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2020

Tan, E. Z. H., Madhukumar, A. S., Sirigina, R. P. & Krishna, A. K. (2020). Impact of cellular interference on uplink UAV communications. Proceedings of 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring). doi:10.1109/VTC2020-Spring48590.2020.9128682

<https://hdl.handle.net/10356/144699>

<https://doi.org/10.1109/VTC2020-Spring48590.2020.9128682>

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Impact of Cellular Interference on Uplink UAV Communications

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Abstract—The impact of cellular interference on uplink unmanned aerial vehicle (UAV) communications is analyzed in this paper for a multi-UAV network. Specifically, the outage probability and finite signal-to-noise ratio (SNR) diversity gain of the multi-UAV network is characterized in the presence of interference from uplink UAVs and cellular base stations. We demonstrate that the operational altitude of the multi-UAV network determines the severity of cellular interference across low-to-high transmit power regimes. In particular, UAVs operating at higher altitudes are less affected by cellular interference, with higher finite SNR diversity gains and lower outage probability floors observed. Thus, interference mitigation techniques may have to be considered when multi-UAV networks are operating at low altitudes in areas with cellular networks.

Index Terms—Unmanned Aerial Vehicle, Finite SNR, Diversity Gain, Rician Fading, Stochastic Geometry.

I. INTRODUCTION

In upcoming generations of wireless networks, e.g., fifth generation (5G) networks and beyond, unmanned aerial vehicles (UAVs), deployed in large numbers, are expected to fulfill a large variety of roles, e.g., UAV-assisted relays and terrain surveying [1]. To realize the full potential of large-scale UAV deployments, cellular networks can be tapped upon to provide control and non-payload communications (CNPC) and non-CNPC links in multi-UAV networks [2]. Doing so enables multi-UAV networks to operate beyond visual line-of-sight range. However, relying on existing cellular infrastructure to facilitate UAV communications can introduce interference to both cellular and multi-UAV networks [2]. In particular, cellular interference can affect link reliability, thus compromising the operational safety of multi-UAV networks.

To this end, there exists some studies analyzing the impact of cellular interference. For instance, beamforming was studied in [2] while the allocation of transmit power and resource blocks were proposed in [3] to mitigate the impact of UAV interference on the cellular network. Other works have also investigated successive interference cancellation (SIC) [4] and UAV positioning [5] techniques. Despite the above studies, there still exists limited literature on analyzing the impact of cellular interference on multi-UAV networks [2]. For instance, the impact of height on the outage probability and finite signal-to-noise ratio (SNR) diversity gain of multi-UAV networks are

unknown.¹ Also, conclusions from similar studies done in the context of cellular networks cannot be fully applied in multi-UAV networks. Specifically, Rayleigh fading channels are a common assumption in cellular communications, while Rician fading channels are more suitable for UAV communications [1], [6]–[8]. Furthermore, the location of base stations (BSs) and user equipments (UEs) are modeled using Poisson point processes (PPPs) in cellular networks. However, binomial point processes (BPPs) are more appropriate when modeling the locations of UAVs functioning as BSs, i.e., aerial base stations (ABSs) or UEs [8], [9].²

Bearing in mind the above discussion, we present closed-form outage probability and diversity gain expressions to analyze the impact of cellular interference on uplink UAV communications. While finite SNR analysis has been previously analyzed in [1] and [6] for manned aerial vehicle and UAV networks, these works have only considered the specific case of one active uplink node without employing stochastic geometry tools. In contrast, the present paper evaluates the finite SNR performance of a multi-UAV network in the presence of cellular interference through stochastic geometry tools that accounts for an arbitrary number of randomly deployed uplink UAVs. To the best of our knowledge, studies on the finite SNR analysis of multi-UAV networks through stochastic geometry tools are lacking in the literature. The remainder of this paper is organized as follows. We introduce the system model in Section II, with outage probability and finite SNR diversity gain expressions derived in Section III. Numerical results are then discussed in Section IV, before the paper concludes in Section V.

II. SYSTEM MODEL

Consider a multi-UAV network comprising N_U UL UAVs and an ABS operating in a suburban environment. In particular, we focus on the communications between the UL UAVs and the ABS in the presence of interference from N_B cellular

¹Finite SNR diversity gain details the decay rate of outage probability at low-to-moderate SNRs. An analysis of the finite SNR diversity gain can be used to reveal outage probability behaviors that may not be present at high SNRs due to small-scale fading [6].

²In cellular networks, an infinite region is assumed when employing a PPP. However, such an assumption may not be practical for multi-UAV networks, which typically operate over a finite region [9].

Fig. 1. Uplink UAV communications between the UL UAVs and the ABS within a multi-UAV network. Each UL UAV communicates with the ABS at a different altitude in the presence of interfering cellular BSs.

BSs (Fig. 1). Transmissions from the UL UAVs and cellular BSs are assumed to occur over Rician fading channels in order to appropriately model the suburban environment [7]. Furthermore, it is assumed that all nodes in the multi-UAV network are equipped with a single omnidirectional antenna and that Doppler shift is compensated at the ABS.

Since all nodes in the multi-UAV network are assumed to be equipped with a single omnidirectional antenna, transmissions from the UL UAVs and interference from the cellular BSs is experienced at the ABS from all directions. Therefore, from the perspective of the ABS, the spatial locations of the UL UAVs and cellular BSs are randomly distributed around a circular area with the ABS as the origin. To model such a scenario, we employ the BPP-based model seen in [8], [9].³ Specifically, it is assumed that the spatial locations of the UL UAVs are uniformly distributed around a disc centered above the origin O , with altitude H_i , radius r_a , and angle $[0, 2\pi)$ [8], [9]. Similarly, the spatial locations of the cellular BSs are assumed to be uniformly distributed around a disc centered at the origin O , with height H_{BS} , radius r_b , and angle $[0, 2\pi)$. Lastly, the ABS is assumed to be located at the center of the disc, i.e., origin O , at an altitude of H_{ABS} .

For the UL UAVs, the Euclidean distance (km) between UL UAV- i and the ABS is denoted as $d_i = \sqrt{D_i^2 + (H_i - H_{ABS})^2}$, where D_i denotes the Euclidean distance between the projection of UL UAV- i onto the ground plane and the ABS, $H_i = H_{ABS} + \frac{i}{N_U}$, and $H_{BS} < H_{ABS} - 1$. The altitude H_i is chosen such that the UL UAVs are closer to the ABS than the cellular BSs. The probability density function (PDF) of d_i is given as $f_{d_i}(w_i) = \frac{2w_i}{r_a^2}$ [8], [9], where $L_{m,i} \leq w_i \leq L_{p,i}$, $L_{m,i} = \sqrt{(H_i - H_{ABS})^2}$ and $L_{p,i} = \sqrt{(H_i - H_{ABS})^2 + r_a^2}$.

For the cellular BSs, the Euclidean distance (km) between BS- k and the ABS is denoted as $d_k = \sqrt{D_k^2 + (H_{BS} - H_{ABS})^2}$, where D_k is defined in the same manner as D_i . The PDF of d_k is similarly defined as $f_{d_k}(w_k) = \frac{2w_k}{r_b^2}$ [8], [9], where

³It is useful to note that the work in [10] applied BPPs for cellular networks.

$$T_{m,k} \leq w_k \leq T_{p,k}, T_{m,k} = \sqrt{(H_{ABS} - H_{BS})^2} \text{ and } T_{p,k} = \sqrt{(H_{ABS} - H_{BS})^2 + r_b^2}.^4$$

At the ABS, detection of the signal-of-interest (SOI) begins with UL UAV- i . The SOI from UL UAV- i is detected in the presence of multi-user interference (MUI) from the remaining $N_U - i$ UL UAVs and cellular interference from the N_B BSs. Once UL UAV- i is detected, the ABS performs successive interference cancellation (SIC) to remove the SOI of UL UAV- i from the received composite signal. The SIC detection process is repeated by the ABS until all UL UAVs are detected.

For each iteration of the SIC detection process, the instantaneous signal-to-interference-plus-noise ratio (SINR) of UL UAV- i at the ABS is:

$$SINR_i = \frac{X_i d_i^{-n}}{1 + \sum_{j=i+1}^{N_U} X_j d_j^{-n} + \sum_{k=1}^{N_B} Y_k d_k^{-n}}, \quad (1)$$

where n is the pathloss exponent, $X_i = P_t |h_i|^2$, $X_j = P_t |h_j|^2$, $Y_k = P_t |h_k|^2$, P_t is the normalized transmit power, $h_x, x \in \{i, j\}$ is the channel between UL UAV- x and the ABS, and h_k is the channel between BS- k and the ABS. The variables X_i , X_j , and Y_k are non-centered Chi-squared distributed random variables (RVs) with Rician K factor $K_x, x \in \{i, j, k\}$.

From (1), $SINR_i$ reduces into the following instantaneous signal-to-interference ratio (SIR) at high P_t regimes:

$$SIR_i = \frac{\bar{X}_i d_i^{-n}}{\sum_{j=i+1}^{N_U} \bar{X}_j d_j^{-n} + \sum_{k=1}^{N_B} \bar{Y}_k d_k^{-n}}, \quad (2)$$

where $\bar{X}_q = |h_q|^2$ for $q \in \{i, j\}$, and $\bar{Y}_k = |h_k|^2$. The RVs, $\bar{X}_q, q \in \{i, j\}$ and $\bar{Y}_k$ are similarly defined as non-centered Chi-squared distributed RVs with respective Rician K factors $\bar{K}_x, x \in \{i, j, k\}$.

With the above system model in mind, the outage probability and finite SNR diversity gain of multi-UAV networks can now be analyzed in a stochastic geometry framework.

III. OUTAGE PROBABILITY AND FINITE SNR DIVERSITY GAIN DERIVATIONS

We present outage probability and finite SNR diversity gain expressions of UL UAV- i in this section based on our prior work in [1], [8].

A. Outage Probability of Uplink UAV- i

Let the transmission rate of UL UAV- i be R_i . Then, based on (1) and (2), the finite SNR outage event (O_i) and asymptotic outage event ($O_{i,\infty}$) of UL UAV- i are defined as:

$$O_i = \left\{ h_x, d_x^{-n}, x \in \{i, j, k\} : SINR_i \leq \gamma_i \right\}, \quad (3)$$

$$O_{i,\infty} = \left\{ h_x, d_x^{-n}, x \in \{i, j, k\} : SIR_i \leq \gamma_i \right\}, \quad (4)$$

⁴The current system model can be extended to consider the case where all UL UAVs are deployed at the same altitude. In such cases, the Euclidean distance (d_i) of the UL UAVs becomes unordered, i.e., UL UAV-1 may not be the closest node to the ABS, and one will need to obtain the necessary PDFs from the set of ordered Euclidean distances between the i th closest UL UAV and the ABS [9].

where $\gamma_i = 2^{R_i} - 1$. Next, the resulting closed-form outage probability expressions for (O_i) and $(O_{i,\infty})$ are presented below in the following theorems.

Theorem 1: The closed-form outage probability for UL UAV- i is:

$$Pr(O_i) = \sum_{q=0}^{K_{tr}} \sum_{l_1+\dots+l_{N_U+N_B-i+1}=q+1} \alpha(q, P_t, K_i, \gamma_i) \Delta(q, i) \times \left(l_1 + \dots + l_{N_U+N_B-i+1} \right) \left(\prod_{j=1}^{N_U-i} E\{X_{j+i}^{l_j}\} \bar{\Delta}(l_j, j+i) \right) \times \left(\prod_{k=1}^{N_B} E\{Y_k^{l_{N_U-i+k}}\} \Xi(l_{N_U-i+k}) \right) \quad (5)$$

where K_{tr} is the truncation order, $\alpha(q, P_t, K_i, \gamma_i) = (-1)^q \exp(-K_i) \frac{L_q^{(i)}(K_i)}{(1+q)!} \left(\frac{(1+K_i)}{P_t} \gamma_i \right)^{q+1}$ is the cumulative distribution function (CDF) expansion of the RV X_i , $L_q^{(0)}(\bullet)$ is the q -th degree, zero-order Laguerre polynomials [1], [6], [8], and $E\{\bullet\}$ is the statistical expectation. Furthermore, $E\{X_j^{l_j}\} = \Gamma(1+l_j) \left[\frac{P_t}{1+K_j} \right]^{l_j} {}_1F_1(-l_j, 1; -K_j)$ is the l_j^{th} moment of X_j [6, eq. (7)], ${}_1F_1(\bullet)$ is the confluent Hypergeometric function, $\Delta(q, i) = \frac{2}{r_a^2 [n(q+1)+2]} \left[L_{p,i}^{n(q+1)+2} - L_{m,i}^{n(q+1)+2} \right]$, $\bar{\Delta}(l_j, j) = \frac{2}{r_a^2 [2-n \cdot l_j]} \left[L_{p,i}^{2-n \cdot l_j} - L_{m,i}^{2-n \cdot l_j} \right]$, and $\Xi(l_j) = \frac{2}{r_b^2 [2-n \cdot l_j]} \left[T_{p,i}^{2-n \cdot l_j} - T_{m,i}^{2-n \cdot l_j} \right]$.

Proof: Applying [8, Lemma 1] on (1) yields (5). ■

Theorem 2: The closed-form asymptotic outage probability for UL UAV- i is:

$$Pr(O_{i,\infty}) = \sum_{q=0}^{K_{tr}} \sum_{l_1+\dots+l_{N_U+N_B-i}=q+1} \alpha(q, 1, \bar{K}_i, \gamma_i) \Delta(q, i) \times \left(l_1 + \dots + l_{N_U+N_B-i} \right) \left(\prod_{j=1}^{N_U-i} E\{\bar{X}_{j+i}^{l_j}\} \bar{\Delta}(l_j, j+i) \right) \times \left(\prod_{k=1}^{N_B} E\{\bar{Y}_k^{l_{N_U-i+k}}\} \Xi(l_{N_U-i+k}) \right) \quad (6)$$

Proof: Applying [6, Lemma 1] on (2) yields (6). ■

From (5), the outage probability of UL UAV- i can be analyzed for low, moderate, and high P_t regimes with the BPP-based stochastic geometry framework taken into consideration. Furthermore, one can employ (6) to characterize the reliability of UL UAV- i in an interference-limited environment.

B. Finite SNR Diversity Gain of Uplink UAV- i

To characterize the outage probability behavior of UL UAV- i at low-to-moderate P_t regimes, one can employ finite SNR diversity gain analysis. In particular, the decay of the outage probability at UL UAV- i when operating at low-to-moderate P_t regimes is quantified through the finite SNR diversity gain [6]. In the following proposition, we present a closed-form expression for finite SNR diversity gain at UL UAV- i .

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Number of UAVs and BSs	$N_U = 3, N_B = 2$
Rician K Factors	10 dB [7, Table V]
Normalized Transmit Power	0 dB $\leq P_t \leq 30$ dB
Transmission Rate	$R_i = 0.015$ b/s/hz
Radius	$r_a = 4$ km, $r_b = 8$ km
ABS Altitude	$0.7 \text{ km} \leq H_{ABS} \leq 4.7 \text{ km}$
BS Altitude	$H_{BS} = 0.01 \text{ km}$
Pathloss Exponent	$n = 2$ [7, Table III]

Proposition 1: The finite SNR diversity gain for UL UAV- i is:

$$d_{f,i} = \frac{-P_t}{Pr(O_i)} \sum_{q=0}^{K_{tr}} \sum_{l_1+\dots+l_{N_U+N_B-i+1}=q+1} \alpha(q, 1, K_i, \gamma_i) \Delta(q, i) \times \left(l_1 + \dots + l_{N_U+N_B-i+1} \right) \left(\prod_{j=1}^{N_U-i} E\{X_{j+i}^{l_j}\} \bar{\Delta}(l_j, j+i) \right) \times \left(\prod_{k=1}^{N_B} E\{Y_k^{l_{N_U-i+k}}\} \Xi(l_{N_U-i+k}) \right) \frac{-q-1+\sum_{j=1}^{N_U+N_B-i} l_j}{(P_t)^{-q-2+\sum_{j=1}^{N_U+N_B-i} l_j}} \quad (7)$$

Proof: Applying [8, eq. (13)] and then taking the derivative with respect to P_t yields (7). ■

Corollary 1: At asymptotic P_t regimes, the asymptotic behavior of $d_{f,i}$ is evaluated as

$$\lim_{P_t \rightarrow \infty} d_{f,i} = 0. \quad (8)$$

Proof: The proof is given in the Appendix. ■

Remark 1: Corollary 1 can also be proven from the fact that the asymptotic outage probability of UL UAV- i exists in (6). In particular, (6) indicates the existence of an error floor. Thus, outage probability does not decay at asymptotic P_t regimes. To see this, applying [8, eq. (13)] on (6) yields zero since (6) is independent of P_t .

As a performance metric, (7) can be used to identify P_t regimes that results in interference-limited UAV communications between UL UAV- i and the ABS. In particular, the SIC detection process at the ABS for UL UAV- i becomes interference-limited when P_t leads $d_{f,i} \rightarrow 0$, as shown in Section IV.

IV. NUMERICAL RESULTS

The numerical and simulation results are presented for UL outage probability and finite SNR diversity gain in the multi-UAV network. Using Table I, Monte Carlo simulations were conducted with 10^5 samples.

Fig. 2 shows the outage probability of UL UAV- i ($Pr(O_i)$) at the ABS. Evidently, UL UAV- i exhibits higher outage probability than UL UAV- j for $i < j$, i.e., $Pr(O_j) < Pr(O_i)$, since it is detected in the presence of cellular interference from the N_B BSs and MUI from the $N_U - i$ remaining UL UAVs. Furthermore, (6) is verified as it can be seen from Fig. 2 that $Pr(O_i)$ approach the asymptotic outage probability ($Pr(O_{i,\infty})$) when $P_t > 20$ dB.

Fig. 2. Outage probability comparison for UL UAV- i in the multi-UAV network for $H_{ABS} = 0.7$ km.

Fig. 3. Finite SNR diversity gain comparison for UL UAV- i in the multi-UAV network.

From Fig. 2, it is straightforward to see that increasing P_t leads to higher outage probability due to stronger cellular interference and MUI. As a result, the decay of the outage probability, i.e., finite SNR diversity gain, also diminishes as P_t is increased due to strong cellular interference and MUI. Such an observation is reflected in Fig. 3, where the finite SNR diversity gain of the UL UAVs ($d_{f,i}$) is plotted for ABS altitude $H_{ABS} \in \{0.7 \text{ km}, 1.5 \text{ km}\}$. At low-to-moderate P_t regimes, i.e., $0 \text{ dB} \leq P_t \leq 20 \text{ dB}$, Fig. 3 shows $d_{f,i}$ to be decreasing as P_t increases for $H_{ABS} \in \{0.7 \text{ km}, 1.5 \text{ km}\}$ due to stronger cellular interference and MUI. As a result, the decay rate of $Pr(O_i)$, i.e., finite SNR diversity gain, reduces in the face of stronger cellular interference and MUI. It is also worth noting that increasing H_{ABS} leads to higher $d_{f,i}$ since weaker cellular interference from the BSs is experienced. At high P_t regimes, i.e., $P_t > 20 \text{ dB}$, the SIC detection process for the UL UAVs at the ABS becomes limited by cellular interference as $d_{f,i} \rightarrow 0$. It is also observed that increasing H_{ABS} does not improve $d_{f,i}$ at high P_t regimes. Therefore, cellular interference can cause UAV communications to be interference-limited, even when the UAVs are operating at high altitudes.

The impact of H_{ABS} on $Pr(O_{i,\infty})$ for the UL UAVs is seen in Fig. 4. It is noted that increasing H_{ABS} leads to a decrease in $Pr(O_{i,\infty})$ for the UL UAVs. In particular, the decrease is greater for UL UAV- j than UL UAV- i for $i < j$. For instance,

Fig. 4. Impact of ABS height H_{ABS} on asymptotic outage probability for UL UAV- i in the multi-UAV network for $0.7 \text{ km} \leq H_{ABS} \leq 4.7 \text{ km}$.

the drop in $Pr(O_{2,\infty})$ for UL UAV-2 is greater than the drop in $Pr(O_{1,\infty})$ for UL UAV-1 when $0.7 \text{ km} \leq H_{ABS} \leq 1 \text{ km}$. Also, increasing H_{ABS} beyond 1.5 km does not lead to any significant drop in $Pr(O_{1,\infty})$ for UL UAV-1 as the ABS SIC detection process is largely limited by MUI from the remaining UL UAVs. Likewise, increasing H_{ABS} beyond 2 km does not lead to any significant drop in $Pr(O_{2,\infty})$ for UL UAV-2 as the ABS SIC detection process is also limited by MUI from UL UAV-3. Finally, for UL UAV-3, the ABS detection process is only limited by interference from the cellular BSs. Thus, $Pr(O_{3,\infty})$ for UL UAV-3 is observed to be monotonically decreasing when H_{ABS} increases.

The behavior of $d_{f,i}$ for the UL UAVs is plotted in Fig. 5 for $0 \text{ dB} \leq P_t \leq 30 \text{ dB}$ and $0.7 \text{ km} \leq H_{ABS} \leq 1.7 \text{ km}$. Starting with UL UAV-1, only a minute improvement in $d_{f,1}$ is observed at very low P_t regimes when H_{ABS} is increased. At moderate-to-high P_t regimes, $d_{f,1}$ is not affected by changes in H_{ABS} as it is limited by MUI. Similar observations are also made for UL UAV-2. For UL UAV-3, $d_{f,3}$ is observed to be increasing at low-to-moderate P_t regimes when H_{ABS} increases. However, at high P_t regimes, increasing H_{ABS} also does not elicit any changes in $d_{f,3}$ as it is limited by cellular interference. Therefore, Fig. 5 shows that increasing the ABS altitude H_{ABS} only leads to a drop in $d_{f,i}$ at low-to-moderate P_t regimes due to strong cellular interference and MUI at moderate-to-high P_t regimes.

Clearly, from the above discussions, cellular interference from surrounding cellular BSs can have a detrimental effect on the reliability of UAV communications. The impact of cellular interference on multi-UAV networks is also more severe in areas that have a dense concentration of cellular BSs, e.g., urban areas. Thus, one may have to rely on interference cancellation techniques or UAV positioning techniques to mitigate the impact of cellular interference for multi-UAV networks.

V. CONCLUSION

In this paper, the outage probability and finite SNR diversity gain of UAV communications in the presence of cellular interference is analyzed in a stochastic geometry framework. We show that the multi-UAV network becomes interference-

Fig. 5. Impact of transmit power P_t and ABS height H_{ABS} on finite SNR diversity gain at UL UAV- i .

limited due to cellular interference at high transmit power regimes. We also demonstrate that the impact of cellular interference varies with the operating height of UAVs. Specifically, increasing the height of the UAVs reduces the impact of cellular interference on finite SNR diversity gains and outage probability. Therefore, to enable a meaningful coexistence of multi-UAV and cellular networks, one may need to employ interference mitigation techniques.

ACKNOWLEDGMENT

This research is supported by the Singapore Ministry of Education Academic Research Fund Tier 1 grants.

APPENDIX

Following the same approach in [6, Appendix C] and [11, Appendix E], $d_{f,i}$ can be further simplified as seen below:

$$d_{f,i} = \frac{1}{Pr(O_i)} \sum_{q=0}^{K_{tr}} \sum_{l_1+\dots+l_{N_U+N_B-i+1}=q+1} \alpha(q, 1, K_i, \gamma_i) \Delta(q, i) \times \left(\frac{l_1 + \dots + l_{N_U+N_B-i+1}}{l_1, \dots, l_{N_U+N_B-i+1}} \right) \left(\prod_{j=1}^{N_U-i} E \left\{ \bar{X}_{j+i}^{l_j} \right\} \bar{\Delta}(l_j, j+i) \right) \times \left(\prod_{k=1}^{N_B} E \left\{ \bar{Y}_k^{l_{N_U-i+k}} \right\} \Xi(l_{N_U-i+k}) \right) \frac{q+1 - \sum_{j=1}^{N_U+N_B-i} l_j}{(P_t)^{-q-1+\sum_{j=1}^{N_U+N_B-i} l_j}} \quad (9)$$

where the expression for $Pr(O_i)$ in (5) can also be simplified in the same manner.

Next, it is useful to note that $\sum_{j=1}^{N_U+N_B-i} l_j = q+1$ when $l_{N_U+N_B-i+1} = 0$. Also, $\lim_{P_t \rightarrow \infty} (P_t)^{-q-1+\sum_{j=1}^{N_U+N_B-i} l_j} = 0$ for $\sum_{j=1}^{N_U+N_B-i} l_j < q+1$. Thus, we only need to consider $\sum_{j=1}^{N_U+N_B-i} l_j = q+1$, i.e., $l_{N_U+N_B-i+1} = 0$, when evaluating $d_{f,i}$ at asymptotic P_t regimes. Finally, substituting $q+1 - \sum_{j=1}^{N_U+N_B-i} l_j = l_{N_U+N_B-i+1}$ in (9) yields:

$$d_{f,i} = \frac{1}{Pr(O_i)} \sum_{q=0}^{K_{tr}} \sum_{l_1+\dots+l_{N_U+N_B-i+1}=q+1} \alpha(q, 1, K_i, \gamma_i) \Delta(q, i) \times \left(\frac{l_1 + \dots + l_{N_U+N_B-i+1}}{l_1, \dots, l_{N_U+N_B-i+1}} \right) \left(\prod_{j=1}^{N_U-i} E \left\{ \bar{X}_{j+i}^{l_j} \right\} \bar{\Delta}(l_j, j+i) \right)$$

$$\times \left(\prod_{k=1}^{N_B} E \left\{ \bar{Y}_k^{l_{N_U-i+k}} \right\} \Xi(l_{N_U-i+k}) \right) \frac{l_{N_U+N_B-i+1}}{(P_t)^{l_{N_U+N_B-i+1}}} \quad (10)$$

From (10), setting $l_{N_U+N_B-i+1} = 0$ results in a zero in the numerator while the denominator becomes independent of P_t . This completes the proof.

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