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# Interference Management in Ultra-Dense 5G Networks With Excessive Drone Usage

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**ABSTRACT** In fifth generation (5G) networks, the densification of small base stations in the coverage region of macro base station (MBS) leads to significant inter-cell interference (ICI). Similarly, drones (a.k.a. unmanned aerial vehicles) have a diverse scope in multifarious 5G assisted applications and, therefore, cause considerable drones interference (DI) as a result of excessive drone usage. This paper investigates the bottleneck uplink (UL) coverage performance of the MBS edge users in the presence of ICI and DI. To mitigate both ICI and DI, we use an efficient resource allocation scheme known as reverse frequency allocation (RFA). Moreover, we use decoupled association (DeCA) in place of coupled association to further improve UL signal-to-interference ratio. The results depict that RFA in conjunction with DeCA overpass all other techniques in terms of improved UL coverage performance because of effective DI and ICI mitigation.

**INDEX TERMS** Coverage probability, coupled association, decoupled association, heterogeneous cellular networks, interference mitigation, reverse frequency allocation.

## I. INTRODUCTION

### A. MOTIVATION

In fifth-generation (5G) networks, ultra-dense deployment of small base stations (SBSs) in the macro base station (MBS)' coverage region, high MBS transmit power, and aggressive frequency reuse lead to significant inter-cell interference (ICI) [1]–[4]. Meanwhile, unmanned aerial vehicles, popularly known as drones, are expected to be used excessively for 5G assisted applications because of their higher maneuverability, hovering, ease of deployment, and lower maintenance and operating costs [5], [6]. The prominent 5G applications of drones include mineral exploration, precision agriculture, smart logistics, air surveillance, disaster assistance, and emergency healthcare [7], [8]. Such applications demand for an excessive use of drones assisted by 5G networks. However,

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such excessive drone usage (EDU) leads to additional traffic load in conjunction with users' traffic load and, hence, causes significant drones interference (DI). In this paper, we explore the effect of DI and ICI on the bottleneck uplink (UL) communication of MBS coverage edge users (M-EUs). Here, the bottleneck UL communication indicates the limitations in UL communications, i.e., (i) lower UL transmit power by user equipment (UE), which leads to lower UL signal-to-interference ratio (SIR), and (ii) limited available power in battery-operated UEs [9], [10].

In two-tier heterogeneous cellular networks (HetNets), coupled association (CA) is often considered, where a user equipment (UE) associates with the same base station (BS) both in downlink (DL) and UL following the maximum received power (MRP) association rule [11], [12]. CA is typically followed when the UEs are closer to the serving BS. However, the M-EUs following CA experience lower signal-to-interference ratio (SIR) because of their longer

distances from the BS [13], [14]. Therefore, decoupled association (DeCA) has attracted considerable attention, where a user associates in UL and DL directions with different tiers of BSs [15]. By using DeCA, UL SIR of M-EUs is significantly increased because of nearest SBS association [15].

In the state-of-the-art, different interference management schemes, such as fractional frequency reuse (FFR) [16] and soft frequency reuse (SFR) [17], have been studied. The SFR scheme achieves better spectral efficiency as a result of frequency reuse, while FFR leads to lower interference due to partitioning of total available bandwidth [18], [19]. Another proactive resource allocation scheme available in the state-of-the-art is reverse frequency allocation (RFA) [20]–[22]. In RFA, the complete bandwidth is made available to both MBS and SBS in a cell. Thus, RFA is spectrally more efficient as compared with both FFR and SFR. Therefore, we employ RFA with DeCA to alleviate ICI and DI (see Sec. II-B2 for details on RFA).

## B. RELATED WORK

In [23], the authors examine the effects of users and device mobility in device-to-device (D2D) and drone-assisted mission-critical machine-type communications. Their results show that D2D links and drone-assisted access lead to 40% improvements in link availability and reliability on top of the cellular-only baseline. The work in [24] investigates the security challenges posed by drones to sensitive installations. The paper also highlights the importance of drone monitoring, which can help to avoid damages to sensitive installations. Diverse drone platform applications and challenges in the network infrastructure are discussed in [25]. Their study highlights the significance of using drones in heterogeneous networks to improve the network capacity and coverage. The work in [26] investigates the use of drones mounted miniaturized BSs to serve the network mobile users. The authors propose that the drones move continuously within the cell. Therefore, their proposed setup reduces the distance between the BS and the UEs and, hence, improves spectral efficiency of the network. The simulation results in [26] indicate that their proposed model leads to improved spectral efficiency as compared with the scenario where drones hover over fixed locations. In [27], the authors evaluate the usage of drones in conventional terrestrial cellular networks. They investigate DL spectral efficiency of the network with optimal altitude and intensity of drones. Their results show that drones' usage provides improved DL spectral efficiency for conventional terrestrial cellular networks. Similarly, the authors in [28] evaluate drones' usage in multiple-input multiple-output (MIMO) and non-orthogonal multiple access assisted networks while utilizing stochastic geometry framework. They derive outage probability expressions for proposed setup. Their results show that rate and coverage of far users rely on power allocation factors.

RFA along with CA and DeCA are considered in [29]. The authors derive DL coverage probability expressions for their proposed setup. Their results show that RFA along with

DeCA overpass other techniques with respect to coverage performance in the DL. In [30], the authors investigate interference mitigation and resource management while employing D2D communications. Moreover, the authors employ DeCA and FFR in conjunction with their proposed setup. Their results show that their proposed model significantly abates the interference.

The work in [31] considers RFA in non-uniform HetNets. It is assumed that the SBSs located near MBS are muted while SBSs remain active in the MBS edge area. The results indicate that non-uniform HetNets with RFA lead to improved UL coverage. The work in [32] proposes modified RFA, which leads to significant coverage improvement as a result of reduced interference.

This work is different from the state-of-the-art as follow:

- 1) The works in [23]–[28] discuss various application scenarios of drone usage. However, they lack the analysis of DI because of 5G assisted EDU. Therefore, in this paper, we investigate both DI and ICI that affect the bottleneck UL SIR of M-EUs.
- 2) The works in [29]–[32] analyze DL coverage in the presence of ICI, however, in this paper, we investigate UL coverage performance in the presence of ICI and DI.

## C. CONTRIBUTIONS

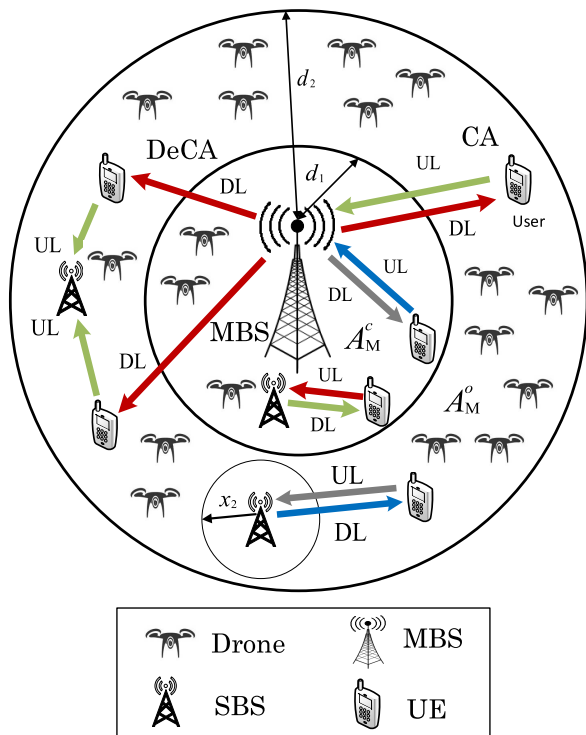
In this paper, we investigate DI due to EDU for 5G assisted applications and ICI due to multi-tier deployment. The coverage region of MBS is split into non-intersecting regions, i.e., center region,  $A_M^c$ , and outer region,  $A_M^o$ , with radii  $d_1$  and  $d_2$ , respectively (see Fig. 1). The analysis is performed on typical user,  $\nu$ , located in  $A_M^o$ . The main contributions of this paper are listed as follows:

- 1) Investigation of bottleneck M-EUs' UL coverage performance in the presence of both DI and ICI.
- 2) Mitigation of DI and ICI by utilizing RFA along with DeCA and, hence, improving UL SIR of the M-EUs.
- 3) Derivations of the UL coverage probabilities for the following network scenarios for  $\nu \in A_M^o$ : (i) RFA, CA, and EDU, and (ii) RFA, DeCA, and EDU.
- 4) The results depict 16% UL coverage improvement as observed at SIR threshold,  $\gamma_M = -10$  dB by DeCA with RFA employment in contrast to CA with RFA employment. Moreover, at  $\gamma_M = -10$  dB and drones density,  $\rho_D = 50$ , DeCA and RFA cause 8% UL coverage improvement in comparison with CA and RFA. Furthermore, increasing  $\rho_D$  from 100 to 150 at  $\gamma_M = -10$  dB leads to 15% UL coverage degradation because of significant DI.

In the results, we show that an increase in  $\rho_D$  causes significant DI and consequently lowers the UL coverage. Moreover, the results indicate that RFA with DeCA produces improved UL coverage as opposed to CA with RFA.

## D. PAPER ORGANIZATION

The rest of the paper is organized as follows. After presenting the system model in Section II, UL coverage probabilities are



**FIGURE 1.** A multi-tier HetNet deployment model with EDU, RFA and DeCA.  $A_M^c$  and  $A_M^o$  denote the center and outer regions of MSB, respectively.

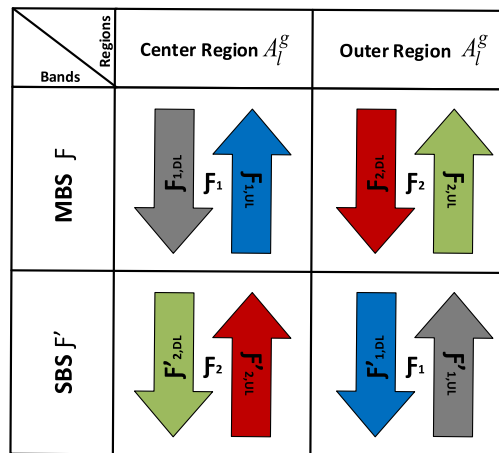
**TABLE 1.** Notation summary.

Notation	Description
'	Decoupled association
"	Coupled association
$\nu$	Typical user
$\alpha$	Path loss exponent
$ h $	Power gain of Rayleigh fading
$\zeta_1$	Ratio of $P_{t,S}^{DL}$ and $P_{t,\nu}^{UL}$
$\zeta_2$	Ratio of $P_{t,D}^{DL}$ and $P_{t,\nu}^{UL}$
$\phi_M, \phi_S, \phi_D$	IHPPPs of MBSs, SBSs, and drones, respectively
$\gamma_M, \gamma_S$	SIR thresholds for MBSs and SBSs, respectively
$d_1, d_2$	Radii of $A_M^c$ and $A_M^o$ , respectively
$\rho_M, \rho_S, \rho_D$	Densities of MBSs, SBSs, and drones, respectively
$r_l, r_k, r_j$	Distances from MBSs, SBSs, and drones, $\forall l \in \{\phi_M\}, k \in \{\phi_S\},$ and $j \in \{\phi_j\}$

derived in Section III. Numerical and simulation results with discussion are presented in Section IV. Finally, Section V concludes our work and presents future directions. The notations used in this paper are listed in Table 1.

## II. SYSTEM MODEL

This section presents the proposed network layout with DI due to EDU for 5G assisted applications and ICI due to



**FIGURE 2.** Frequency allocation in the two-tier HetNets via RFA.

multi-tier deployment. Moreover, DeCA and RFA are employed to abate ICI and DI. Furthermore, in this section, we develop mathematical preliminaries that will be used for the UL coverage analysis afterwards.

### A. NETWORK LAYOUT WITH ASSUMPTIONS

In this paper, we consider a two-tier HetNet, comprising of MBSs, SBSs, and drones with densities  $\rho_M, \rho_S,$  and  $\rho_D,$  respectively. MBSs, SBSs, UEs, and drones are deployed using independent homogeneous Poisson point processes (IHPPPs), i.e.,  $\phi_M, \phi_S, \phi_u,$  and  $\phi_D,$  respectively, as shown in Fig. 1. This work considers frequency division duplex (FDD) systems, where different channels are used for UL and DL as indicated in Fig. 1 and Fig. 2. This work can be extended to incorporate time division duplex (TDD) systems, where the same frequency is used for both UL and DL directions in different time slots [33]. In contrast to FDD systems, TDD system with DeCA leads to lower interference at the cost of increased synchronization signaling [34]. We investigate DI resulting from EDU and ICI because of multi-tier deployment. To mitigate DI and ICI, we use RFA with DeCA as opposed to RFA with CA. Interference is considered to be the dominant performance limiting factor and, thus, noise is ignored. The analysis is performed on  $\nu$  located at the origin by using the Slivnyak Theorem which retains and simplifies the statistical properties of IHPPPs [21], [35]. This work assumes Rayleigh fading for tractability in SIR analysis using Laplace transform (LT) [36]. In particular,  $|h|$  models Rayleigh fading, which is independent and exponentially distributed with unit mean, i.e.,  $|h| \sim \exp(1)$  [37].

### B. OVERVIEW OF SCHEMES

Here, we give a brief overview of the schemes used in this paper from the system model perspective.

#### 1) COUPLED AND DECOUPLED ASSOCIATIONS

According to CA,  $\nu$  associates both in UL and DL with the identical tier  $\omega_1$  following the DL association rule (see

**Definition 1** for the DL association rule) [15]. However, according to DeCA,  $v$  associates in the DL with tier  $\omega_1$  based on the DL association rule and with another tier  $\omega_2$  in the UL based on UL association rule (see **Definition 2** for the UL association rule [29]). Therefore, by following DeCA in our proposed model,  $v$  associates in the DL with MBS following MRP, and with the SBS in the UL based path loss model.

*Definition 1: (DL association rule).* In the DL association rule, a user connects in the DL with tier  $\omega_1$  following MRP scheme [12]. Association with  $\omega_1$  can be expressed as

$$\omega_1 = \arg \max_{i \in (M,S)} P_{t,i}^{DL} r_{i,v}^{-\alpha}. \quad (1)$$

Here,  $P_{t,i}^{DL}$  denotes the transmit power of BS in DL,  $r$  indicate the distance between  $v$  and associated BS, and  $\alpha$  indicates the path loss exponent.

*Definition 2: (UL association rule).* According to UL association rule, a user associates in the UL with tier  $\omega_2$  based on path loss, i.e.,  $r^{-\alpha}$  [29]. The association with  $\omega_2$  can be expressed as

$$\omega_2 = \arg \max_{i \in (M,S)} r_i^{-\alpha}. \quad (2)$$

## 2) REVERSE FREQUENCY ALLOCATION

In HetNets high throughput is obtained by frequency reuse. This, however, leads to severe ICI because of co-channel interference. Therefore, there is a need for effective interference management scheme. Hence, we use RFA (an FDD system) in conjunctions with DeCA to increase spectral efficiency due to lower interference. In RFA, the total available frequency band,  $\mathcal{F}$ , is split into two sub-bands, i.e.,  $\mathcal{F}_1$  and  $\mathcal{F}_2$ , such that  $\mathcal{F} = \bigcup_{j \in 1,2} \mathcal{F}_j$ . Here, frequency sub-bands of MBS, i.e.,  $\mathcal{F}_1$  and  $\mathcal{F}_2$  are used in  $A_M^c$  and  $A_M^o$ , respectively, as shown in Fig. 2. The sub-bands  $\mathcal{F}_1$  and  $\mathcal{F}_2$  are further divided into UL and DL sub-carriers of the MBS and are denoted as  $\mathcal{F}_1 = \mathcal{F}_{1,UL} + \mathcal{F}_{1,DL}$  and  $\mathcal{F}_2 = \mathcal{F}_{2,UL} + \mathcal{F}_{2,DL}$ , in  $A_M^c$  and  $A_M^o$ , respectively [4]. The UL and DL sub-carriers in  $\mathcal{F}_1$  and  $\mathcal{F}_2$  of MBS are used as the frequency sub-carriers in  $\mathcal{F}'_1$  and  $\mathcal{F}'_2$  for the SBS in reverse direction, i.e., DL and UL transmissions with corresponding alternate regions  $A_M^o$  and  $A_M^c$ , respectively [4], [11]. Similarly, the UL and DL sub-carriers of the SBS in  $A_M^c$  and  $A_M^o$  are denoted as  $\mathcal{F}_2 = \mathcal{F}'_{2,UL} + \mathcal{F}'_{2,DL}$  and  $\mathcal{F}'_1 = \mathcal{F}'_{1,UL} + \mathcal{F}'_{1,DL}$ , respectively. RFA provides improved UL coverage because of effective ICI mitigation [20], [29].

## III. ANALYSIS OF COVERAGE PROBABILITY

In this section, we derive UL coverage probability expressions for: (i) EDU, RFA, and CA, (see Sec. III-A), and (ii) EDU, RFA, and DeCA (see Sec. III-B).

### A. UL COVERAGE PROBABILITY WITH CA

The UL coverage probability given that  $v \in A_M^o$ ,  $P_{A_M^o}^{UL''}(\gamma_M)$ , while assuming EDU, RFA, and CA, can be written as [20]

$$P_{A_M^o}^{UL''}(\gamma_M) = P\left(\text{SIR}_M^{UL} > \gamma_M\right). \quad (3)$$

Here,  $\text{SIR}_M^{UL}$  is the UL received SIR by MBS and  $\gamma_M$  is the SIR threshold of MBS. Because of RFA, the UL interference received is the union of MBS-tier UL interference in  $A_M^c$ ,  $I_{\phi_M, A_M^c}^{UL}$ , SBS-tier DL interference in  $A_M^o$ ,  $I_{\phi_S, A_M^o}^{DL}$ , and the interference from EDU,  $I_{\phi_D, A_M^c}^{DL}$ . Therefore,  $\text{SIR}_M^{UL}$  from (3) can be rewritten as

$$\text{SIR}_M^{UL} = \frac{P_{t,v}^{UL} |h_M| r_M^{-\alpha}}{I_{\phi_M, A_M^o}^{UL} + I_{\phi_S, A_M^o}^{DL} + I_{\phi_D, A_M^c}^{DL}}. \quad (4)$$

Eq. (4) can be further expanded as

$$\begin{aligned} \text{SIR}_M^{UL} &= \frac{P_{t,v}^{UL} |h_M| r_M^{-\alpha}}{\sum_{l \in \phi_M} P_{t,l}^{UL} |h_l| r_l^{-\alpha} + \sum_{k \in \phi_S} P_{t,k}^{DL} |h_k| r_k^{-\alpha} + \sum_{j \in \phi_D} P_{t,j}^{DL} |h_j| r_j^{-\alpha}}. \end{aligned} \quad (5)$$

Here,  $P_{t,l}^{UL}$  denotes the UL transmit power of MBS associated  $v$ ,  $P_{t,k}^{DL}$  indicates the SBS transmit power in DL, and  $P_{t,j}^{DL}$  is the drones transmit power in DL. Now, by substituting (4) into (3), we obtain  $P_{A_M^o}^{UL''}(\gamma_M)$  as

$$\begin{aligned} &P_{A_M^o}^{UL''}(\gamma_M) \\ &= P\left(\frac{P_{t,v}^{UL} |h_M| r_M^{-\alpha}}{I_{\phi_M, A_M^o}^{UL} + I_{\phi_S, A_M^o}^{DL} + I_{\phi_D, A_M^c}^{DL}} > \gamma_M\right) \\ &= \mathbb{E}_{r_M, I_{\phi_M, A_M^o}^{UL}, I_{\phi_S, A_M^o}^{DL}, I_{\phi_D, A_M^c}^{DL}} \left[ \exp\left(-\frac{r_M^\alpha \gamma_M}{P_{t,v}^{UL}} \left(I_{\phi_M, A_M^o}^{UL} + I_{\phi_S, A_M^o}^{DL} + I_{\phi_D, A_M^c}^{DL}\right)\right) \right] \\ &= \mathbb{E}_{r_M} \left[ \mathcal{L}_{I_{\phi_M, A_M^o}^{UL}}(s) \times \mathcal{L}_{I_{\phi_S, A_M^o}^{DL}}(s) \times \mathcal{L}_{I_{\phi_D, A_M^c}^{DL}}(s) \right] \Big|_{s = \frac{r_M^\alpha \gamma_M}{P_{t,v}^{UL}}}, \end{aligned} \quad (6)$$

where  $\mathcal{L}(\cdot)$  denotes the LT.

The LT of the interference from MBS-tier in UL, i.e.,  $\mathcal{L}_{I_{\phi_M, A_M^o}^{UL}}(s)$ , is obtained as

$$\begin{aligned} &\mathcal{L}_{I_{\phi_M, A_M^o}^{UL}}(s) \\ &= \exp\left(\frac{\rho_M \pi \gamma_M d_2^{(2-\alpha)} r_M^\alpha}{\alpha/2 - 1} {}_2F_1 \right. \\ &\quad \left. \left(1, 1 - \frac{2}{\alpha}, 2 - \frac{2}{\alpha}, -\gamma_M \left(\frac{r_M}{d_2}\right)^\alpha\right) \right. \\ &\quad \left. - \frac{\rho_M \pi \gamma_M d_1^{(2-\alpha)} r_M^\alpha}{\alpha/2 - 1} {}_2F_1 \right. \\ &\quad \left. \times \left(1, 1 - \frac{2}{\alpha}, 2 - \frac{2}{\alpha}, -\gamma_M \left(\frac{r_M}{d_1}\right)^\alpha\right) \right). \end{aligned} \quad (7)$$

*Proof:* The proof of (7) is given in Appendix A.



We obtain the LT of the interference from SBSs in DL, i.e.,  $\mathcal{L}_{I_{\phi_S A_M^o}}^{\text{DL}}(s)$ , in a way similar to (7), and given as

$$\begin{aligned} \mathcal{L}_{I_{\phi_S A_M^o}}^{\text{DL}}(s) &= \exp\left(\frac{\rho_S \pi \zeta_1 \gamma_M x_2^{(2-\alpha)} r_M^\alpha}{\alpha/2 - 1} {}_2F_1\right. \\ &\quad \left(1, 1 - \frac{2}{\alpha}, 2 - \frac{2}{\alpha}, -\zeta_1 \gamma_M \left(\frac{r_M}{x_2}\right)^\alpha\right) \\ &\quad - \frac{\rho_S \pi \zeta_1 \gamma_M x_1^{(2-\alpha)} r_M^\alpha}{\alpha/2 - 1} {}_2F_1 \\ &\quad \left. \times \left(1, 1 - \frac{2}{\alpha}, 2 - \frac{2}{\alpha}, -\zeta_1 \gamma_M \left(\frac{r_M}{x_1}\right)^\alpha\right)\right). \quad (8) \end{aligned}$$

Here,  $\zeta_1$  is the ratio of  $P_{t,S}^{\text{DL}}$  and  $P_{t,v}^{\text{UL}}$ , where  $P_{t,S}^{\text{DL}}$  is the SBS DL transmit power.

From (8), the LT of the interference from SBSs in UL, i.e.,  $\mathcal{L}_{I_{\phi_S A_M^o}}^{\text{UL}}(s)$ , is obtained as

$$\mathcal{L}_{I_{\phi_S A_M^o}}^{\text{UL}}(s) = \left(\mathcal{L}_{I_{\phi_S A_M^o}}^{\text{DL}}\right) \setminus \zeta_1, \quad (9)$$

where  $(\cdot) \setminus \zeta_1$  denotes the exclusion of  $\zeta_1$  from (8).

The LT of DI due to EDU, i.e.,  $\mathcal{L}_{I_{\phi_D A_M^c}}^{\text{DL}}(s)$ , can be given as

$$\begin{aligned} \mathcal{L}_{I_{\phi_D A_M^c}}^{\text{DL}}(s) &= \exp\left(\frac{\rho_D \pi \zeta_2 \gamma_M d_1^{(2-\alpha)} r_M^\alpha}{\alpha/2 - 1} {}_2F_1\right. \\ &\quad \left(1, 1 - \frac{2}{\alpha}, 2 - \frac{2}{\alpha}, -\zeta_2 \gamma_M \left(\frac{r_M}{d_1}\right)^\alpha\right) \\ &\quad - \frac{\rho_D \pi \zeta_2 \gamma_M y^{(2-\alpha)} r_M^\alpha}{\alpha/2 - 1} {}_2F_1 \\ &\quad \left. \times \left(1, 1 - \frac{2}{\alpha}, 2 - \frac{2}{\alpha}, -\zeta_2 \gamma_M \left(\frac{r_M}{y}\right)^\alpha\right)\right). \quad (10) \end{aligned}$$

In (10),  $\zeta_2$  is the ratio of  $P_{t,D}^{\text{DL}}$  and  $P_{t,v}^{\text{UL}}$ , where  $P_{t,D}^{\text{DL}}$  is the transmit power of drones in  $A_M^c$ .  $y$  and  $d_1$  define the interfering drones area, s.t.,  $y < d_1$ .

Proof: See Appendix B for the proof of (10).

Given that  $v \in A_M^o$ , i.e.,  $v_{A_M^o}$ , and associated with MBS at a distance  $r_M$ , has the PDF of distances given as [38]

$$f_{r_M|v_{A_M^o}}(r_M) = \frac{2\pi\rho_M r_M \exp(-\rho_M \pi r_M^2)}{\exp(-\rho_M \pi d_1^2)}. \quad (11)$$

Similarly, assuming that  $v \in A_M^o$ , i.e.,  $v_{A_M^o}$ , and associated with SBS at a distance  $r_S$ , has the PDF of distances given as

$$f_{r_S|v_{A_M^o}}(r_S) = \frac{2\pi\rho_S r_S \exp(-\rho_S \pi r_S^2)}{\exp(-\rho_S \pi d_1^2)}. \quad (12)$$

The UL coverage probability expression, i.e.,  $P_{A_M^o}^{\text{UL}'}(\gamma_M)$ , for  $v$  associated with MBS in  $A_M^o$  while considering EDU,

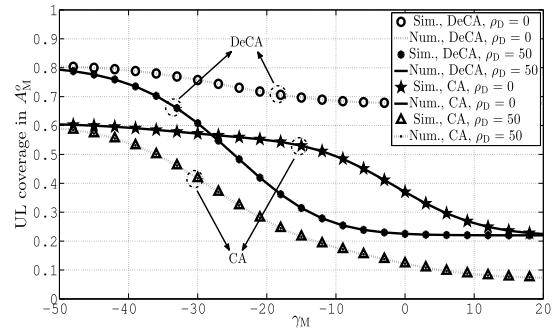


FIGURE 3. UL coverage in  $A_M^o$  with CA and DeCA.

TABLE 2. Simulation parameters.

Parameter	Configuration
MBS, SBS, and drone distributions	IHPPP
Code iterations	5000
$\rho_S$	$15/\pi(1000\text{m})^2$
$\rho_M$	$3/\pi(1000\text{m})^2$
$\rho_D$	$50/\pi(100\text{m})^2$
$P_{t,M}^{\text{UL}}, P_{t,S}^{\text{DL}}, P_{t,v}^{\text{UL}}, P_{t,D}^{\text{DL}}$	40 dBm, 30 dBm, 20 dBm and 20 dBm, respectively
$\alpha_m = \alpha_s = \alpha$	3

RFA, and CA can be written as [39]

$$\begin{aligned} P_{A_M^o}^{\text{UL}'}(\gamma_M) &= \int_{d_1}^{d_2} \mathcal{L}_{I_{\phi_M A_M^o}}^{\text{UL}}(s) \times \mathcal{L}_{I_{\phi_S A_M^c}}^{\text{DL}}(s) \times \mathcal{L}_{I_{\phi_D A_M^c}}^{\text{DL}}(s) \\ &\quad \times f_{r_{M,v}|v_{A_M^o}}(r_{M,v}) dr_{M,v}. \quad (13) \end{aligned}$$

By substituting (7), (8), (10), and (11) into (13), the expression for UL coverage probability, given that  $v$  is associated with MBS in  $A_M^o$ , can be written as (14), shown at the bottom of the next page. In (14),  $\mathcal{J}(\cdot)$  indicates the Gauss-hypergeometric function.

## B. UL COVERAGE PROBABILITY WITH DeCA

The UL coverage probability expression, i.e.,  $P_{A_M^o}^{\text{UL}'}(\gamma_S)$ , assuming EDU, RFA and DeCA, can be written as [29], [40]

$$\begin{aligned} P_{A_M^o}^{\text{UL}'}(\gamma_S) &= \int_{d_1}^{d_2} \left[ \mathcal{L}_{I_{\phi_S A_M^c}}^{\text{UL}}(s) \times \mathcal{L}_{I_{\phi_S A_M^o}}^{\text{DL}}(s) \times \mathcal{L}_{I_{\phi_D A_M^c}}^{\text{DL}}(s) \right] \\ &\quad \times f_{r_S|v_{A_M^o}}(r_S) dr_S. \quad (16) \end{aligned}$$

By substituting (8), (9), (10) and (12) into (16),  $P_{A_M^o}^{\text{UL}'}(\gamma_S)$  can be expressed as (15), shown at the bottom of the next page.

## IV. RESULTS AND DISCUSSION

This section presents simulation and numerical results for the UL coverage probability given that  $v \in A_M^o$ , while considering EDU and RFA for (i) CA, and (ii) DeCA.  $A$  is taken as  $\pi(1000\text{m})^2$ , s.t.,  $A = A_M^c U_{A_M^o}^o$ . Moreover, transmit powers of MBS, SBS, UE, and drone are configured as 40 dBm,

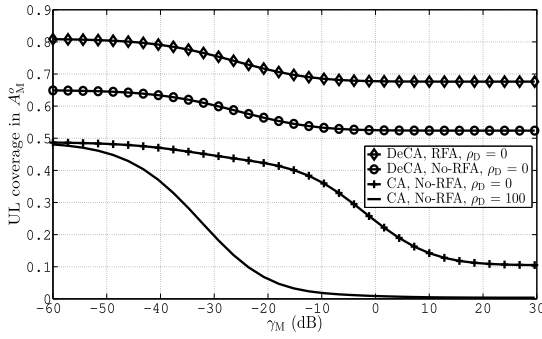


FIGURE 4. UL coverage in  $A_M^O$  with and without RFA.

30 dBm, 20 dBm, and 20 dBm, respectively. Mathematica 11 and MATLAB 2017B have been used to derive and evaluate the coverage probability expressions.

In Figs. 3 and 4, we measure the UL coverage against the predefined threshold,  $\gamma_M$ , and different values of  $\rho_D$  while assuming different network scenarios, such as with and without CA, with and without DeCA, and with and without RFA. In Fig. 3, we compute numerical and simulation results for the UL coverage probabilities taking CA and DeCA into account. This figure validates (14) and (15) and points toward improved UL coverage with DeCA as compared with CA. Moreover, the plots in Fig. 3 indicate that increase in the values of  $\rho_D$  reduces the UL coverage.

The plots in Fig. 4 indicate significant coverage improvement by using RFA as compared with the conventional methods. This is due to the fact that by using RFA, the interference received by  $\nu$  from drones located in  $A_M^c$  is neglected. Moreover, the results demonstrate that DeCA outperforms CA due to users' association with the closest BSs. Furthermore, the results depict that the UL coverage degrades significantly when  $\rho_D = 100$ . Furthermore, the plots in Fig. 4 indicate 16%

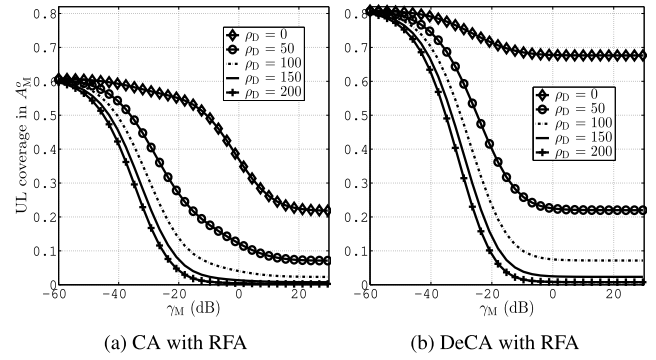


FIGURE 5. UL coverage in  $A_M^O$  against  $\gamma_M$  and  $\rho_D$ .

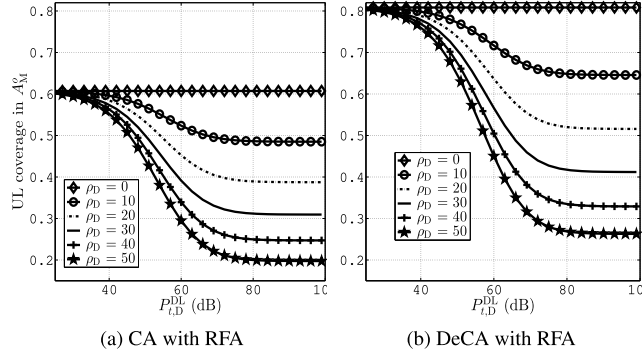
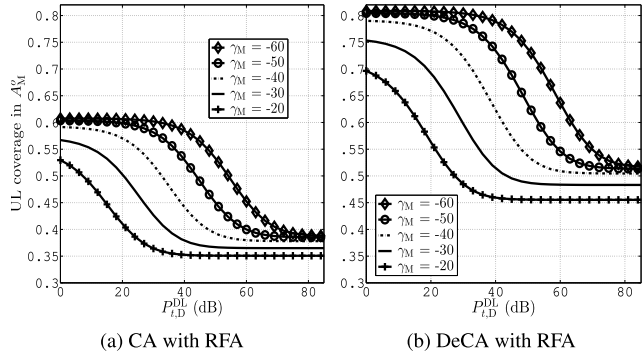
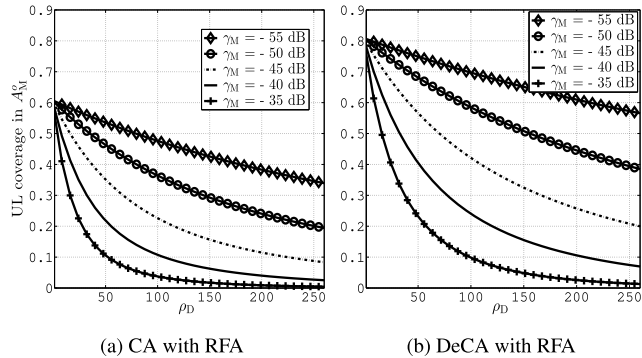
UL coverage improvement as observed at  $\gamma_M = -10$  dB by DeCA with RFA, as compared to CA with RFA.

Figs. 5(a) and 5(b) measure the UL coverage probabilities against  $\rho_D$  while employing CA and DeCA. Both these figures indicate that the UL coverage considerably degrades with an increase in  $\rho_D$ . This is due to the fact that an increase in the values of  $\rho_D$  leads to severe DI. However, Fig. 5(b) indicates improved UL coverage as compared with Fig. 5(a) due to effective interference mitigation by using both DeCA and RFA. Moreover, Figs. 5(a) and 5(b) indicate that, at  $\gamma_M = -10$  dB and  $\rho_D = 50$ , DeCA with RFA leads to 8% UL coverage improvement as opposed to CA with RFA.

In Figs. 6(a) and 6(b), we present the UL coverage probabilities against different values of  $P_{t,D}^{DL}$  and  $\rho_D$  taking CA and DeCA into account, respectively. In both the figures, the value of  $P_{t,D}^{DL}$  ranges from 20 dB to 100 dB while  $\rho_D = 0, 10, 20, 30, 40,$  and  $50$ . The figures depict that an increase in the value of  $P_{t,D}^{DL}$  and  $\rho_D$  leads to reduced UL coverage because of higher DI. This is due to the fact that an increase in the values of  $P_{t,D}^{DL}$  and  $\rho_D$  leads to significant DI. Moreover, in Fig. 6(b),

$$\begin{aligned}
 &P_{A_M^O}^{UL'}(\gamma_M) \\
 &= \frac{2\pi\rho_M}{\exp(-\rho_M\pi d_1^2)} \int_{d_1}^{d_2} \exp\left(\frac{\pi\gamma_M r_M^\alpha}{\alpha/2-1} \left[ \rho_M d_2^{(2-\alpha)} \mathcal{J}\left(\alpha, -\gamma_M \left(\frac{r_M}{d_2}\right)^\alpha\right) - \rho_M d_1^{(2-\alpha)} \mathcal{J}\left(\alpha, -\gamma_M \left(\frac{r_M}{d_1}\right)^\alpha\right) \right. \right. \\
 &\quad \left. \left. + \rho_S \zeta_1 d_1^{(2-\alpha)} \mathcal{J}\left(\alpha, -\gamma_M \zeta_1 \left(\frac{r_M}{d_1}\right)^\alpha\right) - \rho_S \zeta_1 y^{(2-\alpha)} \mathcal{J}\left(\alpha, -\gamma_M \zeta_1 \left(\frac{r_M}{y}\right)^\alpha\right) + \rho_D \zeta_2 d_2^{(2-\alpha)} \mathcal{J}\left(\alpha, -\gamma_M \zeta_2 \left(\frac{r_M}{d_2}\right)^\alpha\right) \right. \right. \\
 &\quad \left. \left. - \rho_D \zeta_2 y^{(2-\alpha)} \mathcal{J}\left(\alpha, -\gamma_M \zeta_2 \left(\frac{r_M}{y}\right)^\alpha\right) \right] - \rho_M \pi r_M^2\right) r_M dr_M. \tag{14}
 \end{aligned}$$

$$\begin{aligned}
 &P_{A_M^O}^{UL'}(\gamma_S) \\
 &= \frac{2\pi\rho_S}{\exp(-\rho_M\pi d_1^2)} \int_{d_1}^{d_2} \exp\left(\frac{\pi\rho_S r_S^\alpha \gamma_S}{\alpha/2-1} \left[ x_2^{(2-\alpha)} \zeta_1 \mathcal{J}\left(\alpha, -\zeta_1 \gamma_S \left(\frac{r_S}{x_2}\right)^\alpha\right) - x_1^{(2-\alpha)} \zeta_1 \mathcal{J}\left(\alpha, -\zeta_1 \gamma_S \left(\frac{r_S}{x_1}\right)^\alpha\right) \right. \right. \\
 &\quad \left. \left. + x_2^{(2-\alpha)} \mathcal{J}\left(\alpha, -\gamma_S \left(\frac{r_S}{x_2}\right)^\alpha\right) - x_1^{(2-\alpha)} \mathcal{J}\left(\alpha, -\gamma_S \left(\frac{r_S}{x_1}\right)^\alpha\right) + \rho_D \zeta_2 d_2^{(2-\alpha)} \mathcal{J}\left(\alpha, -\gamma_M \zeta_2 \left(\frac{r_M}{d_2}\right)^\alpha\right) \right. \right. \\
 &\quad \left. \left. - \rho_D \zeta_2 y^{(2-\alpha)} \mathcal{J}\left(\alpha, -\gamma_M \zeta_2 \left(\frac{r_M}{y}\right)^\alpha\right) \right] - \rho_S \pi r_S^2\right) r_S dr_S. \tag{15}
 \end{aligned}$$


**FIGURE 6.** UL coverage in  $A_M^o$  against  $P_{t,D}^{DL}$  and  $\rho_D$ .

**FIGURE 7.** UL coverage in  $A_M^o$  against  $P_{t,D}^{DL}$  and  $\gamma_M$ .

**FIGURE 8.** UL coverage in  $A_M^o$  for CA, DeCA, and different configurations of  $\gamma_M$  and  $\rho_D$ .

we show significant improvement in the UL coverage due to DeCA and RFA as compared to CA and RFA in Fig. 6(a).

Figs. 7(a) and 7(b) present the UL coverage probabilities against  $P_{t,D}^{DL}$  and  $\gamma_M$  while employing CA and DeCA. The plots in the figures show that raising values of  $P_{t,D}^{DL}$  causes reduced UL coverage as a result of higher DI. Moreover, the plots in the figure show that lower values of  $\gamma_M$  cause higher UL coverage due to improved users association. Furthermore, the results indicate that RFA with DeCA provides improved UL coverage.

Next, in Figs. 8(a) and 8(b), we compute the UL coverage probability for different values of  $\rho_D$  and  $\gamma_M$ . The figures indicate that raising the values of  $\gamma_M$  causes lower

UL coverage due to lower user associations. Moreover, an increase in the values of  $\rho_D$  causes reduced UL coverage because of higher DI. Furthermore, the figures indicate that DeCA in conjunction RFA overpass all other scenarios due to efficient ICI and DI management.

## V. CONCLUSION

In 5G networks, SBS densification in the MBS coverage area give rise to improved spectral efficiency and capacity, however, this causes significant ICI. Moreover, 5G assisted EDU imposes considerable DI on the network. To mitigate both DI and ICI, we use RFA along with DeCA. The results depict that higher values of  $P_{t,D}^{DL}$  and  $\rho_D$  cause lower UL coverage for  $v$  which is located in  $A_M^o$ . Moreover, the results show that RFA and DeCA lead to significant UL coverage improvement and, thus, outperform all other techniques. This work can be further extended by incorporating fractional power control in the proposed setup.

## APPENDIX A PROOF OF THE LT OF (7)

*Proof of (7):* The LT of the UL interference from MBS-tier in  $A_M^o$ , i.e.,  $\mathcal{L}_{I_{\phi_M, A_M^o}^{UL}}(s)$ , is obtained as

$$\begin{aligned}
 & \mathcal{L}_{I_{\phi_M, A_M^o}^{UL}}(s) \\
 & \stackrel{(a)}{=} \mathbb{E}_{I_{\phi_M, A_M^o}^{UL}} \left[ \exp \left( -I_{\phi_M, A_M^o}^{UL} s \right) \right] \Big|_{s = \frac{r_M^\alpha \gamma_M}{P_{t,v}^{UL}}} \\
 & \stackrel{(b)}{=} \mathbb{E}_{I_{\phi_M, A_M^o}^{UL}, |h_l|} \left[ \exp \left( -s \sum_{l \in \phi_M} P_{t,v}^{UL} |h_l| r_l^{-\alpha} \right) \right] \\
 & \stackrel{(c)}{=} \mathbb{E}_{I_{\phi_M, A_M^o}^{UL}, |h_l|} \left[ \prod_{l \in \phi_M} \exp \left( -|h_l| \gamma_M r_M^\alpha r_l^{-\alpha} \right) \right] \\
 & \stackrel{(d)}{=} \mathbb{E}_{I_{\phi_M, A_M^o}^{UL}} \left[ \prod_{l \in \phi_M} \mathbb{E}_{|h_l|} \exp \left( -|h_l| \gamma_M r_M^\alpha r_l^{-\alpha} \right) \right] \\
 & \stackrel{(e)}{=} \mathbb{E}_{I_{\phi_M, A_M^o}^{UL}} \left[ \prod_{l \in \phi_M} \frac{1}{1 + \gamma_M \left( (r_M)^{-1} r_l \right)^{-\alpha}} \right] \\
 & \stackrel{(f)}{=} \exp \left( -2\pi \rho_M \int_{d_1}^{d_2} \frac{r_l dr_l}{1 + \left( \frac{r_l}{\gamma_M^{1/\alpha} r_M} \right)^\alpha} \right) \\
 & \stackrel{(g)}{=} \exp \left( -\pi \rho_M \gamma_M^{2/\alpha} r_M^2 \int_{\left( \frac{d_1}{\gamma_M^{1/\alpha} r_M} \right)^2}^{\left( \frac{d_2}{\gamma_M^{1/\alpha} r_M} \right)^2} \frac{du}{1 + (u)^{\alpha/2}} \right), \tag{17}
 \end{aligned}$$

where equality (a) is achieved by following LT definition [20], equality (b) is achieved by replacing  $I_{\phi_M, A_M^c}^{UL} = \sum_{l \in \phi_M} P_{t,l}^{UL} |h_l| r_l^{-\alpha}$  into equality (a), equality (c) is achieved by replacing  $s = (r_M^\alpha \beta_M) / (P_{t,v}^{UL})$  into equality (b), equality (e) is achieved by evaluating the LT of equality (d) in terms of  $h_j$ , equality (f) is achieved from probability generating functional (PGFL) of IHPPP [39], and equality (g) is achieved by replacing  $u = (r_l / (\zeta_2 \gamma_M)^{1/\alpha} r_M)^2$  into equality (f). Lastly, employing Gauss-hypergeometric function [20] yields (7). ■

**APPENDIX B  
PROOF OF THE LT OF (10)**

*Proof of (10):* The LT of DI received from EDU, i.e.,  $\mathcal{L}_{\phi_D, A_M^c}^{DL}(s)$ , can be shown as

$$\begin{aligned} & \mathcal{L}_{\phi_D, A_M^c}^{DL}(s) \\ & \stackrel{(h)}{=} \mathbb{E}_{I_{\phi_D, A_M^c}^{DL}} \left[ \exp \left( -I_{\phi_D, A_M^c}^{DL} s \right) \right] \Big|_{s = \frac{r_M^\alpha \gamma_M}{P_{t,v}^{UL}}} \\ & \stackrel{(i)}{=} \mathbb{E}_{I_{\phi_D, A_M^c}^{DL}, |h_j|} \left[ \exp \left( -s \sum_{j \in \phi_D} P_{t,j}^{DL} |h_j| r_j^{-\alpha} \right) \right] \\ & \stackrel{(j)}{=} \mathbb{E}_{I_{\phi_D, A_M^c}^{DL}, |h_j|} \left[ \prod_{j \in \phi_D} \exp \left( -|h_j| \zeta_2 \gamma_M r_M^\alpha r_j^{-\alpha} \right) \right] \\ & \stackrel{(k)}{=} \mathbb{E}_{I_{\phi_D, A_M^c}^{DL}} \left[ \prod_{j \in \phi_D} \mathbb{E}_{|h_j|} \exp \left( -|h_j| \zeta_2 \gamma_M r_M^\alpha r_j^{-\alpha} \right) \right] \\ & \stackrel{(l)}{=} \mathbb{E}_{I_{\phi_D, A_M^c}^{DL}} \left[ \prod_{j \in \phi_D} \frac{1}{1 + \zeta_2 \gamma_M (r_j (r_M)^{-1})^{-\alpha}} \right] \\ & \stackrel{(m)}{=} \exp \left( -2\pi \rho_D \int_y^{d_1} \frac{r_j dr_j}{1 + \left( \frac{r_j}{(\zeta_2 \gamma_M)^{1/\alpha} r_M} \right)^\alpha} \right) \\ & \stackrel{(n)}{=} \exp \left( -\pi \rho_D (\zeta_2 \gamma_M)^{2/\alpha} r_M^2 \int_{\left( \frac{y}{(\zeta_2 \gamma_M)^{1/\alpha} r_M} \right)^2}^{\left( \frac{d_1}{(\zeta_2 \gamma_M)^{1/\alpha} r_M} \right)^2} \frac{du}{1 + (u)^{\alpha/2}} \right). \end{aligned} \tag{18}$$

Here, equality (h) is achieved from the LT definition [20], equality (i) is achieved by replacing  $I_{\phi_D, A_M^c}^{DL} = \sum_{j \in \phi_D} P_{t,j}^{DL} |h_j| r_j^{-\alpha}$  into equality (h), equality (j) is achieved by replacing  $s = (r_M^\alpha \beta_M) / (P_{t,v}^{UL})$  into equality (i), equality

(l) is achieved by evaluating the LT of equality (k) with respect to  $h_j$ , equality (m) is achieved by using PGFL of IHPPP, and equality (n) is achieved by replacing  $u = (r_j / (\zeta_2 \gamma_M)^{1/\alpha} r_M)^2$  into equality (m). Finally, by employing Gauss-hypergeometric function to equality (n), we obtain the expression given in (10) ■

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