

# Performance Analysis for Control- and User-Plane Separation based RAN with Non-Uniformly Distributed Users

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**Abstract**—In the control- and user-plane separation (CUPS) based radio access networks (RANs), control-signalling and data are transmitted by the control base stations (CBSs) and data base stations (DBSs), respectively. However, existing studies usually model the C/U-planes as two separate homogeneous networks, neglecting the dependence among the two planes and users. To address this problem, we analyze the coverage probability, spectrum efficiency (SE) and delay considering the dependent features among CBSs, DBSs, and non-uniformly distributed users based on stochastic geometry. Firstly, we present an analytical model for CUPS, where the DBSs are deployed at user hotspots based on Poisson point processes (PPPs), users are clustered around DBSs based on Poisson cluster processes (PCPs), and CBSs are deployed according to a dependent thinning of locations of DBSs based on Matérn hard-core processes (MHCPs). Secondly, we design novel distance-based fractional frequency reuse (FFR) schemes by exploiting the properties of PCP and MHCP to improve the coverage of cell edge users. Thirdly, we derive the distributions of user downlink rates, which are used to analyze the average queueing delay under M/M/C queueing model. Numerical results are presented to verify the efficiency of the proposed model compared to independently distributed BSs and users, and show the dependent BS deployment could significantly improve the coverage of the network.

**Index Terms**—Cellular RANs, control- and user-plane separation, queuing theory, stochastic geometry, Poisson cluster process, Matérn hard-core processes, non-uniformly distributed users.

## I. INTRODUCTION

**A**LONG with the maturity of 5G mobile networks and the emerging 6G discussion [1], the future networks are expected to provide superior performance to support new service and applications. Meanwhile, the higher performance requirements and the scarcity of spectrum resources drive the exploitation of high-frequency bands, which also lead to shranked coverage area due to the more complex channel environment and higher path loss [2]. On the other hand, one of the 6G visions is to provide full-dimensional wireless coverage [3], [4]. As a potential architecture for the wireless networks' coverage enhancement [5], control- and user-plane separation

(CUPS) has been introduced in cellular radio access networks (RANs) as an emerging technology in mobile networks.

CUPS is the key feature of software defined networks (SDN) [6]. Inspired by SDN, the key concept of CUPS in RAN is to separate the signaling required for ubiquitous coverage from those needed to support high-speed data transmission [7]. In fact, the quantity of control signals is quite small compared with that of service data. On the other hand, high-speed data transmission and its related signaling have distinct characteristics and network requirements. Control signalling requires wide coverage and stable transmission, while data transmission focuses more on higher rates. This leads to a layered RAN architecture with a separation between the functionalities of network access and data transfer. The concept of CUPS will drive the mobile network towards the characteristics of flexibility and re-configurability with low cost.

Recently, many works have researched CUPS based cellular networks. To split the control-plane (C-plane) and user-plane (U-plane) in RANs, the control base stations (CBSs) and data base stations (DBSs) have been initially deployed in the same frequency band [8], in which the spectrum allocation to C/U-planes is optimized to achieve better spectrum efficiency (SE) and energy efficiency (EE). To provide ubiquitous coverage to cellular user, the collaborative high and low-frequency base station (BS) deployment relying on CUPS is put forward in [9], [10]. In [9], this architecture is introduced as phantom cellular networks, where a cell covered by a DBS is termed a phantom cell. Phantom cells are only in charge of data transmission in U-plane and operating on high-frequency bands. Meanwhile, their control signaling is carried by their supervising macro cells in C-plane, utilizing different frequency bands. The power and spectrum allocation of phantom cells has been studied in [10] to optimize the EE and SE with imperfect channel state information (CSI). The utilization of a high-frequency band and shorter transmission distances in the U-plane introduces a more complex wireless environment, leading to the coexistence of line-of-sight (LoS) and non-line-of-sight (NLoS) transmissions. In this scenario, the SE, EE, and coverage have been analyzed in [11]. Additionally, the use of unlicensed bands in the U-plane has been explored in [12], [13]. Apart from the C/U-planes operating in LTE and mmWave bands, respectively, an assisting C-plane was deployed in the Wi-Fi band as an intermediate layer, forming a three-tier CUPS model in [14]. In [15], a cloud-based CUPS architecture was presented, where both CBSs and DBSs serve

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as remote radio heads (RRHs) and are connected to the virtual BS cloud through the fronthaul network. Further, benefiting from the flexible framework of CUPS, the storage units and computing units could be deployed on DBSs, to realize edge caching [16] and edge computing [17].

Several existing works use the homogeneous Poisson point process (PPP) to analyze network performance [18], [19], neglecting the non-uniform user distribution. While the PPP model has demonstrated accuracy in macro BS deployments in [20] through comparison with real-world data, it may not be entirely precise for certain dense urban HetNet cases when applied to the distribution of users and small BSs [21], [22]. As for the location of users, a common assumption is that users are distributed uniformly and are independent with BSs' locations. However, in reality, users' distribution is not always even and there exists hot-spots where user gathering like shopping malls or airports. Fortunately, Poisson cluster process (PCP) is appropriate for modeling the non-uniformly distributed users [23], [24]. In addition, the non-independent deployment of small cells has also been considered in the 3GPP models for HetNets [25], in which small BSs (SBSs) are deployed according to the user hot-spots and users are clustered around SBSs. The spatial correlation of user and SBSs locations has been analyzed in [26], [27] and extended to many scenarios of interest in the literature like multi-tier HetNets in [28], [29], device-to-device (D2D) networks in [30], non-orthogonal multiple access (NOMA) networks in [31], [32] and uplink-downlink decoupling in [33]. Another shortcoming of PPP based network model is that it neglects the repulsive characteristics among BSs. Therefore, repulsive point processes including Poisson hard-core point process and Matérn hard-core processes (MHCPs) [34]–[40] are widely applied to capture the spatial repulsion in wireless networks.

In addition to the spatial distribution and channel conditions, traffic queuing at BSs also significantly impacts network performance [41]. Random service requests from users are aggregated at their associated BSs, and channels are allocated for data transfer. Queuing models have been applied to analyze the traffic conditions according to different network models, including  $M/M/1$  [42],  $M/M/C/C$  [11],  $M/G/1$  [43] and interacting queues [41], [44]. [45]–[47] adopt the mean-field approximation to settle the “interacting queue” problem. However, in the case of a non-uniform and non-homogeneous spatial network model, introducing this method would amplify the challenges of analysis. Another assumption proposed by [11], [48], [49] posits that the channel allocation time or channel holding time follows an exponential distribution, simplifying performance analysis.

To manage the interference in the HetNet and improve the edge coverage, several frequency reuse (FR) techniques have been investigated, including fractional frequency reuse (FFR), soft FFR, FFR3, etc. [50]. The basic idea of FFR is to partition the cell into interior and edge regions and assign with different sub-bands. In conventional grid-based cellular network, the region partition is based on a predetermined distance, which is not applicable of stochastic geometry modeled network as the cells has irregular sizes and shapes [51]. To address this problem, [52], [53] categorize the interior and edge users based

on SINR threshold. However, the time-varying instantaneous SINR may lead to random switching between interior and edge users. In [51], [54], a distance-based FFR is introduced to the network based on PPP, where the user classification is according to their distance from their associated and dominant interfering BS. However, the distance-based FFR has not been well investigated in network based on other stochastic geometry model based network like PCP and MHCP.

In this paper, we analyze the coverage probability, delay, and SE performance of RAN relying on CUPS based on PCPs and MHCPs. To the best of our knowledge, the dependent features among CBSs, DBSs and non-uniformly distributed users have not been investigated in the existing research on CUPS. The contributions of this paper are summarized as follows.

1) *A hybrid MHCP-PCP network model*: Existing research neglects the interdependency among CBSs, DBSs, and users. Therefore, we propose a hybrid network model for CUPS that accommodates these interdependent features through a comprehensive use of PCPs and MHCPs. This model aligns with the characteristics of CUPS, where capacity-driven DBSs are placed closer to users, while CBSs providing wider coverage are more sparse and repulsive. Specifically, DBSs are deployed at user hotspots based on PPPs, users are clustered around DBSs based on PCPs, and CBSs are deployed according to a dependent thinning of locations of DBSs based on MHCPs.

2) *Distance-based fractional frequency reuse*: In order to enhance overall coverage performance and mitigate inter-cell interference for cell-edge users, we propose two novel distance-based FFR techniques for control plane and user plane, respectively. Instead of the conventional SINR threshold-based classification, which often leads to random switching, the proposed distance-based classification in the U-plane is achieved by comparing the user's distance with the center DBS and the nearest non-center DBS. In the C-plane, the proposed method is realized by utilizing the hard-core distance.

3) *Performance analysis based on M/M/C queueing model and stochastic geometry*: The CBSs, DBS, and users are dependent in the proposed model. Meanwhile, the proposed FFR techniques separately analyze the interior and edge user, which makes the analysis more complex and challenging. To this end, we derive analytical solutions of coverage probability and spectrum efficiency for both interior/edge users in C/U planes, respectively. In addition, the distribution of downlink rate is derived to analyze the average queueing delay under M/M/C queueing model, on covering the effects of inter-cell interference on delay.

The remainder of this paper are organized as follows. Section II introduces the system model of the proposed RAN relying on CUPS. Section III illustrates and analyzes the distance-based FFR model. Performance analyses of the U-plane and C-plane are presented in Section IV and Section V, respectively. Section VI provides the derivations of queueing delay. Numerical results and conclusions are presented in Section VII and Section VIII, respectively.

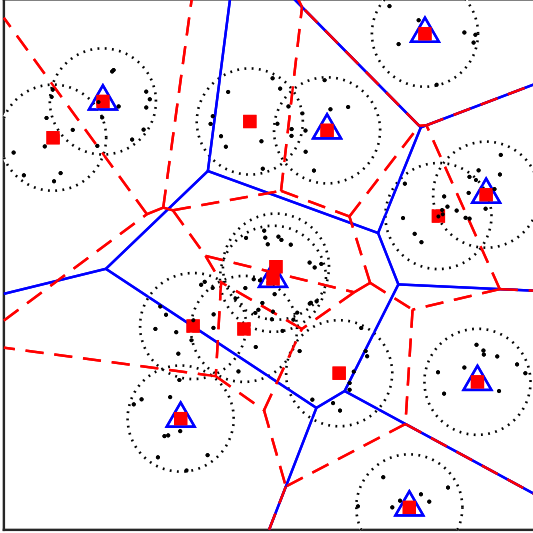


Fig. 1. The deployment of CBSs (blue triangles) following MCHCPs, and DBSs (red squares) following IHPPPs and the distribution of users (black dots) following PCPs.

## II. SYSTEM MODEL

Consider a cellular network consisting of two kinds of BSs, named CBSs and DBSs, respectively. To be specific, the CBSs would take charge of transmitting signals in the C-plane, including control signaling; accordingly, the high-speed data would be transmitted through DBSs in the U-plane. The two kinds of BSs are assumed to work in different frequency bands, which means C-plane could take advantage of low frequency to guarantee the coverage of a wider area, while U-plane could benefit from the wide band in high frequency to achieve higher rate.

As illustrated in Fig. 1, we assume that all BSs and users are randomly deployed according to stochastic geometry. Specifically, the locations of DBSs follow independent homogeneous PPPs (IHPPPs)  $\Phi_d$  with a density of  $\lambda_d$ , CBSs are deployed based on MCHCPs of Type II  $\Phi_c$ , and user distribution follows PCPs.

Many existing studies modeled users as IHPPPs independent with BSs. However, in practice, the location of users is spatially non-uniform [27]. To address this problem, many researches have focused on the user-centric capacity-driven small cell deployments [27], [28]. In [27], the locations of users and base stations are modeled as clustered around geographical centers of user hotspots. In [28], BSs are deployed at the center of user clusters to capture the location correlation between BSs and users. Since DBSs are responsible for high-speed data transmission, similar to [28], we assume that the deployment of DBSs is correlated with users' locations. This is analogous to small cells in regular HetNets that are deployed in crowded places such as malls and stations. On the other hand, users also prefer venues with stable and fast network service. Therefore, users tend to cluster around the DBSs once deployed. As a result, users are assumed to have clustered distributions following PCP [26].

A PCP consists of a parent PPP, and the clusters are scattered independently and with an identical spatial distribution

around the points in the parent PPP. The user distribution is denoted by  $\Phi_u$ , which follows a PCP with a cluster size  $S$ , representing the average number of users per cluster. Here, we assume that the parent process of  $\Phi_u$  is equivalent to  $\Phi_d$  so that DBSs are deployed at the cluster center of users. Any user's location follows an identical distribution with respect to the cluster center.

Here, the analysis is based on a commonly used PCP model: the Matérn cluster process (MCP). In the MCP, each user is uniformly distributed in a ball of radius  $R$  around the DBS, as shown by the dashed circle in Fig. 1. Therefore, the probability density function (PDF) of the users' locations relative to the DBSs in the MCP, denoted by  $f_{\mathbf{X}}^M(\mathbf{x})$ , is given by [56]

$$f_{\mathbf{X}}^M(\mathbf{x}) = \begin{cases} \frac{1}{\pi R^2} & , \quad \|\mathbf{x}\| \leq R \\ 0 & , \quad \text{otherwise.} \end{cases} \quad (1)$$

where  $\mathbf{x} = (y_0, \theta)$  represents the coordinates in the polar coordinate system. Here,  $y_0$  denotes the distance between the user and its center DBS, and  $\theta$  denotes the angle from the center DBS.

Since CBSs play a crucial role in assisting DBSs to maintain ubiquitous coverage, it is essential to consider the interdependence between the two planes. The low-frequency CBSs, responsible for wider coverage, result in a sparse and repulsive distribution. Consequently, we assume that the locations of CBSs follow a MCHCP of Type II, denoted as  $\Phi_c$ . Specifically,  $\Phi_c$  is a dependent thinning of  $\Phi_d$  with a minimum distance  $R_m$  between any two CBSs.

The process  $\Phi_c$  is generated by assigning each point in  $\Phi_d$  a mark uniformly distributed on the interval  $[0, 1]$ , and subsequently removing all points that have a neighbor within a distance of  $R_m$  with a smaller mark. The probability that a given CBS is retained is provided in [34], and it is given by

$$\mathcal{P}_r = \frac{1 - \exp(-\pi \lambda_d R_m^2)}{\pi \lambda_d R_m^2}. \quad (2)$$

The density of  $\Phi_c$  is accordingly  $\lambda_c = \mathcal{P}_r \lambda_d$ .

The BSs in both the C-plane and U-plane employ orthogonal frequency-division multiplexing (OFDM) to support multiple users. Additionally, CBSs and DBSs operate in different frequency bands, so that they do not interfere with each other.

The BSs will communicate with users in the downlink based on users' requests, and the Signal-to-Interference-plus-Noise Ratio (SINR) for a typical C-plane user and a typical U-plane user is given by

$$\text{SINR}_c = \frac{P_c h_c A_c R_c^{-\nu_c}}{\sum_{k \in \Phi_c^I} P_c h_k A_c R_k^{-\nu_c} + n_c}, \quad (3)$$

and

$$\text{SINR}_d = \frac{P_d h_d A_d R_d^{-\nu_d}}{\sum_{k \in \Phi_d^I} P_d h_k A_d R_k^{-\nu_d} + n_d}, \quad (4)$$

where  $P_c$  and  $P_d$  denote the transmit power of CBSs and DBSs, respectively.  $h_c$ ,  $h_d$ ,  $h_k$  represent the channel gains from the associated CBS/DBS and the  $k$ -th interfering BS to the typical user, respectively.  $R_c$ ,  $R_d$ , and  $R_k$  denote the distance from the associated CBS/DBS and the  $k$ -th interfering BS to the typical user, respectively. Additionally, we assume

that all channel gains follow the exponential distribution with a parameter of 1.  $\nu_c$  and  $\nu_d$  denote the path loss exponent in C/U-planes,  $A_c$  and  $A_d$  denote the corresponding path gain at a reference distance of 1 meter in C/U-planes, and  $n_c$  and  $n_d$  denote the noise power in C/U-planes, respectively.  $\Phi_c^I$  and  $\Phi_d^I$  represent the sets of interfering neighboring CBSs/DBSs, respectively, whose density will be derived in the following sections. The subscripts  $c$  and  $d$  represent CBS and DBS in the C/U-planes, respectively.

### III. FREQUENCY REUSE MODEL

The cell-edge users suffer from severe inter-cell interference, as they receive weaker signal power but stronger interference than cell-center users (also known as interior users) from neighboring BSs. To mitigate the inter-cell interference of edge users, several frequency reuse techniques have been put forward, including FFR, soft FFR, etc. Here we apply FFR for our system, and the main idea is to allocate different sub-bands for edge and interior users.

One of the key concerns of FFR is the classification of edge and interior users. Initially, the distance-based classification is widely applied in grid-based network analysis [50]. However, this method is not suitable for the random and irregular cell shape in networks modeled by stochastic geometry. In [52], [53], the classification in a PPP network is based on SINR threshold, i.e., users with SINR greater than a predetermined value would be regarded as interior users. Otherwise, they would be regarded as edge users. A distance-based classification method is introduced in [51], [54], where users would be seen as edge users if the ratio between their distance from the serving BS and the dominant interfering BS (i.e., the second nearest BS) is less than a predetermined threshold. Inspired by that, we propose two novel user classification methods for C/U-plane users, respectively, based on the nature of MHCP and PCP.

#### A. Distance-based FFR for U-plane

Since there exists a center DBS  $D_0$  for each cluster of users, whose distances from users are limited by a small cluster radius  $R$ ,  $D_0$  could become either the serving BS or one of the powerful interference sources. Similar to [51], [54], which classifies edge and interior users according to their distance from their serving and dominant interfering BSs, for the U-plane, the classification is based on the distance between the user with the cluster center DBS  $D_0$  and the nearest non-center DBS  $D_1$ , i.e.,  $R_0$  and  $R_1$ , which is shown as follows.

All the DBSs are divided into two tiers: one is  $\Phi_{d0}$ , which only includes the cluster center DBS (denoted by  $D_0$ ) of the typical user, and the other is  $\Phi_{d1} = \Phi_d \setminus D_0$ , which contains all DBSs except  $D_0$ .  $\Phi_{d1}$  still follows HPPP with the same density as  $\Phi_d$  according to the *Slivnyak Theorem* [56]. We denote the nearest DBS in  $\Phi_{d1}$  as  $D_1$ .

Since there is overlapping between clusters,  $D_0$  may not be the nearest DBS. Therefore, we term the user as U-plane cluster interior user (UIU) if  $R_0 < R_1$ , as it is closer to the cluster center rather than DBSs in other clusters; otherwise, it is termed as U-plane cluster edge user (UEU). Therefore, the

probability that the typical user is classified as UIU is derived by comparing  $R_0$  and  $R_1$  as  $\mathcal{P}_{d,i} = \mathbb{P}(R_0 < R_1)$ , and the probability that a typical user is a UEU is  $\mathcal{P}_{d,e} = 1 - \mathcal{P}_{d,i}$ .

The distribution of  $R_0$  is the marginal distribution of (1) by integrating over  $\theta$  (i.e. the angle from the center DBS to the typical user) in polar coordinates. We denote the PDF and cumulative distribution function (CDF) of  $R_0$  as  $f_{R_0}(r_0)$  and  $F_{R_0}(r_0)$ , which in the case of MCP are given by, respectively,

$$f_{R_0}(r_0) = \begin{cases} \frac{2r_0}{R^2} & , \quad 0 \leq r_0 \leq R \\ 0 & , \quad otherwise \end{cases} \quad (5)$$

and

$$F_{R_0}(r_0) = \frac{r_0^2}{R^2}, \quad 0 \leq r_0 \leq R. \quad (6)$$

Note that although the typical user is dependent on  $D_0$ , the independence still holds between the typical user and the other DBSs except  $D_0$ . Since  $\Phi_{d1}$  still follows the HPPP, if we denote the distance between the typical user and  $D_1$  as  $R_1$ , the PDF and CDF of  $R_1$  are

$$f_{R_1}(r_1) = 2\pi\lambda_d r_1 \exp(-\pi\lambda_d r_1^2), \quad (7)$$

and

$$F_{R_1}(r_1) = 1 - \exp(-\pi\lambda_d r_1^2). \quad (8)$$

Then  $\mathcal{P}_{d,i}$  is given by

$$\mathbb{P}(R_0 < R_1) = \mathbb{E}_{R_0}[\bar{F}_{R_1}(R_0)] = \frac{1 - \exp(-\pi\lambda_d R^2)}{\pi\lambda_d R^2}. \quad (9)$$

and  $\mathcal{P}_{d,e} = 1 - \mathcal{P}_{d,i}$ .

When classified as a UIU, the distribution of  $R_0$  changes accordingly to a conditional distribution. For instance,  $D_0$  being the nearest DBS implies that  $R_0$  is smaller than  $R_1$ . Therefore, the distribution of  $R_0$  should be conditioned on  $R_0 < R_1$ . The conditional CDF of  $R_0$ , denoted as  $F_{R_0}^{d,i}(t)$ , is given by

$$\begin{aligned} & \frac{\mathbb{P}(R_0 < r_0 \mid R_0 < R_1)}{\mathbb{P}(R_0 < r_0, R_0 < R_1)} \\ &= \frac{\mathbb{P}(R_0 < R_1)}{\mathbb{P}(R_0 < R_1)} \\ &\stackrel{(a)}{=} \frac{1}{\mathcal{P}_{d,i}} \int_0^t \left( \int_{r_0}^\infty f_{R_1}(r_1) dr_1 \right) f_{R_0}(r_0) dr_0 \\ &= \frac{1}{\mathcal{P}_{d,i}} \int_0^t \bar{F}_{R_1}(r_0) f_{R_0}(r_0) dr_0, \end{aligned} \quad (10)$$

where (a) holds due to  $\mathcal{P}_{d,i} = \mathbb{P}(R_0 < R_1)$ , and the limits  $R_0 < t$  and  $R_0 < R_1$  define the integral range. Consequently,  $f_{R_0}^{d,i}(r_0)$  is the derivative of  $F_{R_0}^{d,i}(r_0)$  with respect to  $r_0$ , and it is expressed as

$$f_{R_0}^{d,i}(r_0) = \frac{1}{\mathcal{P}_{d,i}} \bar{F}_{R_1}(r_0) f_{R_0}(r_0). \quad (11)$$

The conditional distribution of  $R_1$  when the typical user is classified as a UEU will be obtained in the same way:

$$f_{R_1}^{d,e}(r_1) = \frac{1}{\mathcal{P}_{d,e}} \bar{F}_{R_0}(r_1) f_{R_1}(r_1). \quad (12)$$

Here, we set the reuse factor  $K_d$ . Therefore, all the DBSs would transmit to the UIU using a certain frequency band. The remaining frequency band is divided into  $K_d$  orthogonal

sub-bands, and each DBS randomly selects one of the  $K_d$  sub-bands for the UEs. So, for the UEU, the interfering probability is  $\mathcal{P}_{d,e}^I = 1/K_d$ , while for UIU  $\mathcal{P}_{d,i}^I = 1$ .

### B. Distance-based FFR for C-plane

For the C-plane, we assume that the classification is determined by the hard-core distance  $R_m$ . In the proposed model based on MHCPs, the deployment of CBSs is a dependent thinning of  $\Phi_d$ , and each two CBSs have a minimum distance  $R_m$ . If the distance between two nodes within  $\Phi_d$  is less than  $R_m$ , only one node is retained as a CBS. Specifically, if the cluster center of the typical user is retained as CBS, the users are categorized as C-plane cell interior users (CIUs), otherwise as C-plane cell edge users (CEUs). As a result, the probability of a user being CIU is equal to the retaining probability of MHCP in (2) as  $\mathcal{P}_{c,i} = \mathcal{P}_r$ , while the probability of a user being CEU is  $\mathcal{P}_{c,e} = 1 - \mathcal{P}_r$ .

Accordingly, each CBS applies a dedicated band for CIU and randomly selects one of  $K_c$  sub-bands for CEUs. The interfering probabilities for CIUs and CEUs are  $\mathcal{P}_{c,i}^I = 1$  and  $\mathcal{P}_{c,e}^I = 1/K_c$ , respectively.

## IV. PERFORMANCE ANALYSIS OF USER PLANE

In this part, we will analyze the performance of DBSs in the U-plane. We assume the Max Power Association (MPA) for user-BS association, which means that the typical user would choose the nearest DBS, i.e. the nearest one between  $D_0$  and  $D_1$ . Note that, the performance analysis in this section are conducted conditioned on the users are under the coverage of CBSs.

The interfering neighboring DBSs denoted by  $\Phi_d^I$  is a part of DBSs that reuse the same channel with the typical user. The density of  $\Phi_d^I$  is  $\lambda_d^I = \mathcal{P}_d^I \lambda_d$ , due to that both  $\Phi_{d1}$  and  $\Phi_{d1}/D_1$  follow HPPP and have densities of  $\lambda_d$  under *Slivnyak Theorem*.

We define  $\mathcal{C}_d$  as the coverage probability in U-plane and it could be express by

$$\mathcal{C}_d = \mathbb{P}(\text{SINR}_d > \gamma_d), \quad (13)$$

where  $\gamma_d$  is the threshold.

### A. Conditional Coverage Probability for UIUs

Based on the MPA, the user will connect to the DBS which could provide the maximum expected received power. In the U-plane, there exists two cases, which depend on whether the DBS at users' cluster center (i.e.  $D_0$ ) or the nearest DBS in  $\Phi'$  (i.e.  $D_1$ ) could provide the typical user with the maximum received power. Note that, in the U-plane, the interior users and edge users are also categorized under the same criterion. In the two cases, some key values like the interference power and serving distances are calculated in different manners. Therefore, the coverage probability of UIU and UEU are derived respectively.

The UIUs are closer to  $D_0$  and therefore associated with  $D_0$ , the PDF of serving distance is  $f_{R_0}^{d,i}(r_0)$  in (11), and the

interfering neighboring DBSs are no closer than  $D_0$ , so the coverage probability is given by

$$\begin{aligned} & \mathbb{P}(\text{SINR}_d > \gamma_d) \\ &= \mathbb{P}\left(h_d > \frac{\gamma_d}{P_d A_d R_d^{-\nu_d}} \left( \sum_{k \in \Phi_d^I} P_d A_d h_k R_k^{-\nu_d} + n_0 \right)\right) \\ &\stackrel{(b)}{=} \mathbb{E}_{R_d} [\exp(-\mathcal{N}_d R_d^{\nu_d}) \exp(-\gamma_d R_d^{\nu_d} I_d)] \\ &= \int_0^R \exp(-\mathcal{N}_d r_0^{\nu_d}) \mathcal{L}_{I_d}(\gamma_d r_0^{\nu_d}) f_{R_0}^{d,i}(r_0) dr_0, \\ &= \frac{1}{\mathcal{P}_{d,i}} \int_0^R \exp(-\mathcal{N}_d r_0^{\nu_d}) \\ &\quad \cdot \mathcal{L}_{I_d}(\gamma_d r_0^{\nu_d}) \bar{F}_{R_1}(r_0) f_{R_0}(r_0) dr_0, \end{aligned} \quad (14)$$

where (b) holds because  $h_d$  following exponential distribution. Denote  $s = \gamma_d r_0^{\nu_d}$ ,  $\mathcal{L}_{I_d}(s)$  only contains interference component from  $\Phi_{d1}$ , which is

$$\begin{aligned} & \mathbb{E} \left[ \exp \left( -s \sum_{k \in \Phi_{d1}} h_k r_k^{-\nu_d} \right) \right] \\ &= \mathbb{E} \left[ \prod_{k \in \Phi_{d1}} \exp(-m h_k R_k^{-\nu_d}) \right] \\ &\stackrel{(c)}{=} \exp \left( -2\pi \lambda_d^I \int_{r_0}^{\infty} (1 - \mathbb{E}_h [e^{-s h r^{-\nu_d}}]) r dr \right) \\ &\stackrel{(d)}{=} \exp \left( -2\pi \lambda_d^I \int_{r_0}^{\infty} \left( 1 - \frac{1}{1 + m r^{-\nu_d}} \right) r dr \right) \\ &= \exp \left( -2\pi \lambda_d \frac{s r_0^{2-\nu_d}}{\nu_d - 2} \right) \\ &\quad {}_2F_1 \left[ 1, 1 - \frac{2}{\nu_d}, 2 - \frac{2}{\nu_d}, -r_0^{-\nu_d} s \right], \end{aligned} \quad (15)$$

where  ${}_2F_1[x, y, z, w]$  is a Gauss Hypergeometric function, (c) holds due to the probability generating functional (PGFL) of PPP [56] and no interfering DBS closer than  $r_0$ , (d) is because all  $h_k$  follow i.i.d exponential distributions.

Substituting (15) into (14), we could derive the conditional coverage probability for the UIUs as

$$\mathcal{C}_{d,i} = \frac{1}{\mathcal{P}_{d,i}} \int_0^R \exp(\mathcal{G}_d r_0^2 - \mathcal{N}_d r_0^{\nu_d}) \frac{2r_0}{R^2} dr_0, \quad (16)$$

where  $\mathcal{G}_d = -\pi \lambda_d \left( \frac{{}_2F_1 \left[ 1, 1 - \frac{2}{\nu_d}, 2 - \frac{2}{\nu_d}, -\gamma_d \right]}{\nu_d - 2} + 1 \right)$  and  $\mathcal{N}_d = \frac{\gamma_d n_0}{P_d A_d}$ .

### B. Conditional Coverage Probability for UEUs

In this part, we will derive the conditional probability  $\mathcal{C}_{d,e}$  when the typical user is associated with  $D_1$ , which is the nearest DBS in  $\Phi_{d1}$ . So there coexists interference from  $D_0$  and  $\Phi_{d1}/D_1$ , denoted by  $I_0$  and  $I_1$ , respectively. Following the same procedure, we need to obtain the Laplace transform of  $I_0$  and  $I_1$ , which are denoted by  $\mathcal{L}_{I_0}$  and  $\mathcal{L}_{I_1}$ , respectively.

The derivation of  $\mathcal{L}_{I_1}$  is similar to (15), except that in this

case, the lower limit of the integral is  $r_1$  and is given by

$$\begin{aligned}\mathcal{L}_{I_1}(s) &= \mathbb{E} \left[ \exp \left( -s \sum_{k \in \Phi_d^I} h_k r_k^{-\nu_d} \right) \right] \\ &= \exp \left( -2\pi \lambda_d^I \int_{r_1}^{\infty} \mathbb{E}_h \left[ 1 - e^{-shr^{-\nu_d}} \right] r dr \right) \\ &= \exp \left( -2\pi \frac{\lambda_d}{K_d} \frac{sr_1^{2-\nu_d}}{\nu_d - 2} \cdot \right. \\ &\quad \left. {}_2F_1 \left[ 1, 1 - \frac{2}{\nu_d}, 2 - \frac{2}{\nu_d}, -r_1^{-\nu_d} s \right] \right), \quad (17)\end{aligned}$$

Substitute  $s = \gamma_d r_1^{\nu_d}$  into (17), we derive that

$$\mathcal{L}_{I_1}(\gamma_d r_1^{\nu_d}) = \exp(\mathcal{G}'_d r_1^2), \quad (18)$$

where  $\mathcal{G}'_d = -2\pi \frac{\lambda_d}{K_d} \frac{\gamma_d {}_2F_1 \left[ 1, 1 - \frac{2}{\nu_d}, 2 - \frac{2}{\nu_d}, -\gamma_d \right]}{\nu_d - 2}$ .

$\mathcal{L}_{I_0}$  is more difficult to derive due to the spatial relationship between  $D_0$  and the typical user. Similar to other DBSSs,  $D_0$  also has a probability of  $1/K_d$  to generate interference on the typical users. As a result,  $\mathcal{L}_{I_0}$  can be calculated by

$$\begin{aligned}&\mathbb{E}_{I_0} [\exp(-sI_0)] \\ &\stackrel{(e)}{=} \frac{1}{K_d} \mathbb{E}_{r_0, h_0} [\exp(-sh_0 r_0^{-\nu_d})] + (1 - \frac{1}{K_d}) \exp(0) \\ &\stackrel{(f)}{=} \frac{1}{K_d} \mathbb{E}_{r_0} \left[ \frac{1}{1 + sr_0^{-\nu_d}} \right] + 1 - \frac{1}{K_d}, \quad (19)\end{aligned}$$

where  $h_0, r_0$  are the channel gain and distance between  $D_0$  and user, (e) holds because when  $D_0$  is not an interference source,  $I_0 = 0$  and thus  $\exp(-sI_0) = 1$  with a probability  $1 - 1/K_d$ , (f) holds because  $h_0$  follows exponential distribution.

The PDF of  $r_0$  is derived from (5). However, since  $D_0$  is not the nearest DBS, the calculation of the PDF needs to account for the location of  $D_1$ . When  $R_1 = r_1$ , the PDF of  $R_0$  becomes  $f_{R_0}(r_0 | r_0 > r_1) = \frac{f_{R_0}(r_0)}{F_{R_0}(r_1)}$ . Then,  $\mathcal{L}_{I_0}$  is derived as

$$\begin{aligned}&\frac{1}{K_d} \mathbb{E}_{r_0} \left[ \frac{1}{1 + sr_0^{-\nu_d}} \right] + 1 - \frac{1}{K_d} \\ &= \frac{1}{K_d} \int_{r_1}^{\infty} \frac{1}{1 + sr_0^{-\nu_d}} \frac{f_{r_0}(r_0)}{F_{r_0}(r_1)} dr_0 + 1 - \frac{1}{K_d} \\ &= \frac{1}{K_d} \int_{r_1}^R \frac{1}{1 + sr_0^{-\nu_d}} \frac{2r_0}{R^2 - r_1^2} dr_0 + 1 - \frac{1}{K_d} \\ &= 1 - \frac{1}{K_d} \frac{R^2 \mathcal{G}_1 - r_1^2 \mathcal{G}_2}{R^2 - r_1^2}, \quad (20)\end{aligned}$$

which has the closed-form solution, where  $\mathcal{G}_1 = {}_2F_1 \left[ 1, \frac{2}{\nu_d}, 1 + \frac{2}{\nu_d}, -\frac{R^{\nu_d}}{\gamma_d r_1^{\nu_d}} \right]$  and  $\mathcal{G}_2 = {}_2F_1 \left[ 1, \frac{2}{\nu_d}, 1 + \frac{2}{\nu_d}, -\frac{1}{\gamma_d} \right]$ .

Considering the coexistence of  $\mathcal{L}_{I_0}$  and  $\mathcal{L}_{I_1}$ ,  $\mathcal{C}_{d,e}$  could be expressed as

$$\begin{aligned}\mathbb{P}(SINR_d > \gamma_d) &= \int_0^R \exp(-\mathcal{N}_d r_1^{\nu_d}) \\ &\cdot \mathcal{L}_{I_0}(\gamma_d r_1^{\nu_d}) \mathcal{L}_{I_1}(\gamma_d r_1^{\nu_d}) f_{R_1}^{d,e}(r_1) dr_1. \quad (21)\end{aligned}$$

Substitute  $\mathcal{L}_{I_0}$ ,  $\mathcal{L}_{I_1}$  and  $f_{R_1}^{d,e}(r_1)$  into (21), we could derive

$$\begin{aligned}\mathcal{C}_{d,e} &= \frac{1}{\mathcal{P}_{d,e}} \int_0^R \exp((\mathcal{G}'_d - \pi \lambda_d) r_1^2 - \mathcal{N}_d r_1^{\nu_d}) \\ &\cdot \left( 1 - \frac{1}{K_d} \frac{R^2 \mathcal{G}_1 - r_1^2 \mathcal{G}_2}{R^2 - r_1^2} \right) 2\pi \lambda_d r_1 \left( 1 - \frac{r_1^2}{R^2} \right) dr_1. \quad (22)\end{aligned}$$

Conditioned on the user being covered by a CBS, the overall coverage probability for users in the U-plane is given by

$$\mathcal{C}_d = \mathcal{P}_{d,i} \mathcal{C}_{d,i} + \mathcal{P}_{d,e} \mathcal{C}_{d,e}. \quad (23)$$

### C. SE of U-Plane

The U-plane is responsible for high-speed data transmission, making Spectral Efficiency (SE) a crucial performance metric for U-plane users. Then we would provide the relationship between coverage probability and SE, which is denoted by  $\eta^{SE}$ .

Following a similar method to [20] and considering that  $\mathbb{E}[X] = \int_{t>0} \mathbb{P}(X > t) dt$  holds for any positive random variable  $X$ , we can derive  $\eta$  as follows:

$$\begin{aligned}\eta^{SE} &= \mathbb{E}[\log_2(1 + SINR)] \\ &= \frac{1}{\ln 2} \int_0^{\infty} \mathbb{P}[\ln(1 + SINR) > t] dt \\ &= \frac{1}{\ln 2} \int_0^{\infty} \mathbb{P}[SINR > e^t - 1] dt \\ &= \frac{1}{\ln 2} \int_0^{\infty} \mathcal{C}(e^t - 1) dt. \quad (24)\end{aligned}$$

By substituting  $\gamma = e^t - 1$  into (24), where  $t = \ln(1 + \gamma)$  and  $dt = 1/(1 + \gamma) d\gamma$ , and adjusting the integral range accordingly, the SE can be obtained. So, with the given coverage probability, the ergodic SE of the typical user is given by

$$\eta_d^{SE} = \frac{1}{\ln 2} \int_0^{\infty} \frac{\mathcal{C}_d(\gamma)}{1 + \gamma} d\gamma. \quad (25)$$

## V. PERFORMANCE ANALYSIS OF CONTROL PLANE

Since the control signaling in C-plane is required for the U-plane transmission, the coverage probability of the C-plane has an effect on the overall system performance. With the distance-based FFR schemes introduced in Section III-B, the coverage probability of the C-plane could be derived using properties of MHCP and PCP.

The coverage probability of the C-plane is defined as the probability that the SINR is greater than a threshold, which is given by

$$\mathcal{C}_c = \mathbb{P}(SINR_c > \gamma_c), \quad (26)$$

where  $\gamma_c$  is the SINR threshold.

Since the location of CBSs  $\Phi_c$  follows MHCP, which is a dependent thinning of  $\Phi_d$ . To take advantage of the better coverage of CBSs, we assume that  $R_m \geq 2R$ . In other words, the minimum distance between each pair of CBSs is no smaller than twice the cluster radius to avoid the overlapping of coverage areas for each CBS.

In the C-plane, users follow MPA, which means users will connect to their nearest CBSs because they could provide the maximum expected received power. The coverage analysis of C-plane depends on whether the cluster center of the typical user is retained as CBS.

### A. Coverage probability for CIU

The CIUs are the users whose cluster centers are retained as CBSs, which are denoted by  $C_0$ . Therefore,  $C_0$  shares the location with the center DBS  $D_0$ . Since  $R_m \geq 2R$ , the nearest CBS of the typical user is  $C_0$ . Thus, the distance between the typical user and  $C_0$ , denoted by  $R_{C_0}$ , is same with  $R_0$ , and the PDF of  $R_{C_0}$  is given by

$$f_{R_{C_0}}^{c,i}(r_{c_0}) = \begin{cases} \frac{2r_{c_0}}{R^2} & , 0 \leq r_{c_0} \leq R \\ 0 & , otherwise \end{cases}, \quad (27)$$

Since the PGFL of the MHCP has not been found yet, the Laplace transform of the aggregate interference from interfering CBSs cannot be calculated exactly. To analyze the coverage of a network deployed following the MHCP, a conventional method is to approximate the MHCP by an equal-density PPP with a corresponding exclusion zone. The efficiency of the approximation is demonstrated in [34] and has been widely applied in the literature.

Therefore, in the case where  $C_0$  is retained,  $\mathcal{C}_{c,i}$  could be calculated as

$$\begin{aligned} & \mathbb{P}(SINR_c > \gamma_c) \\ &= \mathbb{P}\left(h_c > \frac{\gamma_c}{P_c A_c R_c^{-\nu_c}} \left( \sum_{k \in \Phi_c^I} P_c A_c h_k R_k^{-\nu_c} + n_0 \right)\right) \\ &= \int_0^R \exp(-\mathcal{N}_c r_{c_0}^{\nu_c}) \mathcal{L}_{I_{C_0}}(\gamma_c r_{c_0}^{\nu_c}) f_{R_{C_0}}^{c,i}(r_{c_0}) dr_{c_0}, \end{aligned} \quad (28)$$

where  $\mathcal{N}_c = \frac{\gamma_c n_0}{P_c A_c}$ ,  $I_c = \sum_{k \in \Phi_c^I} h_k R_k^{-\nu_c}$ ,  $\mathcal{L}_{I_{C_0}}(m)$  is the Laplace transform of  $I_c$ .

Denote  $m = \gamma_c r_{c_0}^{\nu_c}$ ,  $\mathcal{L}_{I_{C_0}}(m)$  only contains the interference component from  $\Phi_C/C_0$ , which is

$$\mathcal{L}_{I_{C_0}}(m) = \mathbb{E} \left[ \exp \left( -m \sum_{k \in \Phi_c^I} h_k R_k^{-\nu_c} \right) \right], \quad (29)$$

where  $R_k$  is the distance between the typical user and the  $k$ -th interfering neighboring CBS.

Following the method in [35], the coordinate system is translated with setting  $C_0$  at the origin and the typical user at the negative side of the  $x$ -axis, as shown in Fig. 2. Therefore,  $R_k$  is derived using the cosine rule, given by

$$R_k = \sqrt{(R_{C_0}^2 + r_i^2 + 2r_i R_{C_0} \cos \phi)}, \quad (30)$$

where  $r_i = \|C_k - C_0\|$  represents the distance between the interfering CBS  $C_k$  and the associated CBS  $C_0$ .

As we assumed  $R_m \geq 2R$ , the integration region is illustrated in Fig. 2. Here we apply the PPP approximation and

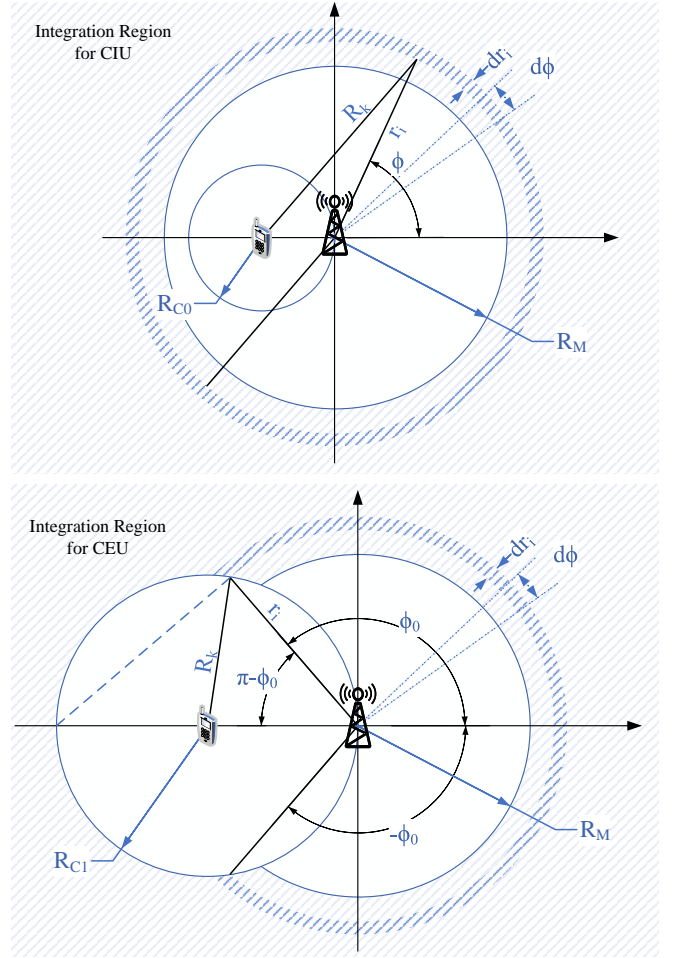


Fig. 2. Integration region for  $\mathcal{L}_{I_{C_0}}(m)$  and  $\mathcal{L}_{I_{C_1}}(m)$ .

use the PGFL of PPP to calculate  $\mathcal{L}_{I_{C_0}}(m)$ , which is given by

$$\begin{aligned} & \mathbb{E} \left[ \exp \left( -m \sum_{k \in \Phi_c^I} h_k R_k^{-\nu_c} \right) \right] \\ & \approx \exp \left( - \int_{R_m}^{\infty} \int_{-\pi}^{\pi} \mathbb{E}_h \left[ 1 - e^{-mh R_k^{-\nu_c}} \right] \Lambda(r_i d\phi dr_i) \right) \\ & = \exp \left( - \int_{R_m}^{\infty} \int_{-\pi}^{\pi} \lambda_d \frac{k(r_i)}{\mathcal{P}_r} r_i \right. \\ & \quad \cdot \left. \left( 1 - \frac{1}{1 + m(r_{c_1}^2 + r_i^2 + 2r_i r_{c_1} \cos \phi)^{\frac{-\nu_c}{2}}} \right) d\phi dr_i \right). \end{aligned} \quad (31)$$

where  $\Lambda(r_i d\phi dr_i) = \frac{\lambda_d k(r_i)}{\mathcal{P}_r} d\phi dr_i$  is the conditional intensity of the approximated PPP [35],  $k(r_i)$  is the probability of two points in the parent PPP separated by a distance  $r_i$  to be both retained in the resulting MHCP process, which is given in [34] by

$$k(r_i) = \begin{cases} 0 & , r < R_m \\ 2 \left( \frac{1 - e^{-\pi R_m^2 \lambda_d} + e^{-\lambda_d V - 1}}{\pi R_m^2} \right) \frac{1}{\lambda_d^2 (V - \pi R_m^2)} & , r \geq R_m \end{cases}, \quad (32)$$

where

$$V = \begin{cases} 2\pi R_m^2 + \sqrt{R_m^2 - \frac{r_i^2}{4}} r_i & , r \leq 2R_m \\ -2 \arccos\left(\frac{r_i}{2R_m}\right) R_m^2 & , r > 2R_m \end{cases} \quad (33)$$

Substitute (31) into (28), we have

$$\mathcal{C}_{c,i} = \int_0^R \exp(-\mathcal{N}_c r_{c_0}^{\nu_c}) \mathcal{L}_{I_{c_0}}(\gamma_c r_{c_0}^{\nu_c}) \frac{2r_{c_0}}{R^2} dr_{c_0}, \quad (34)$$

where  $\mathcal{N}_c = \frac{\gamma_c n_0}{P_c A_c}$  and  $\mathcal{L}_{I_{c_0}}(\gamma_c r_{c_0}^{\nu_c})$  is given by

$$\mathcal{L}_{I_{c_0}}(\gamma_c r_{c_0}^{\nu_c}) = \exp\left(-\int_{R_m}^{\infty} \int_{-\pi}^{\pi} \lambda_d \frac{k(r_i)}{\mathcal{P}_r} r_i \cdot \left(1 - \frac{1}{1 + \gamma_c r_{c_0}^{\nu_c} (r_{c_0}^2 + r_i^2 + 2r_i r_{c_0} \cos \phi)^{\frac{-\nu_c}{2}}}\right) d\phi dr_i\right). \quad (35)$$

### B. Coverage probability for CEU

In contrast, if the cluster center is not retained as a CBS, the typical user is categorized as a CEU and associated with the nearest CBS, which is denoted by  $C_1$ . Note that the residual points  $\Phi_d/\Phi_c$  form another process named the complementary-MHCP (CMHCP). However, it has been proved through simulation [36], [37] that the correlation between the CMHCP and the MHCP thinning from the same parent process is insignificant, and the CMHCP can be approximated as an independent PPP.

Although there is no known closed-form expression for the contact distance based on MHCP, we adopt an approximated distribution, which has been proven to be sufficiently accurate and has been widely applied in the literature [38]–[40], conditioned on the maximum distance between CEU and its associated CBS being  $R_m + R$ . The PDF of the serving distance between the typical user and its associated CBS is given by

$$f_{R_{c_1}}^{c,e}(r_{c_1}) = \frac{2\pi \lambda_c r_{c_1} \exp(-\pi \lambda_c r_{c_1}^2)}{1 - \exp(-\pi \lambda_c (R + R_m)^2)}. \quad (36)$$

In case  $C_0$  is not retained,  $\mathcal{C}_{c,e}$  is expressed as

$$\begin{aligned} & \mathbb{P}(SINR_c > \gamma_c) \\ &= \int_0^R \exp(-\mathcal{N}_c r_{c_0}^{\nu_c}) \mathcal{L}_{I_{c_1}}(\gamma_c r_{c_0}^{\nu_c}) f_{R_{c_1}}^{c,e}(r_{c_1}) dr_{c_1}, \end{aligned} \quad (37)$$

where  $\mathcal{L}_{I_{c_1}}(m)$  is the Laplace transform of aggregated interference from  $\Phi_c/C_1$ .

The derivation of  $\mathcal{L}_{I_{c_1}}(m)$  is similar to  $\mathcal{L}_{I_{c_0}}(m)$ . However, in this case, as the typical user is not in the cluster centered at  $C_1$ , there exists the situation that  $r_i < 2R_{c_1}$ , which reshapes the integration region.

In this case, the upper and lower limits of the integral are changed accordingly, as shown in Fig.2. Due to this,  $\mathcal{L}_{I_{c_1}}(m)$

is given by

$$\begin{aligned} & \mathbb{E} \left[ \exp \left( -m \sum_{k \in \Phi_c^I} h_k r_k^{-\nu_c} \right) \right] \\ & \approx \exp \left( -\int_{R_m}^{\infty} \int_{-\phi_0}^{\phi_0} \mathbb{E}_h \left[ 1 - e^{-m h r_k^{-\nu_c}} \right] \Lambda(r_i) d\phi dr_i \right) \\ & = \exp \left( -\int_{R_m}^{\infty} \int_{-\phi_0}^{\phi_0} \frac{\lambda_d}{K_c} \frac{k(r_i)}{\mathcal{P}_r} r_i \cdot \left( 1 - \frac{1}{1 + m(r_{c_1}^2 + r_i^2 + 2r_i r_{c_1} \cos \phi_u)^{\frac{-\nu_c}{2}}} \right) d\phi dr_i \right), \end{aligned} \quad (38)$$

where the conditional density is changed due to FFR as

$$\Lambda(r_i) d\phi dr_i = \frac{\lambda_d}{K_c} \frac{k(r_i)}{\mathcal{P}_r} r_i. \quad (39)$$

and  $\phi_0$  is given by

$$\phi_0 = \begin{cases} \pi - \arccos \frac{r_i}{2R_{c_1}} & , r_i < 2R_{c_1} \\ \pi & , \text{otherwise} \end{cases}, \quad (40)$$

where  $k_{r_i}$  is same with (32). With  $\mathcal{L}_{I_{c_1}}(m)$  we could derive  $\mathcal{C}_{c,e}$ .

Since that, for the CEU, conditioned on  $C_0$  not being retained, the coverage probability is

$$\mathcal{C}_{c,e} = \int_0^{R+R_m} \frac{2\pi \lambda_c r_{c_1} \exp(-\pi \lambda_c r_{c_1}^2)}{1 - \exp(-\pi \lambda_c (R + R_m)^2)} \cdot \exp(-\mathcal{N}_c r_{c_1}^{\nu_c}) \mathcal{L}_{I_{c_1}}(\gamma_c r_{c_1}^{\nu_c}) dr_{c_1}, \quad (41)$$

where  $\mathcal{N}_c = \frac{\gamma_c n_0}{P_c A_c}$  and  $\mathcal{L}_{I_{c_1}}(m)$  is given by

$$\mathcal{L}_{I_{c_1}}(\gamma_c r_{c_1}^{\nu_c}) = \exp \left( -\int_{R_m}^{\infty} \int_{-\phi_0}^{\phi_0} \frac{\lambda_d}{K_c} \frac{k(r_i)}{\mathcal{P}_r} r_i \cdot \left( 1 - \frac{1}{1 + \gamma_c r_{c_1}^{\nu_c} (r_{c_1}^2 + r_i^2 + 2r_i r_{c_1} \cos \phi)^{\frac{-\nu_c}{2}}} \right) d\phi dr_i \right). \quad (42)$$

The overall coverage probability of C-plane is given by

$$\mathcal{C}_c = \mathcal{P}_r \mathcal{C}_{c,i} + (1 - \mathcal{P}_r) \mathcal{C}_{c,e}. \quad (43)$$

## VI. DELAY ANALYSIS

In this section, we will derive the delay performance of C/U-planes based on queueing theory and stochastic geometry. Since the proposed network is a multi-user system, traffic conditions play a major role in the queueing delay of the system. Therefore, we will first analyze the traffic of both planes.

The traffic of both C/U-planes is modeled by the  $M/M/C$  queueing model [57], where  $C$  represents  $C_{\{c,d\}}$ , which denotes the available channels for C/U-planes. Specifically, we assume that a typical user's request arrives at its associated BS according to a Poisson process with a rate  $\omega$ . Additionally, we assume that the user's requests are divided into two processes with probability  $p$ : one is the control requests with rate  $\omega_c = p\omega$ , and the other is the high-speed data requests with rate  $\omega_d = (1-p)\omega$ . Both processes follow independent Poisson processes, as described in [57].



Here, we assume that the ratio of reserved sub-bands for interior users is  $p_m$ . Consequently, the available channels for interior users and edge users are  $p_m C_{\{c,d\}}$  and  $(1 - p_m)C_{\{c,d\}}/K_{\{c,d\}}$ , respectively.

Due to the functional correlation between the CBSs and DBSs, we introduce a parameter  $\alpha$  to describe the relationship between the total bandwidths of C/U planes as  $W_c = \alpha W_d$ . This implies that operators should allocate a dedicated low-frequency band to assist the coverage of U-plane in high-frequency. Since the DBSs take advantage of the rich spectrum resources in high-frequency,  $\alpha$  should be less than 1. Therefore, the bandwidths per channel for C/U-planes are  $w_{\{c,d\}} = W_{\{c,d\}}/C_{\{c,d\}}$ .

The average aggregated request arrival rate of a BS is  $\Omega = \omega N$ , where  $N$  represents the average number of users in the covered area of the BS. For DBSs,  $N_d = S$  since users' distribution follows PCP, and  $N$  is equivalent to the cluster size. In contrast, for CBSs,  $N_c = S/\mathcal{P}_r$ . Consequently, the average aggregated request arrival rates for interior users and edge users of CBSs and DBSs are respectively given by

$$\Omega_{c,\{i,e\}} = \omega_c S \frac{\lambda_d}{\lambda_c} = \frac{p\omega S}{\mathcal{P}_r} \mathcal{P}_{c,\{i,e\}}, \quad (44)$$

and

$$\Omega_{d,\{i,e\}} = \omega_d S = (1 - p)\omega S \mathcal{P}_{d,\{i,e\}}. \quad (45)$$

Then we will derive the delay performance of the network. According to [57], the probability that  $n$  requests are in the C-server queueing system (including the requests in queueing and in service), denoted by  $p_n$ , is

$$p_n = \begin{cases} p_0 \frac{(C\rho)^n}{n!}, & n \leq C \\ p_0 \frac{\rho^n C^C}{C!}, & n > C \end{cases}, \quad (46)$$

where  $\rho$  and  $p_0$  are given by

$$\rho = \frac{\Omega}{C\mu} < 1, \quad (47)$$

and

$$p_0 = \left[ \sum_{n=0}^{C-1} \frac{(C\rho)^n}{n!} + \frac{(C\rho)^C}{C!(1-\rho)} \right]^{-1}, \quad (48)$$

where  $\Omega$  is the request rate and  $\mu$  is the service rate, i.e. the downlink transmitting rates of BSs.

The queueing probability that all servers are occupied, and new comers have to queue, is given according to *Erlang C formula* [57]:

$$\mathcal{P}_Q(\Omega, C, \mu) = \sum_{n=C}^{\infty} p_n = \frac{p_0 (C\rho)^C}{C!(1-\rho)}, \quad (49)$$

and the average queue length is given by

$$Q(\Omega, C, \mu) = \sum_{n=0}^{\infty} n p_{n+C} = \mathcal{P}_Q \frac{\rho}{1-\rho}. \quad (50)$$

Using *Little's Theorem* [57], the average delay  $T_Q$  that one request waiting in the queue is

$$T(\Omega, C, \mu) = \frac{Q}{\Omega}. \quad (51)$$

Inter-cell interferences lead to spatiotemporal interactions among the queues of different BSs, causing dependent queues of neighboring BSs and making the analysis more challenging. In [45-47], the authors made progress on the "interacting queue" problem under the mean-field approximation. However, in some more complex queueing models, this problem still remains to be addressed. When the service request arrival rates are stable, the queueing delay is determined by the downlink rates. Therefore, in this part, we attempt to analyze the queues based on the distributions of downlink rates.

Conditioned on the downlink rate of users competing for the same sub-band of one typical cell being  $X$ , the conditional expectation of queueing delay is given by

$$\mathbb{E}[T(\Omega, C, \mu)] = \mathbb{E}_X \{ \mathbb{E}[T(\Omega, C, \mu) \mid \mu = X] \}. \quad (52)$$

As a result, if we know the distribution of  $X$ , we could derive the expectation of delay  $T$  through the *Law of Total Expectation*:

$$\mathbb{E}[T(\Omega, C, \mu)] = \int_0^{\infty} \mathbb{E}[T(\Omega, C, \mu) \mid \mu = x] dF_X(x). \quad (53)$$

where  $F_X(x)$  is the CDF of rate  $X$ . For the distribution of rate  $X$ , we have derived the coverage probability of both C/U-planes in different conditions, which can be converted to the CDF of  $X$ , given by

$$\begin{aligned} F_X(x) &= \mathbb{P}(X < x) \\ &= \mathbb{P}(V \log_2(1 + SINR) < x) \\ &= \mathbb{P}(SINR < 2^{\frac{x}{V}} - 1) \\ &= 1 - \mathcal{C}(\gamma(x) \mid \gamma(x) = 2^{\frac{x}{V}} - 1). \end{aligned} \quad (54)$$

where  $V$  denotes  $V_{\{c,d\}} = w_{\{c,d\}}/B_{\{c,d\}}$ , where  $w_{\{c,d\}}$  is the bandwidth per channel for C/U-planes, respectively, and  $B_{\{c,d\}}$  is the data size for one round transmission in C/U-planes, respectively.

The PDF of the rate, which is the derivative of  $F_X(x)$ , is

$$\begin{aligned} f_X(x) &= \frac{d}{dx} F_X(x) = \frac{d}{d\gamma(x)} F_X(\gamma(x)) \cdot \frac{d}{dx} \gamma(x) \\ &= -\frac{2^{\frac{x}{V}} \ln 2}{V} \left\{ \frac{d}{d\gamma(x)} \mathcal{C}(\gamma(x)) \mid \gamma(x) = 2^{\frac{x}{V}} - 1 \right\}. \end{aligned} \quad (55)$$

Therefore we need to derive the derivation of coverage probability  $\mathcal{C}$  with respect to  $\gamma$ , which is list at the top of next page for different situation. Here,  $\mathcal{G}_0 = {}_2F_1 \left[ 1, 1 - \frac{2}{\nu_d}, 2 - \frac{2}{\nu_d}, -\gamma_d \right]$ ,  $\mathcal{A}_0(r_i) = \lambda_d \frac{k(r_i)}{\mathcal{P}_r} r_i$ ,  $\mathcal{B}_0(r_i, \phi_i) = r_{c_0}^{\nu_c} (r_{c_0}^2 + r_i^2 + 2r_i r_{c_0} \cos \phi)^{-\frac{\nu_c}{2}}$ ,  $\mathcal{A}_1(r_i) = \frac{\lambda_d}{K_c} \frac{k(r_i)}{\mathcal{P}_r} r_i$  and  $\mathcal{B}_1(r_i, \phi_i) = r_{c_1}^{\nu_c} (r_{c_1}^2 + r_i^2 + 2r_i r_{c_1} \cos \phi)^{-\frac{\nu_c}{2}}$ .

Substituting  $dF_X(x) = f_X(x)dx$  into (53), we could obtain the average queueing delay of C/U-planes' interior and edge users, denoted by  $T_{c,i}$ ,  $T_{c,e}$ ,  $T_{d,i}$ , and  $T_{d,e}$ , respectively.

The distribution of downlink rates  $X$  has taken the inter-cell interference into consideration. Although we cannot depict the coupling of interacting queues, we could still demonstrate the average delay performance of CUPS from the perspective of conditional expectation through the analysis above, and it will be verified through numerical results.

$$\frac{d\mathcal{C}_{d,i}(\gamma_d)}{d\gamma_d} = \frac{1}{\mathcal{P}_{d,i}} \int_0^R \exp(\mathcal{G}_d r_0^2 - \mathcal{N}_d r_0^{\nu_d}) \frac{2r_0}{R^2} \left( -2\lambda_d \pi r_0^2 \left( \frac{1}{1+\gamma_d} - \mathcal{G}_0 + \frac{\mathcal{G}_0}{\nu_d - 2} \right) - \mathcal{N}_d \gamma_d \right) dr_0. \quad (56)$$

$$\begin{aligned} \frac{d\mathcal{C}_{d,e}(\gamma_d)}{d\gamma_d} &= \frac{1}{\mathcal{P}_{d,e}} \int_0^R \exp((\mathcal{G}'_d - \pi\lambda_d)r_1^2 - \mathcal{N}_d r_1^{\nu_d}) 2\pi\lambda_d r_1 \left(1 - \frac{r_1^2}{R^2}\right) \\ &\cdot \left\{ \frac{2(\mathcal{L}_{I_0} - 1)}{\nu_d \gamma_d} \left( R^2 \mathcal{G}_1 - r_1^2 \mathcal{G}_2 + \frac{\gamma_d r_1^2}{\gamma_d + 1} - \frac{\gamma_d R^2}{\gamma_d + R^{\nu_d} r_1^{-\nu_d}} \right) + \left[ -2\lambda_d \pi r_1^2 \left( \frac{1}{1+\gamma_d} + \frac{\mathcal{G}_0}{K_d(\nu_d - 2)} \right) - \mathcal{N}_d \gamma_d \right] \mathcal{L}_{I_0} \right\} dr_1. \end{aligned} \quad (57)$$

$$\frac{d\mathcal{C}_{c,i}(\gamma_c)}{d\gamma_c} = \int_0^R \exp(-\mathcal{N}_c r_{c_0}^{\nu_c}) \mathcal{L}_{I_{c_0}}(\gamma_c r_{c_0}^{\nu_c}) \frac{2r_{c_0}}{R^2} \left( -\mathcal{N}_c \gamma_c - \int_{R_m}^{\infty} \int_{-\pi}^{\pi} \frac{\mathcal{A}_0(r_i) \mathcal{B}_0(r_i, \phi_i)}{(1 + \gamma_c \mathcal{B}_0(r_i, \phi_i))^2} d\phi dr_i \right) dr_{c_0}. \quad (58)$$

$$\frac{d\mathcal{C}_{c,e}(\gamma_c)}{d\gamma_c} = \int_0^{R_m+R} f_{R_{c_1}}^{c,e}(r_{c_1}) \exp(-\mathcal{N}_c r_{c_1}^{\nu_c}) \mathcal{L}_{I_{c_1}}(\gamma_c r_{c_1}^{\nu_c}) \left( -\mathcal{N}_c \gamma_c - \int_{R_m}^{\infty} \int_{-\phi_0}^{\phi_0} \frac{\mathcal{A}_1(r_i) \mathcal{B}_1(r_i, \phi_i)}{(1 + \gamma_c \mathcal{B}_1(r_i, \phi_i))^2} d\phi dr_i \right) dr_{c_1}. \quad (59)$$

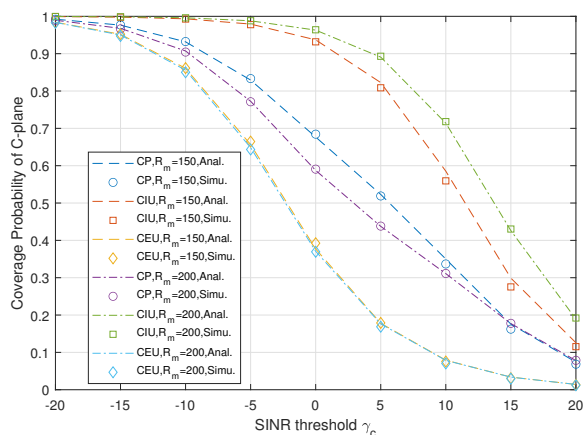
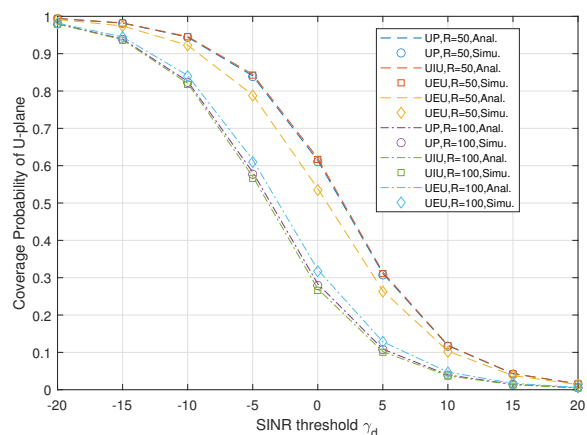
(a) Coverage probability of C-plane versus  $\gamma_c$ (b) Coverage probability of U-plane versus  $\gamma_d$ 

Fig. 3. Monte Carlo simulations of the overall, interior users' and edge users' coverage probability versus SINR threshold of (a) C-plane with different hard-core distance  $R_m$  and (b) U-plane with different cluster radius  $R$ .

## VII. NUMERICAL RESULTS

To validate the performance advantage of the proposed schemes, numerical results are presented in this section. Throughout this section, the settings in Table I are used unless stated otherwise, where the parameters come from [11], [12].

TABLE I  
PARAMETERS

	C-plane	U-plane
Channel number	$C_c = 50$	$C_d = 20$
Total bandwidth	$W_c = \alpha W_d, \alpha = 0.5$	$W_d = 20\text{MHz}$
Transmit power	$P_c = 46\text{dBm}$	$P_d = 30\text{dBm}$
Threshold	$\gamma_c = -6\text{dB}$	$\gamma_d = -6\text{dB}$
Carrier frequency	$f_c = 2\text{GHz}$	$f_d = 6\text{GHz}$
FFR reuse factor	$K_c = 3$	$K_d = 3$
DBS density	$\lambda_d = 2 \times 10^{-5} \text{BSs}/\text{m}^2$	
Request rate	$\omega = 0.5$	
Separation factor	$p = 0.3$	
Noise power density	$n_c = n_d = -174\text{dBm}/\text{Hz}$	
Cluster size	$S = 10$	
Cluster radius	$R = 50\text{m}$	
Hard-core distance	$R_m = 100\text{m}$	

Adopting the path loss model from [12], the path losses for C/U-planes are respectively given by

$$\beta_c(\text{dB}) = 39 + 26 \log_{10}(d[\text{m}]) + 20 \log_{10} \left( \frac{f_c[\text{GHz}]}{5} \right), \quad (61)$$

$$\beta_d(\text{dB}) = 41 + 22.7 \log_{10}(d[\text{m}]) + 20 \log_{10} \left( \frac{f_d[\text{GHz}]}{5} \right), \quad (62)$$

which would determine the corresponding path gains  $A_c$  and  $A_d$  as well as the path loss exponents  $\nu_c$  and  $\nu_d$  of C/U-planes, and influence the SINR of C/U-planes in (3) and (4). By converting (61) and (62) to ratios, it could be obtained that  $A_c = 7.87 \times 10^{-4}$ ,  $\nu_c = 2.6$ ,  $A_d = 5.52 \times 10^{-5}$ , and  $\nu_d = 2.27$ .

Firstly, we verify the accuracy of the proposed analysis through Monte Carlo simulations in comparison with the theoretical derivations we derived in previous sections. In the case of FFR reuse factors  $K_c = 1$  and  $K_d = 1$ , Fig. 3 shows the coverage probabilities of the interior users

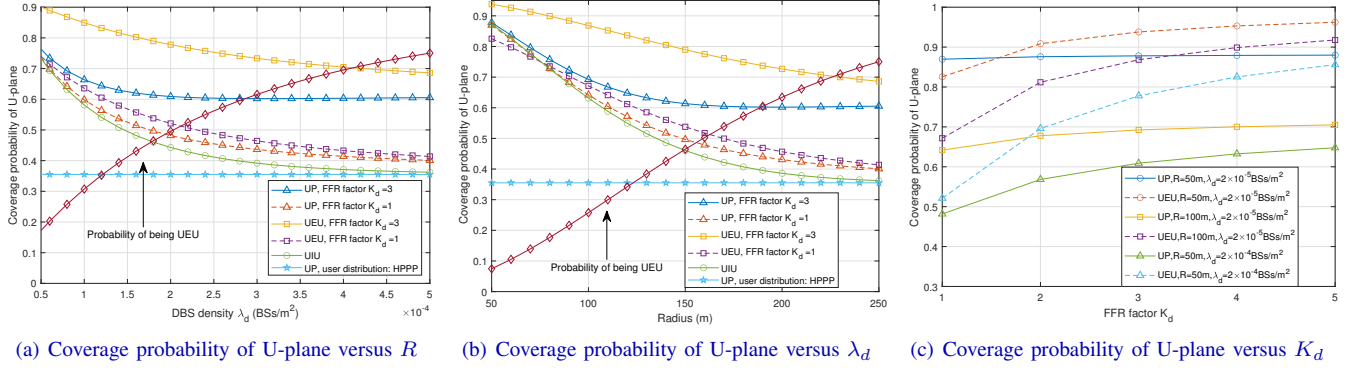


Fig. 4. The overall, interior users' and edge users' coverage probability of U-plane versus (a) the radius of cluster, (b) the density of DBSs, and (c) the FFR factor. (a) and (b) compare results with (1) reuse factor  $K_d = 1$  (dotted lines) and (2) user distribution following independent PPPs (pentagrams).

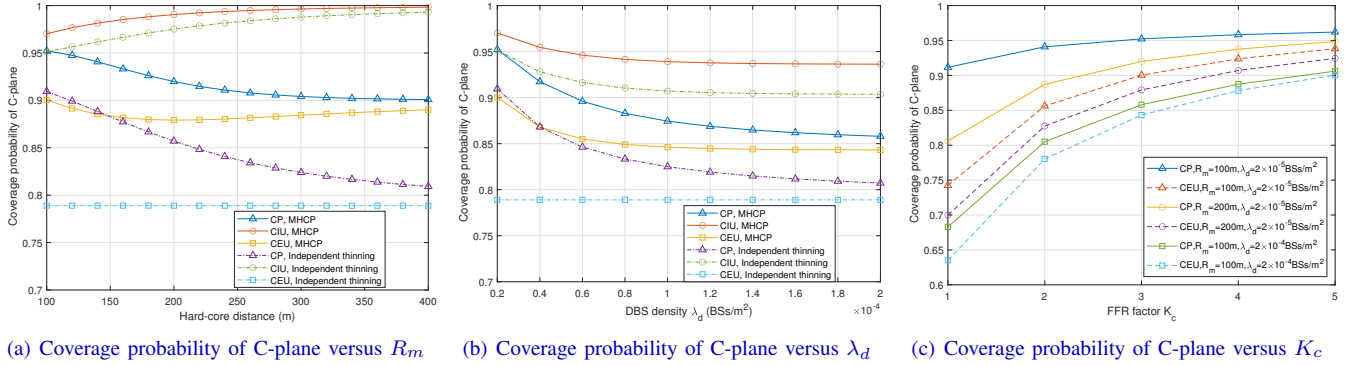


Fig. 5. The overall, interior users' and edge users' coverage probability of C-plane users versus (a) the hard-core distance, (b) the density of DBSs and (c) the FFR factor. (a) and (b) compare results with the independent thinning case (dashed lines), i.e. CBS locations following an independent PPP.

(marked by squares), the edge users (marked by diamonds), and the overall performance (marked by circles) of both C/U planes versus SINR threshold. The analytical derivation of coverage probabilities of U-plane is perfectly matched with the simulation results. While for C-plane, the slight differences between the analytical and simulation results are caused by the approximation methods we adopted. We could also observe the variations of the U-plane coverage probability with different cluster radius  $R$  in Fig. 3(b), as well as the C-plane coverage probability with different hard-core distance  $R_m$  in Fig. 3(a), which are consistent with the results in Fig. 4 and Fig. 5.

Next, we demonstrate the coverage performance of U-plane users versus the range of the cluster, the density of DBSs, and the frequency reuse factors of the U-plane in Fig. 4. The probability of the typical user being classified as UEU, i.e.,  $\mathcal{P}_{d,e}$  from (9), as well as the conditional coverage probabilities of U-plane users  $\mathcal{C}_{d,i}$ ,  $\mathcal{C}_{d,e}$ , and  $\mathcal{C}_d$  from (16), (22), and (23), are given in Fig. 4. From Fig. 4(a), when the radius of the cluster is small, the overlapping between clusters is rare, so the typical user is more likely to be classified as an interior user and associated with the center DBS. Since the contact distances for both UIUs and UEUs are less than  $R$ , a smaller cluster radius leads to higher SINR and better coverage. However, along with the growth of the cluster range, the coverage probability of both UIUs and UEUs would decrease as the associated DBS is further away.

We also make a comparison with users that are indepen-

dently distributed with DBSs following HPPP and not applying FFR, whose performance is unrelated to  $R$ . The coverage of the presented PCP model is better than that of PPP because the contact distance is limited. However, with the increase of  $R$ , the PCP in the proposed scheme will become increasingly similar to ordinary PPP, and users are more likely to associate with  $D_1$ , whose distribution is independent of users' location. If the FFR reuse factor  $K_d = 1$ , the coverage probability will converge to that of the independent deployment case.

From Fig. 4(b), we can draw a similar conclusion to Fig. 4(a). As the DBS density increases, neighboring clusters are more likely to overlap with each other, and the overall user distribution will be more like that of an ordinary PPP, thus  $D_0$  is more difficult to be the nearest DBSs. What should be noticed is that, in this result, the cluster size is fixed, so the increase of DBS density cannot reduce the utilization of DBSs and lead to coverage enhancement. The reduction in coverage is because the received signal power enhancement cannot offset the increased interference power.

From Fig. 4, we can obtain useful guidelines that, for a large cluster range or high DBS density, we can use PPP to approximate PCP and apply PPP-based DBS deployment for CUPS; in other cases, the dependent BS deployment scheme is better. In other words, if the deployment of the DBSs is dense enough or the users are not concentrated enough, then the necessity of dependent deployment will decline.

The effectiveness of the proposed distance-based FFR

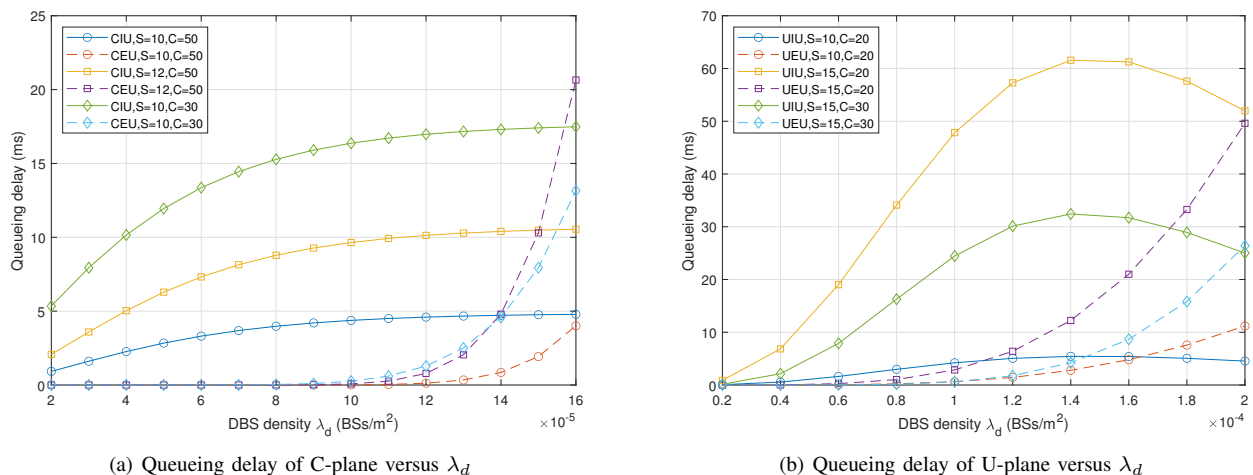


Fig. 6. The delay performance versus the density of DBSs of (a) C-plane and (b) U-plane.

scheme is demonstrated in Fig. 4(c). By implementing FFR, the coverage probability of edge users is substantially enhanced compared to the scenario in which  $K_d = 1$ , signifying that all edge users share the same sub-bands. It is evident that the coverage probability of UEUs consistently improves with increasing  $K_d$ , due to a gradual decrease in interference to the edge users, especially in high inter-cell interference environments.

For the U-plane, when base station densities are lower or the cluster radius is smaller, cluster overlap occurs less frequently. This means that only a few users at the edge of the cell will be classified as edge users. Therefore, an improved reuse factor  $K_d$  does not significantly improve the overall coverage of the U-plane. However, with increased base station density or a larger cluster radius, a greater number of users may be at the cell edges, causing increased inter-cell interference. In these circumstances, a higher reuse factor can substantially improve the coverage probability for edge users, which also results in a more significant overall coverage enhancement of the U-plane.

Fig. 5 demonstrates the coverage performance of the C-plane derived in (34), (41), and (43) with respect to the hard-core distance, the DBS density, and the FFR factors of the C-plane. Since we assume a hard-core distance  $R_m \geq 2R$ , the clusters of CBSs do not overlap with each other, and CIUs will only associate with the center CBSs. Therefore, the increasing of  $R_m$  does not affect their received signal power and makes interfering CBSs further and sparser, which results in the improvement of coverage, as shown in Fig. 5(a).

However, for the CEUs, the coverage probability first decreases and then increases. This occurs because the increasing hard-core distance reduces both the received signal power and the interference power. The rising  $R_m$  not only decreases the density of interfering CBSs but also increases the contact distances of CEUs. The overall performance approaches that of CEU since the proportion of CIUs is decreasing.

In Fig. 5(b), we verify the coverage probability of the C-plane versus DBS density with a fixed hard-core distance. Note that here we analyze the performance of CBSs according to the density of DBSs rather than that of CBSs. The reason is that the CBS deployment is a dependent thinning of DBS

deployment based on MHCP, and the relationship between the densities  $\lambda_c$  and  $\lambda_d$  is nonlinear. With the increase of  $\lambda_d$ , the density of CBSs  $\lambda_c$  first increases and then converges to a constant, which results in the trends of coverage probabilities. Regarding the CIUs, as the density of base stations increases, the interfering power grows. Meanwhile, the contact distance remains stable due to the fixed cluster radius, so the coverage probabilities of CIUs decrease. As for the CEUs, the contact distance is limited by the unchanged  $R + R_m$ , so the coverage probabilities decrease with the increasing density of interfering CBSs.

We also make a comparison with the coverage of CBSs deployment following PPP with the same density of MHCPs (marked by dashed lines in Fig. 5(a) and Fig. 5(b)). In the comparison scheme, the CBSs are also thinned from the DBSs, but the thinning process is independent and does not consider the hard-core distance.

For CIUs, the coverage probability of the comparison scheme has similar trends but is worse than that of MHCP, since there is no hard-core distance to keep interfering neighbors away. However, for CEUs, there is a significant gap between the proposed and comparison model. Since the typical CEU is in the cluster of an eliminated CBS with radius  $R$ , and the distance between the eliminated point and the nearest retained CBS is less than  $R_m$ , so the contact distance of CEUs is less than  $R + R_m$ . This limit does not hold in the comparison model, where the contact distance can be arbitrarily far. So in the proposed model where users cluster around DBSs, if we apply dependent thinning to deploy CBSs, we could achieve a coverage improvement of up to 10 percent, in comparison with the independent thinning scheme.

Therefore, even with the same number of CBSs, the proposed deployment scheme with dependent thinning can significantly improve network coverage. This insight suggests that we should pay more attention to the deployment of BSs adapted to user distribution to achieve better network performance under limited resources.

Fig. 5(c) demonstrates the performance of the proposed distance-based FFR scheme. Increasing the FFR factor leads to a substantial improvement in coverage probability for

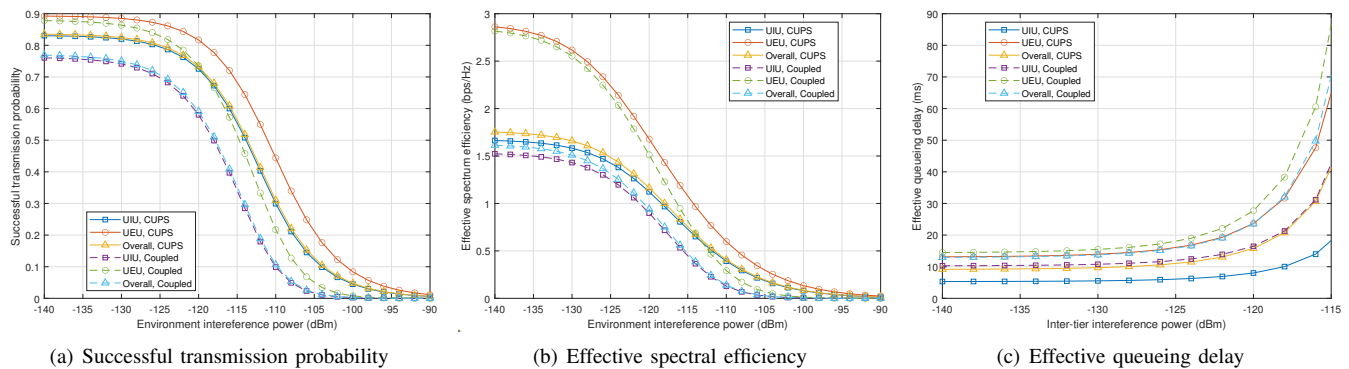


Fig. 7. The network performance versus inter-tier interference power under different performance metric: (a) Successful transmission probability. (b) Effective spectral efficiency. (c) Effective queuing delay.

edge users and overall coverage probabilities. Moreover, the proposed FFR scheme shows better coverage enhancement in situations with high interferences.

Fig. 6 shows the queuing delay of both C/U-planes obtained in (53) in Section VI. The queuing latency is determined by the utilization rate  $\rho = \frac{\Omega}{C\mu}$ . When  $\rho$  approaches 1, there would be a sharp increase in the delay measure. Note that,  $\rho < 1$  since otherwise the system cannot keep up with the request arrivals, and the delay will grow to infinity [57].

As there are dedicated sub-bands for interior and edge users according to FFR, each BS would have two independent queues for the associated interior and edge users. Therefore, we could separately analyze the queuing delay for interior and edge users. For CIUs, from (44) we can obtain that the  $\Omega_{c,i} = \frac{p\omega S}{P_r} \mathcal{P}_{c,i} = p\omega S$ , which is irrelevant to  $\lambda_d$ , so that the queuing delay is inversely proportional to the rates. While for CEUs, the aggregated requests arrival rates  $\Omega_{c,e}$  keep going up, resulting in the sharp increase of queuing delay, as shown in Fig. 6(a).

Since both  $\Omega_{d,i}$  and the rates of UIU are declining with different variation tendencies, the queuing delay for UIU first increases and then decreases, as shown in Fig. 6(b). Finally,  $\Omega_{d,i}$  will take the main role. In contrast, the rapid increase in the proportion of UEUs leads to the increasing queuing delay.

For both planes, the queuing delay of the interior users is limited compared to that of the edge users. The reasons can be divided into two aspects: (1) The proposed FFR strategies assign more users as edge users as the density of BSs increases. (2) Although FFR reduces the interference of edge users, it also reduces the available frequency band for edge users, which worsens the delay. Therefore, despite FFR improving the coverage probability of edge users, when designing FFR schemes, it is necessary to balance multiple performance aspects.

Fig. 7 shows the network performance versus the inter-tier interference under different performance metrics. Here we set a benchmark scheme in which C/U-planes are coupled, and both data and control signaling are transmitted by DBSs.

In the present model, DBSs operate in high-frequency bands to avoid limited spectrum resources in low-frequency bands and achieve high data rates. However, with the continuous

development and utilization of high-frequency bands, the interference environment in these bands is becoming more complex. Here, we assume the existence of another micro-tier consisting of micro BSs operating in the frequency bands of DBSs and deployed close to the proposed CUPS network [28], [54]. This micro-tier introduces additional inter-tier interference to users. Additionally, we assume there is no collaboration in terms of frequency sharing and reuse between the micro-tier and DBSs. To simplify the analysis, we omit the modeling and only consider the effect of inter-tier interference power in the high-frequency band, as shown in Fig. 7.

The CBS in the C-plane is responsible for transmitting essential control signaling, so the C-plane coverage of users should be considered in the U-plane and the overall coverage performance. We use  $\mathcal{P}^{ST}$  to represent the successful transmission probability of a completed data transmission in the U-plane, as shown in Fig. 7(a). It is defined as  $\mathcal{P}^{ST} = \mathcal{C}_c \mathcal{C}_d$ , where  $\mathcal{C}_c$  is from (43), and  $\mathcal{C}_d$  is given by (16) and (22). Following a similar approach, effective spectrum efficiency (ESE) and effective queuing delay (EQD) are defined as the SE and queuing delay of a typical UP user under the coverage of a CBS:  $\eta^{ESE} = \mathcal{C}_c \eta_d^{SE}$  and  $T_d^E = T_d / \mathcal{C}_c$ , where  $\eta_d^{SE}$  is derived from (25), and  $T_d$  is given by (53). These are shown in Fig. 7(b) and Fig. 7(c).

Since CBSs are operating in the stable and clean low-frequency band, in the presented model, CBSs can avoid the high-frequency inter-tier interference. From Fig. 7, it can be seen that the C/U coupled networks experience more performance loss from environmental interference, as both their control signaling and data are transmitted in the high-frequency band. In contrast, CUPS networks are more stable and are easier to maintain connectivity.

Fig. 7(c) compares the queuing delay of the proposed CUPS network with traditional coupled networks versus the inter-tier interference power with  $\lambda_d = 2 \times 10^{-4}$  BSs/m<sup>2</sup>. The sharp increase is mainly caused by the decrease in transmission rates. It can be observed that the deterioration of queuing delay in the CUPS network is slower than that of the coupled network, which takes advantage of the stable channel environment of low-frequency CBSs.

### VIII. CONCLUSION

In this paper, we investigate CUPS-based cellular networks in which control signaling and data are transmitted separately by CBSs and DBSs in the low and high-frequency bands, respectively. In particular, we consider the non-uniformly distributed users modeled by Poisson cluster processes (PCPs) and the correlated CBSs/DBSs deployment modeled by Matérn Hard Core Processes (MHCPs). Additionally, we propose two novel distance-based FFR techniques for C/U-planes, respectively, in which the classification of interior and edge users is based on the properties of MHCPs and PCPs. We derive expressions for coverage probability, spectrum efficiency, and queuing delay to analyze performance. Specifically, the queuing delay is examined based on an M/M/C queuing model according to the derived downlink rate distribution. Finally, in the numerical results, we verify the effectiveness of the proposed scheme by comparing it with the independent deployment scheme and the traditional C/U coupled network.

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