# A Hybrid Cooperation Scheme for sub-6 GHz/mmWave Cellular Networks

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***Abstract*—In this letter, we propose a novel hybrid cooperation scheme in the context of heterogeneous sub-6 GHz/millimeter-wave cellular networks, where users are classified either as cell-center or cell-edge users. Using stochastic geometry tools, we propose an analytical framework to investigate the achieved performance of our proposed scheme. Specifically, analytical expressions for the moments of the conditional success probability are derived and a simple approximation of the meta-distribution is calculated, leveraging the moment-matching method with the Beta-distribution. Our results show that the proposed scheme is beneficial for the cell-edge users, and therefore, the overall network performance is significantly enhanced.**

***Index Terms*—Heterogeneous network, millimeter wave, stochastic geometry, meta-distribution.**

## I. Introduction

The ever-increasing data rate demands of the next-generation cellular networks, motivate the co-design of millimeter wave (mmWave) communications and heterogeneous networks (HetNets) [1]. MmWave communications is a well investigated technology which can provide multi-Gbps rates due to its abundant spectrum resources [2]. However, higher frequencies signals suffer from large attenuation and high sensitivity to blockages, designating mmWave networks unsuitable for outdoor environments [3]. Hence, the ubiquitous coverage performance in next-generation cellular networks is not feasible with the deployment of only mmWave base stations (BSs) [4]. A promising solution is that mmWave BSs will be overlaid on conventional sub-6 GHz networks, where the sub-6 GHz BSs provide a robust coverage and the mmWave BSs provide high data rates for the users in their range. As such, standardization and industry partners [5] have emphasized the importance of multi-radio access technology (RAT) sub-6 GHz/mmWave integration as a cost-effective solution to achieve high capacity, reliability, and low latency for emerging wireless services.

Using stochastic geometry, the performance of heterogeneous sub-6 GHz/mmWave cellular networks has been investigated in several works [6], [7]. These works mainly focus on the average network performance of a user at a random location within a cell. However, the link quality of a user is subjected to its location. In particular, the cell-edge users (CEUs) receive weaker signal power from the serving BS compared to the received interference, resulting in reduced performance. Contrary, the cell-center users (CCUs) experience better performance compared to the CEUs since the received signal strength (RSS) from the serving BS is significantly higher than the received interference [2], [8]. Moreover, a fundamental performance metric for wireless networks is the signal-to-interference-plus-noise ratio (SINR) performance, which indicates the success probability relative to an SINR threshold, evaluated at the typical link. However, the performance of the typical link represents an average over all spatial realizations of the point process (PP), which provides limited information on the individual links [9]. To overcome this limitation, the authors in [10], introduced the concept of meta-distribution (MD), which provides fine-grained information about the performance of the individual links. In [11], the concept of MD is investigated in the context of sub-6 GHz/mmWave cellular networks. However, the classification of users into CCUs and CEUs is not taken into account, and the concept of BS cooperation for enhancing the network performance has not been investigated. In [12], the authors studied the MD of CCUs and CEUs for the downlink two-user non-orthogonal multiple access enabled cellular networks, by exploiting the concept of MD and considered the $90\%$ and $5\%$ percentiles of the overall performance, respectively. However, this approach for classifying a user either as CCU or as CEU is not suitable for next-generation cellular networks. This stems from the fact that users may experience low coverage performance even in the center region of a communication cell, due to blockage effects and high path-losses.

In this letter, we study the MD of the SINR for HetNets, consisting of sub-6 GHz and mmWave BSs. The main contribution of this work is the development of a novel hybrid BS cooperation (HC) scheme. The proposed scheme aims at enhancing the performance of the users at the boundaries of a communication cell and consequently to achieve an ubiquitous coverage performance. Specifically, our proposed scheme elevates the CEUs' performance by exploiting the ability of BSs to jointly transmit data in a non-coherent manner. For the spatial classification of users into CCUs and CEUs, we consider a flexible and widely-adopted RSS-based technique, which includes the conventional classification approach based on the MD as a special case. Furthermore, using stochastic geometry tools, we derive the moments of the conditional

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success probability, and the MD is then calculated based on a Beta-distribution approximation. Our results show that our cooperative scheme can significantly improve the coverage performance of the considered networks, when compared to the conventional association scheme for HetNets.

## II. System model

We consider a two-tier heterogeneous cellular network consisting of sub-6 GHz macro-cells (MCells) overlaid with mmWave small-cells (SCells). Both the MCells and the SCells are spatially distributed according to independent Poisson PPs (PPPs) $\widetilde{\Phi}_{\mathrm{M}}$ and $\widetilde{\Phi}_{\mathrm{S}}$, with densities $\lambda_{\mathrm{M}}$ and $\lambda_{\mathrm{S}}$, respectively. We consider a fixed power transmission allocation scheme, i.e. BSs that belong in $\widetilde{\Phi}_i$, $i \in \{\mathrm{M}, \mathrm{S}\}$, transmit with power $P_i$, where $P_{\mathrm{M}} > P_{\mathrm{S}}$.

A mmWave link can be either line-of-sight (LoS) or non-LoS (NLoS), depending on whether the BS is visible to the user or not, due to the existence of blockages. We consider the scenario where the LoS probability function is given by $p(d) = \exp(-\beta d)$ [3], where $d$ is the distance between the receiver and the transmitter and $\beta$ is determined by the blockage characteristics. In this work, the interference effect from the NLoS signals is ignored, since the dominant interference is caused by the LoS signals [3].

All wireless signals are assumed to experience both large-scale path-loss effects and small-scale fading. Specifically, the small-scale fading between two nodes, denoted as $h$, is modeled by Nakagami fading, where different links are assumed to be independent and identically distributed. Hence, the power of the channel fading is a gamma random variable with shape parameter $\nu$ and scale parameter $1/\nu$. For the large-scale path-loss, we assume an unbounded singular path-loss model, i.e. $L(X,Y) = \|X - Y\|^{-a}$, which assumes that the received power decays with the distance between the transmitter at $X$ and the receiver at $Y$, where $a > 2$ is the path-loss exponent.

We assume the employment of omni-directional antennas for all sub-6 GHz BSs, while all mmWave BSs are equipped with directional antennas. Also, we assume that the users are equipped with two omni-directional antennas, each one responsible for a different RAT. For modeling the antenna directionality of the mmWave BSs, we adopt a sectorized antenna model that approximates the actual beam pattern with sufficient accuracy [2]. The antenna array gain is parameterized by two values: 1) half-power beamwidth $\phi \in [0, \pi]$, and 2) main-lobe gain $Q$ (dB). All users served in mmWave cells are assumed to be in perfect alignment with their serving BSs, resulting in a link gain $Q$, whereas the beams of all interfering links are assumed to be randomly oriented with respect to each other. Thus, the active interfering BSs from each PPP $\widetilde{\Phi}_i$, where $i \in \{\mathrm{M}, \mathrm{S}\}$, form a PPP $\Phi_i$ with inhomogeneous density function $\lambda_i(r) = \lambda_i p(r) p_G$, where $p_G = \frac{\phi}{\pi}$ [13].

## III. Hybrid cooperation scheme for

In this section, we introduce the HC scheme, where each user independently chooses its mode of operation with or without cooperation. For the non-cooperative mode, the user

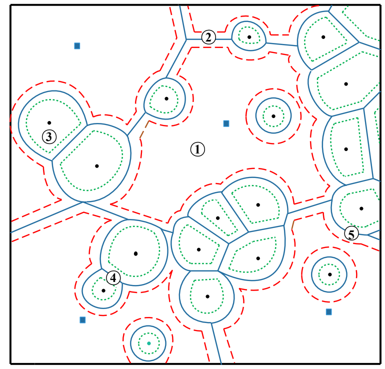

Fig. 1. The Voronoi tessellation of a two-tier multi-band cellular network. Dashed and dotted lines represent the boundaries of the center and edge regions of Mcells and SCells, respectively.

is connected to the BS that provides the maximum RSS, while for the cooperative mode, the user is served by two BSs that cooperate with each other to jointly transmit data to the user. Note that, the association process is carried out in advance by an appropriate protocol and therefore, the impact of signaling overhead on the network performance is ignored. In the cooperative mode, the cooperative BSs are those that provide the strongest and the second-strongest RSS to the user regardless of the corresponding tier, i.e. MCell or SCell. For characterizing the user's operation in either cooperative or non-cooperative mode, a scheme that spatially classifies the users in the cell-center or in the cell-edge regions is required. Thus, we consider a widely-adopted RSS-based technique for the intra- and inter-tier classification of the users [8], which is a more flexible design approach and includes the $90\%$ and $5\%$ percentiles as special cases. Specifically, a user is classified in the cell-center region and therefore operates in a non-cooperative mode, if the RSS from the strongest BS at the user is sufficiently higher than that received from the second-strongest BS. On the other hand, if the RSS at the user from the second-strongest BS is comparable to the signal power received from the strongest BS, the user is classified in the cell-edge region operating in the cooperative mode. Throughout this work, we denote as $x_i$ and $\widetilde{x}_i$ the locations of the strongest and the second-strongest BS of a user from the $i$-th tier, respectively, and $r_x$ is the distance from the BS located at $x$ to the origin, i.e. $r_x = \|x\|$. Due to the different transmit powers between the network tiers, the adopted classification process can be divided into two cases which are as follows.

### A. Intra-tier user classification criteria

Let firstly consider the case where the strongest and the second-strongest BSs of a user belong in the same tier. Due to the equal power allocation between BSs that belong in the same tier, the adopted classification scheme is converted to a distance-based classification scheme. Then, a user is classified as CEU if $r_{x_i}/r_{\widetilde{x}_i} > \zeta$, otherwise as CCU, where $\zeta \in [0,1]$ is a predefined fraction. The following Lemma provides the joint distribution of the distances $x_i$ and $\widetilde{x}_i$ for the $i$-th tier.

**Lemma 1.** *The joint distribution of the distances $r_{x_i}$ and $r_{\widetilde{x}_i}$ for $i = \mathrm{M}$, is given by*

$$f_{x_\mathrm{M},\widetilde{x}_\mathrm{M}}(r_{x_\mathrm{M}}, r_{\widetilde{x}_\mathrm{M}}) = (2\pi\lambda_\mathrm{M})^2 r_{x_\mathrm{M}} r_{\widetilde{x}_\mathrm{M}} e^{-\pi\lambda_\mathrm{M} r^2_{\widetilde{x}_\mathrm{M}}}$$

*and for $i = S$, is given by*

$$f_{x_\mathrm{S},\widetilde{x}_\mathrm{S}}(r_{x_\mathrm{S}}, r_{\widetilde{x}_\mathrm{S}}) = (2\pi\lambda_\mathrm{S})^2 r_{x_\mathrm{S}} r_{\widetilde{x}_\mathrm{S}} \frac{e^{-2\pi\lambda_\mathrm{S} U\left(r_{\widetilde{x}_\mathrm{S}}\right)}}{e^{\beta\left(r_{x_\mathrm{S}}+r_{\widetilde{x}_\mathrm{S}}\right)}}$$

*where $U(r) = \frac{1}{\beta^2}\left(1 - \exp\left(-\beta r\right)\left(1 + \beta r\right)\right)$.*

**Lemma 2.** *The joint distribution of the distances $r_{x_i}$ and $r_{\widetilde{x}_i}$ for $i = \mathrm{M}$the $i$-th tier, is given by [3]*

$$f_{x_i,\widetilde{x}_i}(r_{x_i}, r_{\widetilde{x}_i}) = \begin{cases} (2\pi\lambda_\mathrm{M})^2 r_{x_\mathrm{M}} r_{\widetilde{x}_\mathrm{M}} e^{-\pi\lambda_\mathrm{M} r^2_{\widetilde{x}_\mathrm{M}}}, & \text{if } i = \mathrm{M}, \\ (2\pi\lambda_\mathrm{S})^2 r_{x_\mathrm{S}} r_{\widetilde{x}_\mathrm{S}} \frac{e^{-2\pi\lambda_\mathrm{S} U\left(r_{\widetilde{x}_\mathrm{S}}\right)}}{e^{\beta\left(r_{x_\mathrm{S}}+r_{\widetilde{x}_\mathrm{S}}\right)}}, & \text{if } i = \mathrm{S}, \end{cases} \quad (1)$$

*where $U(r) = \frac{1}{\beta^2}\left(1 - \exp\left(-\beta r\right)\left(1 + \beta r\right)\right)$.*

*Proof.* For the case where $i = \mathrm{S}$, the intensity measure of LoS transmitters from the $i$-th tier is $\Lambda_i(r) = \frac{2\pi\lambda_i}{\beta}(1 - e^{-\beta r}(1 + \beta r))$, and so their density is given by $\lambda_i(r) = d\Lambda_i(r)/dr$. Therefore, the probability density function (pdf) of the distance between a user and its closest BS is [3]

$$f_{x_i}(r_{x_i}) = \begin{cases} 2\pi\lambda_\mathrm{M} r_{x_\mathrm{M}} e^{-\pi\lambda_\mathrm{M} r^2_{x_\mathrm{M}}}, & \text{if } i = \mathrm{M}, \\ 2\pi\lambda_\mathrm{S} r_{x_\mathrm{S}} e^{-\beta r_{x_\mathrm{S}} - 2\pi\lambda_\mathrm{S} U(r_{x_\mathrm{S}})}, & \text{if } i = \mathrm{S}. \end{cases} \quad (2)$$

Following similar methodology as in [15], the joint pdf of the distances $r_{x_i}$ and $r_{\widetilde{x}_i}$ for the $i$-th tier can be calculated. □

Let $\delta^i_\mathcal{B}$ denote the probability that a user is classified as $\mathcal{B} \in \{\mathrm{CCU}, \mathrm{CEU}\}$ with respect to the $i$-th tier. With the use of (1), a user is classified in the cell-center region for the $i$-th tier with probability $\delta^i_\mathrm{CCU} = \mathbb{P}\left[r_{x_i}/r_{\widetilde{x}_i} \leq \zeta\right]$, that is equal to

$$\delta^i_\mathrm{CCU} = \begin{cases} \zeta^2, & \text{if } i = \mathrm{M}, \\ 2\pi\lambda_\mathrm{S} \int_0^\infty r \frac{e^{-2\pi\lambda_\mathrm{S} U\left(\frac{r}{\zeta}\right)-1}}{e^{\beta r + \frac{2\pi\lambda_\mathrm{S}}{\beta^2}}} dr, & \text{if } i = \mathrm{S}, \end{cases}$$

while a user is classified in the cell-edge region for the $i$-th tier with probability $\delta^i_\mathrm{CEU} = 1 - \delta^i_\mathrm{CCU}$.

### B. Inter-tier user classification criteria

The second case refers to the scenario where the strongest and the second-strongest BSs of a user belong in different tiers. Then, a user is classified in the cell-center region of the $i$-th tier if $(P_i r^{-a}_{x_i})/(P_j r^{-a}_{x_j}) > \eta$, otherwise in the cell-edge region formed between a BS from the $i$-th tier and a BS from the $j$-th tier if $(P_i r^{-a}_{x_i})/(P_j r^{-a}_{x_j}) < \eta$, where $\eta$ is a predefined threshold. The following Lemma defines the aforesaid classification probabilities.

**Lemma 3.** *A user is classified in the cell-center region of the BS from the $i$-th tier with probability*

$$\omega_i = \int_0^\infty F_{x_j}\left(\left(\frac{P_i}{\eta P_j}\right)^{1/a} r\right) f_{x_i}(r) dr, \;\; i, j \in \{\mathrm{M}, \mathrm{S}\}, i \neq j \quad (3)$$

*otherwise, in the cell-edge area between the BSs from the $i$-th and $j$-th tier, where $F_{x_i}(r) = \int_{-\infty}^r f_{x_i}(t)dt$, $i \in \{\mathrm{M}, \mathrm{S}\}$ and $f_{x_i}(\cdot)$ denotes the distance distribution and is given by (2).*

*Proof.* We define $\omega_i = \mathbb{P}[P_i r^{-a}_{x_i} > \eta P_i r^{-a}_{\widetilde{x}_i}]$ and by unconditioning the derived expression with $f_{x_i}(r)$ that is given in (2), we conclude to the desired expression. □

### C. The HC Scheme

Fig. 1 shows a realization of a two-tier heterogeneous cellular network, where sub-6 GHz BSs (represented by rectangles) are overlaid with mmWave BSs (represented by dots). A user $u \in \mathbb{R}^2$ can be classified into one of the following disjoint sub-regions of a communication cell:

- Sub-region 1: $\mathfrak{R}_1$ with probability $\varrho_1 = \delta^\mathrm{M}_\mathrm{CCU}\omega_\mathrm{M}$,
- Sub-region 2: $\mathfrak{R}_2$ with probability $\varrho_2 = \delta^\mathrm{M}_\mathrm{CEU}\omega_\mathrm{M}$,
- Sub-region 3: $\mathfrak{R}_3$ with probability $\varrho_3 = \delta^\mathrm{S}_\mathrm{CCU}\omega_\mathrm{S}$,
- Sub-region 4: $\mathfrak{R}_4$ with probability $\varrho_4 = \delta^\mathrm{S}_\mathrm{CEU}\omega_\mathrm{S}$,
- Sub-region 5: $\mathfrak{R}_5$ with probability $\varrho_5 = 1 - \sum_{\kappa=1}^4 \varrho_\kappa$,

where $\bigcup_\kappa \mathfrak{R}_\kappa = \mathbb{R}^2$ and $\kappa \in \{1, \cdots, 5\}$. Specifically, the sub-regions $\mathfrak{R}_1$ and $\mathfrak{R}_3$ are the center regions of MCell and SCell BSs, respectively. Moreover, the sub-region $\mathfrak{R}_2$ ($\mathfrak{R}_4$) represents the edge regions formed between nearby MCell (SCells) BSs. Finally, the sub-region $\mathfrak{R}_5$ denotes the edge regions formed between nearby MCell and SCell BSs.

Aiming to further enhance the CEUs' performance, we assume the employment of a non-coherent cooperative technique. Specifically, if a user is classified at the cell boundaries, its strongest and second-strongest BSs cooperate and jointly transmit data to the user, which combines the received signals by employing the maximum-ratio combining method. This is motivated by the fact that in mmWave communication systems, the dominant interfering BS contributes most of the overall interference power [14]. Note that, the strongest and the second-strongest BSs can independently belong in the MCells or SCells. For the case where the strongest and the second-strongest BSs of a user belong in the same tier, the observed interference at the user solely originates from that particular tier [7], and the observed SINR, is given by

$$\mathrm{SINR}_{\{i\}} = \frac{r^{-a}_{x_i} g_{x_i} + \mathbb{1}^{(i)}_\mathrm{CEU} r^{-a}_{\widetilde{x}_i} g_{\widetilde{x}_i}}{\sum_{y \in \Psi_i} r^{-a}_y g_y + \sigma^2_n/(P_i \tau_i(Q))}, \quad (4)$$

where $g_x = |h_x|^2$ is the power of the channel fading between a receiver and a transmitter located at $x$, $\mathbb{1}^{(i)}_\mathrm{CEU}$ is the indicator function, where $\mathbb{1}^{(i)}_\mathrm{CEU} = 1$ if the user is classified as CEU with respect to the $i$-th tier, otherwise $\mathbb{1}^{(i)}_\mathrm{CEU} = 0$; $\Psi_i$ is the set of active interfering BSs where $\Psi_i = \Phi_i \backslash \{x_i\}$ if $\mathbb{1}^{(i)}_\mathrm{CEU} = 0$, otherwise $\Psi_i = \Phi_i \backslash \{x_i, \widetilde{x}_i\}$, and $\tau_i(X)$ is the directionality gain of a link, where $\tau_i(X) = X$ if $i = \mathrm{S}$, otherwise $\tau_i(X) = 1$. For the case where a user is served by both tiers, i.e. classified in the sub-region $\mathfrak{R}_5$, it jointly communicates with its strongest BS $x_i \in \Phi_i$ and its second-strongest BS $x_j \in \Phi_j$, where $i \neq j$. Hence, the observed SINR, is given by

$$\mathrm{SINR}_{\{i,j\}} = \frac{\sum_{k=i,j} \tau_k(Q) P_k r^{-a}_{x_k} g_{x_k}}{\sum_{z \in \{\mathrm{M},\mathrm{S}\}} \sum_{y \in \Phi_z \backslash \{x_z\}} \tau_z(Q) P_z r^{-a}_y g_y + \sigma^2_n}. \quad (5)$$

Note that, the observed interference for both the CCUs and the CEUs is caused by the tiers that the user is associated with.

## IV. MD for the HC scheme

In this section, we study the MD of the SINR in the context of the HC scheme. The MD of the SINR is defined as $\bar{F}_{P_s(\theta)}(x) = \mathbb{P}^!_o\left[P_s(\theta) > x\right]$, where $\theta \in \mathbb{R}^+$ is the SINR

$$\Upsilon_i(s,\delta)=\begin{cases}\exp\left(-\pi\lambda_{\mathrm{M}}\left(\delta^2-\frac{(sP_{\mathrm{M}}\theta)^{\frac{2}{a}}\Gamma\left[\frac{a-2}{a}\right]\Gamma\left[\frac{2}{a}+b\right]}{\Gamma[b]}-\frac{2\delta^{2+ab}(sP_{\mathrm{M}}\theta)^{-b}{}_2F_1\left[b,\frac{2}{a}+b,1+\frac{2}{a}+b,-\frac{\delta^a}{sP_{\mathrm{M}}\theta}\right]}{2+ab}\right)\right), & \text{if } i=\mathrm{M},\\ \exp\left(-2\pi\lambda_{\mathrm{S}}\int_\delta^\infty\left(1-\left(1+\theta sQP_{\mathrm{S}}r^{-a}\right)^{-b}\right)rp_Q\exp(-\beta r)dr\right), & \text{if } i=\mathrm{S}.\end{cases}\tag{7}$$

$$\Upsilon_{\mathrm{S}}(s,\delta)\approx\exp\left(-\pi\lambda_{\mathrm{S}}p_Q\left(D^2-\delta^2-\frac{2\psi^{\frac{2}{a}}}{a}e^{-\frac{(2+ab)\pi}{a}\mathrm{i}}\left(B_{-\frac{D^a}{\psi}}\left[\frac{2}{a}+b,1-b\right]-B_{-\frac{\delta^a}{\psi}}\left[\frac{2}{a}+b,1-b\right]\right)\right)\right)\tag{8}$$

threshold, $x\in[0,1]$, $P_s(\theta)$ is the success probability conditioned on a PPP $\Phi$, i.e. $P_s(\theta)=\mathbb{P}[\mathrm{SINR}>\theta|\Phi]$ and $\mathbb{P}^!_o$ is the reduced Palm probability [10]. The conditional success probability is given by $P_s(\theta)=\sum_\kappa\varrho_\kappa P_s^{(\kappa)}(\theta)$, where $P_s^{(\kappa)}(\theta)$ is the conditional success probability of a user that is classified in the region $\mathfrak{R}_\kappa$. Based on Alzer's lemma [13], the aforesaid probability is calculated in the following Lemma.

**Lemma 4.** *The conditional success probability of a user that is classified in the region $\mathfrak{R}_\kappa$, where $\kappa\in\{1,\cdots,5\}$, is given by*

$$P_s^{(\kappa)}(\theta)=\sum\nolimits_{\xi=1}^{\nu}(-1)^{\xi+1}\binom{\nu}{\xi}$$
$$\times\begin{cases}\prod_{y\in\Psi_{\mathrm{M}}}\frac{r_y^a\exp\left(-s_\kappa\xi\varpi\sigma_n^2\right)}{r_y^a+s_\kappa\xi\varpi P_{\mathrm{M}}}, & \textit{if } \kappa=\{1,2\},\\ \prod_{y\in\Psi_{\mathrm{S}}}\frac{r_y^a\exp\left(-s_\kappa\xi\varpi\sigma_n^2\right)}{r_y^a+s_\kappa\xi\varpi P_{\mathrm{S}}}, & \textit{if } \kappa=\{3,4\},\\ \prod_z\prod_{y\in\Psi_z}\frac{r_y^a\exp(-s_\kappa\xi\varpi\sigma_n^2)}{r_y^a+s_\kappa\xi\varpi\tau_z(Q)P_z}, & \textit{if } \kappa=\{5\},\end{cases}$$

*where $z\in\{\mathrm{M},\mathrm{S}\}$, $G\in\{Q,q\}$ and $s_i$ is the $i$-th element of*

$$s=\left\{\frac{P_{\mathrm{M}}^{-1}}{r_{x_{\mathrm{M}}}^{-a}},\frac{P_{\mathrm{M}}^{-1}}{r_{x_{\mathrm{M}}}^{-a}+r_{\widetilde{x}_{\mathrm{M}}}^{-a}},\frac{P_{\mathrm{S}}^{-1}}{r_{x_{\mathrm{S}}}^{-a}},\frac{P_{\mathrm{S}}^{-1}}{r_{x_{\mathrm{S}}}^{-a}+r_{\widetilde{x}_{\mathrm{S}}}^{-a}},\frac{1}{\frac{P_{\mathrm{M}}}{r_{x_{\mathrm{M}}}^a}+\frac{QP_{\mathrm{S}}}{r_{x_{\mathrm{S}}}^a}}\right\}.\tag{6}$$

*Proof.* To overcome the difficulty on Nakagami fading, we adopt the Alzer's lemma [13], which relates the ccdf of a gamma random variable into a weighted sum of the ccdfs of exponential random variables. Hence, for $\kappa=5$, $P_s^{(5)}(\theta)$ can be re-written as

$$P_s^{(5)}(\theta)=\mathbb{P}\left[\sum\nolimits_{k=i,j}\tau_k(Q)P_kr_{x_k}^{-a}g_{x_k}>\theta\left(I+\sigma_n^2\right)\right]$$
$$\leq\sum\nolimits_{\xi=1}^{\nu}(-1)^{\xi+1}\binom{\nu}{\xi}\mathbb{E}_I\left(\exp\left(-s\xi\varpi\left(I+\sigma_n^2\right)\right)\right),$$

where $s=\theta/\sum_{k=i,j}\tau_k(Q)P_kr_{x_k}^{-a}$, $\varpi=\nu(\nu!)^{-\frac{1}{\nu}}$, and $I=\sum_{z\in\{\mathrm{M},\mathrm{S}\}}\sum_{y\in\Psi_z}\tau_z(Q)P_zr_y^{-a}g_y$. By using the moment generating function of an exponential random variable, the final expression can be derived. Similarly, the expressions for $P_s^{(\kappa)}(\theta)$, where $\kappa=\{1,2,3,4\}$, can be derived. □

### A. Moments of Conditional Success Probability

Since a direct calculation of the MD is tedious, its evaluation will be made through the moments $M_b(\theta)=\mathbb{E}\left[P_s(\theta)^b\right]$, which are derived in the following Lemma.

**Lemma 5.** *The $b$-th moment of the conditional success probability is given by $M_b(\theta)=\sum_\kappa\varrho_\kappa M_b^{(\kappa)}(\theta)$, where $M_b^{(\kappa)}(\theta)$ is the $b$-th moment of the $P_s^{(\kappa)}(\theta)$, and is given by*

$$M_b^{(\kappa)}(\theta)\leq\sum\nolimits_{\xi=1}^{\nu}(-1)^{\xi+1}\binom{\nu}{\xi}\int_0^\infty e^{-s_\kappa\xi\varpi b\sigma_n^2}$$
$$\times\begin{cases}\Upsilon_{\mathrm{M}}(s_\kappa\xi\varpi,\frac{v}{\zeta})f_{x_{\mathrm{M}}}(v|\mathfrak{R}_1)\,dv, & \textit{if } \kappa=1,\\ \Upsilon_{\mathrm{M}}(s_\kappa\xi\varpi,v)f_{x_{\mathrm{M}}}(v|\mathfrak{R}_2)\,dv, & \textit{if } \kappa=2,\\ \Upsilon_{\mathrm{S}}(s_\kappa\xi\varpi,v)f_{x_{\mathrm{S}}}(v|\mathfrak{R}_3)\,dv, & \textit{if } \kappa=3,\\ \Upsilon_{\mathrm{S}}(s_\kappa\xi\varpi,\frac{v}{\zeta})f_{x_{\mathrm{S}}}(v|\mathfrak{R}_4)\,dv, & \textit{if } \kappa=4,\\ \Upsilon_{\mathrm{M}}(s_\kappa\xi\varpi,v)\Upsilon_{\mathrm{S}}\left(s_\kappa\xi\varpi,(\frac{\eta P_{\mathrm{S}}}{P_{\mathrm{M}}})^{\frac{1}{a}}\right)f_{x_{\mathrm{M}}}(v|\mathfrak{R}_5)\,dv, & \textit{if } \kappa=5,\end{cases}$$

*where $s_i$ is the $i$-th element of* (6) *and $\Upsilon_i(s,\delta)$ is given by* (7).

*Proof.* As mentioned before, a user is classified in the center sub-regions of MCells and SCells, i.e. $\mathfrak{R}_1$ and $\mathfrak{R}_3$, if and only if $r_{x_i}/r_{\widetilde{x}_i}\leq\zeta$, where $i=\mathrm{M}$ and $i=\mathrm{S}$, respectively. Therefore, the conditional cdfs of these distances for $\kappa=\{1,3\}$ become $F_{x_i}(u|\mathfrak{R}_\kappa)=\varrho_\kappa^{-1}\int_u^\infty\int_{u/\zeta}^\infty f_{x_i,\widetilde{x}_i}(u,v)dvdu$. By following similar methodology, the conditional cdfs of the distances for $\kappa=\{2,4,5\}$ can be also derived. Based on the derived conditional cdfs, we can calculate the conditional pdfs of the distances conditioned on the user classification, i.e. $f_{x_i}(v|\mathfrak{R}_\kappa)=d/dv[1-F_{x_i}(u|\mathfrak{R}_\kappa)]$. For the case where a user is classified in the sub-region $\mathfrak{R}_5$ and by leveraging the expressions provided in Lemma 4, the $b$-th moment of the $P_s^{(5)}(\theta)$, i.e. $M_b(\theta)=\mathbb{E}\left[P_s(\theta)^b\right]$, is given by

$$M_b^{(5)}(\theta)\leq\sum\nolimits_{\xi=1}^{\nu}(-1)^{\xi+1}\binom{\nu}{\xi}\int_0^\infty e^{-2\pi\lambda_{\mathrm{M}}\int_v^\infty\frac{\left(1+\frac{s_5\xi\varpi P_{\mathrm{M}}}{r^a}\right)^b-1}{\left(1+\frac{s_5\xi\varpi P_{\mathrm{M}}}{r^a}\right)^b}rdr}$$
$$\times e^{-s_5\xi\varpi b\sigma_n^2-2\pi\lambda_{\mathrm{S}}\int_{\xi(r)}^\infty\left(1-\left(\frac{1}{1+\frac{s_5\xi\varpi QP_{\mathrm{S}}}{r^a}}\right)^b\right)re^{-\beta r}dr}f_{x_{\mathrm{M}}}(v|\mathfrak{R}_5)dv,$$

obtained by the probability generating functional of a PPP $\Phi$, where $\xi(r)=(P_{\mathrm{S}}/(P_{\mathrm{M}}\eta))^{\frac{1}{a}}r$. By following a similar methodology, the $b$-th moments of the remaining conditional success probabilities $P_s^{(\kappa)}(\theta)$ can be also derived. Due to space limitations, the detailed proof for these cases is omitted. □

The above expression provides a general result for the $b$-th moment of the conditional success probability. Even from this general expression, we can extract some observations towards its behavior. Initially, we can easily observe that by increasing the Nakagami parameter $\nu$, the fading becomes less severe providing a better performance. Moreover, by reducing the blockage parameter $\beta$, we can further boost the network performance. In order to gain more insight, we make some additional assumptions in order to further simplify the above expression. Recall that $p(r)=\exp(-\beta r)$ is the LoS probability function defined in Section **??**. In the following lemma, we simplify the analysis by approximating the LoS probability by a step function i.e., $p(d)=\mathbb{1}_{d\leq D}$, where $D$ is the maximum length of an LoS link (i.e. $D\approx\sqrt{2}/\beta$ [2]).

**Lemma 6.** *For the special case where $p(d)=\mathbb{1}_{d\leq D}$, the expression of $\Upsilon_{\mathrm{S}}(s,\delta)$ can be re-written as in* (8)*, where $\psi=sP_{\mathrm{M}}\theta$ and $B_z[\cdot,\cdot]$ is the incomplete Beta function.*

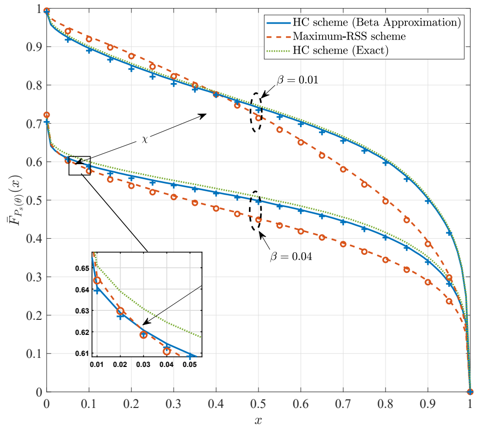


Fig. 2. MD versus $x$ for the HC and maximum-RSS schemes for different $\beta$

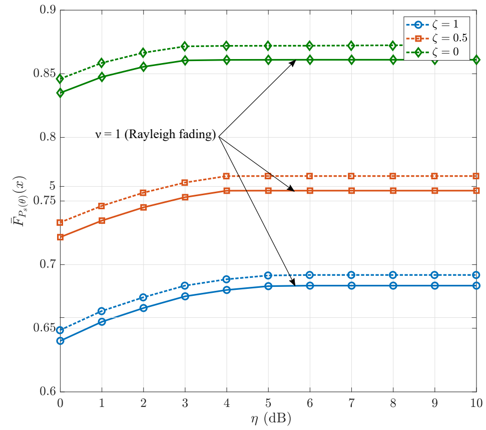


Fig. 3. MD versus $\eta$ for $\zeta = \{0, 0.5, 1\}$; $x = 0.5$

We note that the approximated expressions for the $M_b(\theta)$ by using the expressions of Lemma 6, provide a lower bound of the actual performance, since the actual interference is over-estimated. In addition, we can observe that the approximated expressions $\Upsilon_{\rm M}(s,\delta)$ and $\Upsilon_{\rm S}(s,\delta)$ are relatively efficient to gain insights as they involve simple geometrical functions.

### B. Beta Approximation of MD

Due to the tedious exact evaluation of the MD, the authors in [10] showed that the MD can be approximated by matching the mean and variance of the Beta-distribution with $M_1(\theta)$ and $M_2(\theta)$ given in Lemma 5. The first and second moments of a beta-distributed random variable $X$ with shape parameters $\gamma,\ \epsilon > 0$, are given by $\mathbb{E}[X] = \gamma/(\gamma+\epsilon)$ and $\mathbb{E}\left[X^2\right] = (\gamma+1)/(\gamma+\epsilon+1)$. The following theorem provides the MD of our proposed scheme.

**Theorem 1.** *The approximate MD of the HC scheme for the considered network deployments, is given by*

$$\bar{F}_{P_s(\theta)}(x) = 1 - B\left(\gamma,\epsilon\right)^{-1}\int_0^x t^{\gamma-1}(1-t)^{\epsilon-1}dt. \qquad (9)$$

*where $M_1(\theta)$ and $M_2(\theta)$ are given in Lemma 5, and*

$$\gamma = \frac{M_1(\theta)M_2(\theta) - M_1^2(\theta)}{M_1^2(\theta) - M_2(\theta)}, \epsilon = \frac{(1-M_1(\theta))(M_2(\theta)-M_1(\theta))}{M_1^2(\theta)-M_2(\theta)}.$$

For comparison, the following remark provides the performance achieved with the conventional maximum-RSS scheme.

**Remark 1.** *For $\zeta = 1$ and $\eta = 0$ dB, the HC scheme becomes the conventional maximum RSS scheme [4].*

## V. Numerical Results

We consider the following parameters: $\lambda_{\rm M} = 15$ BSs/km$^2$, $\lambda_{\rm S} = 47$ BSs/km$^2$, $P_{\rm M} = 30$ dB, $P_{\rm S} = 20$ dB, $\theta = 0$ dB, $a = 4$, $\beta = 0.03$, $Q = 10$ dB, $\phi = \frac{\pi}{6}$, $\zeta = 0.7$, $\eta = 6$ dB, $\nu = 2$ and $\sigma_n^2 = -60$ dB.

Fig. 2 shows the network performance achieved with the utilization of both the proposed (Theorem 1) and the conventional scheme (Proposition 1). We can first observe that the analytical results (solid and dashed lines) provide an upper bound for the network performance given by the simulation results (markers); this is expected due to Alzer's Lemma [13]. Moreover, by increasing the blockage constant, the performance decreases for both schemes. Furthermore, at low reliability threshold values, the conventional scheme provides slightly better network performance compared to the HC scheme. However, by increasing the reliability threshold beyond a critical point $\chi$, our proposed scheme overcomes the conventional scheme, providing a significantly enhanced network performance. We can also observe that, the critical reliability threshold point $\chi$, reduces with the increase of the blockage constant. Finally, the close match between the performance achieved using (9) (solid line) and the numerically exact analysis of the MD using the Gil-Pelaez theorem [10] (dotted line), validates the accuracy of the beta distribution approximation for the MD.

Fig. 3 highlights the impact of the range of the edge-regions on the network performance. We can easily observe that the MD increases as the bias factor $\eta$ increases. Moreover, by further increasing the bias factor, the improvement on MD becomes marginal. Regarding the predefined fraction $\zeta$, it is clear that, by increasing the edge-region between BSs from a single tier, the achieved MD also increases due to the utilization of the cooperation technique. Finally, Fig. 3 illustrates the impact of different Nakagami parameters on the network performance.

## VI. Conclusion

In this letter, we proposed a novel hybrid BS cooperation scheme for heterogeneous sub-6 GHz/mmWave cellular networks. Our proposed cooperation scheme exploits the ability of BSs to jointly transmit data in a non-coherent manner, aiming at enhancing the performance of the CEUs. By using stochastic geometry tools, the moments of the conditional success probability were derived analytically and the actual MD was approximated using the moment-matching method for the Beta-distribution. Our numerical results reveal that the proposed HC scheme outperforms the conventional maximum RSS association scheme.

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