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Physical Layer Security in Heterogeneous Networks with Pilot Attack: A Stochastic Geometry Approach

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Abstract—In this paper, we investigate physical layer security in a two-tier heterogeneous network with sub-6 GHz massive multi-input multi-output (MIMO) macro cells and millimeter wave (mmWave) small cells. By considering pilot attacks from the eavesdroppers, we analyze the coverage and secrecy performance using stochastic geometry. For the sub-6 GHz tier, we show that increasing the number of BS antennas is more effective than increasing BS density in improving the coverage performance, whereas densifying BS is more effective for security enhancement. For the mmWave tier, we first derive the success probability of beam alignment based on a beam sweeping based channel training model. It is shown that the mmWave tier may outperform the sub-6 GHz counterpart in terms of both coverage and secrecy through densifying the base stations. Our results also reveal that the mmWave small cell can provide better coverage performance in the high transmission rate region, and can achieve higher security in the low redundant rate region, which reveals the advantage of using mmWave for secure communication. Numerical results verify the analysis.

Index Terms—Massive MIMO, millimeter wave, physical layer security, pilot attack, stochastic geometry.

I. INTRODUCTION

IN the fifth generation (5G) cellular network, technologies such as massive multiple-input multiple-output (MIMO) and millimeter wave (mmWave) are anticipated to be adopted to support the unprecedented growth of mobile data traffic driven by various smart applications [1]. By deploying a large-scale antenna array, massive MIMO can greatly improve the spectrum efficiency since the channels to different users become quasi-orthogonal. Recently, mmWave communication has also received intensive research interests due to the vast available spectrum at mmWave frequencies. Different from the conventional network operated below 6 GHz (sub-6 GHz system), the mmWave signals are more sensitive to blockage and cannot penetrate through buildings. Hence, to realize universal coverage, it is more likely that mmWave small-cell will co-exist with traditional sub-6 GHz macro-cell network [2], [3].

Due to the open nature of wireless channels, wireless transmission is also vulnerable to external eavesdropping or jamming. To ensure secure communication, cryptography-based protocols are usually implemented in the application layer, which not only requires high complexity but also poses great challenges for secret key generation and management

especially for the large scale and heterogeneous networks (HetNets). By utilizing the randomness of wireless channels, security can be achieved at the physical layer without using cryptographic protocols. Hence, physical layer security has received intensive research attention recently [4]–[6]. Physical layer security in a single cell downlink massive MIMO system with passive eavesdropping was discussed in [7]. It was shown that the secrecy capacity was an increasing function of the number of base station (BS) antennas. However, for a multi-cell case, it was shown that the ergodic secrecy rate suffered a ceiling effect due to the presence of pilot contamination [8]. It also revealed that artificial noise (AN) was necessary to achieve a positive ergodic secrecy rate and the random AN transmission scheme could achieve similar performance with the conventional null-space based AN transmission scheme.

Recent studies have shown that by using high gain large antenna arrays, mmWave cellular systems can implement beamforming at the transmitter and receiver to compensate the path loss [9]–[12]. The coverage and rate performance in mmWave cellular networks was evaluated using a stochastic geometry approach by considering different path loss characteristics of line-of-sight (LoS) and non-line-of-sight (NLoS) links [10], [12]. It was shown that mmWave systems were typically noise-limited and the dense mmWave networks could achieve comparable coverage and much higher data rates than conventional cellular systems. Note that since the large antenna arrays can form very narrow beams, signals can be focused in the intended users' directions; thus the mmWave system can significantly improve the secrecy performance. Physical layer security in mmWave ad hoc networks was investigated in [13], considering the impact of mmWave channel characteristics, random blockages, and antenna gains. Wang *et al.* studied the secure connection probability in a noise-limited mmWave cellular network for both non-colluding and colluding eavesdroppers (Eves) in [14]. Different secure transmission strategies were compared in [15] under slow fading channels with multipath propagation in a point-to-point mmWave system. It was demonstrated that the secrecy performance was significantly affected by spatially resolvable paths between the legitimate user and the Eve.

Most of the existing works on physical-layer security assume that the Eves are totally passive. In practice, the Eves may be much smarter than what we have assumed, i.e., the active smart Eve may confound the transmitter about the channel to be estimated by sending the same pilot signal during the channel training phase, resulting in an enhanced signal reception at the Eve [16]–[20]. On the other hand, in the presence of pilot attacks from active Eves, the mmWave trans-

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mitting beam may not be perfectly aligned with the receiving beam resulting in severe performance degradation. Hence, beam alignment is a critical issue in mmWave communication systems and has been studied recently [21]–[24]. In [18], by incorporating pilot contamination and pilot attack¹ from multi-antenna active Eves in a time-division duplex (TDD) multi-cell multi-user massive MIMO system, a closed-form expression of the asymptotic achievable secrecy rate was derived with matched filter precoding and AN. It was proved that the impact of the active Eve can be completely eliminated when the transmit correlation matrices of the users and the Eve are orthogonal, and robust design against the pilot contamination attack was also developed. **More recently, pilot spoofing and jamming attack has been discussed in multi-antenna systems in [25]. Through allocating multiple pilot sequences (PSs) and random PS selection, both the legitimate channel and eavesdropping channel can be estimated.**

Different from [18] wherein the authors focused on transmit signal design, we consider a sub-6 GHz and mmWave hybrid HetNet with spatial randomly distributed nodes and active smart Eves, and investigate the coverage and secrecy performance from the perspective of network design. Physical layer security without pilot attack in such a hybrid HetNet has been explored in [3], where the microwave BS was equipped with a single antenna for the ease of tractability. It was revealed that higher path loss and dense blockage were beneficial to the secure transmission. For the case that the BS is equipped with a large-scale antenna array, the coverage and secrecy performance comparison between the two tiers remain unexplored. Even though both massive MIMO and mmWave can help to boost the secrecy performance, the fundamental question on whether the sub-6 GHz massive MIMO tier or the mmWave tier can provide better performance remains unknown, especially in the presence of pilot attack and pilot contamination. The effect of massive MIMO and small cell on the achievable downlink rate considering pilot contamination has been investigated in [26], where the massive MIMO macro tier and the small-cell tier are assumed to operate in the same frequency band. Thus, the conclusions in [26] cannot be directly used to analyze the secrecy performance in the hybrid sub-6 GHz and mmWave HetNet.

In this paper, we consider a hybrid sub-6 GHz and mmWave HetNet and characterize the coverage and secrecy performance considering active pilot attacks and pilot contamination under stochastic geometry framework. The contributions of this paper are summarized as follows:

- We propose a threshold based average received signal power (ARSP) user association protocol, where each user is associated to the BS providing the largest ARSP and users are forced to associate to the sub-6 GHz tier when the ARSP of the mmWave tier is below a threshold. A closed-form expression of the association probability is derived.
- We analyze the coverage and secrecy performance of the sub-6 GHz massive MIMO macro tier in the presence

of pilot attacks from active Eves and conventional pilot contaminations using the stochastic geometry approach. For the maximal-ratio transmission (MRT) scheme, we reveal that in the presence of pilot attack and pilot contamination, densifying the BS will not always improve the coverage performance. More importantly, increasing the number of BS antennas is more effective than increasing BS density in improving the coverage performance, whereas densifying BS is more effective for security enhancement.

- For the mmWave tier, we first analyze the success probability of beam alignment and then derive the expressions of the coverage and secrecy probabilities. We show that the pilot attack degrades the performance severely and it is possible for the mmWave tier to outperform the sub-6 GHz counterpart in terms of both coverage and secrecy through densifying the SBS.
- We compare the coverage and secrecy performance between the sub-6 GHz tier and mmWave tier. It is shown that an mmWave small cell can provide better coverage performance in the high transmission rate region and the secrecy performance of the mmWave tier outperforms the sub-6 GHz tier in the low redundant rate region, which reveals the advantage of using mmWave for secure communication. For a user that can be associated to either tier, parameters should be carefully chosen to optimize its coverage and secrecy performance.

The rest of this paper is organized as follows. System model including the sub-6 GHz massive MIMO macro tier channel model, the mmWave channel model, user association, and performance metrics is presented in Section II. The coverage and secrecy performance are analyzed in Sections III and IV, respectively. Numerical results and discussions are presented in Section V. Lastly, conclusions are drawn in Section VI.

Notation: Bold symbols in capital and lower-case letter denote matrices and vectors, respectively. $[\cdot]^T$, $[\cdot]^\dagger$, and $[\cdot]^H$ denote the transpose, conjugate, and conjugate transpose operations, respectively. $\mathbf{I}_N$ denotes the $N \times N$ identity matrix. $|\cdot|$, $\|\cdot\|$, and $\mathbb{P}(\cdot)$ represent absolute value, Euclidean norm, and probability, respectively. $\mathcal{CN}(\mu, \sigma^2)$ denotes circularly symmetric complex Gaussian distribution with mean μ and variance σ^2 .

II. SYSTEM MODEL

We consider secure communication in a TDD downlink cellular network, consisting of both sub-6 GHz macro cells and mmWave small cells². The positions of the macro-cell BSs (MBSs) and the small-cell BSs (SBSs) are distributed according to independent Poisson Point Processes (PPPs) Φ_μ and Φ_m , with intensities λ_μ and λ_m , respectively. Each MBS is equipped with massive antennas (N_μ antennas) and each SBS is equipped with N_m antennas. The users are randomly distributed according to an independent PPP with sufficiently high density, and each user can operate in either sub-6 GHz

¹In this paper, we refer “pilot contamination” as conventional co-pilot caused channel estimation error in sub-6 GHz massive MIMO, and “pilot attack” as pilot contamination attack from Eves.

²This will be possible in future 5G networks, where both sub-6 GHz and mmWave band will be used and the mmWave small cells are overlaid under the sub-6 GHz macro cells.

or mmWave opportunistically, as assumed in [2], [3]. We assume that the downlink communication is eavesdropped by some non-colluding Eves whose locations are randomly distributed according to an independent PPP Φ_E with intensity λ_E . Different from [3], each Eve can launch a pilot attack during the uplink channel training process for both MBSs and SBSs. In addition, each Eve can eavesdrop the communication in both sub-6 GHz and mmWave bands. Universal frequency reuse is adopted among different cells.

A. Sub-6 GHz Channel Model

We assume that all sub-6 GHz channels experience independent and identically distributed (i.i.d.) Rayleigh fading as well as a large-scale path loss with a path loss exponent of α_μ . The channel from the k th user in the j th cell to the i th MBS is denoted by

$$\mathbf{h}_{ij}^{(k)} = \sqrt{X_{ij}^{(k)}} \mathbf{u}_{ij}^{(k)}, \quad (1)$$

where $X_{ij}^{(k)}$ denotes the path loss from the k th user in the j th cell to the i th MBS, $\mathbf{u}_{ij}^{(k)}$ is the corresponding small-scale fading vector with distribution $\mathcal{CN}(\mathbf{0}, \mathbf{I})$. Note that the path loss can be calculated by

$$X_{ij}^{(k)} = c_\mu (R_{ij}^{(k)})^{-\alpha_\mu}, \quad (2)$$

where c_μ is the path loss at a reference distance, which is frequency dependent and is commonly set as $(\frac{c}{4\pi f_c})^2$.

We assume perfect synchronization and the downlink channel state information (CSI) can be obtained through the uplink pilot based training method due to channel reciprocity. We assume that the MBS assigns orthogonal pilots for all the K users within its cell, and the k th user in each cell is assigned with the same pilot. Denote $\mathcal{N}_k$ as the point process formed by the location of the k th user in each cell, it is clear that $\mathcal{N}_k$ is non-stationary (non-PPP) due to the correlation with the MBS process. To simplify the analysis, the other-cell scheduled users for the 0th MBS in $\mathcal{N}_k$ is modelled as an inhomogeneous PPP with a density function as has been assumed in [26], [27]

$$\lambda_u(r) = \lambda_\mu (1 - e^{-\pi \lambda_\mu r^2}). \quad (3)$$

where r denotes the distance to the 0th MBS. To further facilitate the analysis, we adopt the exclusion ball model proposed in [28], and assume that $\mathcal{N}_k$ is a homogeneous PPP with density λ_μ outside an exclusion ball centered at the 0th MBS with radius $R_{eq} = \sqrt{1/(\pi \lambda_\mu)}$. In addition, $\mathcal{N}_k$ and $\mathcal{N}_{k'}$ are independent for $k \neq k'$.

In the uplink training stage, after correlating the received signal with the corresponding pilot sequence, the observed channel from the i th MBS to the k th user can be expressed as

$$\mathbf{y}_{ii}^{(k)} = \sum_{j \in \Phi_\mu} \sqrt{P_p} \mathbf{h}_{ij}^{(k)} + \sum_{l \in \Phi_e^{(k)}} \sqrt{P_e} \mathbf{h}_{ie}^{(l)} + \mathbf{n}_i, \quad (4)$$

where P_p and P_e denote the uplink transmitting power levels of the user and Eve, respectively. $\Phi_e^{(k)}$ is the set of Eves launching pilot attack for user k , $\mathbf{n}_i$ is the noise with $\mathcal{CN}(0, \sigma^2)$. Note that since each Eve will randomly choose the pilot sequence from the K sequences, the effective density of

$\Phi_e^{(k)}$ is $\lambda_e^\mu = \frac{\lambda_E}{K}$ according to the independent thinning of PPP. Since the channels are assumed to be i.i.d. Rayleigh faded, the channel of the k th user in the i th cell can be estimated by an MMSE estimator [28], [29]

$$\bar{\mathbf{h}}_{ii}^{(k)} = \frac{\sqrt{P_p} X_{ii}^{(k)}}{\Sigma_{ii}^{(k)}} \mathbf{y}_{ii}^{(k)}, \quad (5)$$

where $\Sigma_{ii}^{(k)} = \sum_{j \in \Phi_\mu} P_p X_{ij}^{(k)} + \sum_{l \in \Phi_e^{(k)}} P_e X_{ie}^{(l)} + \sigma^2$. Then the channel error is

$$\hat{\mathbf{h}}_{ii}^{(k)} = \mathbf{h}_{ii}^{(k)} - \bar{\mathbf{h}}_{ii}^{(k)} \sim \mathcal{CN}\left(\mathbf{0}, X_{ii}^{(k)} \left(1 - \frac{P_p X_{ii}^{(k)}}{\Sigma_{ii}^{(k)}}\right) \mathbf{I}\right). \quad (6)$$

B. mmWave Channel Model

For the mmWave channels, due to the highly directional transmission, small-scale fading is usually ignored [9] and only path loss and blockage effect are considered. Due to the small wavelength, mmWave communication is sensitive to blockage and the link between an SBS and the mmWave user (mmUE) can be either LoS or NLoS link. We adopt the blockage model in [10] and the link between a mmUE and the SBS at a distance r is LoS or NLoS with probabilities

$$p_L(r) = e^{-\beta r} \text{ and } p_N(r) = 1 - e^{-\beta r}, \quad (7)$$

respectively, where β is an environment dependent constant.

Since the shorter mmWave wavelength enables to fit more antenna elements for a fixed antenna aperture, each mmUE is considered to be equipped with a small antenna array. We assume that both the SBS and mmUEs are equipped with only a single RF chain [24], and thus analog beamforming is adopted. For mathematical tractability, we approximate the antenna pattern by a sectorized beam pattern similar to [10], [11]. Denote the main lobe gain, side lobe gain, and beamwidth of mmUE as G_U, g_U, θ_U , respectively. Similar definitions apply to the SBS with $G_{BS}, g_{BS}, \theta_{BS}$, and Eve with G_E, g_E, θ_E , respectively. To further simplify the subsequent analysis, we consider zero side lobe for the SBS³. Denote the channel from the k th mmUE in the j th cell to the i th SBS as $\mathbf{H}_{ij}^{(k)}$, similar to [22], [24], [31], we adopt a geometric channel model with a single path, which can be expressed as

$$\mathbf{H}_{ij}^{(k)} = \sqrt{Y_{ij}^{(k)}} \mathbf{a}_S(\theta_{ij}^{(k)}) \mathbf{a}_U(\varphi_{ij}^{(k)}), \quad (8)$$

where $\mathbf{a}_S(\cdot)$ and $\mathbf{a}_U(\cdot)$ are the steering vectors at the SBS and mmUE, $\theta_{ij}^{(k)}$ and $\varphi_{ij}^{(k)}$ are the angle of arrival (AoA) and angle of departure (AoD) at the SBS and mmUE. The AoAs and AoDs of all links are uniformly distributed in $[0, 2\pi]$. Note that $Y_{ij}^{(k)}$ is the path loss between mmUE and SBS and is given by

$$Y_{ij}^{(k)} = \begin{cases} c_L (R_{ij}^{(k)})^{-\alpha_L}, & \text{for LoS link,} \\ c_N (R_{ij}^{(k)})^{-\alpha_N}, & \text{otherwise.} \end{cases} \quad (9)$$

³This assumption is reasonable since mmWave BS usually use very large antenna array and the front-to-back ratio can be larger than 30dB [30]. Note that similar assumption has also been adopted in [22], [23].

Fig. 1. Beam sweeping based beam alignment.

Note that c_L and c_N are the path loss for LoS and NLoS links at a reference distance. To align the transmit and receive beams, a codebook based sweeping method is considered.

Similar to [22], we assume that each SBS has a codebook of N_c possible beamforming vectors $\mathbf{v}_1, \dots, \mathbf{v}_{N_c}$, and the patterns of these beamforming vectors have non-overlapping main lobes. Hence, the angular domain can be divided by the main lobes of the beamforming patterns into N_c sectors, and the n th angular sector is defined as $[\frac{2\pi(n-1)}{N_c}, \frac{2\pi n}{N_c}]$. Similar definitions apply to mmUE and Eves, where each mmUE and Eve has M_c and M_e beamforming vectors, denoted by $\mathbf{f}_1, \dots, \mathbf{f}_{M_c}$ and $\mathbf{t}_1, \dots, \mathbf{t}_{M_e}$, respectively. Define the set of AoA covered by the main lobe of $\mathbf{v}_n$ as $\mathcal{R}_n$, i.e., $\mathcal{R}_n = \{\theta \in [0, 2\pi] \mid |\mathbf{a}_S(\theta)\mathbf{v}_n|^2 = G_{BS}\}$. Then the AoD covered by the main lobe of $\mathbf{f}_m$ and $\mathbf{t}_l$ are $\mathcal{T}_m = \{\varphi \in [0, 2\pi] \mid |\mathbf{a}_U(\varphi)\mathbf{f}_m|^2 = G_U\}$ and $\mathcal{T}_{E,l} = \{\varphi \in [0, 2\pi] \mid |\mathbf{a}_E(\varphi)\mathbf{t}_l|^2 = G_E\}$, respectively. Following that, the average beamforming gains for the mmUE and Eve are given by $D_U = g_U + \frac{\theta_U}{2\pi}(G_U - g_U)$ and $D_E = g_E + \frac{\theta_E}{2\pi}(G_E - g_E)$, respectively. The SBS and the mmUE are assumed to be perfectly synchronized. Similar to [21], in the uplink training, the mmUE sends the pilot towards its serving SBS, and SBS sweeps the beams in each sector and determines the beamforming direction for its associated users by steering to the beam sector that achieves maximal signal power, as shown in Fig. 1. We assume that orthogonal pilot sequences are assigned among different mmUEs, i.e., no pilot contamination is present. This is because: 1) due to the single RF chain, time-division-multiple-access (TDMA) is usually adopted at SBSs, and only one mmUE is served in each time slot, and 2) those nearby SBSs will be assigned orthogonal pilot sequences and those far way SBSs will cause minor interference due to the severe path loss. This is different from the sub-6 GHz system where usually multiple users are served by an MBS. On the other hand, we assume that the Eves have perfectly synchronized with the SBS and randomly selects one pilot sequence to confound the SBS⁴.

Without loss of generality, we assume that the AoA of the typical mmUE is located in the first sector of the SBS. Then the received signal in the n th sector in the beam sweeping process after correlating with the corresponding pilot

is approximated by

$$y_n = \mathbb{1}(n=1)\sqrt{P_p}\mathbf{v}_n^H\mathbf{H}_{00}^{(0)}\mathbf{f}_m + \sum_{l \in \Phi_e^m} \sqrt{P_e}\mathbf{v}_n^H\mathbf{H}_{0e}^{(l)}\mathbf{t}_l + \mathbf{v}_n^H\mathbf{n}_i, \quad (10)$$

where $\mathbb{1}(\cdot)$ is the indicator function, $\mathbf{v}_n$ is the beamforming vector for the n th sector, $\mathbf{H}_{0e}^{(l)} = \sqrt{Y_{0e}^{(l)}}\mathbf{a}_S(\theta_{0e}^{(l)})\mathbf{a}_E(\varphi_{0e}^{(l)})$ denotes the Eve's channel. Φ_e^m denotes the Eves that share the same pilot with the mmUE and whose AoAs lie within the main lobe of the first beamforming vector of SBS. With the zero side lobe of SBS and the independent thinning of PPP, the effective intensity of Φ_e^m is $\lambda_e^m = \frac{\lambda_E}{K} \frac{\theta_{BS}}{2\pi}$. Then the average received signal power in the n th sector can be expressed as

$$E_n = \mathbb{1}(n=1)P_pY_{00}^{(0)}G_{BS}G_U + \sum_{l \in \Phi_e^m} P_eY_{0e}^{(l)}G_{BS}D_E + \sigma_m^2. \quad (11)$$

After sweeping all the beam sectors, the SBS will select the optimal beamforming vector by

$$\mathbf{v}_{n^*} = \arg \max_{n=1, \dots, N_c} E_n. \quad (12)$$

The success probability of beam pairing is defined as $p_s = \mathbb{P}(n^* = 1)$.

C. Mobile Association Rule

Each user is assumed to be associated to the BS providing the largest average received signal power (ARSP), and the users are offloaded to the macro-cell when the ARSP from the mmWave BS is below a threshold τ . The ARSP of a typical user associated with each tier is defined as

$$\begin{cases} \text{ARSP}_\mu = \frac{P_\mu}{K} N_\mu X_{00}^{(0)}, \\ \text{ARSP}_m = P_m G_M Y_{00}^{(0)}. \end{cases} \quad (13)$$

To derive the association probability, we first check the path loss property, given in the following lemma.

Lemma 1. *The complementary cumulative distribution function (CCDF) of the path loss from a typical user to the nearest MBS and SBS is given by [2], [3], [32]*

$$\bar{F}_{X_{00}^{(0)}}(x) = 1 - \exp\left(-\pi\lambda_\mu\left(\frac{c_\mu}{x}\right)^{\frac{2}{\alpha_\mu}}\right), \quad (14)$$

and

$$\bar{F}_{Y_{00}^{(0)}}(y) = 1 - \exp\left(-\pi\lambda_m\Lambda\left(\frac{1}{y}\right)\right), \quad (15)$$

respectively, where

$$\Lambda(y) = 2\frac{\gamma(2, \beta(c_L y)^{\frac{1}{\alpha_L}}) - \gamma(2, \beta(c_N y)^{\frac{1}{\alpha_N}})}{\beta^2} + (c_N y)^{\frac{2}{\alpha_N}}. \quad (16)$$

Lemma 2. *The probability that a typical user is associated with the sub-6 GHz tier is given by*

$$\mathcal{A}_\mu = 1 - \pi\lambda_m(\Xi_L - \Xi_N), \quad (17)$$

⁴The Eves have perfect knowledge about all the pilot sequences used by mmUEs.

Fig. 2. The association probability under different threshold and SBS density, where $\lambda_\mu = 10$ BSs/km², $P_\mu = 43$ dBm, $P_m = 30$ dBm, $K = 10$.

where

$$\Xi_s = \int_0^{\frac{PGM}{\tau}} f_s(l) e^{-\pi\lambda_m \Lambda(l) - \pi\lambda_\mu (c_\mu \vartheta l)^{\frac{2}{\alpha_\mu}}} dl, s = \{L, N\}, \quad (18)$$

$$f_s(l) = \frac{2c_s^{\frac{2}{\alpha_s}}}{\alpha_s} \left(\frac{l^{\frac{2}{\alpha_s}-1}}{e^{\beta(c_s l)^{\frac{1}{\alpha_s}}}} - \mathbb{1}(s=N)l^{\frac{2}{\alpha_s}-1} \right), \quad (19)$$

and $\vartheta = \frac{P_\mu N_\mu K}{P_m G_M}$.

Proof. The proof is omitted here. ■

We can readily prove the analysis in Lemma 2, as shown in Fig. 2. We can observe that the theoretical results match well with the simulations and by increasing the density of mmWave BSs, the association probability to the mmWave tier is increased.

D. Performance Metrics

We assume that both MBS and SBS use Wyner's encoding scheme for secure information transmission, as has been adopted in [14], [15], [33]. Let R_b and R_s denote the transmitted codeword rate and secrecy rate, respectively, then the rate difference $R_e \triangleq R_b - R_s$ can be regarded as the intentionally added redundancy to provide secrecy against eavesdropping. Particularly, we consider a fixed-rate transmission, i.e., the rate of the codeword R_b and the rate of the secrecy information R_s are determined before transmission. Due to the channel variance, connection and secrecy cannot be always guaranteed. Specifically, the coverage probability is defined as the probability that the instantaneous capacity is larger than R_b , i.e.,

$$p_{cov} = \mathbb{P}(\tau_u W_u \log_2(1 + \text{SINR}) > R_b) = \mathbb{P}(\text{SINR} > T), \quad (20)$$

where τ_u and W_u are the available time and bandwidth for each user, $T = 2^{\frac{R_b}{\tau_u W_u}} - 1$. Similarly, the secrecy probability is defined as the probability that the eavesdropping capacity

C_e is below the redundancy rate R_e . Since the Eves are non-colluding, the secrecy probability can be expressed as

$$p_{sec} = \mathbb{P}\left(\max_{l \in \Phi_E} \tau_u W_u \log_2(1 + \text{SINR}_{e_l}) < R_e\right) \\ = \mathbb{P}\left(\max_{l \in \Phi_E} \text{SINR}_{e_l} < T_e\right), \quad (21)$$

where $T_e = 2^{\frac{R_b - R_s}{\tau_u W_u}} - 1$. Thus, the rate coverage and secrecy probability of a typical user can be expressed as

$$p_{cov} = \mathcal{A}_\mu p_{cov}^\mu + \mathcal{A}_m p_{cov}^m \quad (22)$$

and

$$p_{sec} = \mathcal{A}_\mu p_{sec}^\mu + \mathcal{A}_m p_{sec}^m, \quad (23)$$

respectively, where p_{cov}^μ , p_{cov}^m , p_{sec}^μ , and p_{sec}^m denote the coverage and secrecy in the sub-6 GHz tier and the mmWave tier, respectively.

III. COVERAGE PERFORMANCE ANALYSIS

A. Sub-6 GHz Tier

We assume that each MBS serves K users simultaneously by using MRT precoding and null space based AN transmission is adopted. For simplicity, we consider equal power allocation among the K users, then the transmitted signal at the i th BS can be expressed as

$$\mathbf{x}_i = \sum_{k=0}^{K-1} \sqrt{\frac{\phi P_\mu}{K}} \mathbf{w}_{ii}^{(k)} s_{ii}^{(k)} + \sqrt{(1-\phi)P_\mu} \mathbf{V}_i \mathbf{n}_a, \quad (24)$$

where ϕ is the power allocation between the information bearing signal and the AN, P_μ is the total transmit power, $s_{ii}^{(k)}$ is the information bearing signal with $\mathbb{E}\left[\left|s_{ii}^{(k)}\right|^2\right] = 1$, $\mathbf{n}_a$ is an artificial noise vector with i.i.d. entries $n_a \sim \mathcal{CN}(0, \frac{1}{N_\mu - K})$. Note that $\mathbf{w}_{ii}^{(k)}$ denotes the beamforming vector of the k th user at the i th BS, $\mathbf{V}_i \in \mathbb{C}^{N_\mu \times (N_\mu - K)}$ denotes the null space of $\bar{\mathbf{H}}_i$, where $\bar{\mathbf{H}}_i = [\bar{\mathbf{h}}_{ii}^{(0)}, \bar{\mathbf{h}}_{ii}^{(1)}, \dots, \bar{\mathbf{h}}_{ii}^{(K-1)}]$. Then the received signal at the typical user can be expressed as

$$y_{00}^{(0)} = \sqrt{\bar{P}_\mu} \bar{\mathbf{h}}_{00}^{(0)H} \mathbf{w}_{00}^{(0)} s_{00}^{(0)} + \sqrt{\bar{P}_\mu} \hat{\mathbf{h}}_{00}^{(0)H} \mathbf{w}_{00}^{(0)} s_{00}^{(0)} \\ + \sum_{k=1}^{K-1} \sqrt{\bar{P}_\mu} \mathbf{h}_{00}^{(0)H} \mathbf{w}_{00}^{(k)} s_{00}^{(k)} + \sum_{i \in \Phi_\mu \setminus \{0\}} \left[\sum_{k=0}^{K-1} \sqrt{\bar{P}_\mu} \right. \\ \left. \mathbf{h}_{i0}^{(0)H} \mathbf{w}_{ii}^{(k)} s_{ii}^{(k)} + \sqrt{(1-\phi)P_\mu} \mathbf{h}_{i0}^{(0)H} \mathbf{V}_i \mathbf{n}_a \right] + n_0, \quad (25)$$

where $\bar{P}_\mu = \frac{\phi P_\mu}{K}$, $\mathbf{h}_{ij}^{(k)}$ denotes the downlink channel from the i th BS to the k th user in the j th cell. We assume that each BS adopts $\mathbf{w}_{ii}^{(k)}$ as a scaled version of the channel estimation given by

$$\mathbf{w}_{ii}^{(k)} = \frac{\bar{\mathbf{h}}_{ii}^{(k)}}{\left|\bar{\mathbf{h}}_{ii}^{(k)}\right|} = \frac{\mathbf{y}_{ii}^{(k)}}{\left|\mathbf{y}_{ii}^{(k)}\right|}. \quad (26)$$

Then the SINR of the typical user can be expressed as

$$\text{SINR}_0^\mu = \frac{|\hat{\mathbf{h}}_{00}^{(0)H} \mathbf{w}_{00}^{(0)}|^2}{I_0 + I_i + \frac{\sigma^2}{P_\mu}}, \quad (27)$$

where

$$\begin{aligned} I_0 &= \mathbb{E} \left[|\hat{\mathbf{h}}_{00}^{(0)H} \mathbf{w}_{00}^{(0)}|^2 \right] + \sum_{k=1}^{K-1} \mathbb{E} \left[|\mathbf{h}_{00}^{(0)H} \mathbf{w}_{00}^{(k)}|^2 \right] \\ &= \frac{\mathbb{E} \left[|\hat{\mathbf{h}}_{00}^{(0)H} \mathbf{y}_{00}^{(0)}|^2 \right]}{|\mathbf{y}_{00}^{(0)}|^2} + \sum_{k=1}^{K-1} \frac{\mathbb{E} \left[|\mathbf{h}_{00}^{(0)H} \mathbf{y}_{00}^{(k)}|^2 \right]}{|\mathbf{y}_{00}^{(k)}|^2}, \end{aligned} \quad (28)$$

$$\begin{aligned} I_i &= \sum_{i \in \Phi_\mu \setminus 0} \left[\sum_{k=0}^{K-1} \mathbb{E} \left[|\mathbf{h}_{i0}^{(0)H} \mathbf{w}_{ii}^{(k)}|^2 \right] + K\xi \left| \mathbf{h}_{i0}^{(0)H} \mathbf{V}_i \right|^2 \right] \\ &= \sum_{i \in \Phi_\mu \setminus 0} \left[\sum_{k=0}^{K-1} \frac{\mathbb{E} \left[|\mathbf{h}_{i0}^{(0)H} \mathbf{y}_{ii}^{(k)}|^2 \right]}{|\mathbf{y}_{ii}^{(k)}|^2} + K\xi \left| \mathbf{h}_{i0}^{(0)H} \mathbf{V}_i \right|^2 \right], \end{aligned} \quad (29)$$

and $\xi = \frac{\phi^{-1}-1}{N_\mu-K}$. Since universal frequency reuse is adopted, we only consider the interference-limited case and the thermal noise is neglected. By substituting the previous results into (27), the SIR can be approximated by

$$\text{SIR}_0^\mu \approx \frac{P_p(N_\mu+1)(X_{00}^{(0)})^2}{X_{00}^{(0)}\Delta_0 + \Sigma_{00}^{(0)} \left((K-1)X_{00}^{(0)} + \Delta_1 + (1+\xi_0)\Delta_2 \right)}, \quad (30)$$

where $\xi_0 = \frac{\phi^{-1}-1}{N_\mu}$. Note that $\Delta_0 = \sum_{j \in \Phi_\mu \setminus 0} P_p X_{0j}^{(0)} + \sum_{l \in \Phi_e^{(0)}} P_e X_{0e}^{(l)} + \sigma^2$, $\Delta_1 = P_p \sum_{i \in \Phi_\mu \setminus 0} (X_{i0}^{(0)})^2 / \Sigma_{ii}^{(0)}$, and $\Delta_2 = K \sum_{i \in \Phi_\mu \setminus 0} X_{i0}^{(0)}$.

Proof. Please refer to Appendix A. ■

Following that, the coverage probability can be derived as follows.

Proposition 1. *The rate coverage probability of the typical user associated with the sub-6 GHz tier in the presence of pilot contamination and attack is approximated by*

$$\begin{aligned} p_{cov}^\mu &\approx \sum_{n=1}^N \binom{N}{n} (-1)^{n+1} \exp \left(-\frac{nvTA_4}{A_0} \right) \\ &\int_0^\infty \exp \left(-\frac{nvT(A_1 t^{\frac{\alpha_\mu}{2}} + A_2 t + A_3 t^{1+\frac{\alpha_\mu}{2}})}{A_0} \right) f(t) dt, \end{aligned} \quad (31)$$

where $f(t) = \pi \lambda_\mu e^{-\pi \lambda_\mu t}$, $v = (N!)^{-\frac{1}{N}}$, N is the number of terms used in the approximation. Note that $A_0 = P_p(N_\mu+1)c_\mu^2$, $A_1 = K\bar{\Delta}_0 c_\mu$, $A_2 = P_p a_3 + (1+\xi_0)K P_p c_\mu a_4$, $A_3 = (1+\xi_0)K\bar{\Delta}_0 a_4$, $A_4 = (K-1)P_p c_\mu^2$, $\bar{\Delta}_0 = P_p a_1 + P_e a_2 + \sigma^2$. In addition, $a_1 = \frac{2c_\mu(\pi\lambda_\mu)^{\frac{\alpha_\mu}{2}}}{\alpha_\mu-2}$, $a_2 = \frac{4c_\mu(\pi\lambda_\mu)^2}{\alpha_\mu-2} \int_0^\infty r^{3-\alpha_\mu} e^{-\pi\lambda_\mu r^2} dr$, $a_3 = \frac{\pi\lambda_\mu c_\mu}{\alpha_\mu-1}$, and $a_4 = \frac{2\pi c_\mu \lambda_\mu}{\alpha_\mu-2}$.

Fig. 3. The coverage probability versus the MBS density, where $N_\mu = 64$, $\alpha_\mu = 2.6$, $K = 2$, $\phi = 0.7$, and $R_b = 20$ Mbps.

Proof. Please refer to Appendix B. ■

From (31), we can prove that the coverage probability of the sub-6 GHz tier is an increasing function of N_μ . However, the impact of MBS density λ_μ on the coverage probability can not be readily obtained due to the complicated expression in (31). Here we provide some intuitive explanations. For a weak pilot attack (e.g., density of Eves is very low), by increasing the MBS density, the pilot contamination will be increased. Thus, the received signal power of a typical user scales strictly less than $\lambda_\mu^{\frac{\alpha_\mu}{2}}$, but the interference power scales larger than $\lambda_\mu^{\frac{\alpha_\mu}{2}}$, resulting in a decrease in coverage performance. However, when the pilot attack from Eves dominates pilot contamination, we can observe that $\Sigma_{00}^{(0)} \approx \Delta_0 \approx \sum_{l \in \Phi_e^{(0)}} P_e X_{0e}^{(l)}$, both of them scales strictly less than $\lambda_\mu^{\frac{\alpha_\mu}{2}}$. On the other hand, the numerator in (30) scales as $\lambda_\mu^{\alpha_\mu}$. In this case, by increasing the MBS density, the coverage performance will be improved. The coverage probability under different Eve density is evaluated in Fig. 3. We can observe that when λ_E is very small, the coverage probability gradually decreases to a constant, whereas for a large λ_E , the coverage first increases and then converges to a constant, which validated the analysis.

Remark 1. For the cases without pilot reuse, i.e., all the users are assigned with orthogonal pilot sequences and only pilot attack is present, a_1 and a_3 reduce to 0. For the perfect CSI case without pilot attack and pilot contamination, a_1 , a_2 , and a_3 reduce to 0.

B. mmWave Tier

In this subsection, we characterize the coverage performance of the mmWave tier taking into the account the impact of the pilot attack. Due to the single-path channel model and the zero SBS side lobe assumptions, we first define the following two events: 1) the SBS and mmUE beams are successfully aligned (SA event), which captures the case of the beamforming pair with the maximal SBS and mmUE beamforming gains, i.e., $D_{BS} = G_{BS}$ and $D_U = G_U$, and 2) the SBS and mmUE beams are unsuccessfully aligned

(UA event), which captures the case of the beamforming pair with SBS main lobe gain and mmUE side lobe gain, i.e., $D_{BS} = G_{BS}$ and $D_U = G_U$. Then the coverage probability can be expressed as

$$p_{cov}^m = \mathbb{P}(\text{SINR}_0^m > T \mid \text{SA})\mathbb{P}(\text{SA}) + \mathbb{P}(\text{SINR}_0^m > T \mid \text{UA})\mathbb{P}(\text{UA}). \quad (32)$$

The SINR of the typical user under the SA and UA cases can be expressed as

$$\text{SINR}_{0,\text{SA}}^m = \frac{P_m G_{BS} G_U Y_{00}^{(0)}}{I_m + N_0}, \quad (33)$$

and

$$\text{SINR}_{0,\text{UA}}^m = \frac{P_m G_{BS} G_U Y_{00}^{(0)}}{I_m + N_0}, \quad (34)$$

respectively, where $I_m = \sum_{i \in \Phi_m^{(1)} \setminus \{0\}} P_m G_{BS} D_U Y_{i0}^{(0)}$. Note that $\Phi_m^{(1)}$ denotes the interfering SBSs whose AoAs lie within the main lobe, based on the independent thinning of PPP, the effective intensity of $\Phi_m^{(1)}$ is $\lambda_m^{(1)} = \lambda_m \theta_{BS}/2\pi$.

Lemma 3. *The success probability of beam alignment is lower bounded by*

$$p_s \geq \left(1 - \int_0^\infty e^{-\pi \lambda_m \Lambda(\frac{y}{\alpha_E})} f_{Y_E^{-1}}(y) dy\right)^{N_c-1}. \quad (35)$$

Note that

$$f_{Y_E^{-1}}(y) = \pi \lambda_m \Lambda'(y) e^{-\pi \lambda_m \Lambda(y)}, \quad (36)$$

where $\Lambda'(y)$ is the first derivative of $\Lambda(y)$ and $\alpha_E = \frac{P_e D_E}{P_p G_U}$.

Proof. The received pilot attack signal power can be approximated by the received power from the nearest Eve, i.e.,

$$\sum_{l \in \Phi_e^m} Y_{0e}^{(l)} \approx \max_{l \in \Phi_e^m} (Y_{0e}^{(l)}) \triangleq Y_E. \quad (37)$$

Since the Eve's position is independent with the mmUE, Y_E follows a similar distribution with $Y_{00}^{(0)}$. Hence the success probability can be approximated as

$$\begin{aligned} p_s &= \mathbb{P}\left(E_1 \geq \max_{n=2,\dots,N_c} E_n\right) \\ &\geq \left[\mathbb{P}\left(P_p Y_{00}^{(0)} G_{BS} G_U \geq P_e G_{BS} D_E Y_E\right)\right]^{N_c-1} \\ &= \left[\mathbb{P}\left(Y_{00}^{(0)} \geq \alpha_E Y_E\right)\right]^{N_c-1} \\ &= \left(1 - \int_0^\infty e^{-\pi \lambda_m \Lambda(\frac{y}{\alpha_E})} f_{Y_E^{-1}}(y) dy\right)^{N_c-1}. \end{aligned} \quad (38)$$

By substituting the result in Lemma 1, we can obtain (35). ■

The success probability of beam alignment versus the Eve's density is shown in Fig. 4, with the parameters given in Section V. We can observe that the gap between the theoretical results and simulation results is negligible. In addition, the success probability increases with λ_m and decreases with λ_E . This is because Y_E increases with λ_E and $Y_{00}^{(0)}$ increases with λ_m .

Fig. 4. The success probability of beam alignment.

Proposition 2. *The rate coverage probability of the typical user associated with the mmWave tier is lower bounded by*

$$p_{cov}^m \geq p_s \left[1 - \int_0^\infty e^{-\Lambda_m(0, A_m)} f_{(Y_{00}^{(0)})^{-1}}(y) dy\right], \quad (39)$$

where $f_{(Y_{00}^{(0)})^{-1}}(y)$ is the pdf of the path loss from the mmUE to SBS and can be derived from Lemma 1. Note that $A_m = \frac{P_m G_{BS} G_U}{uT(\sigma_m^2 + \mu_I)}$, μ_I is the average value of the inter user interference and is given by

$$\begin{aligned} \mu_I &= 2\pi \lambda_m^{(1)} P_m G_{BS} D_U \left[c_L \int_{(c_L y)^{\frac{1}{\alpha_L}}}^\infty t^{1-\alpha_L} e^{-\beta t} dt \right. \\ &\quad \left. + c_N \int_{(c_N y)^{\frac{1}{\alpha_N}}}^\infty t^{1-\alpha_N} (1 - e^{-\beta t}) dt \right]. \end{aligned} \quad (40)$$

Proof. When the beams are not aligned, the SINR is usually very low, hence the coverage probability will be dominated by the SA case, i.e.,

$$p_{cov}^m \geq \mathbb{P}(\text{SINR}_0^m > T \mid \text{SA})\mathbb{P}(\text{SA}). \quad (41)$$

Conditioning on the success beam alignment, the SINR coverage probability can be derived as

$$\begin{aligned} \mathbb{P}(\text{SINR}_0^m > T \mid \text{SA}) &= \mathbb{P}\left(Y_{00}^{(0)} \geq \frac{T(I_m + \sigma_m^2)}{P_m G_{BS} G_U}\right) \\ &= \mathbb{E}_{Y_{00}^{(0)}} \left[1 - \exp\left(-\pi \lambda_m \Lambda\left(\frac{P_m G_{BS} G_U}{T(\sigma_m^2 + I_m)}\right)\right)\right], \end{aligned} \quad (42)$$

and the interference term can be approximated by

$$\begin{aligned} \mu_I &= \sum_{i \in \Phi_m^{(1)} \setminus \{0\}} P_m G_{BS} D_U Y_{i0}^{(0)} \\ &= 2\pi \lambda_m^{(1)} P_m G_{BS} D_U \int_{(\frac{c}{Y_{00}^{(0)}})^{\frac{1}{\alpha}}}^\infty cr^{-\alpha} p(r) dr. \end{aligned} \quad (43)$$

By considering both the LoS and NLoS cases, (43) can be calculated. By taking an average of (43) over $Y_{00}^{(0)}$, we can obtain (39). ■

Corollary 1. When only the LoS link is considered, i.e., $p_L(r) = \mathbb{1}(r < R_L)$, the rate coverage probability reduces to

$$p_{cov}^m = p_s(1 - e^{-\pi\lambda_m\varpi^2}), \quad (44)$$

$$\text{where } \varpi = \min\left(R_L, \left(\frac{P_m G_{BS} G_U c_L}{T\sigma_m^2}\right)^{\frac{1}{\alpha_L}}\right),$$

Proof. When only the LoS link is present, by analyzing the intensity measure of the path loss process [2], we can obtain

$$\Lambda(y) = \min(R_L^2, (c_L y)^{\frac{2}{\alpha_L}}). \quad (45)$$

Then the conditional rate coverage probability under SA becomes

$$\mathbb{P}\left(X_{00}^{(0)} \geq \frac{T\sigma_m^2}{P_m G_{BS} G_U}\right) = 1 - e^{-\pi\lambda_m\varpi^2}. \quad (46)$$

By multiplying the success probability, we can obtain (44). ■

For the special case that only the LoS link with $p_L(r) = \mathbb{1}(r < R_L)$, we can also obtain the following corollary.

Corollary 2. The necessary condition that enables the coverage performance of the mmWave tier to outperform the counterpart of the sub-6 GHz tier in the presence of the pilot attack is given by

$$\lambda_m \geq \frac{-\ln(1 - p_{cov}^\mu/p_s)}{\pi\varpi^2}. \quad (47)$$

IV. SECRECY PERFORMANCE ANALYSIS

A. Sub-6 GHz Tier

For the Eves, we consider the worst case by assuming that they have zero noise power and also have multi-user decoding capability [14], [32], [34], i.e., they can resolve the concurrent transmission of information signals from nearby BSs using successive interference cancellation, and thus the SIR of the l th Eve can be expressed as

$$\text{SIR}_{e_l}^\mu = \frac{\bar{P}_\mu \left| \mathbf{g}_{0e}^{(l)H} \mathbf{w}_{00}^{(0)} \right|^2}{\sum_{i \in \Phi_\mu} \phi P_\mu \xi \left| \mathbf{g}_{ie}^{(l)H} \mathbf{V}_i \right|^2} = \frac{\left| \mathbf{g}_{0e}^{(l)H} \mathbf{y}_{00}^{(0)} \right|^2}{\left| \mathbf{y}_{00}^{(0)} \right|^2 \sum_{i \in \Phi_\mu} \xi K \left| \mathbf{g}_{ie}^{(l)H} \mathbf{V}_i \right|^2}. \quad (48)$$

Following similar procedures for coverage performance analysis, we can derive the secrecy outage probability which is given by the following proposition.

Proposition 3. The secrecy probability of the typical user associated with the sub-6 GHz tier with pilot contamination and attack is lower bounded by

$$p_{sec}^\mu \geq \exp(-\pi\lambda_E\Theta), \quad (49)$$

where Θ is given by

$$\Theta = \sum_{n=1}^N \binom{N}{n} (-1)^{n+1} \int_0^\infty e^{-\frac{nvT_e B_0}{B_1 t^{-\frac{\alpha_\mu}{2}} + B_2 t^{-\alpha_\mu}}} dt. \quad (50)$$

Note that N is the number of terms used for calculation, $v = (N!)^{-\frac{1}{N}}$, and $B_0 = \xi_0 a_4 K \bar{\Delta}$, $B_1 = \bar{\Delta} c_\mu$, $B_2 = N_\mu P_e c_\mu^2$, $\bar{\Delta} = \bar{\Delta}_0 + 2P_p \pi \lambda_\mu c_\mu \int_0^\infty r^{1-\alpha_\mu} e^{-\pi\lambda_\mu r^2} dr$.

Proof. Please refer to Appendix C. ■

Then we can obtain the following property.

Property 1. The secrecy probability of the AN-aided sub-6 GHz system is an increasing function of the MBS density λ_μ and is a decreasing function of N_μ and the Eve's density λ_E .

The property of λ_E can be readily proved. Since the distance from the l th Eve to the i th MBS $\sum_{i \in \Phi_\mu} X_{ie}^{(l)}$ scales as $\lambda_\mu^{\frac{\alpha_\mu}{2}}$, and $X_{0e}^{(l)}$ is independent with λ_μ due to the Slivnyak's theorem, then from (68), we can observe that the SIR of the l th Eve decreases with λ_μ . On the other hand, since the Eves are assumed to be able to resolve the information from nearby BSs, the average aggregate interference power will be independent with N_μ . Therefore, the SIR of the l th Eve increases with N_μ , as shown in (67).

Remark 2. When only pilot contamination is present, $B_2 = 0$, $a_2 = 0$, the integration in Θ produces a closed-form expression. In particular, for the perfect CSI case, $B_1 = c_\mu$, and $B_2 = 0$.

B. mmWave Tier

For the mmWave system, since the Eves can resolve information from different SBSs, then the SNR of the l th Eve can be expressed as

$$\text{SNR}_{e_l}^m = \frac{P_m D_{BS} D_E Y_{0e}^{(l)}}{\sigma_m^2}. \quad (51)$$

Due to the existence of the pilot attack, the exact expression of the secrecy probability is nontrivial to be derived. However, since all the Eves are non-colluding, the maximal SNR is usually determined by the nearest Eve. Then the approximated expression of the secrecy probability of the mmWave system can be derived, which is given by the following proposition.

Proposition 4. The secrecy probability of the typical user associated with the mmWave tier with pilot attack is approximated by

$$p_{sec}^m \approx p_s e^{-\pi\lambda_E \frac{\theta_{BS}}{2\pi} \Lambda(\mu)} + (1 - p_s) e^{-\pi\lambda_E \Lambda(\mu)}, \quad (52)$$

where $\mu = \frac{P_m G_{BS} D_E}{T_e \sigma_m^2}$.

Proof. Please refer to Appendix D. ■

Note that the success probability of beam alignment is usually close to 1, and the secrecy probability under the SA case is much larger than the UA case. This is because in the UA case the SBS beam is steered to the Eve. Hence the secrecy probability will be dominated by the first term in (52), and we can obtain the following property.

Property 2. The secrecy probability is a decreasing function of the Eve's density λ_E and is an increasing function of λ_m .

Remark 3. From (52), we observe that the mmWave system can achieve a secrecy probability ϱ if

$$p_s \geq \varrho e^{\pi\lambda_E \frac{\theta_{BS}}{2\pi} \Lambda(\mu)}. \quad (53)$$

Fig. 5. The coverage probability of the sub-6 GHz tier and the mmWave tier under different CSI cases, where $\lambda_\mu = \lambda_m = \lambda_E = 20$ BSs/km², $\phi = 0.7$, $K = 1$.

In addition, the secrecy probability achieved by the mmWave small cell outperforms the sub-6 GHz counterpart, when $p_{sec}^\mu = \varrho$ and p_s satisfies (53).

Due to the complicated expression of the secrecy probability for the sub-6 GHz tier and the mmWave tier, it is difficult to directly obtain the explicit expressions of the conditions that enable the mmWave tier to outperform the sub-6 GHz tier. Hence, we only compare the performance through numerical results in the next section.

V. NUMERICAL RESULTS AND DISCUSSIONS

In this section, simulation results are presented to verify the theoretical analysis. We assume that the sub-6 GHz carrier frequency is 1 GHz with a bandwidth of 20 MHz and the mmWave system operates in 28 GHz with a bandwidth of 1 GHz. The path loss exponent is set as $\alpha_\mu = 2.6$, $\alpha_L = 2$, $\alpha_N = 2.9$, respectively, and the LoS probability parameter is $1/\beta = 20$. In addition, the path loss constant is set to be $c_\mu = -38.46$ dB, $c_L = -61.4$ dB, and $c_N = -72$ dB, respectively. The MBS is equipped with $N_\mu = 64$ antennas and the mmWave antenna beam patterns of the SBS, mmUE, and Eve are $(G_{BS}, \theta_{BS}) = (10 \text{ dB}, \frac{2\pi}{N_m})$, $(G_U, \theta_U) = (3 \text{ dB}, -3 \text{ dB}, \frac{2\pi}{3})$, $(G_E, \theta_E) = (10 \text{ dB}, -5 \text{ dB}, \frac{\pi}{3})$, respectively. The noise power is calculated by $\sigma^2 = -174 + 10 \log_{10}(BW) + N_f$ with the noise figure $N_f = 10$ dB. The transmitting power levels of the MBS and SBS are $P_\mu = P_m = 30$ dBm, respectively, unless stated otherwise. The pilot transmitting power levels of the user and Eve are $P_p^\mu = P_p^m = 30$ dBm, and $P_p^m = P_p^m = 30$ dBm.

We first verify the coverage probability of the sub-6 GHz system and mmWave system under different CSI conditions in Fig. 5. We can observe that the approximation for the sub-6 GHz system match well with the simulation results and the mmWave lower bound strictly follows the trend of the simulations with a small gap, which validate the theoretical analysis. We can observe that the coverage performance is severely degraded by the pilot attack and contamination. Comparing the coverage performance between the sub-6 GHz

Fig. 6. The coverage performance comparison between the sub-6 GHz tier and the mmWave tier, where $\lambda_E = 20$ BSs/km², $\phi = 0.7$, $K = 1$.

tier and the mmWave tier, we can observe that the sub-6 GHz system outperforms the mmWave counterpart at low data rate region, whereas the mmWave system outperforms the sub-6 GHz system at high data rate region. This is because mmWave system with much larger band width can achieve much higher capacity than the sub-6 GHz system. However, mmWave signals also suffer severe path loss and blockage, which greatly limits the coverage performance at low data rate region.

We then present the coverage performance comparison between the sub-6 GHz tier and the mmWave tier under different BS density and antenna configurations in Fig. 6. For fair comparisons, we assume that each MBS only serves one user in each time slot, i.e., $K = 1$. We observe that both increasing the number of antennas at MBS and densifying the MBS density can improve the coverage performance of the sub-6 GHz system under the given parameters, which has been explained in Section III-A. More importantly, we also observe that increasing the number of antennas at MBS is more effective than densifying the MBS density for coverage improvement, due to the pilot contamination. For example, when $\lambda_\mu = 10^{-5}$, increasing the number of antennas at MBS from 40 to 160, we can achieve 37% performance improvement, whereas densifying MBS to 4×10^{-5} can only obtain a gain of 15.7%. On the other hand, by increasing the SBS density, the mmWave coverage performance will be improved and can also outperforms the sub-6 GHz counterpart. This is because increasing λ_m not only improves the success probability of the beam alignment but also increases the average received signal power since the mmWave network is usually noise limited.

The corresponding secrecy performance is presented in Fig. 7. For the sub-6 GHz system, we can observe that the derived lower bound follows the trend of the simulation results, and the secrecy probability under the perfect CSI case outperforms the other two cases. This is because, on one hand, the AN is perfectly injected in the null space of the intended user's channel when the user's CSI is perfectly acquired, on the other hand, both the pilot contamination and pilot attack

Fig. 7. The secrecy probability of the sub-6 GHz tier and the mmWave tier under different CSI cases, where $\lambda_\mu = \lambda_m = \lambda_E = 20$ BSs/km², $\phi = 0.7$, $K = 1$.

Fig. 8. The secrecy performance comparison between the sub-6 GHz tier and the mmWave tier, where $\lambda_E = 20$ BSs/km², $\phi = 0.7$, $K = 1$.

will steer the beamforming vector to deviate from the user's channel, resulting in more information leakage. However, the secrecy probability with both pilot contamination and pilot attack outperforms the case that has only pilot attack. This is because when only pilot attack is present, the beamformer at the MBS will move towards the Eve more thus increasing its received signal power. For the mmWave system, we can also observe that the pilot attack can greatly increase the eavesdropping capacity resulting in a lower secrecy probability compared with the no pilot attack case. Note that due to the approximation of the beam alignment success probability, there exists a small gap between the simulation and theoretical results. Different from the coverage performance, we can observe from Fig. 7 that at a low redundant rate region, the mmWave system always outperforms the sub-6 GHz system. This is because the directional transmission of mmWave signal is more resistant to eavesdropping, which shows the advantages of using mmWave to secure transmission. While at a high redundant rate region, the sub-6 GHz system gradually outperforms the mmWave system. This is because the AN and

Fig. 9. The coverage probability of a typical user, where $\lambda_\mu = 20$ BSs/km², $\lambda_E = 40$ BSs/km², $P_\mu = 43$ dBm, $\phi = 0.7$, $K = 10$, $\tau = -10$ dBm.

Fig. 10. The secrecy probability of a typical user, where $P_\mu = 43$ dBm, $\phi = 0.7$, $K = 10$, $R_e = 5$ Mbps, $\tau = -10$ dBm.

inherent inter-cell interference in the sub-6 GHz system can degrade the Eves and thus limits the maximal eavesdropping capacity.

Similar to Fig. 6, the secrecy performance comparison between the sub-6 GHz tier and the mmWave tier is presented in Fig. 8. We can observe that the secrecy performance will be improved by increasing the MBS density and is degraded by increasing the number of antennas at MBS, which validate Property 1. Hence, densifying MBS is more effective than increasing MBS antennas in improving the secrecy performance in the sub-6 GHz tier. Moreover, we observe that by densifying SBS, it is always possible for the mmWave tier outperforms the sub-6 GHz tier.

Lastly, the coverage and secrecy probabilities of a typical user are evaluated in Figs. 9 and 10, respectively. From Fig. 9, we can observe that by increasing the SBS density λ_m , the coverage performance will be improved, which is straightforward. However, increasing the number of antennas at MBS will not always improve the coverage performance. Since increasing N_μ will force more users to be associated with the sub-6 GHz tier, and the mmWave tier achieves

better coverage performance at high data rate region as has been explained before. Thus, the coverage performance will be degraded by increasing N_μ when the target rate R_b is very high. For the secrecy performance, since the secrecy probability increases with the BS density in either the sub-6 GHz tier or the mmWave tier, we can observe that the secrecy performance will be improved by either increasing MBS density or SBS density, as shown in Fig. 10.

VI. CONCLUSIONS

In this paper, the physical layer security in a sub-6 GHz and mmWave hybrid network has been investigated, where all the nodes are distributed according to independent PPPs. By taking into account the pilot attack from the Eves, we provide an analytical framework to characterize the coverage and secrecy probabilities. For the sub-6 GHz tier, it has revealed that increasing the number of MBS antennas is more effective than increasing MBS density in improving the coverage performance, whereas densifying MBS is more effective for security enhancement. Moreover, it has shown that the coverage and secrecy in the mmWave tier can outperform the sub-6 GHz counterpart through densifying the SBS.

APPENDIX

A. Derivation of (30)

Similar to the proof in [28] and [26], we approximate the large-scale fading coefficients of interfering cells by their means. Thus,

$$\begin{aligned} \left| \bar{\mathbf{h}}_{00}^{(0)H} \mathbf{y}_{00}^{(0)} \right|^2 &\stackrel{(a)}{=} \frac{P_p (X_{00}^{(0)})^2}{(\Sigma_{00}^{(0)})^2} \left| \mathbf{y}_{00}^{(0)} \right|^4 \\ &\stackrel{(b)}{\approx} \frac{P_p (X_{00}^{(0)})^2}{(\Sigma_{00}^{(0)})^2} \mathbb{E} \left| \mathbf{y}_{00}^{(0)} \right|^4 \\ &\stackrel{(c)}{=} P_p (X_{00}^{(0)})^2 (N_\mu^2 + N_\mu), \end{aligned} \quad (54)$$

where (a) follows from (5), (b) follows from the fact that $\left| \mathbf{y}_{00}^{(0)} \right|^4 \rightarrow \mathbb{E} \left| \mathbf{y}_{00}^{(0)} \right|^4$ when $N_\mu \rightarrow \infty$, (c) follows from the fact that $\mathbb{E} \left| \mathbf{y}_{00}^{(0)} \right|^4 = (N_\mu^2 + N_\mu)(\Sigma_{00}^{(0)})^2$. For the interference term caused by channel estimation error, we have

$$\begin{aligned} \mathbb{E} \left| \hat{\mathbf{h}}_{00}^{(0)H} \mathbf{y}_{00}^{(0)} \right|^2 &= \frac{1}{N_\mu} \mathbb{E} \left| \hat{\mathbf{h}}_{00}^{(0)} \right|^2 \mathbb{E} \left| \mathbf{y}_{00}^{(0)} \right|^2 \\ &= \frac{1}{N_\mu} N_\mu X_{00}^{(0)} \left(1 - \frac{P_p X_{00}^{(0)}}{\Sigma_{00}^{(0)}} \right) N_\mu \Sigma_{00}^{(0)} \\ &= N_\mu X_{00}^{(0)} \Delta_0. \end{aligned} \quad (55)$$

Similarly, for the inter-user interference, we have

$$\sum_{k=1}^{K-1} \frac{\left| \mathbf{y}_{00}^{(0)} \right|^2}{\left| \mathbf{y}_{00}^{(k)} \right|^2} \mathbb{E} \left| \mathbf{h}_{00}^{(0)H} \mathbf{y}_{00}^{(k)} \right|^2 = \sum_{k=1}^{K-1} N_\mu X_{00}^{(0)} \Sigma_{00}^{(0)}. \quad (56)$$

For the interference from other BSs, we have

$$\begin{aligned} &\mathbb{E} \left| \mathbf{h}_{i0}^{(0)H} \mathbf{y}_{ii}^{(k)} \right|^2 \\ &= \mathbb{E} \left| P_p^{\frac{1}{2}} \sum_{j \in \Phi_\mu} \mathbf{h}_{i0}^{(0)H} \mathbf{h}_{ij}^{(k)} + P_e^{\frac{1}{2}} \sum_{l \in \Phi_e^{(k)}} \mathbf{h}_{i0}^{(0)H} \mathbf{h}_{ie}^{(l)} + \mathbf{h}_{i0}^{(0)H} \mathbf{n}_0^{(k)} \right|^2 \\ &\stackrel{(d)}{=} P_p \sum_{j \in \Phi_\mu} \mathbb{E} \left| \mathbf{h}_{i0}^{(0)H} \mathbf{h}_{ij}^{(k)} \right|^2 \\ &\quad + P_e \sum_{l \in \Phi_e^{(k)}} \mathbb{E} \left| \mathbf{h}_{i0}^{(0)H} \mathbf{h}_{ie}^{(l)} \right|^2 + N_\mu X_{i0}^{(0)} \sigma^2, \end{aligned} \quad (57)$$

where (d) holds due to the fact that $\mathbf{h}_{i0}^{(0)H} \mathbf{h}_{ij}^{(k)}$ and $\mathbf{h}_{i0}^{(0)H} \mathbf{h}_{ie}^{(l)}$ are uncorrelated zero-mean random variables. Note that when $k = j = 0$, we have

$$\mathbb{E} \left| \mathbf{h}_{i0}^{(0)H} \mathbf{h}_{ij}^{(k)} \right|^2 = \mathbb{E} \left| \mathbf{h}_{i0}^{(0)} \right|^4 = (N_\mu^2 + N_\mu)(X_{i0}^{(0)})^2, \quad (58)$$

when $(k, j) \neq (0, 0)$, we have

$$\mathbb{E} \left| \mathbf{h}_{i0}^{(0)H} \mathbf{h}_{ij}^{(k)} \right|^2 = N_\mu X_{i0}^{(0)} X_{ij}^{(k)}. \quad (59)$$

Similarly,

$$\mathbb{E} \left| \mathbf{h}_{i0}^{(0)H} \mathbf{h}_{ie}^{(l)} \right|^2 = N_\mu X_{i0}^{(0)} X_{ie}^{(l)}. \quad (60)$$

Note that when N_μ approaches infinity, $\left| \mathbf{h}_{i0}^{(0)H} \mathbf{V}_i \right|^2 \rightarrow (N - K) X_{i0}^{(0)}$, thus

$$\begin{aligned} &\sum_{k=0}^{K-1} \frac{1}{\left| \mathbf{y}_{ii}^{(k)} \right|^2} \mathbb{E} \left| \mathbf{h}_{i0}^{(0)H} \mathbf{y}_{ii}^{(k)} \right|^2 + K \xi \left| \mathbf{h}_{i0}^{(0)H} \mathbf{V}_i \right|^2 \\ &= P_p N_\mu \frac{(X_{i0}^{(0)})^2}{\Sigma_{ii}^{(0)}} + K X_{i0}^{(0)} + \xi K (N - K) X_{i0}^{(0)}, \end{aligned} \quad (61)$$

By combining the above results, we can obtain (30).

B. Proof of Proposition 1

Due to the exclusion ball model and by using the Campbell's theorem [35], we have

$$\mathbb{E} \left[\sum_{j \in \Phi_\mu \setminus \{0\}} X_{ij}^{(0)} \right] = 2\pi \lambda_\mu c_\mu \int_{R_{eq}}^\infty x^{-\alpha_\mu} x dx = a_1. \quad (62)$$

Similarly, for the Eves, we have $\mathbb{E} \left[\sum_{l \in \Phi_e^{(0)}} X_{0e}^{(l)} \right] = a_2$. Hence, we have $\bar{\Delta}_0 = \mathbb{E} \Delta_0 = P_p a_1 + P_e a_2 + \sigma^2$, $\mathbb{E} \Sigma_{00}^{(0)} = P_p \mathbb{E} X_{00}^{(0)} + \bar{\Delta}_0$. For the interference from nearby MBSSs, by using the Campbell's theorem, we have

$$\mathbb{E} \left[\sum_{i \in \Phi_\mu \setminus 0} (X_{i0}^{(0)})^2 \right] = 2\pi \lambda_\mu c_\mu^2 \int_{R_0}^\infty x^{-2\alpha_\mu} x dx = a_3 R_0^{2-2\alpha_\mu}, \quad (63)$$

and

$$\mathbb{E} \left[\sum_{i \in \Phi_\mu \setminus 0} X_{i0}^{(0)} \right] = 2\pi\lambda_\mu c_\mu \int_{R_0}^{\infty} x^{-\alpha_\mu} x dx = a_4 R_0^{2-\alpha_\mu}. \quad (64)$$

Combining the above results, we have $\mathbb{E}[\Sigma_{00}^{(0)} \Delta_1] = P_p N_\mu a_3 R_0^{2-2\alpha_\mu}$ and $\mathbb{E}[\Delta_2] = K a_4 R_0^{2-\alpha_\mu}$. Hence, the SINR can be rewritten as

$$\text{SINR}_0^\mu \approx \frac{A_0}{A_1 R_0^\alpha + A_2 R_0^2 + A_3 R_0^{2+\alpha_\mu} + A_4}. \quad (65)$$

Then conditioning on R_0 , the coverage probability can be calculated by

$$\begin{aligned} & \mathbb{P}(\text{SINR}_0^\mu > T \mid R_0) \\ &= \mathbb{P} \left(1 > \frac{T(A_1 R_0^\alpha + A_2 R_0^2 + A_3 R_0^{2+\alpha_\mu} + A_4)}{A_0} \right) \\ &\stackrel{(e)}{\approx} \mathbb{P} \left(u > \frac{T(A_1 R_0^\alpha + A_2 R_0^2 + A_3 R_0^{2+\alpha_\mu} + A_4)}{A_0} \right) \\ &\stackrel{(f)}{=} \sum_{n=1}^N \binom{N}{n} (-1)^{n+1} \exp \left(-\frac{nvTA_4}{A_0} \right) \\ &\quad \times \exp \left(-\frac{nvT(A_1 R_0^\alpha + A_2 R_0^2 + A_3 R_0^{2+\alpha_\mu})}{A_0} \right) \end{aligned} \quad (66)$$

where in (e), u is a normalized gamma random variable with shape parameter N and the approximation is due to the fact that a normalized gamma variable converges to identity when its shape parameter goes to infinity. (f) follows from the Alzer's inequality. By de-conditioning on R_0 , we can directly obtain (31).

C. Proof of Proposition 3

Similar to the proof in Appendix B, we have

$$\left| \mathbf{g}_{0e}^{(l)T} \mathbf{y}_{00}^{(0)} \right|^2 = N_\mu X_{0e}^{(l)} \Sigma_{00}^{(0)} + \mathbb{1}(S_{e_l}) N_\mu^2 P_e (X_{0e}^{(l)})^2, \quad (67)$$

where $\mathbb{1}(S_{e_l}) = 1$ when $e_l \in \Phi_e^{(0)}$, else $\mathbb{1}(S_{e_l}) = 0$. Note that since $\left| \mathbf{g}_{ie}^{(l)T} \mathbf{V}_i \right|^2 \xrightarrow{N_\mu \rightarrow \infty} (N_\mu - K) X_{ie}^{(l)}$, the SIR of the l th Eve in (48) can be expressed as

$$\text{SIR}_{e_l}^\mu = \frac{N_\mu X_{0e}^{(l)} \Sigma_{00}^{(0)} + \mathbb{1}(S_{e_l}) N_\mu^2 P_e (X_{0e}^{(l)})^2}{\xi K (N_\mu - K) \Sigma_{00}^{(0)} \sum_{i \in \Phi_\mu} X_{ie}^{(l)}}. \quad (68)$$

Equation (68) can be further simplified as

$$\begin{aligned} \text{SIR}_{e_l}^\mu &= \frac{\mathbb{1}(S_{e_l}) N_\mu P_e c_\mu^2 (R_{0e}^{(l)})^{-2\alpha_\mu} + \bar{\Delta} c_\mu (R_{0e}^{(l)})^{-\alpha_\mu}}{\xi_0 K a_4 \bar{\Delta}} \\ &\leq \frac{B_2 (R_{0e}^{(l)})^{-2\alpha_\mu} + B_1 (R_{0e}^{(l)})^{-\alpha_\mu}}{B_0}. \end{aligned} \quad (69)$$

Hence, for the l th Eve, we have

$$\begin{aligned} \mathbb{P}(\text{SIR}_{e_l}^\mu > x) &= \mathbb{P} \left(1 > \frac{B_0 x}{B_1 (R_{0e}^{(l)})^{-\alpha_\mu} + B_2 (R_{0e}^{(l)})^{-2\alpha_\mu}} \right) \\ &= \sum_{n=1}^N \binom{N}{n} (-1)^{n+1} \exp \left(-\frac{nvB_0 x}{B_1 (R_{0e}^{(l)})^{-\alpha_\mu} + B_2 (R_{0e}^{(l)})^{-2\alpha_\mu}} \right), \end{aligned} \quad (70)$$

where the last equation is obtained by approximating the unit variable as a gamma variable with unit mean and shape parameter N and using the Alzer's inequality. Following that, the secrecy probability can be expressed as

$$\begin{aligned} \mathbb{P}(\text{SIR}_E^\mu < T_e) &= \mathbb{P} \left(\max_{e_l \in \Phi_E} \text{SIR}_{e_l}^\mu < T_e \right) \\ &= \mathbb{E}_{\Phi_E} \left[\prod_{e_l \in \Phi_E} \mathbb{P}(\text{SIR}_{e_l}^\mu < T_e) \right] \\ &\stackrel{(g)}{\geq} \exp \left(-2\pi\lambda_E \int_0^\infty \sum_{n=1}^N (-1)^{n+1} e^{-\frac{nvT_e B_0}{B_1 R^{-\alpha_\mu} + B_2 R^{-2\alpha_\mu}}} R dR \right), \end{aligned} \quad (71)$$

where (g) follows from the probability generating functional (PGFL) over PPP, and the equality holds when $K = 1$, i.e., all the Eves share the same pilot with the typical user.

D. Proof of Proposition 4

Due to the zero side lobe of the SBS, $D_{BS} = G_{BS}$ when the beam of e_l is aligned with the transmit beam of SBS, otherwise $D_{BS} = 0$. We consider the two different cases:

Case 1: When the beams between the SBS and the typical user are successfully aligned, we denote the set of Eves whose AOA lie $\mathcal{R}_0$ as $\Phi_e^{(0)}$ with intensity $\frac{\theta_{BS}}{\pi} \lambda_E$.

$$\mathbb{P}(\text{SNR}_{E,SA}^m \leq T_e) \approx \mathbb{P} \left(\max_{l \in \Phi_e^m} Y_{0e}^{(l)} \leq \frac{1}{\mu} \right) \stackrel{(h)}{=} e^{-\pi \frac{\theta_{BS}}{\pi} \lambda_E \Lambda(\mu)}, \quad (72)$$

where (h) is derived by using the CCDF of the path loss of the Eve, similar to Lemma 1.

Case 2: When the beams between the SBS and the typical user are unsuccessfully aligned, i.e., the transmit beam of SBS is aligned with one of the Eves, then we have

$$\mathbb{P}(\text{SNR}_{E,UA}^m \leq T_e) \approx \mathbb{P} \left(\max_{l \in \Phi_E} Y_{0e}^{(l)} \leq \frac{1}{\mu} \right) = e^{-\pi \lambda_E \Lambda(\mu)}. \quad (73)$$

Thus,

$$\begin{aligned} p_{sec}^m &= \mathbb{P}(\text{SINR}_{E,SA}^m < T_e \mid \text{SA}) \mathbb{P}(\text{SA}) \\ &\quad + \mathbb{P}(\text{SINR}_{E,UA}^m < T_e \mid \text{UA}) \mathbb{P}(\text{UA}). \end{aligned} \quad (74)$$

By substituting (73) and (74), and the success probability in (38), we can obtain (52). This completes the proof.

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