Full-Duplex Two-Tier Heterogeneous Network With Decoupled Access: Cell Association, Coverage, and Spectral Efficiency Analysis

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ABSTRACT The ever increasing thirst for the higher capacity demands radical changes in the design of cellular networks, such as a leap from single-tier homogeneous networks to multi-tier heterogeneous networks and the use of millimeter wave frequency band. A typical point-to-point full-duplex transmission link can double the link rate by simultaneously using the same spectrum for bidirectional traffic. However, the characterization of full-duplex two-tier heterogeneous networks is not as straightforward as that of point-to-point full-duplex systems, specially when the different tiers of the heterogeneous network use different frequency bands (millimeter wave and microwave) for their transmissions. This paper characterizes a full-duplex two-tier heterogeneous network with decoupled access, where both tiers operate on different frequency bands (millimeter wave and microwave). To evaluate the achievable spectral efficiency and association behavior of users and base stations, a two-tier heterogeneous network model is proposed in which all users and base stations are modeled using Poisson point processes. First a signal-to-interference-plus-noise-ratio optimal user association scheme is characterized. Based on the user association scheme, the spectral efficiencies of the uplink and downlink transmission links are derived. In addition, a thorough analysis of the signal-to-interference-plus-noise-ratio coverage is also provided. Moreover to render the analytical model more comprehensive and robust, i.e., different from the convention of noise-limited millimeter wave network, the interference in millimeter wave networks is also accounted for in the analytical model. Lastly, the pragmatic value of full-duplex heterogeneous networks and decoupled access is discussed in detail through numerous numerical and simulation results.

INDEX TERMS Decoupled access, full-duplex transmission, heterogeneous network, millimeter wave.

I. INTRODUCTION

Whenever the hush of expectancy of a new generation of communication systems falls upon their predecessor, lots of ideas silently take birth in the research laboratories of both academia and industry. Some of these ideas scream their way out to commercial use and some of them remain on the dissecting table of researchers, only to be found again on a later date. The recent advancement in available computing power and the evolution in signal processing provide ample room for innovative and out of the box ideas for the fifth-generation (5G) communication systems [1]–[3]. Some of the main requirements imposed on 5G are seamless coverage, hotspot high capacity, low end-to-end latency, and massive connections [4], [5]. To address these requirements, network densification and the use of extremely high frequencies (EHF) are two promising solutions. In this context, EHF, commonly known as the millimeter wave (mmWave) band, provides an unprecedented large bandwidth, while the network densification pushes for the paradigm shift of single-tier homogeneous cellular networks towards multi-tier heterogeneous cellular networks (HetNets) [6]. In HetNets the typical transmit power of a base station (BS) varies with respect to its tier resulting in significantly different interference levels [7]. Therefore the optimality of the conventional way of cell association i.e., coupled access, where a user connects to a single BS for both uplink and downlink transmission came under scrutiny. The authors in [8]–[10] revisited the conventional way of cell association and proposed a decoupled wireless access. The decoupled wireless access grants liberty to
user equipment (UE) to choose different BSs for their uplink and downlink transmissions. In a two-tier HetNet that employs significantly different frequency bands in each tier, decoupled access can potentially be more effective due to zero inter-tier interference. After the initial analytical analysis in [11], [12], the decoupled access has been studied and analyzed against its coupled counterpart in detail for different network scenarios in [13]–[17]. On the other hand, its performance analysis against a coupled full-duplex system, which should have been the more intuitive choice due to the parallel it has with the simultaneous uplink and downlink transmissions of full-duplex system, has not been addressed in the literature. In this paper, a full-duplex two-tier HetNet, which employs decoupled access is analytically modeled and discussed. The resulting performance is compared against its coupled counterpart.

A. NOVELTY AND CONTRIBUTIONS

The main goal of this paper is to investigate the efficacy of decoupled access in a full-duplex two-tier HetNet employing two different frequency bands in each tier i.e., mmWave and microwave. Therefore, a more robust and comprehensive analytical model is derived to analyze the probability of associations, spectral efficiency, and coverage. The novelty of the derived analytical model is that it accommodates variable transmit powers, different pathloss exponents for different tiers, and accounts for the interference in mmWave networks. Typically, a mmWave network and a microwave network are assumed to be noise limited and interference-limited, respectively. To make the proposed analytical model more robust and comprehensive, we account for inter-user interference, inter-cell interference, full-duplex interference, and self-interference due to the full-duplex nature of the network, in both tiers as shown in Fig. 1(b). To the best of the authors’ knowledge, this is the first analytical model accommodating all of the aforementioned interference, variable transmit powers, as well as different pathloss exponents for different tiers. The key contributions of this paper are listed as follows.

- The development of full-duplex signal-to-interference-plus-noise-ratio (SINR) model in a two-tier network with decoupled access.
- The developed analytical model takes into account the interference of the mmWave network.
- The development of new analytical expressions of the SINR optimal probability of associations.
- The development of new analytical expressions for the average spectral efficiency of both uplink and downlink transmissions based on the derived SINR model and the probability of associations.
- The development of analytical expressions of the SINR coverage in a network.
- The validation by rigorous simulation of all analytically derived results.
- The comparison of the analytical and simulation results, of a full-duplex two-tier HetNet which employs decoupled access, against its coupled counterpart.

B. ORGANIZATION

The rest of the paper is organized as follows. Section II discusses the related work. In Section III, the system model, spatial distributions, propagation assumptions, and
cell association criteria are described. In Section IV, analytical expressions of the probability of associations, coverage of SINR in a network, and the average spectral efficiency are derived. In Section V, numerical and simulation results are presented. In addition, an in-depth and detailed discussion on the obtained results and the effect of different system parameters on the performance of the overall network is provided. Finally, Section VI concludes the paper.

II. RELATED WORK

The topic of multi-tier HetNets, more specifically two-tier HetNets, is not new to the research community. It has been under a critical lens of both academia and industry for a significantly long time. For example, a thorough analysis of two-tier cellular systems with universal frequency reuse has been undertaken in [18]. The authors investigated the cross-tier interference and the ‘near-far’ deadspot coverage in a two-tier network. In addition, they also provided a location-assisted power control scheme to regulate transmit powers of femtocell BSs. A detailed mathematical framework based on stochastic geometry to model a multi-tier mmWave cellular networks is provided in [19]. The author provided a rather generalized theoretical framework on the impact of decoupled access by analyzing its spectral and energy efficiencies.

In [15], the authors derived new analytical results for the average user rate in decoupled access for two different types of UE’s distributions, namely uniform and clustered distributions, modeled as Poisson point process and Neyman–Scott cluster process, respectively. In [16], the authors derived cell association probabilities with respect to the load balancing in BSs for a multi-user multiple-input multiple-output (MIMO) HetNet with decoupled access. In addition, they also analytically showed the suppression of interference by multiple antennas at BSs and its effect on the spectral efficiency.

In [17], the authors used tools from stochastic geometry and provided a rather generalized theoretical framework on the impact of decoupled access in multi-tier HetNet. In our previous work [13], we provided a semi-analytical analysis on the efficacy of decoupled access for a two-tier HetNet employing mmWave and microwave frequency bands. Later, this work was extended in [14] and new closed-form results were derived for the probability of associations, distance distributions of UEs to their tagged BSs, and the average spectral efficiency using Fox’s H-function. In [20], the authors proposed various handover schemes for LTE networks with decoupled access. Through simulations, they showed the impact of signalling in LTE networks with decoupled access and compared it with its coupled counterpart.

A recent work explored the full-duplex HetNet with decoupled access [21] where the authors provided an analysis of the average link rate performance and proposed full-duplex scheduling algorithms to maximize the bidirectional traffic. In [22], the authors formulated the association problem of a full-duplex HetNet with decoupled access as a convex geometric programming problem to maximize sum-rate. In addition, they also proposed low-complexity distributed solutions for the association problem.

III. SYSTEM MODEL

A. SPATIAL DISTRIBUTIONS

A full-duplex two-tier HetNet is considered where sub-6GHz (i.e., conventional microwave or macro-cell (Mcell)) BSs and mmWave (i.e., small-cell (Scell)) BSs are modeled according to independent homogeneous Poisson point processes (PPP). All the BSs are uniformly distributed in $\mathbb{R}^2$ in a circular area with a radius $\mu$. $\Phi_k$ denotes the set of points obtained through PPP with density $\lambda_k$, that can be explicitly written as

$$\Phi_k \triangleq \{x_k,i \in \mathbb{R}^2 : i \in \mathbb{N}_+\},$$

where the index $k \in \{M, S\}$ for Mcell and Scell BSs, respectively. Similarly, all the UEs are also modeled according to PPP $\Phi_u$ with density $\lambda_u$, that can also be explicitly written as

$$\Phi_u \triangleq \{u_j \in \mathbb{R}^2 : j \in \mathbb{N}_+\}.$$

B. PROPAGATION ASSUMPTIONS

The major assumptions critical to the analytical analysis are listed as follows.

- Since the addition of a node at the origin of the area of concern does not change the distribution of a point process [23], it is assumed that a typical full-duplex UE is located at $u_j = (0, 0)$.
- Since in a hybrid BSs deployment, such as the case in our manuscript, the Mcell BSs provide an umbrella coverage to all UEs, while, Scell BSs mainly focus on the high capacity links with individual UEs. Therefore, it is assumed that beamforming gains from massive array of antenna elements exist only in the Scell BSs tier [8], [9], [14]. It is worth mentioning that since system level analysis and simulations are adopted in this work, therefore, the impact of massive array of antenna elements are emulated by including beamforming gain instead of link level signal processing at each antenna element.
- Since microwave and mmWave spectra do not interfere with each other, therefore it is assumed that there is no inter-tier interference.
Since typically UE density $\lambda_u$ is much greater than the BS density $\lambda_k$ (i.e., $\lambda_u \gg \lambda_k$) [8], [9], [14], [15], it is assumed that there exists at least one UE in the association region of every BS as shown in Fig. 1(a).

It is assumed that the network can have different fractions of full-duplex and half-duplex BSs i.e., the PPP $\Phi_k$ of BSs can have different number of full-duplex and half-duplex BSs. Similarly, the PPP $\Phi_u$ of UEs can also have different number of full-duplex and half-duplex UEs.

It is assumed that each BS has enough orthogonal resources to serve all the UEs in its association region. Thus two UEs tagged to one BS can not interfere with each other, i.e., interference can only come from the UEs associated with the other BSs and from the other BSs using the same resources.

It is assumed that both microwave and mmWave communication links are subject to Rayleigh fading. It is worth mentioning that, in principle, more general fading distributions can be assumed such as the Nakagami distribution [24], however this would result in additional complexity in the derivation of analytical expressions without providing any new design insights. The rationale behind this is that performance trends are kind of robust to the underlying fading distribution as far as the employed fading distribution has distance-dependent channel components [25]. Therefore, the Rayleigh distribution’s well-established mathematical tractability makes it a key ingredient in the analysis of mmWave systems as well [26].

### C. FULL-DUPLEX SINR MODEL AND CELL ASSOCIATION CRITERIA

To make the association criteria SINR optimal, a typical UE associates with a BS in uplink at $x^* \in \Phi_l$, where $l \in \{S, M\}$ if and only if

$$\text{SINR}_{UL,l}(x^*) \geq \text{SINR}_{UL,k}(x), \quad \forall k \in \{S, M\}. \quad (1)$$

Similarly, a typical UE associates with a BS in downlink at $x^* \in \Phi_l$ if and only if

$$\text{SINR}_{DL,l}(x^*) \geq \text{SINR}_{DL,k}(x), \quad \forall k \in \{S, M\}. \quad (2)$$

Moreover, based on the aforementioned propagation assumptions and the system model, the uplink/downlink SINRs of both tiers take the following form

$$\text{SINR}_{UL,SD} = \frac{Q_M G_M h_{0,\star} ||x^*||^{-\alpha_M}}{I_{UL,SD} + \epsilon_u P_M + \sigma_M^2},$$

$$\text{SINR}_{DL,SD} = \frac{P_M G_M h_{x,\star,0} ||x^*||^{-\alpha_M}}{I_{DL,SD} + \epsilon_u Q_M + \sigma_M^2},$$

$$\text{SINR}_{UL,FD} = \frac{Q_S G_S h_{0,\star} ||x^*||^{-\alpha_S}}{I_{UL,FD} + \epsilon_u P_S + \sigma_S^2},$$

$$\text{SINR}_{DL,FD} = \frac{P_S G_S h_{x,\star,0} ||x^*||^{-\alpha_S}}{I_{DL,FD} + \epsilon_u Q_S + \sigma_S^2}, \quad (3)$$

where, $P_k$ and $Q_k$ are the transmit powers for downlink and uplink transmission links, respectively, for the $k$th tier of BSs. $\sigma_k^2$, $h$, and $\alpha_k$ denote the noise variance for the UE-$k$cell BS communication link, small scale fading power gain and path loss exponent, respectively. $e_0(\epsilon_u)$ is the self-interference suppression factor of BS (UE) and $I_{UL,k}(I_{DL,k})$ is the interference in uplink (downlink) UE-$k$cell BS communication link.

It is worth mentioning that the self-interference in a full-duplex communication system is characterised by the presence of transceiver non-linearity, whose power is not ideally proportional to the transmit power. Though the recent progress in self-interference cancellation techniques have enabled the mitigation of this interference to within acceptable levels through a combination of passive interference mitigation, and active cancellation in both the analog and digital domains [27]–[29]. Therefore most of the research works investigating the performance of full-duplex communication either assume perfect self-interference cancellation [30]–[32], or consider the self-interference to be mitigated to a noise floor like level [33], [34]. Moreover, even for the case of millimeter-wave communication, recently the authors in [35] proposed a method to mitigate self-interference to the level of ideal full-duplex communication system. Therefore, the adopted self-interference model is not ideal, but still effectively emulates the existence of self-interference in the full-duplex communication system under consideration.

In a full-duplex network interference comes from UEs and also from other BS in both uplink and downlink. Therefore, the total interference can be formulated as two separate summations over two independent Poisson point processes.

$$I_{UL,k} = I_{UL,k}^{UL} + I_{UL,k}^{DL}$$

$$= \sum_{i : x_i \in \Phi_k, FD \setminus \{x\}} \frac{P_k h_{k,i}}{||x^* - x_i||^{\alpha_k}} + \sum_{j : x_j \notin \Phi_k} Q_k g_{k,j}$$

$$I_{DL,k} = I_{DL,k}^{DL} + I_{DL,k}^{UL}$$

$$= \sum_{i : x_i \in \Phi_k, FD \setminus \{x\}} \frac{P_k h_{k,i}}{||x^* - x_i||^{\alpha_k}} + \sum_{j : x_j \notin \Phi_k} Q_k g_{k,j}$$

$$= \sum_{i : x_i \in \Phi_k, FD \setminus \{x\}} \frac{P_k h_{k,i}}{||x^* - x_i||^{\alpha_k}} + \sum_{j : x_j \notin \Phi_k} Q_k g_{k,j}, \quad (4)$$

where $I_{UL,k}(I_{DL,k})$ and $I_{UL,k}(I_{DL,k})$ denote the interference from other BSs and UEs, respectively, in UL(DL). $\Phi_k, FD$ is the PPP of full-duplex BSs in the $k$th tier which can be generated by thinning $\Phi_k, FD$ is the PPP of interfering UEs tagged to the $k$th tier BSs which can be generated by thinning $\Phi_u, h_{k,i}(h_{k,i})$ and $g_{k,i}(g_{k,i})$ are the channel gains from interfering BSs to a typical UE and from interfering UEs to a typical UE’s tagged BS, respectively, in UL(DL). Moreover, Table 1 lists
TABLE 1. Notations of variables, symbols, and parameters.

| Symbol       | Definition                                           | Symbol       | Definition                                           |
|--------------|------------------------------------------------------|--------------|------------------------------------------------------|
| $\Phi_k$     | PPP of $k$th tier of BSs                             | $\Phi_u$     | PPP of UEs                                           |
| $x_{k,i}$    | Coordinates of BS $i$ in $k$th tier                  | $u_j$        | Coordinates of UE $j$                                |
| $\lambda_k$ | Density of BSs in $k$th tier                        | $\lambda_u$ | Density of UEs                                       |
| $Q_k$        | Transmit power of UEs tagged to BS in $k$th tier     | $P_k$        | Transmit power of BS in $k$th tier                   |
| $G_k$        | Antenna gain of $k$th tier of BS                     | $h_{0,x}$    | Channel gain from typical UE at the origin to its tagged BS |
| $h_{k,e,0}$  | Channel gain from a BS to a typical UE at the origin | $c_0(\epsilon_*)$ | Self-interference suppression factor of BS(UE) |
| $\sigma_k^2$ | Noise variance                                       | $I_{UL,k}$ (I_{DL,k}) | Interference in uplink (downlink) UE-$k$cell BS communication link. |
| $\Phi_{k,F,D}$ | Set of $k$th tier of full-duplex BSs              | $\Phi_{I,k}$ | Set of interfering UEs tagged to $k$th tier of BSs       |
| $\Phi_{I,u,F,D,k}$ | Set of full-duplex interfering UEs                     | $h_{k,i}(\tilde{h}_{k,i})$ | Channel gain from an interfering BS to a typical UE in UL(DL) |
| $g_{k,j}(\tilde{g}_{k,j})$ | Channel gain from an interfering UE to a typical UE's tagged BS in UL(DL) | $\lambda_{I,u,F,D,k}$ | Density of full-duplex interfering UEs tagged to BSs in $k$th tier |
| $\lambda_{I,u,k}$ | Density of interfering UEs tagged to BSs in $k$th tier | $\tilde{F}_{\text{SINR}_{DL,k}}(z)$ (\tilde{F}_{\text{SINR}_{UL,k}}(z)) | CCDF of DL(UL) SINR |
| $f_{\text{SINR}_{DL,k}}(z)$ (\text{PDF of DL(UL) SINR}) | | $\text{2F1}([; ; ; ; ;])$ | Gauss hypergeometric function |
| $r, y$       | variables used in the numerical integration to represent distance between UE and BS | $z$          | variable used in numerical integration to represent SINR threshold. |

the definitions and notations of the main variables, symbols, and functions used in this paper.

IV. PERFORMANCE ANALYSIS

In this section, we derive all the necessary ingredients required to evaluate the performance of the proposed system model.

A. ASSOCIATION PROBABILITIES

To understand the UEs behavior in the cell association phase, we start by deriving the cell association probabilities for all the possible association cases with respect to the criteria defined in Section III-C.

- Case 1: Downlink BS = $M_{cell}$ BS
- Case 2: Downlink BS = $S_{cell}$ BS
- Case 3: Uplink BS = $M_{cell}$ BS
- Case 4: Uplink BS = $S_{cell}$ BS

We denote $\text{Pr}_{DL,M}$, $\text{Pr}_{DL,S}$, $\text{Pr}_{UL,M}$, and $\text{Pr}_{UL,S}$ as the probability of Case 1, 2, 3, and 4, respectively. To derive these association probabilities based on the SINR optimal criteria mentioned in Section III-C, first the complementary cumulative distribution function (CCDF) and the probability density function (PDF) of their respective SINRs are derived in the following four Lemmas.

Lemma 1: The SINR$_{DL,k}$ CCDF which is required to numerically evaluate the downlink cell association probabilities is mathematically formulated in (6).

$$\tilde{F}_{\text{SINR}_{DL,k}}(z) = \int_{r>0}^\infty 2\pi r \lambda_k \exp(-\pi \lambda_k r^2) \exp\left(\frac{-zr^{\alpha_k}}{P_k G_k} (\epsilon_*, Q_k + \sigma_k^2)\right)$$

$$\times \exp\left(-2\pi \lambda_k \frac{r^{2-\alpha_k}}{\alpha_k (\alpha_k - 2)} \frac{zr^{\alpha_k} P_k}{P_k G_k}\right)$$

$$\times \text{2F1}\left[1, 1 - \frac{2}{\alpha_k}, 2 - \frac{2}{\alpha_k}; -\frac{z Q_k}{P_k G_k}\right]$$

$$\times \text{2F1}\left[1, 1 - \frac{2}{\alpha_k}, 2 - \frac{2}{\alpha_k}; -\frac{z Q_k}{P_k G_k}\right] \text{dr}. \quad (6)$$

Proof: The development and proof are shown in Appendix A.

Lemma 2: The PDF of SINR$_{DL,k}$ which is required to numerically evaluate the downlink cell association probabilities is mathematically formulated in (7), as shown at the bottom of the next page.
Proof: The development and proof are shown in Appendix B.

Lemma 3: The $\text{SINR}_{UL,k}$ CCDF which is required to numerically evaluate the uplink cell association probabilities is mathematically formulated in (8).

$$\tilde{F}_{\text{SINR}_{UL,k}}(z) = \int_{r>0} \frac{2\pi r \lambda_k \exp(-\pi \lambda_k r^2)}{\sqrt{\pi \lambda_k}} \exp\left(\frac{-z^2}{Q_k G_k} (\epsilon_0 P_k + \sigma_k^2)\right) \times \exp\left(-\frac{2\pi \lambda_k r^2}{Q_k G_k} \frac{z^2}{\alpha_k} P_k\right) F_I\left[1, 1 - \frac{2}{\alpha_k}, 2 - \frac{2}{\alpha_k}; \frac{-z}{Q_k G_k}\right] \times \exp\left(-\frac{2\pi \lambda_k r^2}{Q_k G_k} \frac{z^2}{\alpha_k} Q_k\right) F_I\left[1, 1 - \frac{2}{\alpha_k}, 2 - \frac{2}{\alpha_k}; \frac{-z}{Q_k G_k}\right] dr. \quad (8)$$

Proof: The proof is similar to that of Lemma 1 provided in Appendix A.

Lemma 4: The PDF of $\text{SINR}_{UL,k}$ which is required to numerically evaluate the uplink cell association probabilities is mathematically formulated in (9), as shown at the bottom of this page.

Proof: The proof is similar to that of Lemma 2 provided in Appendix B.

Now we have all the ingredients to derive the association probabilities according to (1) and (2). The following Theorem states the downlink and uplink association probabilities, separately, for each tier.

Theorem 1: The association probabilities $\text{Pr}_{DL,M} \text{ , Pr}_{DL,S}, \text{Pr}_{UL,M}, \text{ and Pr}_{UL,S}$ for the received SINR optimal criteria mentioned in Section III-C are derived as follows

$$\text{Pr}_{DL,M} = \int_0^{\infty} \tilde{F}_{\text{SINR}_{DL,M}}(z) f_{\text{SINR}_{DL,S}}(z) dz, \quad (10)$$

$$\text{Pr}_{DL,S} = 1 - \text{Pr}_{DL,M}. \quad (11)$$
Similarly, the association probabilities \( Pr_{UL,M} \) and \( Pr_{UL,S} \) can be formulated as follows

\[
Pr_{UL,M} = \int_0^\infty \tilde{F}_{SINR_{UL,M}}(z) f_{SINR_{UL,S}}(z) dz, \quad (12)
\]

\[
Pr_{UL,S} = 1 - Pr_{UL,M}, \quad (13)
\]

Proof: Following the association criteria mentioned in Section III-C, the association probabilities \( Pr_{DL,M} \) and \( Pr_{UL,M} \) can easily be derived using Lemma 1, Lemma 2, Lemma 3, and Lemma 4.

\[
Pr_{DL,M} = Pr(SINR_{DL,M} > SINR_{DL,S})
= E_{SINR_{DL,S}}[\tilde{F}_{SINR_{DL,M}}(s)]
= \int_0^\infty \tilde{F}_{SINR_{DL,M}}(z) f_{SINR_{DL,S}}(z) dz. \quad (14)
\]

\[
Pr_{UL,M} = Pr(SINR_{UL,M} > SINR_{UL,S})
= E_{SINR_{UL,S}}[\tilde{F}_{SINR_{UL,M}}(s)]
= \int_0^\infty \tilde{F}_{SINR_{UL,M}}(z) f_{SINR_{UL,S}}(z) dz. \quad (15)
\]

where \( Pr_{DL,S} \) and \( Pr_{UL,S} \) in (11) and (13), respectively, directly follow from the fact that \( Pr_{DL,M} + Pr_{DL,S} = 1 \) and \( Pr_{UL,M} + Pr_{UL,S} = 1 \).

B. SINR COVERAGE

In the previous subsection, the SINR CCDF of both downlink and uplink transmission links are derived in Lemma 1 and 3. Since the SINR CCDF denotes the probability of coverage of its respective tier, therefore using the probability of association of each tier for both downlink and uplink derived in Theorem 1, we can compute the total SINR coverage as formulated in the following Corollary.

Corollary 1: For both downlink and uplink transmission links, SINR coverage of the full-duplex two-tier network can be expressed as the summation of the SINR CCDF of each tier weighted by their association probabilities.

\[
P_{c,SINR_{DL}}(z) = Pr_{DL,M} \tilde{F}_{SINR_{DL,M}}(z) + Pr_{DL,S} \tilde{F}_{SINR_{DL,S}}(z) \quad (16)
\]

\[
P_{c,SINR_{UL}}(z) = Pr_{UL,M} \tilde{F}_{SINR_{UL,M}}(z) + Pr_{UL,S} \tilde{F}_{SINR_{UL,S}}(z) \quad (17)
\]

C. AVERAGE SPECTRAL EFFICIENCY

To calculate the average spectral efficiency of the whole full-duplex HetNet in downlink and uplink transmission, first the average spectral efficiency of both downlink and uplink are derived separately for the \( k \)th tier in the following Theorem.

Theorem 2: The average downlink spectral efficiency for the \( k \)th tier can be formulated as the summation of 1) the spectral efficiency of the fraction of time a typical UE chooses to decouple and 2) spectral efficiency of the fraction of time a typical UE chooses to transmit in a conventional way. Since there would not be any self interference when a typical UE chooses to decouple because of the different frequency bands for its downlink and uplink transmission links, therefore in this case \( \varepsilon = 0 \).

\[
SE_{DL,k} = |Pr_{DL,k} - Pr_{UL,k}| f_{SE_{DL,k}}(0) + (1 - |Pr_{DL,k} - Pr_{UL,k}|) f_{SE_{DL,k}}(\varepsilon), \quad (18)
\]

where \( f_{SE_{DL,k}}(\varepsilon) \) is given by

\[
f_{SE_{DL,k}}(\varepsilon) = \int_{z>0} \int_{r>0} 2\pi r \lambda_k \exp(-\pi \lambda_k r^2) \times \exp\left(-\frac{(\exp(z) - 1)^{\alpha_k}}{P_k G_k} (\varepsilon P_k + \sigma_k^2)\right) \times \exp\left(-\frac{2\pi \lambda_k (\exp(z) - 1)^{\alpha_k} P_k}{(\alpha_k - 2) P_k G_k} \right) \times \exp\left(-\frac{2\pi \lambda_k (\exp(z) - 1)^{\alpha_k} Q_k}{(\alpha_k - 2) Q_k G_k} \right) \times \left[1, 1 - 2(\frac{2}{\alpha_k} - \frac{\varepsilon}{\alpha_k})\right] dz dr. \quad (19)
\]

Similarly, the average uplink spectral efficiency for the \( k \)th tier can be formulated as

\[
SE_{UL,k} = |Pr_{DL,k} - Pr_{UL,k}| f_{SE_{UL,k}}(0) + (1 - |Pr_{DL,k} - Pr_{UL,k}|) f_{SE_{UL,k}}(\varepsilon), \quad (20)
\]

where \( f_{SE_{UL,k}}(\varepsilon) \) is given by

\[
f_{SE_{UL,k}}(\varepsilon) = \int_{z>0} \int_{r>0} 2\pi r \lambda_k \exp(-\pi \lambda_k r^2) \times \exp\left(-\frac{(\exp(z) - 1)^{\alpha_k}}{Q_k G_k} (\varepsilon P_k + \sigma_k^2)\right) \times \exp\left(-\frac{2\pi \lambda_k (\exp(z) - 1)^{\alpha_k} P_k}{(\alpha_k - 2) P_k G_k} \right) \times \exp\left(-\frac{2\pi \lambda_k (\exp(z) - 1)^{\alpha_k} Q_k}{(\alpha_k - 2) Q_k G_k} \right) \times \left[1, 1 - 2(\frac{2}{\alpha_k} - \frac{\varepsilon}{\alpha_k})\right] dz dr. \quad (21)
\]

Proof: The development and proof are shown in Appendix C.
Corollary 2: Based on the probability of association in Theorem 1 and the spectral efficiency of each tier in Theorem 2, the average spectral efficiency of the whole full-duplex HetNet for both uplink and downlink transmissions can be formulated as

$$SE_{DL} = Pr_{DL,M} SE_{DL,M} + Pr_{DL,S} SE_{DL,S}$$

$$SE_{UL} = Pr_{UL,M} SE_{UL,M} + Pr_{UL,S} SE_{UL,S}$$

V. NUMERICAL AND SIMULATION RESULTS

In this section, to highlight the performance insights of the system under consideration, rigorous numerical and simulation results are presented. The analytical results are validated by Monte Carlo simulations for randomly located UEs and BSs according to their respective densities. It is assumed that all UEs and BSs can communicate in full-duplex mode unless they are decoupling. We did system level simulations, where we deployed BSs and UEs in a circular area of radius \( \mu \) with the help of tools from stochastic geometry. Then, based on their coordinates, randomly generated fading coefficients, transmit powers, and antenna gains, we calculated all types of interferences. All these ingredients help us calculate the SINRs which eventually derive the association criteria. All the simulation results are obtained by averaging over 10,000 independent realizations in MATLAB. The default system parameters are selected according to the 3GPP specifications [36] and existing research works [9], [11], [12], where their values are listed in Table 2.

### A. ASSOCIATION PROBABILITIES

Fig. 2(a) and 2(b) illustrate the association probabilities derived in Theorem 1 against the ratio of Scell to Mcell density for \( G_S = 18dBi \) and \( G_S = 32dBi \), respectively. It is observed that there is a close match between the simulation and analytical results, which validates the analysis. The significant gap between the downlink and uplink association probabilities for both Scell and Mcell BSs represents the decoupling gain. In other words, this gap defines the decoupled access where UEs prefer to connect with two different BSs for their uplink and downlink transmissions. Fig. 2(a) shows that almost 10% of the UEs choose to decouple at \( \lambda_S/\lambda_M = 40 \). Moreover, the decrease in the decoupling gain from 35% for \( \lambda_S/\lambda_M = 5 \) to 10% for \( \lambda_S/\lambda_M = 40 \) is due to the fact that as we increase the density of Scell BSs, the UEs prefer to connect to Scell BSs for both downlink and uplink transmissions due to its antenna gain and close proximity. Fig. 2(b) shows that a higher antenna gain for mmWave BSs significantly reduces the decoupling gain. This stems from the fact that higher antenna gain of mmWave BSs make them SINR optimal for both downlink and uplink transmissions.

Fig. 3 illustrates the effect of the number of full-duplex UEs and BSs in a network on the association probabilities. The 100% and 10% in the legend of the figure represent the fraction of full-duplex UEs and BSs. Therefore Fig. 3 compares the association probabilities of two scenarios: 1) when all the UEs and BSs can communicate in full-duplex mode and 2) when only 10% of them can communicate in full-duplex mode. The full-duplex transmission mode gives birth to two additional interference components. A self-interference and full-duplex interference that comes from the

### TABLE 2. System parameters.

| Parameters | Value |
|------------|-------|
| Mcell BS transmit power \( P_M \) (dBm) | 46 |
| Scell BS transmit power \( P_S \) (dBm) | 30 |
| Antenna Gain for Mcell BS \( G_M \) (dBi) | 0 |
| Antenna Gain for Scell BS \( G_S \) (dBi) | 18 |
| UE’s transmit power to Mcell BS \( Q_M \) (dBm) | 23 |
| UE’s transmit power to Scell BS \( Q_S \) (dBm) | 20 |
| Radius of the circular area of simulation \( \mu \) (m) | 1500 |
| Pathloss exponent for sub-6GHz tier \( \alpha_M \) | 3 |
| Pathloss exponent for millimeter wave tier \( \alpha_S \) | 4 |
| Self-interference suppression factor of BS(UE) \( \kappa_S(\sigma) \) | \( 10^{-\frac{\sigma}{10}} \) |
| Microwave or sub-6GHz bandwidth \( B_M \) (MHz) | 20 |
| mmWave bandwidth \( B_S \) (GHz) | 1 |
| Noise power \( \sigma^2 \) | \(-174 \text{ dBm/Hz} + 10 \log_{10}(B_k) + 10dB\) |
other full-duplex UEs in downlink and the other full-duplex BSs in uplink. It is intriguing to see that the additional full-duplex interference does not measurably change or modify the association curves. The rationale behind this is related to the fact that the additional full-duplex interference is only a small fraction of the total interference (i.e., inter-user interference, inter-cell interference, self interference, full-duplex interference), therefore it does not affect the association curves notably. The zoomed-in window in the figure shows the insignificant effect of the additional full-duplex interference on the association curves.

In Fig. 4, the association probabilities are plotted for different values of the self-interference suppression factor. Since it is assumed that $\epsilon_0 = \epsilon_*$, therefore the subscript of $\epsilon$ is omitted from the legend of Fig. 4. The additional curves are plotted with 50% decrease and 100% increase in the default value of the self-interference suppression factor, i.e. $10^{-5}$. Fig. 4 illustrates that the increase or decrease in the self-interference suppression factor does not change the trends of association probabilities in a measurable way. This is because, after suppression, the self-interference is only a small fraction of the total interference. Moreover, the slight difference in the downlink association probabilities for different values of the self-interference suppression factor is due to the difference of transmit powers of the $M_{cell}$ and $S_{cell}$ BSs. Similarly, since the difference between the transmit powers of the UEs for both microwave and millimeter-wave links is no significant, compared to the difference of transmit powers of the $M_{cell}$ and $S_{cell}$ BSs, therefore the curves of uplink association probabilities overlap for different values of self-interference suppression factor.

**B. SINR COVERAGE**

In this part, SINR coverage analysis is validated by rigorous simulations. Fig. 5 shows that the analytical expressions sharply match the corresponding simulation results, which gives us the confidence to use the analysis for further insights in the following results. Fig. 6 illustrates the effect of the assumption of a typical noise-limited mmWave network and
FIGURE 7. Spectral efficiency of decoupled and coupled full-duplex two-tier HetNet and validation of analysis.

compares it with the proposed model, which accounts for all kinds of interference for both mmWave and sub-6GHz networks. It can be seen that for a fairly dense mmWave network i.e., \( \lambda_S = 200/\text{km}^2 \), the noise-limited assumption closely matches with the proposed model i.e., \( \text{SINR} \approx \text{SNR} \). However, as we move into the realm of ultra-dense networks (UDNs) [37], [38] where the density of access points is greater than the density of UEs [39], the typical noise-limited assumption does not remain valid. For example for \( \lambda_S = 1000/\text{km}^2 \) at \( z = 30 \text{dB} \), there is a significant gap of 20\% between SNR and SINR coverage. This result not only reaffirms the assumption that the interference in the mmWave network should also be accounted for, specially when moving into the realm of UDN, but also validates the robustness of the proposed model.

C. SPECTRAL EFFICIENCY

Fig. 7 compares the spectral efficiency of full-duplex two-tier HetNet with decoupled access with its coupled counterpart for both uplink and downlink separately. It can be seen that decoupled access outperforms its coupled counterpart for a fairly large range of densities. The rationale behind this gain in spectral efficiency is the BS diversity caused by decoupled access. Moreover, to understand the small bump on the uplink spectral efficiency curve of the decoupled case at \( \lambda_S/\lambda_M = 5 \), we have to take a look at Fig. 2(a) again. In this context, it is observed that from \( \lambda_S/\lambda_M = 1 \) to \( \lambda_S/\lambda_M = 5 \), there is a sharp increase in the association probability of Scell BSs, which means more UEs connect with Scell BSs. Moreover, since uplink coverage of Scell BSs is better than Mcell BSs, as shown in Fig. 8, therefore in Fig. 7 the uplink spectral efficiency curve of the decoupled case at \( \lambda_S/\lambda_M = 5 \) has a sharp bump. Furthermore, the slight decrease in the uplink spectral efficiency curve of the decoupled case from \( \lambda_S/\lambda_M = 6 \) to \( \lambda_S/\lambda_M = 15 \) is due to the decrease in the decoupling gain for this range of the ratio of the density of BSs. The rise in the curve afterward is due to the very high association probability of Scell BSs. In addition, Fig. 9 shows the effect of decoupling on uplink energy efficiency. It can be noted that the average uplink energy efficiency, which is defined as the uplink channel capacity normalized by the UE’s transmit power, for the system with decoupled access is always superior to that of the system without decoupling. This is due to the fact that with decoupled access UEs transmits to Scell BSs with less transmit power.

Fig. 10 illustrates the effect of the number of full-duplex UEs and BSs in a network on the spectral efficiency. The 100\%, 50\%, and 10\% in the legend of the figure represent the fraction of the full-duplex UEs and BSs. Since the downlink transmit power of a BS is always significantly greater than the uplink transmit power of a UE, therefore the added full-duplex interference does not affect the spectral efficiency of downlink measurably. On the other hand, the notable effect of full-duplex interference can be seen on the uplink spectral efficiency.
PROOF OF LEMMA 1

The proof of Lemma 1 involves deriving the coverage probability of a full-duplex network. The coverage probability can be written as:

\[ \Pr(h_{\text{DS},0} > (d_{\text{DL}} + \epsilon_s Q_k + \sigma_k^2 r^{a_k} z) P_k G_k) \]

where (a) follows from the fact that the PDF of the distance \( r \) by the null probability of a 2D PPP [23] is given by

\[ f_r(r) = 2\pi \lambda_k r \exp(-\pi \lambda_k r^2), \quad r \geq 0. \]

Using the assumption that \( h_{\text{DS},0} \sim \exp(1) \), the coverage probability can be written as:

\[ \Pr(h_{\text{DS},0} > (d_{\text{DL}} + \epsilon_s Q_k + \sigma_k^2 r^{a_k} z) P_k G_k) = \exp\left(-\frac{z r^{a_k}}{P_k G_k} (\epsilon_s Q_k + \sigma_k^2)ight) \mathcal{L}_{DL,k}(z) \]

where (b) simply follows from the fact that the Laplace transform of a non-negative random variable \( Z \).

\[ \mathcal{L}_{DL,k}(z) = \mathbb{E}[\exp(-s Z)] \text{ for } s > 0 \] is the Laplace transform of a non-negative random variable \( Z \).

\[ \mathcal{L}_{DL,k}(z) = \mathbb{E}[\exp(-s Z)] = \mathbb{E}[\exp(-s z r^{a_k} P_k G_k)] \]

where (d) follows from the fact that the total downlink interference is the summation over two independent point processes as formulated in (5).

\[ \mathbb{E}\left[\frac{z r^{a_k}}{P_k G_k} I_{DL,k} \right] = \exp\left(-2\pi \lambda_k (\alpha - 2) P_k G_k \right) \frac{z r^{a_k} P_k G_k}{\alpha_k} \]

where (e) and (f) follow the same steps as mentioned in the proof of Theorem 1 in Appendix C of [14] and the equality given in section 3.194 of [40]. This concludes the proof.

APPENDIX B

PROOF OF LEMMA 2

Since a PDF of a function is simply the derivative of its CDF, we can write \( f_{\text{SINR}_{DL,k}}(z) \) as follows:

\[ f_{\text{SINR}_{DL,k}}(z) = \frac{d}{dz} \left( 1 - F_{\text{SINR}_{DL,k}}(z) \right) = -\frac{d}{dz} \left( F_{\text{SINR}_{DL,k}}(z) \right). \]
Since \( F_{\text{SINR}_{DL,k}}(z) \) involves the product of three exponential functions having the differentiable variable \( z \) in their arguments, therefore its derivative can easily be solved using the typical product rule of derivatives. Moreover, the differentiation of the Gauss hypergeometric function \([41]\) involves the following equality

\[
\frac{d}{dz}(2F_1[1, 1 - c, 2 - c, -dz]) = (1 - c) \left( \frac{1}{dz+1} - 2F_1[1, 1 - c, 2 - c, -dz] \right) \frac{1}{z}. \tag{29}
\]

Now using (29) and the typical product rule of derivatives yields (7), which concludes the proof.

**APPENDIX C**

**PROOF OF THEOREM 2**

In Theorem 2, (18) and (20) define the total spectral efficiency of the downlink and uplink transmission links, respectively. Both (18) and (20) are the summation of 1) the spectral efficiency for the fraction of time a typical UE chooses to decouple and 2) the spectral efficiency for the fraction of time a typical UE chooses to transmit in conventional way. Since the derivation of \( f_{SE_{DL,k}}(\epsilon_s) \) and \( f_{SE_{UL,k}}(\epsilon_s) \) involves similar steps, only the detailed derivation of \( f_{SE_{DL,k}}(\epsilon_s) \) is provided here.

\[
f_{SE_{DL,k}}(\epsilon_s) \triangleq \mathbb{E}\left[ \ln(1 + \text{SINR}_{DL,k}) \right] \tag{30}
\]

\[
= \int_0^\infty \int_0^\infty 2\pi r \lambda_k \exp(-\pi \lambda_k r^2) \times \mathbb{P}(\text{SINR}_{DL,k} > \exp(z) - 1) \, dr \, dz.
\]

Using the fact that \( h_{k*,0} \sim \exp(1) \), the \( \mathbb{P}(h_{k*,0} > (I_{DL,k} + \epsilon_s Q_k + \sigma_k^2 r^{\alpha_k} \exp(z) - 1)) \) can be written as

\[
\mathbb{P}(h_{k*,0} > (I_{DL,k} + \epsilon_s Q_k + \sigma_k^2 r^{\alpha_k} \exp(z) - 1)) = \exp \left( \frac{-(\exp(z) - 1) r^{\alpha_k}}{P_k G_k} (\epsilon_s Q_k + \sigma_k^2) \right)
\times \mathbb{E}_{I_{DL,k}} \left[ \exp \left( \frac{-(\exp(z) - 1) r^{\alpha_k}}{P_k G_k} I_{DL,k} \right) \right],
\]

where (i) follows from the fact that \( \mathcal{L}(s) = \mathbb{E}(\exp(-sZ)) \) for \( s > 0 \) is the Laplace transform of a non-negative random variable \( Z \). Moreover \( \mathcal{L}_{I_{DL,k}} \left( \frac{-(\exp(z) - 1) r^{\alpha_k}}{P_k G_k} I_{DL,k} \right) \) can be written as follows

\[
\mathcal{L}_{I_{DL,k}} \left( \frac{-(\exp(z) - 1) r^{\alpha_k}}{P_k G_k} I_{DL,k} \right) \leqslant \mathbb{E} \left( \frac{-(\exp(z) - 1) r^{\alpha_k} I_{DL,k}}{P_k G_k} \right).
\tag{32}
\]

where (j) follows from the fact that the total downlink interference is the summation over two independent Poisson point processes. In addition, following (27), the two expectations over the interference point processes in (32) can be formulated as

\[
\mathbb{E} \left( \frac{-(\exp(z) - 1) r^{\alpha_k} I_{DL,k}}{P_k G_k} \right) = \exp \left( -2\pi \lambda_k \frac{r^{2-\alpha_k}}{(\alpha_k - 2)} \left( \exp(z) - 1 \right) r^{\alpha_k} P_k G_k \right)
\times \mathbb{P}(\text{SINR}_{DL,k} > \exp(z) - 1) \, dr \, dz.
\]

This concludes the proof.

**REFERENCES**

[1] J. Zhang, E. Bjørnson, M. Matthaiou, D. W. K. Ng, H. Yang, and D. J. Love, “Prospective multiple antenna technologies for beyond 5G,” IEEE J. Sel. Areas Commun., vol. 38, no. 8, pp. 1637–1660, Aug. 2020.

[2] V. W. Wong, Key Technologies for 5G Wireless Systems. Cambridge, U.K.: Cambridge Univ. Press, 2017.

[3] Y. Sun, D. W. K. Ng, Z. Ding, and R. Schober, “Optimal joint power and subcarrier allocation for full-duplex multicarrier non-orthogonal multiple access systems,” IEEE Trans. Commun., vol. 65, no. 3, pp. 1077–1091, Mar. 2017.

[4] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. Soong, and J. C. Zhang, “What will 5G be?” IEEE J. Sel. Areas Commun., vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[5] B. Yang, G. Mao, M. Ding, X. Ge, and X. Tao, “Dense small cell networks: From noise-limited to dense interference-limited,” IEEE Trans. Veh. Technol., vol. 67, no. 5, pp. 4626–4677, May 2018.

[6] J. G. Andrews, H. Claussen, M. Dohler, S. Rangan, and M. C. Reed, “Femtocells: Past, present, and future,” IEEE J. Sel. Areas Commun., vol. 30, no. 3, pp. 497–508, Apr. 2012.

[7] J. G. Andrews, “Seven ways that HetNets are a cellular paradigm shift,” IEEE Commun. Mag., vol. 51, no. 3, pp. 136–144, Mar. 2013.

[8] H. Elshaer, F. Boccardi, M. Dohler, and R. Irmer, “Downlink and uplink decoupling: A disruptive architectural design for 5G networks,” in Proc. IEEE Global Commun. Conf., Dec. 2014, pp. 1798–1803.

[9] H. Elshaer, M. N. Kulkarni, F. Boccardi, J. G. Andrews, and M. Dohler, “Downlink and uplink cell association with traditional macrocells and millimeter wave small cells,” IEEE Trans. Wireless Commun., vol. 15, no. 9, pp. 6244–6258, Sep. 2016.
[10] F. Boccardi, J. Andrews, H. Elsner, M. Dohler, S. Parkvall, P. Popovski, and S. Singh, “Why to deploy the uplink and downlink in cellular networks and how to do it,” IEEE Commun. Mag., vol. 54, no. 3, pp. 110–117, Mar. 2016.

[11] K. Smiljковiћ, P. Popovski, and L. Gavrilовска, “Analysis of the decoupled access for downlink and uplink in wireless heterogeneous networks,” IEEE Wireless Commun. Lett., vol. 4, no. 2, pp. 173–176, Apr. 2015.

[12] K. Smiljковiћ, L. Gavrilовска, and P. Popovski, “Efficiency analysis of downlink and uplink decoupling in heterogeneous networks,” in Proc. IEEE Int. Conf. Commun. Workshop (ICCW), Jun. 2015, pp. 125–130.

[13] Z. Sattar, J. V. C. Evangelista, G. Kaddoum, and N. Batani, “Analysis of the cell association for decoupled wireless access in a two-tier network,” in Proc. IEEE 28th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC), Oct. 2017, pp. 1–6.

[14] Z. Sattar, J. V. C. Evangelista, G. Kaddoum, and N. Batani, “Spectral efficiency analysis of the decoupled access for downlink and uplink in two-tier network,” IEEE Trans. Veh. Technol., vol. 68, no. 5, pp. 4871–4883, May 2019.

[15] L. Zhang, W. Nie, G. Feng, F.-C. Zheng, and S. Qin, “Uplink performance improvement by decoupling Uplink/Downlink access in HetNets,” IEEE Trans. Veh. Technol., vol. 66, no. 8, pp. 6862–6876, Aug. 2017.

[16] R. Li, K. Luo, T. Jiang, and S. Jin, “Uplink spectral efficiency analysis of decoupled access in multiuser MIMO HetNets,” IEEE Trans. Veh. Technol., vol. 67, no. 5, pp. 4290–4302, May 2018.

[17] M. Shi, K. Yang, C. Xing, and R. Fan, “Decoupled heterogeneous networks with millimeter wave small cells,” IEEE Trans. Wireless Commun., vol. 17, no. 9, pp. 5871–5884, Sep. 2018.

[18] V. Chandrasekhar, M. Kontouris, and J. G. Andrews, “Coverage in multi-antenna two-tier networks,” IEEE Trans. Wireless Commun., vol. 8, no. 10, pp. 5314–5327, Oct. 2009.

[19] M. Di Renzo, “Stochastic geometry modeling and analysis of multi-tier millimeter wave cellular networks,” IEEE Trans. Wireless Commun., vol. 14, no. 9, pp. 5063–5075, Sep. 2015.

[20] M. K. Giluka, M. S. A. Khan, G. M. Krishna, T. A. Atif, V. Sathya, and B. R. Tamma, “On handovers in Uplink/Downlink decoupled LTE HetNets,” in Proc. IEEE Wireless Commun. Netw. Conf. Workshops (WCNCW), Apr. 2016, pp. 1–6.

[21] C.-H. Liu and H.-M. Hu, “Full-duplex heterogeneous networks with decoupled user association: Rate analysis and traffic scheduling,” IEEE Trans. Commun., vol. 67, no. 3, pp. 2084–2100, Mar. 2019.

[22] S. Sekander, H. Tabassum, and E. Hossain, “Decoupled uplink-downlink user association in multi-tier full-duplex cellular networks: A two-sided matching game,” IEEE Trans. Mobile Comput., vol. 16, no. 10, pp. 2778–2791, Oct. 2017.

[23] S. N. Chiu, D. Stoyan, W. S. Kendall, and J. Mecke, Stochastic Geometry and Its Applications. Hoboken, NJ, USA: Wiley, 2013.

[24] J. G. Andrews, T. Bai, M. N. Kulkarni, A. Alkhateeb, A. K. Gupta, and R. Heath Jr., “Modeling and analyzing millimeter wave cellular systems,” IEEE Trans. Commun., vol. 65, no. 1, pp. 403–430, Jan. 2017.

[25] C. Saha and H. S. Dhillon, “Millimeter wave integrated access and backhaul in 5G: Performance analysis and design insights,” IEEE J. Sel. Areas Commun., vol. 37, no. 12, pp. 2669–2684, Dec. 2019.

[26] S. Singh, M. N. Kulkarni, A. Ghosh, and J. G. Andrews, “Tractable model for rate in self-backhauled millimeter wave cellular networks,” IEEE J. Sel. Areas Commun., vol. 33, no. 10, pp. 2196–2211, Oct. 2015.

[27] S. Sekharwal, P. Schniter, D. Guo, D. Xiao, S. Rangarajan, and R. Wichman, “In-band full-duplex wireless: Challenges and opportunities,” IEEE J. Sel. Areas Commun., vol. 32, no. 9, pp. 1637–1652, Sep. 2014.

[28] S. Hong, J. Brand, J. Choi, M. Jain, J. Mehmehn, S. Katti, and P. Levis, “Applications of self-interference cancellation in 5G and beyond,” IEEE Commun. Mag., vol. 52, no. 2, pp. 114–121, Feb. 2014.

[29] E. Everett, A. Sahai, and A. Sabharwal, “Passive self-interference suppression for full-duplex infrastructure nodes,” IEEE Trans. Wireless Commun., vol. 13, no. 2, pp. 680–694, Feb. 2014.

[30] N. H. Mahmood, G. Berardiinelli, F. M. Tavares, and P. Mogensen, “On the potential of full duplex communication in 5G small cell networks,” in Proc. IEEE 81st Veh. Technol. Conf. (VTC Spring), May 2015, pp. 1–5.

[31] S. Goyal, P. Liu, S. Panwar, R. Yang, R. A. DiFazio, and E. Bala, “Full duplex operation for small cells,” 2014, arXiv:1412.8708. [Online]. Available: http://arxiv.org/abs/1412.8708

[32] X. Xie and X. Zhang, “Does full-duplex double the capacity of wireless networks?” in Proc. IEEE IEEE Conf. Comput. Commun. (INFOCOM), Apr. 2014, pp. 253–261.

[33] Z. Tong and M. Haenggi, “Throughput analysis for wireless networks with full-duplex radios,” in Proc. IEEE Wireless Commun. Netw. Conf. (WCNC), Mar. 2015, pp. 1–6.

[34] T. Riihonen, S. Werner, and R. Wichman, “Hybrid full-duplex/half-duplex relaying with transmit power adaptation,” IEEE Trans. Wireless Commun., vol. 10, no. 9, pp. 3074–3085, Sep. 2011.

[35] I. P. Roberts, H. B. Jain, and S. Vishwanath, “Equipping millimeter-wave full-duplex with analog self-interference cancellation,” 2020, arXiv:2002.02127. [Online]. Available: http://arxiv.org/abs/2002.02127

[36] Z. Xie, J. Liu, M. Sheng, Y. Zhang, and J. Li, “Effect of interference correlation on the performance of ultra-dense networks,” in Proc. IEEE Int. Conf. Commun. (ICC), May 2019, pp. 1–7.

[37] J. Liu, M. Sheng, and J. Li, “Improving network performance scaling law in ultra-dense small cell networks,” IEEE Trans. Wireless Commun., vol. 17, no. 9, pp. 6218–6230, Sep. 2018.

[38] M. Kamel, W. Hamouda, and A. Youssef, “Ultra-dense networks: A survey,” IEEE Commun. Surveys Tuts., vol. 18, no. 4, pp. 2522–2545, 4th Quart., 2016.

[39] I. S. Gradshteyn and I. M. Ryzhik, Table of Integrals, Series, and Products. New York, NY, USA: Academic, 2014.

[40] F. W. Olver, D. W. Lozier, and R. F. Boisvert, NIST Handbook of Mathematical Functions Hardback and CD-ROM. Cambridge, U.K.: Cambridge Univ. Press, 2010.

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