groups. The outage performance and diversity gains under dynamic and open-loop protocols were investigated, and numerical results show that dynamic protocol effectively improves the outage performance. Moreover, the analytical expressions for the exact and approximated EC were derived in [21]. The secrecy performance of NOMA-aided SGF was investigated in [22] wherein the analytical expressions for the Secrecy Outage Probability (SOP) for the scenarios with a single GF user and multiple GF users were derived, respectively. In [23], an Intelligent Reconfigurable Surface (IRS)-assisted SGF NOMA system was investigated, in which the IRS enhanced the channel gains for GB and GF users. The sum rates of GF users were maximized by jointly optimizing the sub-carrier assignment, the power allocation of GF users, and the IRS amplitude and phase shift.

Table I outlines related works on performance analysis of NOMA-aided SGF systems.

B. Motivation and contributions

In light of the above-discussed works, the performance of uplink NOMA systems with the SGF scheme has been studied in varying scenarios. However, there still needs to be more research contributions on investigating the performance of UAV communication systems with the SGF scheme, which motivates this work. In this work, we dedicate ourselves to developing new SGF schemes utilized in UAV-enabled downlink NOMA communication systems. The impacts of the UAV’s location and altitude on outage performance are studied. The main contributions of this paper are outlined as follows:

1) We investigate the outage performance of the GF user and the analytical expression for the exact OP is derived. We also analyze the asymptotic OP and the achievable diversity orders in the higher-signal-to-noise ratio (SNR) region to obtain more insights. The results demonstrate that no-zero diversity order can be achieved only under stringent conditions on users’ quality of service requirements.

2) An efficient Dynamic Power Allocation (DPA) scheme is proposed to guarantee no floor without any conditions on users’ target rates. The analytical expressions for the exact and asymptotic OP of the GF user with the DPA scheme are derived. The results demonstrate no OP floor for all the users’ target rates when the DPA scheme is utilized.

3) Monte Carlo simulation results are presented to validate the correctness of the derived analytical expressions and demonstrate the effects of the UAV’s location and altitude on the OP of the GF user.

4) Relative to [16] - [19] wherein the performance of the uplink NOMA-aided SGF systems was investigated, the transmit power and the Channel State Information (CSI) of GB users must be known at the GF user to realize the power control. This work studied the performance of the downlink NOMA-aided SGF systems, where the power allocation is utilized at the base station and the GF user need not know the CSI of the GB user.

C. Organization

The rest of this paper is organized as follows. Section II describes the considered system model and the SGF scheme utilizing in downlink NOMA systems. The OP of the GF user with Fixed Power Allocation (FPA) and DPA are analyzed in Sections III and IV respectively. Section V presents the simulation results to demonstrate the analysis and the paper is concluded in Section VI.

II. SYSTEM MODEL

A. System model

As shown in Fig. 1 we consider a UAV-enabled downlink NOMA system that consists of an aerial base station (U), a GB user ($D_B$), and a GF user ($D_F$). Similar to [16], $D_B$ is allocated to one dedicated resource block and $D_F$ will gain admission to the resource block opportunistically. Without loss

1 Although only two users are considered in this work, our results can be easily extended to NOMA systems with more than two users by utilizing the hybrid multiple access scheme proposed in [24], [25], [26].
TABLE I: Recent literature related to performance analysis of NOMA-aided SGF systems.

| Reference | downlink/uplink NOMA | Method | Performance Metrics |
|-----------|----------------------|--------|---------------------|
| [4]       | downlink             | ✓      | Performance analysis | OP, EC |
| [5]       | downlink             | ✓      | Performance analysis | OP, EC |
| [6]       | downlink             | ✓      | Performance analysis | CP     |
| [7]       | uplink               | ✓      | Optimization        | Sum rate |
| [8]       | downlink             | ✓      | Optimization        | Sum rate |
| [9]       | downlink             | ✓      | Optimization        | EE     |
| [10]      | downlink             | ✓      | Optimization        | Flight time |
| [11]      | uplink               | ✓      | Optimization        | SE, EE |
| [12]      | uplink, SGF          |        | Performance analysis | OP     |
| [13]      | uplink, SGF          |        | Performance analysis | OP     |
| [14]      | uplink, SGF          |        | Performance analysis | OP     |
| [15]      | uplink, SGF          |        | Performance analysis | EC     |
| [16]      | uplink, SGF          |        | Performance analysis | SOP    |
| [17]      | uplink, SGF          |        | Performance analysis | OP     |

Fig. 1: A downlink UAV-based NOMA communication system consisting of one UAV (U) and two legitimate users (D_B and D_F).

Due to possible obstacles between the Air-to-Ground (A2G) links, Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) connections are probabilistically considered in this work. As a result, the average path loss between U and D_X (X ∈ {B, F}) is expressed as

\[ d_X = \sqrt{(x - x_U)^2 + (y - y_U)^2 + z_U^2} \]  (1)

where \( \eta_L \) and \( \eta_{NL} \) signify the attenuation factor to the LoS and NLoS links, respectively. \( P_X^L \) signifies the probability of LoS connection, \( P_X^L = \left(1 + a_0 e^{-b_0 \theta_X} \right)^{-1} \), \( a_0 \) and \( b_0 \) are environmental parameters as listed in Table I and II of [28], \( \theta_X = \arcsin \left( \frac{H_X}{d_X} \right) \) denotes elevation angle (in radians), \( P_X^{NL} = 1 - P_X^L \), and \( \alpha_X \) is the path loss exponent. The relationship between \( \alpha_X \) and \( \theta_X \) is expressed as [29]

\[ \alpha_X (\theta_X) = b_1 P_X^L + b_2 \]  (3)

where \( b_1 \approx \alpha_Z - \alpha_0 \) and \( b_2 \approx \alpha_0 \). In this work, we set \( \alpha_Z = 2 \) and \( \alpha_0 = 4 \).

It is assumed that the fading coefficients, \( h_X \), in the A2G links experience independent and identically (i.i.d) Nakagami-\( m \) fading. Denoting \( G_X = \frac{h_X}{\bar{g}_X} \) the Probability Density Function (PDF) and the CDF of \( G_X \) are expressed by

\[ F_{G_X} (x) = 1 - e^{-\lambda_X x} \sum_{i=0}^{m-1} \frac{(\lambda_X x)^i}{i!} \]  (4)

\[ f_{G_X} (x) = \frac{\lambda_X^m}{\Gamma (m)} x^{m-1} e^{-\lambda_X x} \]  (5)

where \( m \) denotes the fading parameter that is integer, \( \lambda_X = \frac{\rho g_X}{\bar{g}_X} \), and \( \Gamma (\cdot) \) is the Gamma function as defined by [30] (8.310.1).

B. SGF schemes

To ensure the \( D_B \)’s Quality-of-Service (QoS) in the worst scenario, the \( D_B \)’s rate is constrained as [16]

\[ \log_2 \left( 1 + \frac{\rho g_B \Theta_B - \rho G_B}{\rho G_B (1 + \rho G_B) + \Theta_B - 1} \right) \geq R_{th} \]  (6)

where \( \rho = \frac{\rho g_B}{\bar{g}_X} \), \( P \) is the transmit power of U, \( \sigma^2 \) is the variance of complex zero mean Additive White Gaussian Noise (AWGN), \( 0 \leq \omega \leq 1 \) denotes the power allocation coefficient for \( D_B, \omega = 1 - \omega \), and \( R_{th} \) denotes the Reliability Rate Threshold (RRT) of \( D_B \).

Then, we have

\[ \omega \geq \frac{(\rho G_B + 1) (\Theta_B - 1)}{\rho G_B \Theta_B} \]  (7)

\[ \rho \geq \frac{\Theta_B - 1}{G_B (\Theta_B \omega - (\Theta_B - 1))} \]  (8)

\[ G_B \geq \frac{\Theta_B - 1}{\rho (1 - \Theta_B \omega)} \]  (9)
where $\Theta_B = 2^{R_{th}^B}$. Eqs. (7), (8), and (9) denote the conditions in which the power allocation coefficient, the transmission SNR, and the channel coefficient of $D_B$ must meet for the other given parameters.

**Remark 1.** When $\omega = 1$, one can easily find that decoding its own signal would fail at $D_B$ if $\log_2 (1 + \rho G_B) < R_{th}^B$, which means to ensure that $D_B$ decodes its own signal successfully, there is a constraint

$$G_B > \varepsilon_1$$

where $\varepsilon_1 = \frac{\Theta_B - 1}{\rho}$. It must be noted that the SGF scheme only guarantees that admitting the GF user is transparent to the GB user whose QoS experience is the same when it occupies the channel alone [22]. In other words, the SGF scheme does not always guarantee no outage for $D_B$. When the fading over the link between $U$ and $D_B$ is too strong, the constraint in (10) cannot be satisfied thereby the SGF scheme can not be utilized because there are no signals to $D_F$ to avoid any performance degradation for $D_B$.

Considering the decoding order at $D_F$ for given $\omega$ and $\rho$, according to the principle of SIC in NOMA, if the $D_B$'s signal can be successfully decoded in the first stage of SIC and deleted from the superimposed signal received at $D_F$, the interference can be eliminated and the maximum achievable rate can be obtained. Because

$$\log_2 \left( 1 + \frac{\rho G_F}{1 + \rho G_F} \right) = \log_2 \frac{1 + \rho G_F}{1 + \rho G_F}$$

is an increasing function of $x$ and

$$\log_2 \left( 1 + \frac{\rho G_F}{1 + \rho G_F} \right) > R_{th}^B$$

holds when $G_F > G_B$. Then, the condition of $D_F$ decoding $D_B$'s signal at the first stage of SIC is $G_F > G_B$. According to this, there are two different decoding orders at $D_F$, which is stated as follows:

- Case 1: $U$ is located in the region where the channel condition of $D_F$ is stronger than that of $D_B$, namely $G_F > G_B$. In this scenario, $D_B$'s signal can be decoded at the first stage or the second stage of SIC. Accordingly, $D_F$ will achieve a data rate of $\log_2 \left( 1 + \omega G_F \right)$ or $\log_2 \left( 1 + \frac{\omega G_F}{1 + \rho G_F} \right)$. To maximize its data rate, $D_F$ will decode $D_B$'s signal at the first stage of SIC due to $\log_2 \left( 1 + \frac{\omega G_F}{1 + \rho G_F} \right) < \log_2 (1 + \omega G_F)$. Then, the achievable rate of $D_F$ in this scenario is expressed as

$$R_1^F = \log_2 \left( 1 + \omega G_F \right)$$

- Case 2: $U$ is located in the region where the channel condition of $D_F$ is weaker than that of $D_B$, namely $G_F < G_B$. In this scenario, $D_B$ cannot decode $D_B$'s signal at the first stage of SIC since $G_F < G_B$ leads to $\log_2 \left( 1 + \frac{\omega G_F}{1 + \rho G_F} \right) < R_{th}^B$. Therefore, $D_F$ must decode its own signal firstly, which achieves the data rate as

$$R_2^F = \log_2 \left( 1 + \frac{\omega G_F}{1 + \rho G_F} \right)$$

Then, the achievable rate of $D_F$ is expressed as

$$R_F = \left\{ \begin{array}{ll} R_1^F, & G_F > G_B \\ R_2^F, & G_F < G_B \end{array} \right.$$
Due to $\varepsilon_1 \to 0$, $\varepsilon_2 \to 0$, $\varepsilon_4 \to 0$, $\varepsilon_5 \to 0$ when $\rho \to \infty$, we have $T_{01}^\infty \to 0$, $T_{11}^\infty \to 0$, $T_{12b}^\infty \approx 1 - A_1 \sum_{i=0}^{m-1} \frac{\lambda_i \Gamma(i+m)}{i!A_2 i^m}$, which is a constant independent of $\rho$.

**Remark 3.** According to the results presented in Corollary 1, one can realize there is an OP floor when $\Theta_{th} > 1 + \frac{1}{\Theta_{th} - 1}$.

Utilizing $G_4 = - \lim_{\rho \to \infty} \log \frac{P_{\text{out}}}{\log \rho}$, the diversity order with the SGF scheme is obtained as

$$G_{4}^{\text{FPA}} = \begin{cases} m, & \Theta_{th} < \frac{\Theta_B}{\Theta_B - 1} \\ 0, & \Theta_{th} > \frac{\Theta_B}{\Theta_B - 1} \end{cases} \quad (17)$$

### IV. OUTAGE PERFORMANCE ANALYSIS WITH DYNAMIC POWER ALLOCATION

In this section, a DPA scheme is proposed to avoid the OP floor and the analytical expression for the OP with the DPA scheme is derived.

**A. Proposed dynamic power allocation scheme**

In the previous analysis, $D_B$ is always allocated to a fixed power $\omega$ that just gives priority to meet its QoS requirement, while the other power is allocated to $D_F$. One can observe from Corollary 1 that there is OP floor when $\Theta_{th} > 1 + \frac{1}{\Theta_{th} - 1}$.

Recalling when $G_F > G_B$, $D_B$’s signal can be decoded firstly at $D_F$ and the achievable rate of $D_F$ is expressed as $R_F^1 = \log_2 (1 + \rho \omega G_F)$. If $G_F < G_B$, $D_F$ has not enough capacity to decode $D_B$’s signal at the first stage of SIC, the achievable rate of $D_F$ is expressed as $R_F^3 = \log_2 \left(1 + \frac{\rho \omega G_F}{1 + \rho \omega G_F}ight)$. It must be noted that in the scenarios wherein $G_F < G_B$, $U$ can increase $\omega$ to $\omega_2$ to make sure that $D_F$ can decode $D_B$’s signal at the first stage of SIC, then the achievable rate will be changed from $R_F^2 = \log_2 (1 + \rho \omega_2 G_F)$ to $R_F^2 = \log_2 (1 + \rho \omega_2 G_F)$, where $\omega_2 = 1 - \omega_2$ and $\omega_2 = 1 - \frac{G_F}{G_B}$. The goal of the DPA scheme is to maximize $D_F$’s achievable rate. Hence, the power allocation coefficient must be chosen according to the relationship between $R_F^2$ and $R_F^3$. Specifically, if $R_F^2 > R_F^3$, the power allocation coefficient for $D_B$ is $\omega$ otherwise $\omega_2$. Due to $R_F^2 > R_F^3 \iff \frac{\Theta_B G_B}{\Theta_B G_B + 1} < G_F < G_B$, the achievable rate of $D_F$ with the DPA scheme is expressed as

$$R_F = \begin{cases} R_F^1, & G_F > G_B \\ R_F^2, & G_F < \frac{\Theta_B G_B}{\Theta_B G_B + 1} < G_B < G_B \\ R_F^3, & \frac{\Theta_B G_B}{\Theta_B G_B + 1} < G_F < G_B \end{cases} \quad (18)$$
B. Outage performance analysis with dynamic power allocation scheme

On the ground of (13), the OP with the DPA scheme is expressed as (19), shown at the top of this page, where $T_0$ and $T_1$ are given in Theorem 1. $T_2$ denotes $D_F$’s signal that is decoded at the first stage when power allocation coefficient is $\omega$, and $T_3$ denotes $D_F$’s signal that is decoded at the second stage when power allocation coefficient is $\omega_2$.

The following theorem provides the analytical expression for the OP of $D_F$ with the DPA scheme.

**Theorem 2.** The OP of $D_F$ with the DPA scheme, $P_{\text{out}}^{\text{DPA}}$, is expressed as

$$P_{\text{out}}^{\text{DPA}} = \begin{cases} T_0 + T_{11} + T_{2a}^3 + T_3, & \Theta_B > \frac{1}{\Theta_{th} - 1} \\ T_0 + T_{11} + T_{2b}^3 + T_3, & \Theta_B < \frac{1}{\Theta_{th} - 1} \end{cases}$$

where $T_{2a} = \tilde{T}_{GB}(\xi_1) - A_1\Phi_5$, $T_{2b} = \tilde{T}_{GB}(\xi_1) - A_1g_1\left(\frac{1}{\rho}, \xi_1, \xi_3\right) - A_1g_2\left(\frac{1}{\rho}, \xi_1, \xi_6\right)$.

$$T_3 = A_1\Phi_5 - \tilde{T}_{GB}(\xi_0)\tilde{T}_{GB}(\xi_0) - A_1\sum_{i=0}^{m-1} \left\{ A_{(i)}\Phi_2 \right\}^i + \Phi_6 = \underbrace{\frac{T(i+m,A_5\tilde{\varepsilon}) - T(i+m,A_5\varepsilon)}{A_2^m}}_{A_2^m}.$$ 

**Proof:** Please refer to Appendix C.

Eq. (20) provides an exact relationship between the OP of $D_F$ with the DPA scheme and the system parameters. In addition to the insights mentioned in Theorem 1, an interesting phenomenon can be found. Intuitively, increasing the transmit power of $D_B$ tends to stronger inter-user interference on $D_F$, which deteriorates the performance of $D_F$. However, in the DPA scheme, under some conditions, appropriately increasing the transmit power of $D_B$ ensures the signal of $D_B$ can be decoded successfully on $D_F$. The achievable rate of $D_F$ can be enhanced through the SIC technique; thus the performance is improved. Similar to [17] and [22], the collaboration among the GB and GF users not only improves resource utilization, but also enhances the GF users’ performance while not affecting the GB’s QoS.

To obtain more insights, we derive the analytical expressions for the asymptotic OP of $D_F$ with the DPA scheme.

**Corollary 2.** When $\rho \rightarrow \infty$, the asymptotic OP of $D_F$ is expressed as (21), shown at the top of this page, where

$$T_{2b}^\infty = \frac{\ln \frac{\Theta_{th}}{\rho}}{m!} \left( \frac{\ln \frac{\Theta_{th}}{\rho}}{m!} \right)^m \left( 1 - \left( \frac{\xi \rho}{\rho} \right)^m \right),$$

$$T_{2a}^\infty = \frac{\ln \frac{\Theta_{th}}{\rho}}{m!} \left( \frac{\ln \frac{\Theta_{th}}{\rho}}{m!} \right)^m + \frac{\ln \frac{\Theta_{th}}{\rho}}{m!} \left( \frac{\ln \frac{\Theta_{th}}{\rho}}{m!} \right)^m - A_1\sum_{i=0}^{m-1} \left\{ A_{(i)}\Phi_2 \right\}^i + \Phi_2 = \frac{\ln \frac{\Theta_{th}}{\rho}}{m!} \left( \frac{\ln \frac{\Theta_{th}}{\rho}}{m!} \right)^m.$$ 

**Proof:** Please refer to Appendix D.

Because of $T_{0}^\infty \propto \rho^{-m}$, $T_{11}^\infty \propto \rho^{-m}$, $T_{2a}^\infty \propto \rho^{-m}$, $T_{2b}^\infty \propto \rho^{-m}$, $T_3^\infty \propto \rho^{-m}$, we obtain $P_{\text{out}}^{\text{DPA}} \propto \rho^{-m}$.

**Remark 4.** It can be realized from Corollary 2 that OP floors can be avoided when DPA scheme is adopted.

Similar to [17], the diversity order with DPA scheme is obtained as

$$G_{d}^{\text{DPA}} = m$$

**V. NUMERICAL RESULTS**

In this section, Monte-Carlo simulations are presented to prove our analysis on the outage performance of the aerial SGF NOMA system by varying the parameters, such as transmit SNR and power allocation coefficient. The main parameters are set as $m = 2$, $R_{th} = 0.2$ bps/Hz, $R_{th} = 2$ bps/Hz, $(x_B, y_B) = (50, -50)$, $(x_F, y_F) = (50, 50)$, and $(x_U, y_U, z_U) = (0, 0, 100)$, unless stated otherwise. In all the figures, ‘Sim’, ‘Ana’, and ‘Asy’ denote the simulation, numerical, and asymptotic results, respectively.

Fig. 2 presents the effect of UAV’s position and $\rho$ on the OP of $D_F$ with $\Theta_{th} < 1 + \frac{1}{\Theta_{th} - 1}$.

Fig. 3 demonstrates the effect of UAV’s position and the transmission SNR on the OP of $D_F$ when $\Theta_{th} > 1 + \frac{1}{\Theta_{th} - 1}$. It can be observed from Fig. 3(a) and Fig. 3(c) that the OP deteriorates as $\rho$ decreases at lower-$\rho$ region. However, there is a floor for OP, which denotes that the OP gradually approaches a constant at the higher-$\rho$ region. This is because the base
station needs to allocate more power to $B$, resulting in too much interference on $D_F$. When the signals for $B$ cannot be decoded on $D_F$ with increasing transmit SNR, the SINR at $D_F$ tends to a constant, which is independent of $\rho$. As shown in Fig. 3(b) and Fig. 3(d), one can also observe that the outage performance with the DPA scheme outperforms that with the FPA scheme. Moreover, it can be found that the outage performance of $D_F$ in the DPA scheme will also improve with the increase of $\rho$ in the case of high-$\rho$ region. Specifically, the OP floor problem is solved by the DPA scheme. The reason is that more power allocated to $B$ ensures that $D_F$ can decode the signal of $B$ successfully. With the SIC technology, the inter-user interference is deleted and the achievable rate of $D_F$ is improved, thereby the performance is enhanced.

Furthermore, it can be seen in Figs. 2 and 3 that OP is improved as the distance between $U$ and $D_F$ decreases. The reason is given as follows. Compared with the probability of loss propagation, the main factor on OP is path loss, which decreases with distance.

Fig. 4 demonstrates the impact of RRT of $B$ and $D_F$ on the OP of $D_F$. It can be observed that the larger the $R_{th}^B$ and $R_{th}^F$, the larger the OP, which is easy to follow because larger RRT denotes higher requirement. As demonstrated in Fig. 4(a) and Fig. 4(c), it can be observed that the relationship between the RRT for $B$ and $D_F$ under the condition in which the resources can be shared also significantly affects the OP of $D_F$, which is testified in Theorem 1. Furthermore, the results in Fig. 4(b) and Fig. 4(d) verify that the DPA scheme solves the OP floors perfectly. Then, the effectiveness of the DPA scheme is testified. It must be noted that the power allocation in the DPA scheme not only depends on the global CSI but also on the RRT of $B$, which is expressed in Eq. (18). Thus, jointly designing the RRT of $B$ and $D_F$ based on the global CSI can maximize the achievable rate of GF users while ensuring the QoS of the GB user, which will be part of future work.

Figs. 5 and 6 demonstrate the impact of the UAV’s position and altitude on the OP of $D_F$ with $R_{th}^B = 0.2$ and $R_{th}^F = 2$.
is related to the environment, the altitude of the UAV, and the transmission SNR. Optimizing the outage performance of the GF user by designing the trajectory of the UAV will be conducted as part of our future work.

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APPENDIX A

PROOF OF THEOREM 1

Based on (4), we obtain \( T_0 = F_{G_B} (\varepsilon_1) \).

On the ground of (13), \( T_1 \) is expressed as

\[
T_1 = \text{Pr} \left\{ G_B > \varepsilon_1, G_F > G_B, R_F^B < R_{th}^F \right\} \frac{T_{t1}}{T_{t2}} + \text{Pr} \left\{ G_B > \varepsilon_1, G_F < G_B, R_F^2 < R_{th}^F \right\}
\]

(23)

where \( T_{t1} \) denotes the OP of the GF user under the DPA scheme, which is obtained by comparing Fig. 5(a) and Fig. 6(a). However, the effect of the relationship between the RRT for \( D_B \) and \( D_F \) makes a big difference to the OP of \( D_F \) in the same environments with the DPA scheme. The same conclusion can also be observed by comparing Fig. 5(b) and Fig. 6(b). The reason is that the CSI of \( D_F \) is also considered in the DPA scheme, which is expressed in Eq. (13).

VI. CONCLUSIONS

This work analyzed the outage performance of an aerial SGF NOMA system. Firstly, the outage performance of UAV-enabled downlink NOMA systems was analyzed with the SGF transmission scheme. The exact and asymptotic expressions for the OP of the GF user under the DPA scheme were derived. It was found that there are OP floors under stringent conditions on quality of service requirements. A DPA scheme was proposed to eliminate the OP floor at the high-SNR region. The analytical expressions for the exact and asymptotic OP of the GF user were derived applicable to this later scheme. Numerical and simulation results demonstrate that the outage performance of the GF user was improved by utilizing the proposed DPA scheme. And the effects of system parameters, such as UAV location and altitude, on the outage performance were analyzed. It was observed that there is an optimal position for the UAV to minimize \( D_F \)’s OP. The optimal placement
where \( \varepsilon_0 = \varepsilon_1 + \varepsilon_2 = \frac{\Theta_n \Theta_{\Theta n} - 1}{\rho} \) and \( \chi_1 \) is expressed as

\[
\chi_1 = \Pr \left\{ G_F < \frac{\varepsilon_2 G_B}{G_B - \varepsilon_1} < \varepsilon_1 < G_B < \varepsilon_0 \right\}
\]

\[= \int_{\varepsilon_1}^{\varepsilon_0} f_{G_B}(x) F_{G_F} \left( \frac{x - \varepsilon_1}{\varepsilon_2} \right) dx \quad (26) \]

where \( A_1 = \frac{\lambda}{m_i} \) and \( \Phi_1 = \sum_{i=0}^{m-1} \frac{\lambda_i}{i!} \int_{\varepsilon_1}^{\varepsilon_0} y^{m-1} \frac{1}{(y-a)^i} e^{-\lambda_B y - \lambda F(y)} dy. \)

To obtain the closed-form expression of \( \Phi_1. \) To facilitate the following analysis, we define

\[
g_1(a, b, s, t) = \sum_{i=0}^{m-1} \frac{(\lambda_B b)^i}{i!} \int_{s}^{t} y^{m+i-1} \frac{1}{(y-a)^i} e^{-\lambda_B y - \lambda F(y)} dy \]

Utilizing Gaussian-Chebyshev quadrature, we obtain

\[
g_1(a, b, s, t) = \frac{\pi}{N} \sum_{i=0}^{m-1} \frac{(\lambda_B b)^i}{i!} \sum_{n=1}^{N} \frac{(\mu_n(s, t))^m}{\mu_n(s, t) - \frac{1}{2}} \left( \frac{\mu_n(s, t) - a}{\mu_n(s, t) - b} \right)^i \]

where \( \mu_n(s, t) = \frac{t-s}{\sqrt{\pi}} + \frac{2n-1}{\sqrt{2N}} \) and \( N \) is the summation terms, which reflects accuracy vs. complexity. Then, we obtain \( \Phi_1 = g_1(\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_0). \)

Utilizing (30), \( \chi_2 \) is obtained as

\[
\chi_2 = \Pr \left\{ G_B < G_F, \varepsilon_1 < G_B < \varepsilon_0 \right\}
\]

\[= \int_{\varepsilon_1}^{\varepsilon_0} f_{G_B}(y) F_{G_F}(y) dy \]

\[= F_{G_B}(\varepsilon_0) - F_{G_B}(\varepsilon_1) - \frac{\lambda_B}{\Gamma(m)} \sum_{i=0}^{m-1} \frac{\lambda_i}{i!} \int_{\varepsilon_1}^{\varepsilon_0} e^{-(\lambda_B + \lambda F)(y)} y^{m+i-1} dy \]

\[= F_{G_B}(\varepsilon_0) - F_{G_B}(\varepsilon_1) - A_1 \sum_{i=0}^{m-1} \frac{\lambda_i}{i!} \Phi_2 \]

where \( A_2 = \lambda_B + \lambda F, \) \( \Phi_2 = \frac{\Gamma(i+m, 2\varepsilon_0) - \Gamma(i+m, A_{2\varepsilon_1})}{2^m}, \) and \( \Gamma(\cdot, \cdot) \) is lower incomplete Gamma function as defined by (8.350.2).

Similar to \( T_{11}, T_{12} \) is expressed as

\[
T_{12} = \Pr \left\{ G_B > \varepsilon_1, G_F < G_B, \right\}
\]

\[\log_2 \left( 1 + \frac{\rho G_F}{1 + \rho \omega G_F} \right) < R_{th}^F \]

\[= \Pr \left\{ G_B > \varepsilon_1, G_F < G_B, \right\}
\]

\[
\rho \left( 1 - \Theta_{th} \omega \right) G_F < \Theta_{th} - 1 \}
\]

Since there is

\[
\Pr \left\{ \rho \left( 1 - \Theta_{th} \omega \right) G_F < \Theta_{th} - 1 \right\} = \Pr \left\{ 1 - \Theta_{th} \omega < 0 \right\}
\]

\[+ \Pr \left\{ G_F < \frac{\varepsilon_4 G_B}{G_B - \varepsilon_3}, 1 - \Theta_{th} \omega > 0 \right\} \]

(31)

Where \( \varepsilon_3 = \frac{\Theta_{n} - 1}{\rho (\Theta_{th} - \Theta_{n} - \Theta_{th} - 1)} \) and \( \varepsilon_4 = \frac{\rho (\Theta_{th} - \Theta_{n} - \Theta_{th} - 1)}{\rho (\Theta_{th} - \Theta_{n} - \Theta_{th} - 1)} \). Furthermore, we obtain the following result

\[
\Pr \left\{ 1 - \omega \Theta_{th} < 0 \right\}
\]

\[= \Pr \left\{ 1 - \frac{\rho \Theta_{th} G_B - \rho G_B + \Theta_{th} - 1}{\rho \Theta_{th} G_B} \Theta_{th} < 0 \right\} \]

\[= \Pr \left\{ 1 - \frac{\Theta_{th}}{\Theta_{th} - 1} \right\} G_B < \Theta_{th} \}

Thus, the relationship between \( \Theta_{th} \) and \( \frac{\Theta_{th}}{\Theta_{th} - 1} \) must be considered first.

1) When \( \Theta_{th} < \frac{\Theta_{n}}{\Theta_{n} - 1} \), we have

\[
\Pr \left\{ 1 - \omega \Theta_{th} < 0 \right\} = \Pr \{ G_B < \varepsilon_3 \}
\]

Thus, we have

\[
\Pr \left\{ 1 - \Theta_{th} \omega G_F < \Theta_{th} - 1 \right\} \}

\[= \Pr \{ G_B < \varepsilon_3 \}
\]

\[+ \Pr \left\{ G_F < \frac{\varepsilon_4 G_B}{G_B - \varepsilon_3}, G_B > \varepsilon_3 \right\} \]

Substituting (34) into (30), we have

\[
T_{12a} = \Pr \{ G_F < G_B, \varepsilon_1 < G_B < \varepsilon_3 \}
\]

\[+ \Pr \{ G_B > \varepsilon_3, G_F < \min \left( G_B, \frac{\varepsilon_4 G_B}{G_B - \varepsilon_3} \right) \}
\]

The 2nd term in (35) is derived as

\[
\Pr \left\{ G_B > \varepsilon_3, G_F < \min \left( G_B, \frac{\varepsilon_4 G_B}{G_B - \varepsilon_3} \right) \}
\]

\[= \Pr \{ G_B > \varepsilon_3, G_F < \frac{\varepsilon_4 G_B}{G_B - \varepsilon_3} \}
\]

\[+ \Pr \{ G_B > \varepsilon_3, G_F < \frac{\varepsilon_4 G_B}{G_B - \varepsilon_3} \}
\]

\[= \Pr \{ G_B > \varepsilon_3, G_F < \min \left( G_B, \frac{\varepsilon_4 G_B}{G_B - \varepsilon_3} \right) \}
\]

\[+ \Pr \{ G_B > \varepsilon_3, G_F < \min \left( G_B, \frac{\varepsilon_4 G_B}{G_B - \varepsilon_3} \right) \}
\]

\[= \Pr \{ G_B > \varepsilon_3, G_F < \min \left( G_B, \frac{\varepsilon_4 G_B}{G_B - \varepsilon_3} \right) \}
\]

where \( \varepsilon_5 = \varepsilon_3 + \varepsilon_4 = \frac{\Theta_{n} - 1}{\rho (\Theta_{th} + \Theta_{n} - \Theta_{th} - 1)} \). Then, \( T_{12a} \) is expressed as

\[
T_{12a} = \Pr \{ G_F < G_B, \varepsilon_1 < G_B < \varepsilon_3 \}
\]

\[+ \Pr \{ G_F < G_B, \varepsilon_1 < G_B < \varepsilon_3 \}
\]

\[+ \Pr \{ G_F < \frac{\varepsilon_4 G_B}{G_B - \varepsilon_3}, G_B > \varepsilon_3, G_B > \varepsilon_3 \}
\]

\[= \Pr \{ G_F < \frac{\varepsilon_4 G_B}{G_B - \varepsilon_3}, G_B > \varepsilon_3, G_B > \varepsilon_3 \}
\]

\[= \Pr \{ G_B > \varepsilon_3, G_F < \min \left( \frac{\varepsilon_4 G_B}{G_B - \varepsilon_3}, G_B > \varepsilon_3, G_B > \varepsilon_3 \right) \}
\]

(37)

With the same method as (29), we obtain

\[
\chi_3 = F_{G_B}(\varepsilon_5) - F_{G_B}(\varepsilon_1) - A_1 \sum_{i=0}^{m-1} \frac{\lambda_i}{i!} \Phi_3
\]
where $\Phi_3 = \mathcal{T}(i+m, A_2\varepsilon_1) - \mathcal{T}(i+m, A_2\varepsilon_2)$. With the similar method as (26), $\chi_4$ is obtained as

$$\chi_4 = \Pr \left\{ G_F < \frac{\varepsilon_4G_B}{G_B - \varepsilon_3}, G_B > \varepsilon_5 \right\}$$

$$= \int_{\varepsilon_3}^{\infty} f_{G_B}(y) F_{G_F} \left( \frac{\varepsilon_4y}{y - \varepsilon_3} \right) dy$$

$$= \tilde{F}_{G_B}(\varepsilon_5) - A_1 \Phi_4$$

(39)

where $\tilde{F}_{G_B}(x) = 1 - F_{G_B}(x)$ and $\Phi_4 = \sum_{n=0}^{m-1} \frac{\left(\lambda F\varepsilon_2\right)^n}{n!} \int_{\varepsilon_3}^{\infty} e^{-\lambda B y} \frac{\lambda B y^n}{n!} dy$. To facilitate the following analysis, we define

$$g_2(a, b, c) = \sum_{i=0}^{m-1} \left(\frac{\lambda F\varepsilon_2}{i!}\right)^{i} \int_{\varepsilon_3}^{\infty} e^{-\lambda B y} \frac{\lambda B y^{m+i-1}}{(y-a)^i} dy$$

$$= \sum_{i=0}^{m-1} \left(\frac{\lambda F\varepsilon_2}{i!}\right)^{i} \sum_{n=1}^{N} w_n e^{-\left(\lambda B \mu_n(0, c) + \frac{\lambda B \mu_n(0, c)}{\mu_n(0, c) - a}\right) \frac{\lambda B y^n}{\mu_n(0, c) - a}}$$

$$= \sum_{i=0}^{m-1} \left(\frac{\lambda F\varepsilon_2}{i!}\right)^{i} \sum_{n=1}^{N} \mu_n(0, c) \frac{\lambda B \mu_n(0, c)}{- \mu_n(0, c) + a}$$

$$= \sum_{i=0}^{m-1} \left(\frac{\lambda F\varepsilon_2}{i!}\right)^{i} \frac{\lambda B \mu_n(0, c)}{- \mu_n(0, c) + a}$$

(41)

where $\mu_n$ is the nth zeros of Laguerre polynomials and $w_n$ is the Gaussian weight, which are given in Table (25.9). Then, we obtain $\Phi_4 = g_2(\varepsilon_3, \varepsilon_4, \varepsilon_5)$.  

2) When $\Theta_{ih} > \Theta_{B-1}^\omega$, due to $\Pr \{1 - \omega \Theta_{ih} < 1\} = 1$, we obtain

$$T_{12b} = \Pr \{ G_F < G_B, G_B > \varepsilon_1 \}$$

$$= \int_{\varepsilon_1}^{\infty} f_{G_B}(y) F_{G_F} (y) dy$$

$$= \tilde{F}_{G_B}(\varepsilon_1) - A_1 \sum_{i=0}^{m-1} \frac{\lambda B \Gamma(i + m, A_2\varepsilon_1)}{i! A_2^{i+m}}$$

(42)

where $\Gamma(\cdot, \cdot)$ is upper incomplete Gamma function, which is defined by (30) (3.351.2).

**APPENDIX B**

**PROOF OF COROLLARY 1**

Utilizing $e^x = \sum_{j=0}^{\infty} \frac{x^j}{j!}$, we obtain $\sum_{j=0}^{n-1} \frac{x^j}{j!} = e^x - \frac{x^n}{n!} + O(x^n)$, then we have $F_{G_B}(x) \rightarrow \frac{(A_2\varepsilon_1)^m}{m!}$ when $x \rightarrow 0$. Thus, we have $T_{0}^\infty = F_{G_B}(\varepsilon_1) = \frac{(A_2\varepsilon_1)^m}{m!}$.

When $\rho \rightarrow \infty$, we have $\varepsilon_1 \rightarrow 0$, $\varepsilon_2 \rightarrow 0$, $\varepsilon_3 \rightarrow 0$, $\varepsilon_4 \rightarrow 0$, and $\frac{\varepsilon_2G_B}{G_B - \varepsilon_3} \rightarrow \varepsilon_2$, by utilizing $\mathcal{T}(n, x) \approx \frac{x^n}{n!}$, $T_{11}^\infty$ is obtained as

$$T_{11}^\infty = \Pr \{ G_B < G_F < \varepsilon_2, \varepsilon_1 < G_B < \varepsilon_5 \}$$

$$= \int_{\varepsilon_1}^{\varepsilon_5} f_{G_B}(y) \left( F_{G_F}(\varepsilon_2) - F_{G_F}(y) \right) dy$$

$$= \int_{\varepsilon_1}^{\varepsilon_5} f_{G_B}(y) \frac{\lambda B \varepsilon_2^m}{m!} dy$$

$$- \int_{\varepsilon_1}^{\varepsilon_5} f_{G_B}(y) \left( 1 - e^{-\lambda F y} \sum_{i=0}^{m-1} \frac{\lambda F y^i}{i!} \right) dy$$

$$= \left( \frac{(\lambda F \varepsilon_2)^m}{m!} - 1 \right) \int_{\varepsilon_1}^{\varepsilon_5} f_{G_B}(y) dy$$

$$+ \frac{\lambda B \varepsilon_2^m}{\Gamma(m)} \sum_{i=0}^{m-1} \frac{\lambda F y^i}{i!} \int_{\varepsilon_1}^{\varepsilon_5} e^{-(\lambda B + \lambda F) y} dy$$

$$\approx \frac{\lambda B \varepsilon_2^m}{\Gamma(m)} \left( \frac{(\lambda F \varepsilon_2)^m}{m!} - 1 \right)$$

$$+ \frac{\lambda B \varepsilon_2^m}{\Gamma(m)} \sum_{i=0}^{m-1} \frac{\lambda F \varepsilon_5^m - \varepsilon_1^{i+m}}{i! (i + m)}$$

(43)

**APPENDIX C**

**PROOF OF THEOREM 2**

$T_0$ and $T_{11}$ are given in Theorem 1. Substituting (12) into (19), $T_2$ is expressed as

$$T_2 = \Pr \left\{ G_B > \varepsilon_1, G_F < \frac{\Theta_B G_B}{\rho G_B + 1} \right\}$$

$$= \Pr \left\{ G_B > \varepsilon_1, G_F < \frac{\Theta_B G_B}{\rho G_B + 1} \right\}$$

$$+ (1 - \Theta_{ih}^\omega) \rho G_F < \Theta_{ih} - 1 \right\}$$

(48)
1) When $\Theta_{th} < \frac{\Theta_B}{\Theta_B - 1}$, we obtain

$$T_{2a} = \Pr \left\{ G_B > \varepsilon_1, G_F < \frac{\Theta_B G_B}{\rho G_B + 1}, G_B < \varepsilon_3 \right\}$$

$$+ \Pr \left\{ G_B > \varepsilon_1, G_F < \frac{\Theta_B G_B}{\rho G_B + 1}, G_B > \varepsilon_3 \right\}$$

$$G_F < \frac{\varepsilon_4 G_B}{G_B - \varepsilon_3}, G_B > \varepsilon_3 \right\}$$

$$= \Pr \left\{ G_F < \frac{\Theta_B G_B}{\rho G_B + 1}, G_B > \varepsilon_3 \right\} \left\{ \Theta_B > \frac{1}{\Theta_B - 1}, G_B > \varepsilon_3 \right\}$$

$$+ \Pr \left\{ G_F < \frac{\Theta_B G_B}{\rho G_B + 1}, G_B > \varepsilon_3 \right\}$$

$$= \Phi_6$$

(49)

Considering the relationship between $\frac{\Theta_B G_B}{\rho G_B + 1}$ and $\frac{\varepsilon_4 G_B}{G_B - \varepsilon_3}$, we obtain

$$\Pr \left\{ \frac{\varepsilon_4 G_B}{G_B - \varepsilon_3} - \frac{\Theta_B G_B}{\rho G_B + 1} > 0 \right\}$$

$$= \left\{ \begin{array}{ll}
\frac{1}{\Theta_B - 1}, & G_B > \varepsilon_3 \\
\frac{\Theta_B}{\Theta_B - 1}, & G_B < \varepsilon_3 
\end{array} \right\}$$

$$= \Pr \left\{ G_F < \frac{\Theta_B G_B}{\rho G_B + 1}, G_B > \varepsilon_3 \right\}$$

(50)

where $\varepsilon_6 = \frac{\Theta_B G_B}{\rho G_B + 1}$. Then, we obtain $\chi_6$

$$= \Pr \left\{ G_F < \frac{\Theta_B G_B}{\rho G_B + 1}, G_B > \varepsilon_3 \right\}$$

For $\Theta_B < \frac{1}{\Theta_B - 1}$, we have

(51)

$$= \Phi_2$$

Due to $\varepsilon_6 - \varepsilon_3 = \frac{(\Theta_B - 1)}{\Theta_B (1 - (\Theta_B - 1) / \Theta_B)} > 0$, we obtain $\Phi_5$, shown at the top of the next page.

2) When $\Theta_{th} > \frac{\Theta_B}{\Theta_B - 1}$, we have

$$T_{2b} = \Pr \left\{ G_F < \frac{\Theta_B G_B}{\rho G_B + 1}, G_B > \varepsilon_1 \right\} = T_{2a}$$

(54)

With the similar method, $T_3$ is obtained as $\Phi_5$, shown at the top of the next page, where $\Phi_5 = \Phi_2 - \frac{1}{\rho} \frac{\Theta_B}{\rho}, \varepsilon_1 \right\}$.

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\[ T_{2a} = \Pr \left\{ G_F < \frac{\Theta_B G_B}{\rho G_B + 1}, \varepsilon_1 < G_B < \varepsilon_6 \right\} + \Pr \left\{ G_F < \frac{\varepsilon_A G_B}{G_B - \varepsilon_3}, G_B > \varepsilon_6 \right\} = \int_{\varepsilon_1}^{\varepsilon_6} f_{G_B}(y) F_G \left( \frac{\Theta_B y}{\rho y + 1} \right) dy + \int_{\varepsilon_6}^{\infty} f_{G_B}(y) F_G \left( \frac{\varepsilon_A y}{y - \varepsilon_3} \right) dy = \lambda_B^m \Gamma(m) \sum_{i=0}^{m-1} \left( \frac{\lambda_B \Theta_B}{\rho^i} \right)^i \int_{\varepsilon_1}^{\varepsilon_6} y^{m-1-i} e^{-\lambda_B y - \frac{\lambda_B \Theta_B}{\rho^i} y^{m-i+1}} \left( y - \varepsilon_3 \right)^i dy \] (53)

\[ T_3 = \Pr \left\{ G_B > \varepsilon_1, \frac{\Theta_B G_B}{\rho G_B + 1} < G_F < G_B, G_F < \varepsilon_0 \right\} = \Pr \left\{ \frac{\Theta_B G_B}{\rho G_B + 1} < G_F < G_B, \varepsilon_1 < G_B < \varepsilon_6 \right\} + \Pr \left\{ \frac{\Theta_B G_B}{\rho G_B + 1} < G_F < \varepsilon_0, G_B > \varepsilon_6 \right\} = F_{G_F}(\varepsilon_0) \int_{\varepsilon_6}^{\infty} f_{G_B}(y) dy + \int_{\varepsilon_1}^{\varepsilon_6} f_{G_B}(y) F_{G_F}(y) dy - \int_{\varepsilon_1}^{\varepsilon_6} f_{G_B}(y) F_G \left( \frac{\Theta_B y}{\rho y + 1} \right) dy = F_{G_F}(\varepsilon_0) \tilde{F}_{G_B}(\varepsilon_0) + \int_{\varepsilon_1}^{\varepsilon_6} f_{G_B}(y) F_{G_F}(y) dy - \left( 1 - F_{G_B}(\varepsilon_1) \right) - \lambda_B^m \Gamma(m) \sum_{i=0}^{m-1} \left( \frac{\lambda_B}{\rho^i} \right)^i \Phi_2 \] (55)

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